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Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the Agriculture, Forestry and Other Land Use (AFOLU) sector

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Abstract

The agriculture, forestry and other land use (AFOLU) sector is responsible for approximately 25% of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management. Mitigation from the sector is thus extremely important in meeting emission reduction targets. The sector offers a variety of cost-competitive mitigation options with most analyses indicating a decline in emissions largely due to decreasing deforestation rates. Sustainability criteria are needed to guide development and implementation of AFOLU mitigation measures with particular focus on multifunctional systems that allow the delivery of multiple services from land. It is striking that almost all of the positive and negative impacts, opportunities and barriers are context specific, precluding generic statements about which AFOLU mitigation measures have the greatest promise at a global scale. This finding underlines the importance of considering each mitigation strategy on a case-by-case basis, systemic effects when implementing mitigation options on the national scale, and suggests that policies need to be flexible enough to allow such assessments. National and international agricultural and forest (climate) policies have the potential to alter the opportunity costs of specific land-uses in ways that increase opportunities or barriers for attaining climate change mitigation goals. Policies governing practices in agriculture and in forest conservation and management need to account for both effective mitigation and adaptation and can help to orient practices in agriculture and in

forestry toward global sharing of innovative technologies for the efficient use of land resources. Different policy instruments, especially economic incentives and regulatory approaches, are currently being applied however for its successful implementation it is critical to understand how land use decisions are made and how new social, political and economic forces in the future will influence this process.

1. Introduction

The agriculture, forestry and other land use sector (AFOLU) includes mitigation activities in agriculture and livestock, as well as in forestry. Mitigation options in the sector can be seen from the supply side (see table 1); as well as from the demand side (e.g. changes in human behaviour towards less emission-intensive products or reduced losses in the food supply chain) (Smith *et al.*, 2013b). Since the publication of the IPCC Fourth Assessment Report (AR4), there have been a few new estimates of the greenhouse gas mitigation potential in either agriculture (Smith *et al.*, 2008), forestry (Kindermann *et al.*, 2008; Golub *et al.*, 2009; Sohngen, 2009; Rose & Sohngen, 2011), or across the land based sectors (McKinsey&Company, 2009; UNEP-WCMC, 2011; Rose *et al.*, 2012). The economic mitigation potentials do not differ greatly from those presented in AR4, except where additional measures have been considered (e.g. the inclusion of avoided deforestation; Rose & Sohngen, 2011). The level of implementation of mitigation activities in the agriculture, forestry and other land use (AFOLU) sector depends to a large extent on the balance between the direct benefits on GHG emission and carbon sinks, the co-benefits on social and natural systems afforded by mitigation actions (section 2) and the reduction of trade-offs and barriers (section 3) as well as the economic costs arising from their implementation. There are still significant non-economic barriers and opportunities that are not accounted for in estimates of economic mitigation potentials (Smith, 2012). Policy aims to enable a balance between co-benefits, costs and trade-offs, and to reduce or remove barriers to implementation. Here we review potential co-benefits, adverse-effects and trade-offs (section 2), barriers to, and opportunities from, implementation (section 3), and policies that have been implemented around the world to encourage GHG mitigation in the AFOLU sector (section 4), before presenting our conclusions (section 5). In this review, we cannot cover all issues exhaustively or always differentiate by country or ecological region; rather the purpose is to raise major emerging issues, and to provide the reader with a framework to either explore the wider literature or to further analyse specific cases.

2. Potential co-benefits, trade-offs and adverse-effects

Implementation of AFOLU mitigation measures will result in a range of outcomes beyond changes in GHG balances. A global assessment of the co-benefits, adverse-effects and trade-offs of AFOLU mitigation measures is challenging for a number of reasons. First, these effects depend on the development context and the scale of the intervention (size; Figure 1), (Forner *et al.*, 2006; Koh & Ghazoul, 2008; Trabucco *et al.*, 2008; Zomer *et al.*, 2008; Alig *et al.*, 2010; Alves Finco & Doppler, 2010; Colfer, 2011; Albers & Robinson, 2013; Davis *et al.*, 2013; Muys *et al.*, 2013). Thus the effects are site-specific and generalizations are difficult. Second, effects do not necessarily overlap geographically, socially or temporally. Third, there is no agreement on how to attribute co-benefits and adverse-effects to specific AFOLU mitigation measures; and fourth there are no standardized metrics for quantifying many of these effects.

Modelling frameworks are being developed which allow an integrated assessment of multiple outcomes at landscape (Bryant *et al.*, 2011), project (Townsend *et al.*, 2012) and smaller scales (Smith *et al.*, 2013a). Maximising co-benefits of AFOLU mitigation measures can increase efficiency in achieving the objectives of other international agreements, including the United Nations Convention to Combat Desertification (UNCCD, 2011)(UNCCD, 2011) or the Convention on Biological Diversity (CBD), and may also contribute to a broader global sustainability agenda (Harvey *et al.*, 2010; Gardner *et al.*, 2012). Table 2 presents an overview of the potential effects from AFOLU mitigation measures, which are discussed in more detail in this section, under the broad headings of institutional, socio-economic effects, environmental effects and public perception.

Institutional effects

AFOLU mitigation measures may have impacts on *land tenure and land use rights* for indigenous peoples, local communities and other social groups, who are dependent on natural assets. Co-benefits from AFOLU mitigation measures can be that land tenure is clarified and land rights are harmonized. Potential adverse-effects are lack of recognition of customary rights, loss of tenure or possession rights, and in some cases even displacement of social groups (Sunderlin *et al.*, 2005, 2014; Chhatre & Agrawal, 2009; Blom *et al.*, 2010; Sikor *et al.*, 2010; Larson, 2011; Robinson *et al.*, 2011; Rosemary, 2011; Rosendal & Andresen, 2011). Whether the impact on land tenure and use rights is positive or negative for local actors depends upon two factors: a) the institutions regulating land tenure and land use rights (e.g. laws, policies) and b) their level of enforcement (Corbera & Brown, 2008; Araujo *et al.*, 2009; Rosemary, 2011; Albers & Robinson, 2013; Larson *et al.*, 2013). For example the context in Latin America, where over 25% of the forest is managed by local communities, facilitates that these communities get benefits from mitigation activities in the forest sector (Larson et al. 2013, 2010). Nevertheless where there is no clarity about tenure and use rights by local actors, these tend to be excluded of institutional co-benefits (Grifiths and Martone, 2009; Pesket and Broding, 2011). More research is needed on how specific tenure forms (e.g. individual property, state ownership or community rights), obtain positive or adverse effects from AFOLU measures and which enabling conditions promote co-benefits in different regions or under specific circumstances (Sunderlin *et al.*, 2005; Katila, 2008; Chhatre & Agrawal, 2009; Blom *et al.*, 2010; Sikor *et al.*, 2010; Larson, 2011; Robinson *et al.*, 2011; Rosemary, 2011; Rosendal & Andresen, 2011).

Socio-economic effects

The potential impact of AFOLU mitigation measures on *food security* has recently received attention (Smith *et al.*, 2013b). Both efforts to reduce hunger and malnutrition and improved incomes will increase per-capita food demand in many developing countries, and population growth will increase the number of individuals requiring food sovereignty. Thus, a net increase in food production seems necessary for securing sustainable development (Ericksen *et al.*, 2009; FAO, WFP, and IFAD, 2012). AFOLU mitigation measures linked to increases in food production (e.g. agroforestry, sustainable intensification of agricultural production, higher efficiency use of fertilizers or integrated systems) can increase food availability and access especially at the local level. In contrast, other measures (e.g. large scale forestry or energy crop plantations) can reduce food production, at least locally (Foley *et al.*, 2005; McMichael *et al.*, 2007; Pretty, 2008; Godfray *et al.*, 2010; Jackson & Baker, 2010; Graham-Rowe, 2011; Jeffery *et al.*, 2011a). Further, it is important to consider possible displacement effects, e.g. GHG emissions in other regions resulting from the production of food that is imported rather than locally produced (Searchinger *et al.*, 2008; Gavrilova *et al.*, 2010).

Regarding *human health,* reduced emissions / increased sinks in AFOLU may also improve air, soil and water quality (Townsend *et al.*, 2012; Smith *et al.*, 2013a), providing benefits to human health and well-being. Demand-side measures aimed at reducing the proportion of livestock products in human diets (Ripple *et al.*, 2014), in circumstances where the consumption of animal products is higher than recommended, are associated with multiple health benefits, especially in industrialized countries (McMichael *et al.*, 2007; Marlow *et al.*, 2009; Stehfest *et al.*, 2009).

A major concern is the potential impacts of AFOLU mitigation measures on *equity*.

Impacts on equity can be actual (objectively measurable) or perceived (e.g. when all others got a benefit, but a reduced group doesn't) (Madlener *et al.*, 2006a). When distribution of socio-economic benefits, responsibilities (burden-sharing), access to decision-making, financing mechanisms and technology are defined in a participatory manner and clearly communicated, AFOLU mitigation measures can promote inter- and intra- generational equity (Combes Motel *et al.*, 2009; Cattaneo *et al.*, 2010; Rosemary, 2011; Di Gregorio *et al.*, 2013). Conversely, if policy instruments and/or the implementation schemes do not consider social distribution and/or promote concentration of co-benefits or risks, they can end up increasing inequity and land conflicts, or marginalize small scale farm/forest owners or users (Robinson *et al.*, 2011; Huettner, 2012; Kiptot *et al.*, 2012; Mattoo & Subramanian, 2012).

Much attention is being paid to the impacts of *large-scale land acquisition*, (or "land grabbing"), when related to promoting AFOLU mitigation measures (especially for production of bioenergy crops). Concerns include the impact of such practices on sustainable development in general, and equity in particular (Cotula *et al.*, 2009; Mwakaje, 2012; Scheidel & Sorman, 2012; German *et al.*, 2013; Messerli *et al.*, 2013).

The implementation of agricultural and forestry systems with positive impacts in terms of GHG reductions is often limited by capital (see also section on economic barriers), and *carbon payments or compensation mechanisms* may provide a new source of finance (Tubiello *et al.*, 2009). For instance, in some cases, mitigation payments can help to make production of non-timber forest products (NTFP) economically viable, further *diversifying income* at the local level (Singh, 2008). However, if financing mechanisms are accessible only for a reduced number of social groups(payments, compensation or other) economic benefits can become concentrated, marginalizing many local stakeholders (Combes Motel *et al.*, 2009; Alig *et al.*, 2010; Asante *et al.*, 2011; Asante & Armstrong, 2012). The realisation of economic co-benefits is related to the design of the specific mechanisms and depends 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)* (Corbera & Brown, 2008; Skutsch *et al.*, 2011).

Environmental effects

Availability of land and land competition can be affected by AFOLU mitigation measures. Different stakeholders may have different views on what land is available. When considering several AFOLU mitigation measures for the same area, there can be different perceptions about the importance of the ecosystem goods and services provided. For example, some AFOLU measures can increase food production but reduce other environmental services. Increasing land rents and food prices due to a reduction in land availability for agriculture in developing countries is another possible adverse outcome (Muller, 2009; Smith *et al.*, 2010, 2013b; de Vries & de Boer, 2010; Godfray *et al.*, 2010; Rathmann *et al.*, 2010; Amigun *et al.*, 2011; Harvey & Pilgrim, 2011; Janzen, 2011; Cotula, 2012; Scheidel & Sorman, 2012; Haberl *et al.*, 2013). Thus decision makers need to be aware of potential site-specific trade-offs within the sector.

Some AFOLU mitigation options promote the conservation of *biological diversity* (Smith *et al.*, 2013a) both by reducing deforestation (Chhatre *et al.*, 2012; Murdiyarso *et al.*, 2012; Putz & Romero, 2012; Visseren-Hamakers *et al.*, 2012), and by using reforestation/afforestation to restore biologically diverse communities on previously developed farmland (Harper *et al.*, 2007; Galatowitsch, 2009). If such options reduce local food production and result in increased food imports, biodiversity pressures related to food production may increase in other regions (Haberl *et al.*, 2009; Meyfroidt *et al.*, 2013) and the net effect becomes difficult to determine. Other potential land use changes related to mitigation can have adverse side-effects, reducing biodiversity (e.g. energy crop monocultures in biologically diverse and valuable regions)(Koh & Wilcove, 2008; Beringer *et al.*, 2011; Gardner *et al.*, 2012; Hertwich, 2012; Pandit & Grumbine, 2012; Ziv *et al.*, 2012).

Land-use intensity also drives the three main N loss pathways (nitrate leaching, denitrification and ammonia volatilization) and typical *N balances* for each land use indicate that total N losses also increase with increasing land-use intensity (Stevenson *et al.*, 2010). Leakages from the N cycle can cause air (e.g. NH_3^+, NO_x), soil (NO_3^-) and water pollution (e.g. eutrophication) and agricultural intensification can lead to a variety of other adverse environmental impacts (Smith *et al.*, 2013a). Combined strategies (e.g. diversified crop rotations and organic N sources) or single-process strategies (e.g. reduced N rates, nitrification inhibitors, and changing chemical forms of fertilizer) can reduce N losses (Bambo *et al.*, 2009; Gardner & Drinkwater, 2009). Integrated systems may be an alternative approach to reduce leaching.

AFOLU mitigation measures can have positive or negative *impacts on water resources*, depending on the mitigation measure used, site conditions (e.g. soil thickness and slope, hydrological setting, climate) and management of the particular mitigation measure. Water yields are affected by forest management, afforestation, reforestation, forest thinning and deforestation (Jackson *et al.*, 2005). Water quality can also be affected by AFOLU in several ways. For example, minimum tillage systems have been reported to reduce water erosion and thus sedimentation of water courses (Lal, 2001). Deforestation is well known to increase erosion and thus efflux of silt; avoiding deforestation will prevent this. In other situations, watershed scale reforestation can result in the restoration of water quality (e.g. Townsend *et al.*, 2012). Furthermore, strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances and protect livestock. Windbreaks can reduce erosion associated with the loss of soil carbon (Harper *et al.*, 2010; Chappell *et al.*, 2013) or both stubble retention (Robinson *et al.*, 2004). Various types of AFOLU mitigation can result in degradation of water sources through the losses of pesticides and nutrients to water (Smith *et al.*, 2013a).

AFOLU mitigation measures can have several *impacts on soil*. Increasing soil organic carbon (SOC) can improve soil health and can help to mitigate climate change. Although there is a limit on the amount of organic carbon that can be stored in soils, many management practices that are effective in increasing SOC are also effective in improving crop and pasture yields (Lal, 2011). Management practices that increase carbon sequestration can reduce soil erosion improving soil functions. For example, increasing or maintaining carbon stocks in living biomass (e.g. through forest or agroforestry systems) will reduce wind erosion by acting as wind breaks.. Efficient manure and fertilizer management provide nutrients for crops reducing losses of reactive nitrogen (Delgado *et al.*, 2011). Reforestation, conservation, forest management, agricultural systems or bioenergy systems can be used to restore degraded or abandoned land (Smith, 2008; Chatterjee & Lal, 2009; Stickler *et al.*, 2009; Wicke *et al.*, 2011; Sochacki *et al.*, 2012). Silvopasture systems can promote soil fertility (Tripathi *et al.*,

2013) may help to control land degradation and increase productivity sustainably in this environment (Steinfeld *et al.*, 2008, 2010b; Janzen, 2011). Further examples include the protection of soil and livestock with windbreaks (Bird, 1998), of soil by stubble retention (Lal & Kimble, 1997) and management of landscape water balances through reforestation (Robinson *et al.*, 2006) . Impacts from biochar production on carbon mineralization priming effects depend on the soil type, production temperature regimes, the specific placement and the feedstock tree species (Luo *et al.*, 2011; Zimmerman *et al.*, 2011).

AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options also increase agricultural and silvicultural efficiency. At any given level of demand for agricultural products, intensification increases output per unit area and per year and would therefore, if all else were equal*,* allow the reduction in farmland area which would in turn free land for C sequestration and/or bioenergy production (Smith *et al.*, 2013b). For example, a recent study calculated potentially large 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.*, 2010). However, in real-world situations increases in yield may result in feedbacks such as increased consumption ("rebound effects"; Lambin & Meyfroidt, 2011; Erb, 2012). Such increases in consumption may be regarded as "co-benefit" if it helps to reduce hunger and malnutrition but may be less positive in contexts where consumption of food and/or animal products exceeds recommendations for healthy diets.

There are also *co-benefits and trade-offs between mitigation and adaptation actions*. Mitigation choices taken in a particular land-use sector may affect resilience to climate variability and change within or across sectors. In light of the multiple, and often competing, pressures on land, and shifting demographics and consumption patterns (e.g. O'Brien *et al.*, 2004; Sperling *et al.*, 2008; Hunsberger *et al.*, 2012), land-use choices driven by mitigation concerns (e.g. forest conservation, afforestation) may have consequences for adaptive responses and/or development objectives of other sectors (e.g. expansion of agricultural land). 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 plantations, if they reduce biological diversity may diminish adaptive capacity to climate change (e.g. Chum *et al.*, 2011). Primary forests tend to be more resilient to climate change and other human induced environmental changes than secondary forests and plantations (Thompson *et al.*, 2009). The impact of plantations on the carbon balance is dependent on the land-use system they replace. Smith & Olesen (2010) identified a number of synergies between options that deliver climate mitigation in agriculture while also enhancing resilience to future climate change, the most prominent of which was enhancement of soil carbon stocks.

Adaptation measures in return may help maintain the mitigation potential of land-use systems. For example, projects that prevent large fires and restore degraded forest ecosystems also prevent release of GHGs and enhance carbon stocks (CBD and GiZ, 2011). Mitigation and adaptation benefits can be achieved within broader level objectives of AFOLU measures, which are linked to sustainable development. Given the exposure of many livelihoods and communities to multiple stressors, recommendations from case studies suggest that climate risk management strategies need to appreciate the full hazard risk envelope, as well as the compounding socioeconomic stressors (O'Brien *et al.*, 2004; Sperling *et al.*, 2008). Within this broad context, the potential trade-offs and synergies between mitigation, adaptation and development strategies need to be considered. Forest and biodiversity conservation, protected areas and afforestation with mixed species afforestation are practices that can help to maintain or enhance carbon stocks, while also enhancing resilience of forest ecosystems to climate change (Ravindranath, 2007).

Many options for adaptation to climate change have positive impacts on mitigation. In the agriculture sector, cropland adaptation options that contribute to mitigation are: soil management practices that reduce fertilizer use; increased crop diversification; promotion of legumes in crop rotations; the availability of quality seeds and integrated crop/livestock/forestry 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, 2009a). Agroforestry provides mitigation-adaptation synergy in the AFOLU sector, since trees sequester carbon and their products provide livelihood to communities, especially during drought years (Mbow *et al.*, 2014). For forestry, examples of mitigation and adaptation vary between plantations and natural forests. Booth (2013) describes adaptation strategies for eucalypt plantations, and several of these (e.g. genotype selection, stand management, site selection, fire management, management of pests and diseases) also have the potential to affect carbon mitigation, although this is not quantified.

Public perception

Mitigation measures that support sustainable development are likely to be perceived positively by the public, but a large scale drive towards mitigation without inclusion of key stakeholders could provoke opposition (Smith & Wollenberg, 2012). 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 & Doppler, 2010), or afforestation/reforestation resulting in competition for farmland (Mitchell *et al.*, 2012), or lack of agricultural development possibilities and flexibility resulting from measures to halt or land conversion (Harvey & Pilgrim, 2011).

Further, lack of clarity regarding the role of AFOLU mitigation measures in any future international climate regime is perceived as a threat for long-term planning and investments (Streck, 2012; Visseren-Hamakers *et al.*, 2012). Certain technologies, such as animal feed additives and genetically modified organisms are banned in some jurisdictions due to concerns over health and/or environmental risks. When considering government policy regarding such technologies public perception is often as important as scientific evidence of hazards and risks in (Royal Society, 2009; Smith & Wollenberg, 2012).

Emerging knowledge on ecosystem services as a means for climate change mitigation and adaptation has brought attention to the role of ecosystem management for achieving development goals, even beyond addressing climate change. As a response, in some jurisdictions emerging ecosystem markets are developing (MEA, 2005; Engel *et al.*, 2008; Deal & White, 2012; Wünscher & Engel, 2012) and including valuation of various components of land-use changes, in addition to climate change mitigation (Mayrand & Paquin, 2004; Barbier, 2007). Different quantification approaches are used; in some cases the individual components are considered singly (bundled), in other situations they are considered together (stacked; Deal & White, 2012). Ecosystem market approaches provide one framework to value the overall merits of mitigation actions at various scales (Farley & Costanza, 2010). Developing ecosystem market approaches promotes evolution of methodologies for valuing the individual components (e.g. water quality response to reforestation, timber yields), and other types of ecosystem service (e.g. biodiversity, social amenity value; Bryan *et al.*, 2013).

3. Barriers and opportunities

Conditions related to the development context can enable and facilitate (opportunities) or hinder (barriers) the full use of AFOLU mitigation measures (Figure 1). AFOLU programmes and policies can help to overcome barriers, but countries affected by many barriers will need time, financing and capacity support. International negotiations have recognised such context differences between countries and have proposed case-specific approaches (e.g. a phased approach in the REDD+, Green Climate Fund; see section 4).

Corresponding to the development framework presented in section 2, the following types of barriers and benefits are discussed: socio-economic, environmental, institutional, technological and infrastructural.

Socio-economic barriers and opportunities

The *design and coverage of the financing mechanisms* is key to realisation of the full AFOLU mitigation potential. Questions remain over which costs are covered by such mechanisms. If financing mechanisms fail to cover at least transaction and monitoring costs, these costs will become a barrier to the full implementation of AFOLU mitigation. According to some studies, opportunity costs also need to be fully covered by any financing mechanism for the AFOLU sector, especially in developing countries, as otherwise AFOLU mitigation measures would be less attractive compared to returns from alternative land uses (Angelsen, 2008; Cattaneo *et al.*, 2010; Böttcher *et al.*, 2012). Conversely, if financing mechanisms are designed to modify economic activity, they could provide an opportunity to leverage a larger proportion of AFOLU mitigation potential.

*Scale of financing s*ources can become either a barrier (if a relevant financial volume is not secured) or create an opportunity (if financial sources for AFOLU suffice) for realising

AFOLU mitigation potentials (Streck, 2012). Further, *accessibility to AFOLU financing* is key for farmers and forest stakeholders (Tubiello *et al.*, 2009; Colfer, 2011; Havemann, 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 duration, are potential risks for AFOLU measures, especially in developing countries, and when land holders use market mechanisms (e.g. Afforestation/Reforestation under Clean Development Mechanism; Madlener *et al.*, 2006).

Poverty is characterized not only by low income, but also by insufficient food availability in terms of quantity and/or quality, limited access to decision making and social organization, low levels of education and reduced access to resources (e.g. land or technology;UNDP International Poverty Centre, 2006). High levels of poverty can limit the possibilities for using AFOLU mitigation options, because of short-term priorities and lack of resources. 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, and can increase the risk of displacement, with other potential adverse side-effects (Huettner, 2012; Smith & Wollenberg, 2012). This is especially relevant when protection or extension of forest area competes with land requirements of other development projects e.g. increasing land for agriculture or mining (Forner *et al.*, 2006), or when large scale bioenergy compromises food security (Nonhebel, 2005). *Cultural values and social acceptance* can determine the feasibility of AFOLU measures, becoming a barrier or an opportunity depending of the specific circumstances (de Boer *et al.*, 2011).

Institutional barriers and opportunities

Transparent and accountable governance and solid institutional establishment are very important for a sustainable implementation of AFOLU mitigation measures. This includes the need to have *clear land tenure and use rights* regulations and a certain level of enforcement, as well as clarity about ownership of mitigation benefits (often referred as carbon ownership) (Markus, 2011; Palmer, 2011; Rosendal & Andresen, 2011; Thompson *et al.*, 2011; Murdiyarso *et al.*, 2012).

Lack of institutional capacity (as a means for securing creation of equal institutions among social groups and individuals) 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 *et al.*, 2011). *Lack of an international agreement* that supports a wide implementation of AFOLU measures can become a major barrier for realizing the mitigation potential from the sector globally (see section 4).

Ecological barriers and opportunities

The mitigation potential in the agricultural sector is highly site-specific, even within the same region or cropping system (Baker *et al.*, 2007; Chatterjee & Lal, 2009). Long- and short-term considerations as well as global differences in resource use/access to resources are relevant when deciding how to weigh competing land and water requirements. Limited resources can become an ecological barrier, and decisions on their use affect both ecological integrity and societal goals (Jackson, 2009).

At the local level, the *specific soil conditions, water availability, GHG emission reduction potential as well as natural variability and resilience* to specific systems will determine the feasibility different AFOLU measures (Baker *et al.*, 2007; Halvorson *et al.*, 2011). Frequent droughts in Africa and changes in the hydro-meteorological regimes in Asia and Central and South America are important in defining the specific regional potential (Bradley *et al.*, 2006; Rotenberg & Yakir, 2010). Ecological saturation (limits to soil carbon stocks or crop yield) means that some AFOLU mitigation options have their own limits. 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).

Technological barriers and opportunities

Technological barriers refer to the limitations in generating, procuring and applying 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 there are less technological barriers for these options, but others (e.g. some livestock dietary additives, crop trait manipulation) are still at the development stage. The *ability to manage and re-use knowledge* for scientific communication, technical documentation and learning is lacking in many areas where mitigation could take place. Future developments present opportunities for additional mitigation if efforts to deliver ease-of-use and range-of-use are guaranteed. There is also a need to adapt technology to local needs by focussing on existing local opportunities (Kandji *et al.*, 2006), as proposed in Nationally Appropriate Mitigation Actions (NAMAs; see section 4).

Barriers and opportunities related to *monitoring, reporting and verification* of AFOLU mitigation measures are also relevant. Monitoring activities, aimed at reducing uncertainties, provide the opportunity of increasing credibility in the AFOLU sector. However there are technical challenges. For instance, monitoring forest carbon in forests with high spatial variation in tree density and species composition can pose a technical barrier to the implementation of some AFOLU activities (e.g. REDD+; Baker *et al.*, 2010; see section 4). The IPCC National Greenhouse Gas Inventory Guidelines (Paustian *et al.*, 2006) provide an opportunity, because they offer standard scientific methods that countries already use to report AFOLU emissions and removals under the UNFCCC (Ogle *et al.*, 2013, 2014). Field research in high-biomass forests (Gonzalez *et al.*, 2010) shows that remote sensing data and Monte Carlo quantification of uncertainty offer a technical opportunity for implementing REDD+. Using the existing *human skills* within a country is essential for realising full the AFOLU potential. A lack of trained people can become a barrier to implementation of appropriate technologies (Herold & Johns, 2007).

Technology improvement and technology transfer are two crucial components for the sustainable increase of agricultural production in developed and developing regions with positive impacts in terms of mitigation, soil and biodiversity conservation (Tilman *et al.*, 2011). Policy instruments are relevant to foster technology transfer and to support research and development, overcoming technological barriers.

4. Sectoral policies to deliver AFOLU GHG mitigation

Climate change is likely to influence, and be influenced by, policy and/or management choices. This is critical for agriculture and forestry because these are dependent upon climate variables, but also contribute as sources of, and sinks for, greenhouse gases (Golub *et al.*, 2009). Further, these ecosystems provide multitude of goods and services that are vital to human wellbeing, climate change mitigation being just one. Thus successful mitigation policies need to consider how to address the multi-functionality of the sector, promote co-benefits and reduce barriers.

National and international agricultural and forest (climate) policies have the potential to alter the opportunity costs of specific land-uses in ways that increase opportunities or barriers for attaining climate change mitigation goals. Policy interactions within and across sectors could be synergistic (e.g. research and development investments and economic incentives for integrated production systems) or conflicting (e.g. policies promoting land conversion *vs*. conservation policies) (see Table 3). Adequate policies can help to orient practices in agriculture and in forestry toward global sharing of innovative technologies for the efficient use of land resources, to support effective mitigation options.

As of December 2010 forty-three countries have proposed Nationally Appropriate Mitigation Actions (NAMAs) to the UNFCCC. Agriculture and forestry activities were considered as options to reduce GHG emissions in 59% and 94%, respectively, of the proposed NAMAs. For the least developed countries, the forestry sector was quoted in all, while the agricultural sector was represented in 70% of the NAMAs (Bockel *et al.*, 2010). Policies in the AFOLU sector that affect mitigation are discussed below according to their implementation instruments (economic incentives, regulatory and control approaches, information, communication and outreach, research and development). The effectiveness of economic incentives and regulatory approaches depend highly on national context. Investments in research, development and diffusion (e.g. improved fertilizer use efficiency, livestock management improvement, better forestry management practices) could result in positive and synergistic impacts for adaptation and mitigation.

Economic Incentives

Emissions trading: A review of existing offset programmes was provided by (Kollmuss *et al.*, 2010). Compliance markets (Kyoto offset mechanisms, mandatory cap-and-trade systems and other mandatory GHG systems) are created and regulated by mandatory national, regional or international carbon reduction regimes. The three Kyoto Protocol mechanisms are part of the regulatory market: Clean Development Mechanism (CDM), Joint Implementation (JI) and the

Emissions Trading System (ETS). Currently, AFOLU projects in CDM only include specific types of projects: for agriculture - methane avoidance (manure management), biogas projects, agricultural residues for biomass energy; for afforestation and reforestation (A/R). By June 2013, the total number of registered CDM projects was 6989. Of these projects, 0.6% were related to afforestation/reforestation and 2.5% to agriculture. (http://cdm.unfccc.int/Statistics/); so finance streams coming from A/R CDM Projects are marginal from the global perspective. An analysis of A/R CDM projects suggests crucial performance factors including initial funding support, sufficient technical expertise to guarantee sound design and implementation and occurrence on land with unambiguous property rights (Thomas *et al.*, 2010).

There are compliance schemes outside the scope of the Kyoto Protocol, carried out exclusively at the national level, with no relation to the Protocol. In 2011, Australia started the Carbon Farming Initiative (CFI) that allows generating tradable carbon offsets from farmland, forestry projects and through methane management from intensive livestock (e.g. piggeries) and relict landfill sites. In early 2014, of 102 projects producing 4.2 Mt CO_2-e of carbon credits (ACCUs), 29 were AFOLU projects, with these producing 7% of the total mitigation[1]. The CFI followed several years of State-based and voluntary activity that resulted in 65,000 ha of A/R projects (Mitchell *et al.*, 2012). Further the Western Arnhem Land Fire Abatement Project (WALFA), a fire management project in Australia initiated in 2006 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). In Canada, the Alberta's offset credit system is a

[1] www.cleanenergyregulator.gov.au/Carbon-Farming-Initiative/Register-of-Offsets-Projects/Pages/default.aspx. Accessed 9 January 2014.

compliance mechanism for entities regulated under the province's mandatory GHG emission intensity-based regulatory system. In the case of N_2O emissions from agriculture, the Alberta Quantification Protocol for Agricultural N2O Emissions Reductions issues C offset credits for on-farm reductions of N2O emissions and fuel use associated with the management of fertilizer, manure, and crop residues for each crop type grown. Other N2O emission reduction protocols (e.g. Millar *et al.*, 2010) are being considered for the Verified Carbon Standard (voluntary market), the American Carbon Registry, and the Climate Action Reserve (Robertson *et al.*, 2013).

The European Union Emissions Trading Scheme (EU ETS) - by far the largest existing carbon market - does not cover AFOLU activities; however, it may indirectly affect land use because it ignores the CO_2 emissions resulting from indirect land use change when calculating GHG emission reductions from the substitution of bioenergy for fossil fuels (Haberl *et al.*, 2012). Forestry entered the New Zealand Kyoto Protocol compliant ETS in 2008, and mandatory reporting for agriculture began in 2012, although full entry of agriculture into the scheme has been delayed indefinitely (www.climatechange.govt.nz). California's Cap-and-Trade Regulation took effect on January 1, 2012. The enforceable compliance obligation began on January 1, 2013 and projects were approved as eligible include: avoidance of methane emissions from installation of anaerobic digesters on farms, carbon sequestration in urban and rural forestry, and destruction of ozone depleting substances (http://www.arb.ca.gov).

Voluntary carbon markets operate outside of the compliance markets and enable businesses, governments, NGOs, and individuals to offset their emissions by purchasing offsets that were created either through the CDM or in the voluntary market (Verified or Voluntary Emissions Reductions - VERs). The voluntary offset market includes a wide range of programs, entities, standards and protocols (e.g. Verified Carbon Standard, Community & Biodiversity

Standards, Gold Standard, Plan Vivo among others). Voluntary carbon credits are mainly purchased by the private sector. Corporate social responsibility and public relations are the most common motivations for buying carbon credits. Forest projects are increasing in the voluntary markets. In 2012, voluntary actors contracted 101 million tonnes of carbon offsets ($MtCO_2e$) for immediate or future delivery – 4% more than in 2011- committing US$523 million (Peters-Stanley & Yin, 2013).

Reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks (REDD+): REDD+ consists of forest-related activities in developing countries that lead to real and monitoreable climate change mitigation. REDD+ was introduced in the agenda of the Climate Change Convention (UNFCCC) in 2005, and has since motivated research leading in an improved understanding of the potential positive and negative impacts, methodological issues, safeguards, and financial aspects associated with its implementation. Here, we first address the REDD+ discussions under the UNFCCC, but also introduce other REDD+-related initiatives. Novel aspects of REDD+ are its aim to act at the national level and its broader coverage, in contrast to project-based mitigation activities (e.g. under the Clean Development Mechanism of the Kyoto Protocol). A phased approach to REDD+ was agreed at the UNFCCC, building from the development of national strategies or action plans, policies and measures, and evolving into results-based actions that should be fully measured, reported and verified – MRV (UNFCCC Dec. 1/16). REDD+ payments are expected for results-based actions, but the financing architecture for the REDD+ mechanism is still under negotiation under the UNFCCC.

Meanwhile, and as a result to the explicit request from the UNFCCC for early actions in REDD+, regional and global programmes and partnerships address forest management and conservation and readiness for REDD+ (Table 3). Initiatives include multilateral activities (e.g. UN-REDD Programme, Forest Carbon Partnership Facility, Forest Investment Program), bilateral activities (e.g. Tanzania-Norway, Indonesia-Norway), country driven initiatives (in addition to 16 UN-REDD Programme countries, the Programme also supports 31 other partner countries across Africa, Asia-Pacific and Latin America and the Caribbean – (UN-REDD programme website)

REDD+ can be a cost effective option for mitigating climate change and could supply a large share of global abatement of emissions from the AFOLU sector from the extensive margin of forestry, especially through reducing deforestation in tropical regions (Golub *et al.*, 2009). Environmental and socio-economic concerns for REDD+ implementation should be addressed through the REDD+ safeguards and in line with the UNFCCC Cancun Agreement including: defining social and environmental objectives, assessing potential benefits and risks from REDD+, assessing current safeguard systems, drafting a strategic plan or policy, and establishing a governance system.

A growing body of literature has analysed different aspects related to the implementation, effectiveness and scale of REDD+, as well as the interactions with other social and environmental co-benefits (e.g. Angelsen *et al.*, 2008, 2012; Levin *et al.*, 2008; Gardner *et al.*, 2012). Results-based REDD+ actions, which are entitled to results-based finance, require internationally agreed rules for measuring, reporting and verification (MRV). Measuring and monitoring the results will most likely rely on a combination of remotely-sensed data with ground-based inventories. The design of a REDD+ policy framework, modalities and procedures will have a significant impact on monitoring costs (Angelsen *et al.*, 2008, 2012; Böttcher *et al.*, 2009). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests. Although the majority of forests continue to be owned formally by governments, some studies indicated 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 *et al.*, 2010).

Some studies have addressed the potential displacement of emissions (i.e. a reduction of emissions in one place resulting in an increase of emissions elsewhere or leakage; (Santilli *et al.*, 2005; Forner *et al.*, 2006; Nabuurs *et al.*, 2007; Strassburg *et al.*, 2008, 2009). The national coverage of REDD+ might ameliorate the issue of emissions displacement, a major drawback of project-based approaches (Herold & Skutsch, 2011). To minimize transnational displacement of emissions, REDD+ needs to stimulate the largest number of developing countries to engage voluntarily. Future studies would be needed to address potential changes in trade following REDD+ that could result in shifts of emissions between countries or regions. There are concerns about the impacts of REDD+ design and implementation options on biodiversity conservation, as 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). Additionally, transnational displacement could cause deforestation to move into intact areas of biodiversity value, or into countries that currently have little deforestation (Putz & Redford, 2009).

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 N_2O 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 was abolished in 2010) would have been on average 160 tons or 2% higher without the tax (Mohlin, 2013). 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. The emission mitigation potential of GHG weighted consumption taxes on animal food products was estimated for the EU using a model of food consumption (Wirsenius *et al.*, 2011). A 7% reduction of current GHG emission in EU agriculture was estimated with a GHG weighted tax on animal food products of 60 /t CO_2eq.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) (Programa Agricultura de Baixo Carbono, Ministerio da Agricultura, Brazil).

Regulatory and Control Approaches

Deforestation control and land planning: This section discusses regulatory approaches to control or plan land use, including deforestation, through creation of 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 by nearly 25% during the last decade, compared with the net forest loss during the 1990s. Public policies have had a significant impact by reducing deforestation rates in some tropical countries (e.g. in the Brazilian Amazon deforestation rates decreased by 77% from 2004 to 2011, from 27,772 km^2/yr to 6,418 km^2/yr) (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 increase of new protected areas (Soares-Filho *et al.*, 2010). It combines 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 whether intensification of agriculture reduces cultivated areas and results in land sparing by concentrating production on smaller land areas, , and to what extent it also induces increases in consumption through rebound effects (Lambin & Meyfroidt, 2011; Erb, 2012). Land sparing would allow using land area not required for agriculture to sequester carbon, provide other environmental services, and protect biodiversity (Fischer *et al.*, 2008). In the United States, over 13 Mha of former cropland are enrolled in the US Conservation Reserve Program (CRP), with biodiversity, water quality, and carbon sequestration benefits (Gelfand *et al.*, 2011). The Grain for Green Program or Sloping Land Conversion Program was launched in China as a national measure to control erosion and increase vegetation cover in 1999, which targets cropland and barren land, and has converted over 20 Mha of land into primarily tree-based plantations, and generated carbon sequestration over its 10 first years between ~800 to 1700 Mt CO_2eq (Moberg, 2011).

Control of GHGs and their precursors through environmental regulation: 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 EU Nitrates Directive (1991) sets limits on the use of fertilizer N and animal manure N in nitrate-vulnerable zones. Across the 27 EU Member States, 39.6% of territory is subject to related action programmes.

In terms of the effectiveness of environmental policies and agriculture, there has been considerable progress in controlling point pollution, but efforts to control non-point pollution of nutrients have been less successful, and potential synergies from various soil-management strategies could be better exploited. Emission targets for the AFOLU sector were also introduced by different countries (e.g. Climate Change Acts in UK and Scotland; European Union).

Bioenergy targets: By 2012, in response to many different policy objectives, including climate change mitigation, energy security, and rural development, many countries worldwide have put in place targets and/or mandates for bioenergy. The bulk of mandates continue to come from the EU-27 but 13 countries in the Americas, 12 in Asia-Pacific, and 8 in Africa also have mandates or targets in place (Petersen, 2008; www.biofuelsdigest.com). 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 programmes (Jull *et al.*, 2007). A recent study analysed the consequences of renewable targets of EU member states on the CO_2 sink of 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 has already caused a number of trade disputes, because of subsidies and non-tariff barriers (Oosterveer & Mol, 2010). Trade-related indirect effects ('iLUC') can also have considerable consequences for the total GHG emission effects of bioenergy policies (Chum *et al.*, 2011).

Information schemes, voluntary actions and agreements

Acceptability by land managers and practicability of mitigation measures is important, because the efficiency of a policy is determined by the cost of achieving a goal. Therefore, costs related to education and communication of policies should be taken into account (Jakobsson *et al.*, 2002). Organizations created to foster the use of science in environmental policy, management, and education can facilitate the flow of information from science to society, increasing awareness of environmental problems (Osmond *et al.*, 2010). 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 activities by developing standards and educational campaigns.

Certification schemes support sustainable agricultural practices. Climate-friendly criteria reinforce existing certification criteria and provide additional value. Different certification systems also consider improvements in forest management, reduced 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, 2009b). 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). In the forestry sector, many governments have worked towards a common understanding of sustainable forest management (Auld *et al.*, 2008). Certification bodies certify that farms or groups comply with standards and policies (e.g. Rainforest Alliance Certified). In some, specific voluntary climate change adaptation and mitigation criteria are included.

Forest certification as an instrument to promote sustainable forest management and biodiversity maintenance was evaluated by (Rametsteiner & Simula, 2003); they indicated that standards used for issuing certificates upon compliance are diverse, but often include elements that set higher than minimum standards.

Independent audits are an incentive for improving forest management. In spite of many difficulties, forest certification can help in raising awareness, disseminating knowledge on the SFM concept worldwide, and providing a tool for a range of applications other than the assessment of sustainability, e.g. verifying carbon sinks. Another evaluation of certification schemes for conserving biodiversity (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 biofuel production pathways include multiple actors and several successive segments. The length and complexity of the biofuel supply chains make the sustainability issue very challenging (Kaphengst *et al.*, 2009).

Innovative agricultural practices and technologies can play a central role in climate change mitigation and adaptation, with policy and institutional changes needed to encourage the innovation and diffusion of these practices and technologies to developing countries. Under the UNFCCC, the 2007 Bali Action Plan identified technology development and transfer as a priority area. A Technology Mechanism was established by Parties at the COP16 in 2010 to facilitate the implementation of enhanced action on technology development and transfer, to support action on mitigation and adaptation, in order to achieve the full implementation of the Convention (http://unfccc.int).

Additionally, adaptation measures in agriculture can generate significant mitigation effects, making them a highly worthwhile investment. (Lobell *et al.* (2013) investigated the co-benefits of helping farmers adapt to climate change, thereby avoiding some of the emissions associated with land-use change and concluded that that broad-based efforts to adapt agriculture to climate change have mitigation co-benefits that are inexpensive relative to many activities aimed at climate change mitigation, especially in developed countries.

Conclusions

The AFOLU sector is responsible for approximately 25% of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management. The mitigation potential of the sector is extremely important in meeting emission reduction targets. The sector offers a variety of cost-competitive mitigation options and most approaches indicate a decline in emissions largely due to decreasing deforestation rates. In spite of emission reduction in the sector, the realisation of the mitigation potential depends upon a complex system of social, institutional, economical institutional and biophysical variables. While this review offers a framework to discuss these aspects at a global level, more regional analyses are needed in order to understand this complexity in specific contexts. The size and regional distribution of future mitigation potential and associated co-benefits and adverse-effects are difficult to estimate accurately due to factors as population growth, economic and technological developments, changes in behaviour over time, and how these impact the demand of different goods and services as well as sector development. Additionally, policies governing practices in agriculture and in forest conservation and management need to account for both mitigation and adaptation. Sustainability criteria are needed to guide development and implementation of AFOLU mitigation measures with particular focus on multifunctional systems that allow the delivery of multiple services from land.

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Figure legends

Figure 1. Dynamic interactions between the development context and AFOLU.

Table 1. Summary of mitigation options available in the AFOLU sector

Categories	Mitigation Options	References
Forestry	Reducing deforestation	Reyer *et al.*, 2009; FAO, 2010
	Afforestation/reforestation	Reyer *et al.*, 2009; FAO, 2010
	Forest management	Reyer *et al.*, 2009; FAO, 2010
	Forest restoration	Reyer *et al.*, 2009; FAO, 2010
Land-based agriculture	Cropland management: croplands-plant management, croplands – nutrient management, croplands – tillage/residues management, croplands – water management, croplands – rice management, rewet peatlands drained for agriculture, croplands – set aside and LUC, biochar application	Delgado *et al.*, 2011
	Grazing and land management: Grazing lands – plant management, grazing lands – animal management, grazing land fire management	Delgado *et al.*, 2011
	Revegetation	Delgado *et al.*, 2011
	Restoration of organic soils	Joosten *et al.*, 2012
	Biosolids applications	Delgado *et al.*, 2011
Livestocks	Livestock-feeding	Hristov *et al.*, 2013
	Livestock – breeding and other long term management	Hristov *et al.*, 2013
	Manure management	Delgado *et al.*, 2011
Integrated systems	Agroforestry (including agropastoral and agrosilvopastoral systems)	Delgado *et al.*, 2011
	Other mixed biomass production systems	Delgado *et al.*, 2011
	Integration of biomass production with subsequent processing in food and bionenergy sectors	Delgado *et al.*, 2011

Table 2 Summary of potential co-benefits (green arrows) and adverse side-effects (orange arrows) from AFOLU mitigation measures; arrows pointing up/down denote positive/negative effect on the respective issue. These effects depend on the specific context (including bio-physical, institutional and socio-economic aspects) as well as on the scale of implementation.

	Issue	**Potential co-benefit or adverse-side effect**	**Scale**	**AFOLU mitigation measure**
Institutional	Land tenure and use rights	Improving (↑) or diminishing (↓) tenure and use rights for local communities and indigenous peoples, including harmonization of land tenure and use regimes (e.g. with customary rights)	Local to national	Forestry (4, 5, 6, 8, 9,12, 21)
	Sectoral policies	Promoting (↑) or contradicting (↓) the enforcement of sectoral (forest and/or agriculture) policies	National	Forestry (5, 6, 9, 2, 21); land-based agriculture (7, 20, 21)
	Cross-sectoral policies	Cross-sectoral coordination (↑) or clashes (↓) between forestry, agriculture, energy and/or mining policies	Local to national	Forestry (7, 21); agriculture (7, 20, 21)
	Participative mechanisms	Creation/use of participative mechanisms (↑) for decision-making regarding land management (including participation of various social groups e.g. indigenous peoples or local communities)	Local to national	Forestry (4, 5, 6, 8, 9, 14, 21); agriculture (21, 33); integrated systems (21, 35)
	Benefit sharing mechanisms	Creation/use of benefits-sharing mechanisms (↑) from AFOLU mitigation measures	Local to national	Forestry (4, 5, 6, 21,8)
Social	Food security	Increase (↑) or decrease (↓) on food availability and access	Local to national	Forestry (18, 19); agriculture (7, 18, 19,15, 24, 29, 31); livestock (2, 3, 19, 36, 37); integrated systems (18,19); biochar (17, 27)

	Local/traditional knowledge	Recognition (↑) or denial (↓) of indigenous and local knowledge in managing (forest/agricultural) land	Local /sub-national	Forestry (4, 5, 6, 21, 8), agriculture (21,29); integrated systems (2); livestock (2, 3, 36); biochar (2)
	Animal welfare	Changes in perceived or measured animal welfare (perceived due to cultural values or measured e.g. through amount of stress hormones)	Local to national	Livestock(32, 2, 36, 38, 39)
	Cultural values	Respect and value cultural habitat and traditions (↑), reduce (↓) or increase (↑) existing conflicts or social discomfort (4, 5, 6, 21, 8)	Local to trans-boundary	Forestry (4, 5, 6, 9, 21)
	Human health	Impacts on health due to dietary changes specially in societies with a high consumption of animal protein (↓)	Local to global	Changes in demand patterns (32, 37)
	Equity	Promote (↑) or not (↓) equal access to land, decision-making, value chain and markets as well as to knowledge and benefit-sharing mechanisms	Local to global	Forestry (4, 5, 6,10, 21, 8, 9); agriculture (20, 24, 33)
Economic	Income	Increase (↑) or decrease (↓) in income. There are concerns regarding income distribution (↑)	Local	Forestry (6, 7, 8, 16, 21, 22, 23); agriculture (16, 19, 21, 24, 29); livestock (2, 3); integrated systems (7, 21); biochar (25); changes in demand patterns (2)
	Employment	Employment creation (↑) or reduction of employment (especially for small farmers or local communities) (↓)	Local	Forestry (8, 21), agriculture (21, 24); livestock (2, 3); integrated systems (7, 21)
	Financing mechanisms	Access (↑) or lack of access (↓) to new financing schemes	Local to global	Forestry (6, 8, 16, 21); agriculture (16, 21); livestock (2, 3)

	Economic activity	Diversification and increase in economic activity (↑) while concerns on equity (↑)	Local	Forestry (6, 7, 21, 8); land based agriculture (16, 19, 21, 24, 29); livestock (2, 3)
Environmental	Land availability	Competition between land uses and risk of activity or community displacement (↑)	Local to trans-boundary	Forestry and land based-agriculture (5, 6, 15, 18, 21, 30, 31); livestock (2, 3, 30, 41)
	Biodiversity	Monocultures can reduce biodiversity (↓). Ecological restoration increases biodiversity and ecosystem services (↑) by 44 and 25% respectively (28) Conservation, forest management and integrated systems can keep biodiversity(↑) and/or slow desertification (↓)	Local to trans-boundary	Forestry (1, 21, 19, 28) On conservation and forest management (1, 19, 22, 28, 31); agriculture and integrated systems (15, 19, 21, 29, 31);
	Albedo	Positive impacts (↑) on albedo and evaporation and interactions with ozone	Local to global	(49, 50)
	N and P cycles	Impacts on N and P cycles in water (↓/↑) especially from monocultures or large agricultural areas	Local to trans-boundary	Agriculture (19, 24, 31, 36); livestock (2, 3, 31)
	Water resources	Monocultures and /or short rotations can have negative impacts on water availability (↓). Potential water depletion due to irrigation (↓).Some management practices can support regulation of the hydrological cycle and protection of watersheds (↑)	Local to trans-boundary	Forestry (1, 21, 19, 28); land based agriculture (31, 44); integrated systems (2, 31, 44)
	Soil	Soil conservation (↑) and improvement of soil quality and fertility (↑). Reduction of erosion. Positive or negative carbon mineralization priming effect (↑/↓)	Local	Forestry (45, 46) Land- based agriculture (13, 19, 24, 29, 31), integrated systems biochar (40, 41)

	New products	Increase (↑) or decrease (↓) on fibre availability as well as non-timber/non-wood products output	Local to national	Forestry (18,19, 42, 43); agriculture (7, 18, 19,15, 24, 29, 31); integrated systems (18, 19)
	Ecosystem resilience	Increase (↑) or reduction (↓) of resilience, reduction of disaster risks (↓)	Local to trans-boundary	Forestry, integrated systems (11, 34)
Technology	Infrastructure	Increase (↑) or decrease (↓) in availability of and access to infrastructure. Competition for infrastructure for agriculture (↑), can increase social conflicts	Local	Agriculture (21, 47, 48)
	Technology innovation and transfer	Promote (↑) or delay (↓) technology development and transfer	Local to global	Forestry (7, 13, 26); agriculture (24), livestock (2, 3)
	Technology acceptance	Can facilitate acceptance of sustainable technologies (↑)	Local to national	Forestry (7, 13, 26); livestock (2, 3, 36)

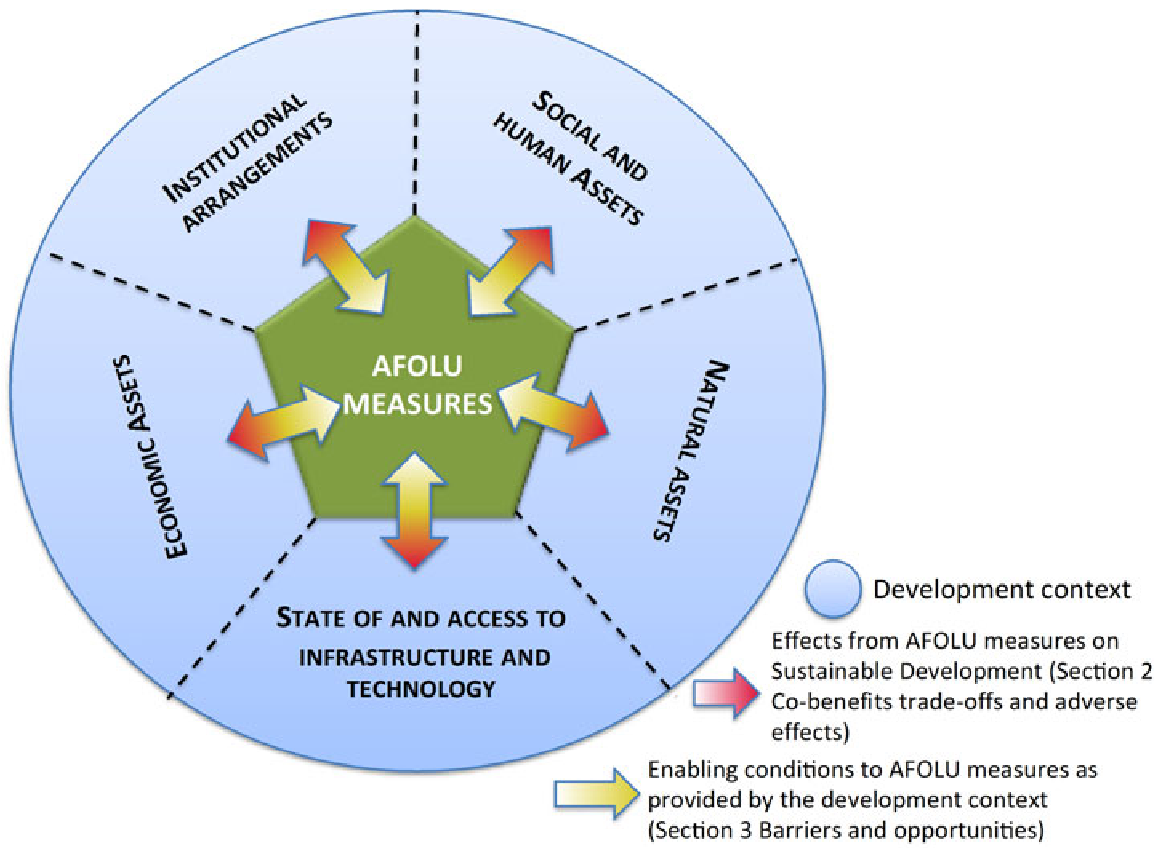
Sources: 1) Trabucco *et al.* (2008); 2) Steinfeld *et al.* (2010); 3) Gerber *et al.* (2010); 4) Sikor *et al.* (2010); 5) Rosemary (2011); 6) Pettenella & Brotto (2011); 7) Jackson & Baker (2010); 8) Corbera & Schroeder (2011); 9) Colfer (2011); 10) Blom *et al.* (2010); 11) Halsnæs & Verhagen (2007); 12) Larson (2011); 13) Lichtfouse *et al.* (2009); 14) Thompson *et al.* (2011); 15) Graham-Rowe (2011); 16) Tubiello *et al.* (2009); 17) Barrow (2012); 18) Godfray *et al*. (2010); 19) Foley *et al.* (2005); 20) Halsnæs & Verhagen (2007); 21) Madlener *et al.* (2006); 22) Strassburg *et al.* (2012); 23) Canadell & Raupach (2008); 24) Pretty (2008); 25) Galinato *et al.* (2011); 26) Macauley & Sedjo (2011); 27) Jeffery *et al.* (2011); 28) Benayas *et al.* (2009); 29) Foley *et al.* (2011); 30) Haberl *et al.* (2013); 31) Smith *et al.* (2013a); 32) Stehfest *et al.* (2009); 33) Chhatre *et al.* (2012); 34) Seppälä *et al*. (2009); 35) Murdiyarso *et al.* (2012); 36) de Boer *et al.* (2011); 37) McMichael *et al.* (2007); 38) Koknaroglu & Akunal (2013); 39) Kehlbacher *et al.* (2012); 40) Zimmerman *et al.* (2011); 41) Luo *et al.* (2011); 41) Mirle (2012); 42) Albers & Robinson (2013); 43) Smith *et al.* (2013b); 44) Chatterjee & Lal (2009); 45) Smith (2008); 46) Ziv *et al*. (2012); 47) Beringer *et al.* (2011); 48) Douglas *et al.* (2009); 49) Arneth *et al.* (2010); 50) Isaksen *et al*, (2012)

Table 3 Some regional and global programs and partnerships related to illegal logging, forest management and conservation and REDD+.

Program / Institution/Source	Context	Objectives and Strategies
Forest Law Enforcement and Governance (FLEG) / World Bank/ www.worldbank.org/eapfleg	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/ www.enpi-fleg.org	Regional cooperation in the European Neighbourhood 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/ www.euflegt.efi.int/	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 elements 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 on Forests (PROFOR) / multiple donors including the	Well-managed forests have the potential to	Provide in-depth analysis and technical assistance on key

European Union, European countries, Japan and the World Bank/ www.profor.info	reduce poverty, spur economic development and contribute to a healthy local and global environment	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/ www.un-redd.org	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).
REDD+ Partnership / International effort (50 different countries)/ www.reddpluspartnership.org	The UNFCCC has encouraged the Parties to coordinate their efforts to reduce emissions from deforestation and forest degradation. As a response, countries attending the March 2010 International Conference on the Major Forest Basins, hosted by the Government of France, agreed on the need to forge a strong international	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 facilitate knowledge transfer, capacity enhancement, mitigation actions and technology development and transfer among others.

	partnership on REDD+.	
Forest Investment Program (FIP) / Strategic Climate Fund (a multi-donor Trust Fund within the Climate Investment Funds) www.climateinvestmentfunds.org/cif/	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/ www.forestcarbonpartnership.org	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/ www.iafcp.or.id	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.


Institutional Arrangements
Social and Human Assets
AFOLU Measures
Economic Assets
Natural Assets
State of and access to infrastructure and technology
Development context
Effects from AFOLU measures on Sustainable Development (Section 2 Co-benefits trade-offs and adverse effects)
Enabling conditions to AFOLU measures as provided by the development context (Section 3 Barriers and opportunities)