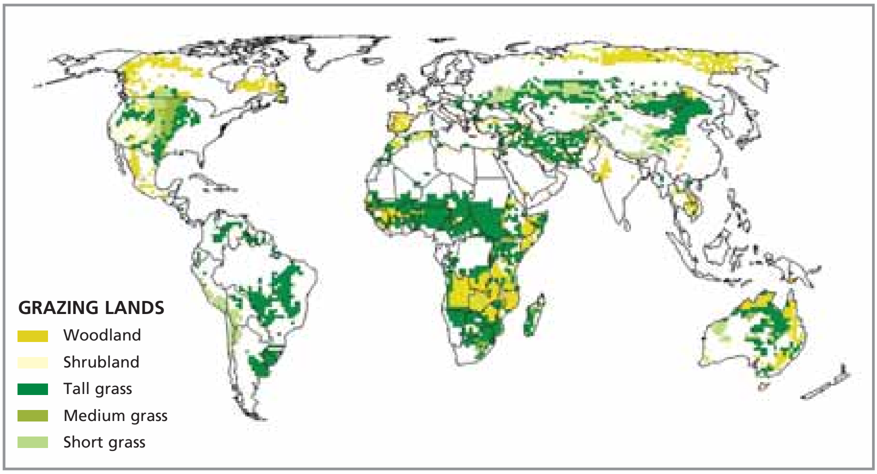
CHAPTER 2
Background

GRASSLANDS COVER BROAD AREAS, CONTRIBUTE SUBSTANTIALLY TO LIVELIHOODS AND ARE VULNERABLE

Grasslands, including rangelands, shrublands, pastureland, and cropland sown with pasture and fodder crops, covered approximately 3.5 billion ha in 2000, representing 26 percent of the world land area and 70 percent of the world agricultural area, and containing about 20 percent of the world's soil carbon stocks (FAOSTAT, 2009; Ramankutty *et al.*, 2008; Schlesinger, 1977). People rely heavily upon grasslands for food and forage production. Around 20 percent of the world's native grasslands have been converted to cultivated crops (Figure 1) (Ramankutty *et al.*, 2008) and significant portions of world milk (27 percent) and beef (23 percent) production occur on grasslands managed solely for those purposes. The livestock industry – largely based on grasslands – provides livelihoods for about 1 billion of the world's poorest people and one-third of global protein intake (Steinfeld *et al.*, FAO, 2006).



Source: Connant and Paustian, 2000

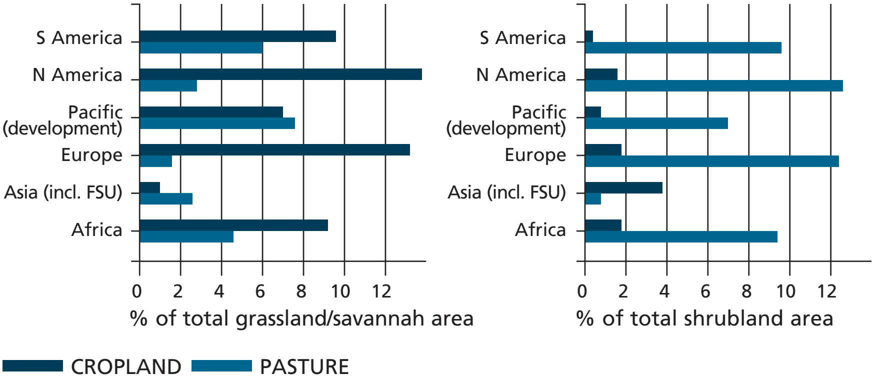


FIGURE 1: **Percentage of native grassland/savannah and shrubland that has been converted to cropland and pasture**

Source: Ramankutty *et al*., 2008

The development challenges faced by the populations of the world's dry grasslands systems vividly illustrate the tightening linkage between ecosystem services and enhanced human well-being: 2 billion people inhabit dryland regions, yet dryland regions have only 8 percent of the world's renewable water supply. This means that people have access to water that meets only two-thirds of the minimum per capita requirements, population growth rates are faster in drylands than anywhere else, but production potential is lower than anywhere else. Traditional socio-ecological systems have evolved to cope with climatic and economic uncertainty, but population and economic pressures are increasingly taxing traditional systems (Verstraete, Scholes and Stafford Smith, 2009).

Primary production in rangelands is relatively low, varies substantially from place to place, and is strongly limited by precipitation (Le Houerou, 1984). Even where rainfall is high (some grassland areas receive as much as 900 mm of precipitation per year), almost all of the precipitation falls during distinct rainy seasons and evapotranspiration demands exceed precipitation during most of the year. Moreover, precipitation, and thus production, varies considerably from year to year, with coefficients of variation averaging 33 percent, and as high as 60 percent in some of the drier areas (Ellis and Galvin, 1994). Grasslands are thus highly vulnerable to climate change (Thornton *et al*., 2007; 2009).

GRASSLANDS ARE INTENSIVELY USED AND DEGRADATION IS WIDESPREAD

A large part of the world's grasslands is under pressure to produce more livestock by grazing more intensively, particularly in Africa's rangelands, which are vulnerable to climate change and are expected nonetheless to supply most of the beef and milk requirements in Africa (Reid *et al.*, 2004). As a result of past practices, 7.5 percent of the world's grasslands have been degraded by overgrazing (Oldeman, 1994). Previous research has documented that improved grazing management could lead to greater forage production, more efficient use of land resources, and enhanced profitability and rehabilitation of degraded lands (Oldeman, 1994). The strong bond between ecosystem services and human well-being in the world's dryland systems demonstrates the need for a new, integrated approach to diagnosing and addressing sustainable development priorities, including maintenance of the supply of critical ecosystem services.

One of the reasons for the intensive use of grasslands is the high natural soil fertility. Grasslands characteristically have high inherent soil organic matter content, averaging 333 Mg[1] ha^{-1} (Schlesinger, 1977). Soil organic matter – an important source of plant nutrients – influences the fate of organic residues and inorganic fertilizers, increases soil aggregation, which can limit soil erosion, and also increases action exchange and water holding capacities (Miller and Donahue, 1990; Kononova, 1966; Allison, 1973; Tate, 1987). It is a key regulator of grassland ecosystem processes. Thus, a prime underlying goal of sustainable management of grassland ecosystems is to maintain high levels of soil organic matter and soil carbon stocks.

Portions of the grasslands on every continent have been degraded owing to human activities, with about 7.5 percent of grassland having been degraded because of overgrazing (Oldeman, 1994). More recently, the Land Degradation Assessment in Drylands (LADA) concluded that about 16 percent of rangelands are currently undergoing degradation and that rangelands comprise 20–25 percent of the total land area currently

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[1] mega grams

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being degraded. This process affects the livelihoods of over 1.5 billion people worldwide (Bai *et al.*, 2008). Present degradation is probably taking place in addition to historic degradation (Bai *et al.*, 2008). Cultivation of native grasslands has contributed substantially to the transfer of about 0.8 Mg of soil carbon to the atmosphere annually (Schlesinger, 1990). Soil organic matter losses due to conversion of native grasslands to cultivation are both extensive and well documented (Kern, 1994; Donigian *et al.*, 1994; Follett, Kimble and Lal, 2001). Removal of large amounts of aboveground biomass, continuous heavy stocking rates and other poor grazing management practices are important human-controlled factors that influence grassland production and have led to the depletion of soil carbon stocks (Conant and Paustian, 2002a; Ojima *et al.*, 1993). However, good grassland management can potentially reverse historical soil carbon losses and sequester substantial amounts of carbon in soils.

CHAPTER 3

Opportunities

CARBON SEQUESTRATION IN GRASSLANDS

Disturbance – defined as removing biomass, changing the vegetation or altering soil function – is an integral part of traditional grassland management systems, which fosters dependable yields of forage. However, disturbance through overgrazing, fire, invasive species, etc. can also deplete grassland systems of carbon stocks (Smith *et al.*, 2008). Harvesting a large proportion of plant biomass enhances yields of useful material (e.g. for forage or fuel), but decreases carbon inputs to the soil (Figure 2) (see Box 1) (Wilts *et al.*, 2004).

Primary production in overgrazed grasslands can decrease if herbivory reduces plant growth or regeneration capacity, vegetation density and community biomass, or if community composition changes (Chapman and Lemaire, 1993). If carbon inputs to the soil in these systems decrease because of decreased net primary production or direct carbon removal by livestock, soil carbon stocks will decline.

Like carbon sequestration in forests or agricultural land, sequestration in grassland systems – primarily, but not entirely in the soils – is brought about by increasing carbon inputs. It is widely accepted that *continuous excessive* grazing is detrimental to plant communities (Milchunas and Lauenroth, 1993) and soil carbon stocks (Conant and Paustian, 2002a). When management practices that deplete soil carbon stocks are reversed, grassland ecosystem carbon stocks can be rebuilt, sequestering atmospheric CO_2 (Follett, Kimble and Lal, 2001).

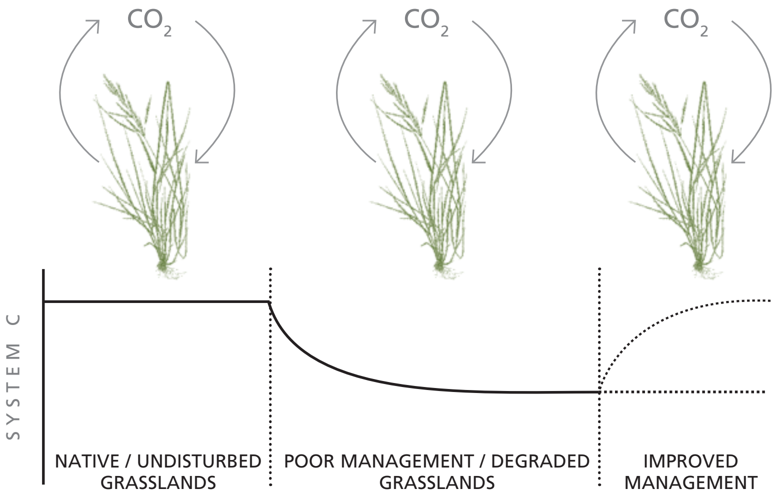

FIGURE 2: **Conceptual diagram illustrating how past land management has led to depletion of grassland soil carbon stocks due to practices that decrease carbon uptake. Implementation of improved management practices can lead to enhanced carbon uptake, restoring ecosystem carbon stocks and sequestering atmospheric CO_2 in grassland soils.**

BOX 1: **Carbon stocks are a function of carbon inputs and outputs**

All ecosystems – forested ecosystems, agro-ecosystems, grassland ecosystems, etc. – take up atmospheric CO_2 and mineral nutrients and transform them into organic products. In grasslands, carbon assimilation is directed towards the production of fibre and forage by manipulating species composition and growing conditions. Ecosystems are a major source and sink for the three main biogenic greenhouse gases (GHG) – CO_2, nitrous oxide (N_2O) and methane (CH_4). In undisturbed ecosystems, the carbon balance tends to be positive: carbon uptake through photosynthesis exceeds losses from respiration, even in mature, old-growth forest ecosystems (Luyssaert *et al.*, 2008; Gough *et al.,* 2008;

Stephens *et al.,* 2007). Disturbance, such as fire, drought, disease or excessive forage consumption by grazing, can lead to substantial losses of carbon from both soils and vegetation (Page *et al.,* 2002; Ciais *et al.*, 2005; Adams *et al.*, 2009). Disturbance is a defining element of all ecosystems that continues to influence the carbon uptake and losses that determine long-term ecosystem carbon balance (Randerson *et al.,* 2002).

Human land-use activities function much like natural activities in their influence on ecosystem carbon balance. CO_2 is produced when forest biomass is burned, and soil carbon stocks begin to decline soon after soil disturbances (Lal, Kimble and Stewart*,* 2000). Like natural disturbances such as fire and drought, land-use change affects vegetation and soil dynamics, often prompting further increased carbon releases and decreased carbon uptake. Deforestation, degradation of native grasslands and conversion to cropland have prompted losses of biomass and soil carbon of 450–800 Gt/CO_2 – equivalent to 30–40 percent of cumulative fossil fuel emissions (Houghton *et al.,* 1983; DeFries et *al.,* 1999; Marland, Boden and Andres, 2000; Olofsson and Hickler, 2008**)** Emissions from conversion from forests to cropland or other land use have dominated carbon losses from terrestrial ecosystems (DeFries *et al.,* 1999), but substantial amounts of carbon have been lost from biomass and soils of grassland systems as well (Shevliakova *et al.*, 2009).

The basic processes governing the carbon balance of grasslands are similar to those of other ecosystems: the photosynthetic uptake and assimilation of CO_2 into organic compounds and the release of gaseous carbon through respiration (primarily CO_2 but also CH_4).

Biomass in grassland systems, being predominantly herbaceous (i.e. non-woody), is a small, transient carbon pool (compared to forest) and hence soils constitute the dominant carbon stock. Grassland systems can be productive ecosystems, but restricted growing season length, drought periods and grazing-induced shifts in species composition or production can reduce carbon uptake relative to that in other ecosystems. Soil organic carbon stocks in grasslands have been depleted to a lesser degree than for cropland (Ogle, Conant and Paustian*,* 2004), and in some regions biomass has increased due to suppression of disturbance and subsequent woody encroachment. Much of the carbon lost from agricultural land soil and biomass pools can be recovered with changes in management practices that increase carbon inputs, stabilize carbon within the system or reduce carbon losses, while still maintaining outputs of fibre and forage.

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Many management techniques intended to increase livestock forage production have the potential to augment soil carbon stocks, thus sequestering atmospheric carbon in soils. Methods of improved management include fertilization, irrigation, intensive grazing management and sowing of favourable forage grasses and legumes. Grassland management to enhance production (through sowing improved species, irrigation or fertilization), minimizing the negative impacts of grazing or rehabilitating degraded lands can each lead to carbon sequestration (Conant and Paustian, 2002a; Follett, Kimble and Lal, 2001; Conant, Paustian and Elliott, 2001). Improved grazing management (management that increases production) leads to an increase of soil carbon stocks by an average of 0.35 Mg C ha^{-1} yr^{-1} (Conant, Paustian and Elliott, 2001).

Agroforestry enhances carbon uptake by lengthening the growing season, expanding the niches from which water and soil nutrients are drawn and, in the case of nitrogen (N)-fixing species, enhancing soil fertility (Nair, Kumar and Nair, 2009). The result is that when agroforestry systems are introduced in suitable locations, carbon is sequestered in the tree biomass and tends to be sequestered in the soil as well (Jose, 2009). Improved management in existing agroforestry systems could sequester 0.012 Tg[1] C yr^{-1} while conversion of 630 million ha of unproductive or degraded croplands and grasslands to agroforestry could sequester as much as 0.59 Tg C annually by 2040 (IPCC, 2000), which would be accompanied by modest increases in N_2O emissions as more N circulates in the system (see Box 2 for information on grassland emissions of other GHGs).

Using seeded grasses for cover cropping, catch crops and more complex crop rotations all increase carbon inputs to the soil by extending the time over which plants are fixing atmospheric CO_2 in cropland systems. Rotations with grass, hay or pasture tend to have the largest impact on soil carbon stocks (West and Post, 2002). Adding manure to soil builds soil organic matter in grasslands (Conant, Paustian and Elliott, 2001). The synthesis by Smith *et al.* (2008) suggests that adding manure or biosolids to soil could sequester between 0.42 and 0.76 t C ha^{-1} yr^{-1} depending on the region (sequestration rates tend to be greater in moist regions than in dry). Rapid incorporation of manure into fields

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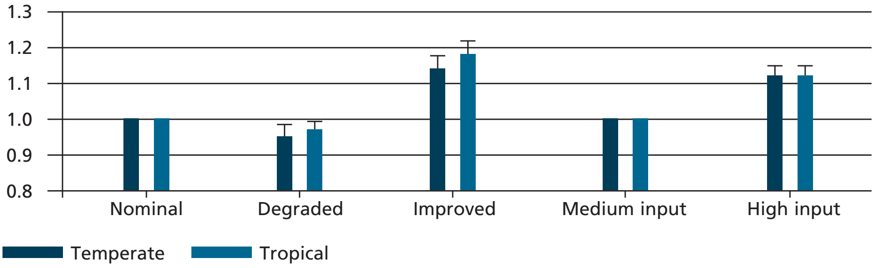
[1] $Tg = 10^{12}g$

BOX 2: **Full GHG accounting**

When mineral soil N content is increased by N additions (i.e. fertilizer), a portion of that N can be transformed into N_2O as a by-product of two microbiological processes (nitrification and denitrification), and lost to the atmosphere. Coincidental introduction of large amounts of easily decomposable organic matter and NO_3^- from either a plough down of cover crop or manure addition greatly stimulates denitrification under wet conditions (Mosier, Syers and Freney, 2004). Some practices intended to sequester atmospheric carbon in soil could prompt increases in N_2O fluxes.

For example, fertilization increases soil mineral N concentrations, leading to increased N_2O fluxes, particularly in wetter environments. N_2O is the most potent biogenic GHG in terms of global warming potential, with a radioactive forcing 296 times that of CO_2 (IPCC, 2001). Management activities that add mineral or organic N – fertilization, plant N_2 fixation, manure additions, etc. – augment naturally occurring N_2O emissions from nitrification and denitrification by 0.0125 kg N_2O kg N applied^{-1} (Mosier *et al.,* 1998). Agriculture contributes significantly to total global N_2O fluxes through soil emissions (35 percent of total global emissions), animal waste handling (12 percent), nitrate leaching (7 percent), synthetic fertilizer application (5 percent), grazing animals (4 percent) and crop residue management (2 percent). Agriculture is the largest source of N_2O in the United States of America (78 percent of total N_2O emissions), Canada (59 percent) and Mexico (76 percent).

CH_4 emissions from ruminant animals comprise about one-third of non-CO_2 GHG emissions from agriculture (IPCC, 2007a). To the extent that practices that sequester carbon lead to increased stocking rates, CH_4 fluxes would increase, potentially offsetting mitigation due to sequestration (Soussana *et al.,* 2007). CH_4 emissions from ruminant animals are a measure of production inefficiency – more CH_4 emitted means less of the carbon consumed by livestock is converted to product (FAO, 2006; Leng, 1993). The complement is also largely true: increasing production efficiency reduces CH_4 emission. Consequently, investments to reduce CH_4 emissions will lead to increased production efficiency.



These factors estimate proportional carbon sequestration or loss (i.e. through degradation) given departure from nominal management practices. Medium inputs require one external input (e.g. fertilizer improved species, etc.) whereas high inputs require more than one external input. These management factors are presented as proportional increases in carbon stocks rather than carbon sequestration rates, so that the factors can be applied to all soils.

FIGURE 3: **Grassland management factors for temperate and tropical regions**

Source: Figure reproduced from Ogle, Conant and Paustian, 2004

would reduce the time that manure decomposes in anaerobic piles and lagoons, reducing emissions of CH_4 and N_2O. IPCC (2007a) estimates the technical potential for reduction of CH_4 emissions from manure to be 12.3 Tg C yr^{-1} by 2030; N_2O emissions could also be reduced. Adding manure in one place to build soil carbon stocks is offset by removal, or what would be carbon inputs in another place (by forage or feed harvest). The balance between these has not been well characterized. Summary data synthesized by climate region are presented in Figure 3.

Globally, an estimated 0.2—0.8 Gt[2] CO_2 yr^{-1} could be sequestered in grassland soils by 2030, given prices for CO_2 of USD20–50/tonne (IPCC, 2007a). Although both fertilization and fire management could contribute to carbon sequestration, most of the potential sequestration in non-degraded grasslands is due to changes in grazing management practices. Estimated rates of carbon sequestration per unit are lower than those for sequestration on agricultural land, but sequestration potential is comparable to that of croplands because grasslands cover such a large portion of the earth's surface (Figure 4). Nearly 270 million ha of grassland worldwide have been degraded to some degree

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[2] $Gt = 10^{15}g$

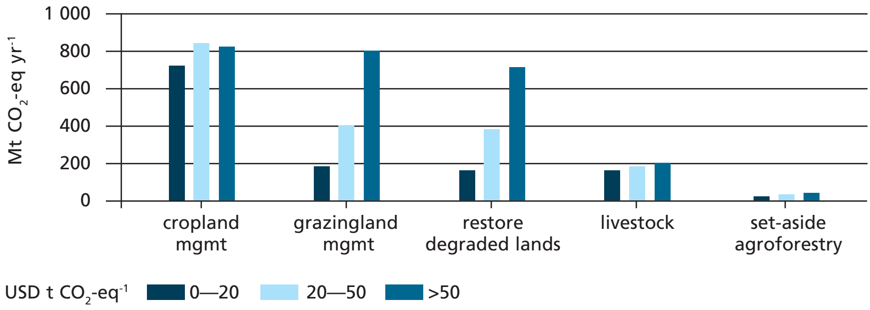

FIGURE 4: **Estimates of carbon sequestration potential for several mitigation measures at varying carbon prices**

Source: IPCC, 2007a

by mismanagement (Oldeman, 1994; Bridges and Oldeman, 1999). Much of this land can be rehabilitated by enhancing plant productivity, capturing water resources and using them more efficiently, or improving soil fertility; doing so could sequester about as much carbon as could be sequestered in grasslands (0.15—0.7 Gt CO_2 yr^{-1} depending on carbon prices) (IPCC, 2007a).

REDUCED CARBON EMISSIONS THROUGH REDUCED GRASSLAND DEGRADATION

Grasslands contain a substantial amount of the world's soil organic carbon. Integrating data on grassland areas (FAOSTAT, 2009) and grassland soil carbon stocks (Sombroek, Nachtergaele and Hebel, 1993) results in a global estimate of about 343 billion tonnes of C – nearly 50 percent more than is stored in forests worldwide (FAO, 2007).

Just as in the case of forest biomass carbon stocks, grassland soil carbon stocks are susceptible to loss upon conversion to other land uses (Paustian, Collins and Paul, 1997) or following activities that lead to grassland degradation (e.g. overgrazing). Current rates of carbon loss from grassland systems are not well quantified. Over the last decade, the grassland area has been diminishing while arable land area has been growing, suggesting continued conversion of grassland to croplands (FAOSTAT, 2009). When grasslands are converted to agricultural land, soil carbon stocks tend to decline by an average of about 60 percent (Paustian, Collins and Paul, 1997; Guo and Gifford, 2002).

Grassland degradation has also expanded (Bai *et al.*, 2008), probably contributing to the loss of grassland ecosystem carbon stocks. Arresting grassland conversion and degradation would preserve grassland soil carbon stocks. The magnitude of the impact on atmospheric CO_2 is much smaller than that due to deforestation, but preserving grassland soil carbon stocks serves to maintain the productive capacity of these ecosystems that make a substantial contribution to livelihoods.

PRACTICES THAT SEQUESTER CARBON IN GRASSLANDS OFTEN ENHANCE PRODUCTIVITY

An important argument in favour of grassland carbon sequestration is that implementation of practices to sequester carbon often lead to increased production and greater economic returns. Forage removal practices that disturb the system and prompt carbon losses usually reflect attempts to enhance forage utilization, but the complement is not necessarily true: practices that sequester carbon do not necessarily result in reduced forage utilization.

Reducing the amount of carbon inputs removed, or increasing production, carbon inputs or below-ground allocation, could all lead to increasing soil carbon stocks (Conant, Paustian and Elliott, 2001). Grazing management can lead to decreased carbon removal if grazing intensities are reduced or if grazing is deferred while forage species are most actively growing (Kemp and Michalk, 2007). Sustainable grazing management can thus increase carbon inputs and carbon stocks without necessarily reducing forage production. Grazing management can also be used to restore productive forage species, further augmenting carbon inputs and soil carbon stocks.

Other practices that enhance production, such as sowing more productive species or supplying adequate moisture and nutrients, also result in greater carbon uptake, ecosystem carbon stocks and forage production (Conant, Paustian and Elliott, 2001) (Box 3).

BOX 3: Which grassland management practices increase carbon stocks?

1. **Grazing management** can be improved to reverse grazing practices that continually remove a very large proportion of aboveground biomass. Implementing a grazing management system that maximizes production, rather than offtake, can increase carbon inputs and sequester carbon.

2. **Sowing improved species** can lead to increased production through species that are better adapted to local climate, more resilient to grazing, more resistant to drought and able to enhance soil fertility (i.e. N-fixing crops). Enhancing production leads to greater carbon inputs and carbon sequestration.

3. **Direct inputs of water, fertilizer or organic matter** can enhance water and N balances, increasing plant productivity and carbon inputs, potentially sequestering carbon. Inputs of water, N and organic matter all tend to require energy and can each enhance fluxes of N_2O, which are likely to offset carbon sequestration gains.

4. **Restoring degraded lands** enhances production in areas with low productivity, increasing carbon inputs and sequestering carbon.

5. **Including grass in the rotation cycle** on arable lands can increase production return organic matter (when grazed as a forage crop), and reduce disturbance to the soil through tillage. Thus, integrating grasses into crop rotations can enhance carbon inputs and reduce decomposition losses of carbon, each of which leads to carbon sequestration.

Improved management techniques can increase forage production and reduce feed costs, financially benefiting producers. As forage production increases, an ancillary benefit may lie in increased sequestration of atmospheric carbon. Indeed, Gifford *et al.* (1992) noted that improved pasture management is an important consideration when computing a

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national carbon budget. A variety of grassland management practices lead to near-term increases in both production and sequestration of carbon, and practices that sequester carbon often enhance producer income. Practices that reduce offtake – through grazing or harvest – tend to enhance carbon inputs, building carbon stocks. Thus, grazing management practices that increase carbon inputs by increasing production can sequester carbon. Also, practices that increase production inputs by enhancing soil fertility or sowing more productive species can help to build up soil carbon stocks. Directly introducing more carbon to the system through organic matter (e.g. manure) additions will also lead to increased carbon stocks, although it has been pointed out that increases are gained at the expense of carbon inputs where feed crops are grown (Conant, Paustian and Elliott, 2001).

In addition to enhancing forage production and food security, many land management practices that sequester carbon prompt other changes in environmental processes that are beneficial for other reasons. Practices that sequester carbon in grassland soils tend to maximize vegetative cover, reducing wind and water-induced erosion (Follett, Kimble and Lal, 2001). Reducing sediment load increases water quality while reducing airborne particulate matter improves air quality. Carbon sequestering practices can also enhance ecosystem water balance; building soil organic matter stocks tends to enhance water infiltration and soil moisture status in arid-semi-arid environments (Unger *et al.*, 1991). In many cases practices that sequester carbon can lead to greater biodiversity (Bekessy and Wintle, 2008).

	CO_2	CH_4	N_2O	AGREEMENT	EVIDENCE
Grazing intensity	+/-	+/-	+/-	*	*
Increased productivity (e.g. through fertilization)	+		+/-	**	*
Nutrient management	+		+/-	**	**
Fire management	+	+	+/-	**	*
Species introductions (incl. legumes)	+		+/-	*	**

TABLE 1: **Mitigative effects of various aspects of grazing land improvement**

Source: Reproduced from IPCC, 2007a

Most grassland management practices with the potential to sequester carbon were developed to address issues other than carbon sequestration. For example, expanding grasslands through agricultural set-asides and rehabilitating degraded rangelands are often intended to arrest wind and water erosion (Lal, 2009a). Practices that preserve the habitat, like grassland preservation, rehabilitation, etc., can preserve species and biodiversity. A variety of practices that integrate grass species into arable crop rotation (for example, catch crops used to retain nutrients, cover crops to reduce erosion, grass crops in rotation) sequester carbon and also retain nutrients in agricultural systems, reducing downstream pollution (Stevens and Quinton, 2009).

PRACTICES THAT SEQUESTER CARBON IN GRASSLANDS CAN ENHANCE ADAPTATION TO CLIMATE CHANGE

Mitigation investments are crucially important for reducing the impacts of climate change, but GHG concentrations will continue to increase for decades despite implementation of even the most aggressive climate policies (IPCC, 2007a). Therefore, adaptation is an important response to climate change that should begin now (IPCC, 2007b). Because yield reductions under drought, heat stress, floods and other extreme events will be the most consequential, negative impacts of climate change, efforts to adapt to a changing climate should focus on increasing the resilience of management systems (FAO, 2008a; WMO, 2007). The increasing frequency of droughts in the drylands (Thornton *et al.*, 2008) and droughts of longer duration are expected to have a substantial negative effect on the sustainability and viability of livestock production systems in semi-arid regions. Grassland management practices maximize the infiltration, capture and utilization of precipitation for production (Woodfine, 2009). In cases where sustainable grazing management increases soil carbon stocks, soil water holding capacity increases. Both facets of enhancing water balance will increase drought resilience.

Grassland management practices that sequester carbon tend to make systems more resilient to climate variation and climate change: increased soil organic matter (and carbon stocks) increases yields (Vallis *et al.*, 1996; Pan *et al.*, 2006); soil organic matter also enhances soil fertility, reducing reliance on external N inputs (Lal, 2009b). Surface cover, mulch and soil organic matter all contribute to a decrease in interannual variation in yields (Lal *et al.*, 2007); and practices that diversify cropping systems, such as grass and forage crops in rotation, sequester carbon and enhance yield consistency.

Agricultural practices intended to mitigate GHG emissions could increase vulnerability to climate variation and climate change, if they increase the energy supply from food production systems (e.g. to supply biomass energy), or prevent arable land from being cultivated (e.g. afforestation). Similarly, actions intended to foster adaptation could lead to increased emissions: e.g. increased N fertilization (and N_2O release) to enhance yields or harvest of stover for conversion to biofuels (IPCC, 2007a). However, practices that minimize soil disturbance and maintain good ground cover, restore soil carbon stocks and related soil biological activity, diversify crops and integrate crop/livestock production, will tend to increase soil carbon stocks and enhance resilience to drought and climate change (Woodfine, 2009).

POTENTIAL INCOME FOR PRACTICES THAT SEQUESTER CARBON

One of the main arguments for grassland sequestration is that the impending climate impacts are real and potentially severe, so all options to reduce GHG emissions should be pursued. The principle of comparative advantage suggests that a wider range of options should generate lower costs initially and overall. The potential contribution of grassland, forestry and agricultural sequestration to mitigate GHG emissions is large – together rivalling the potential emission reductions from the energy supply, transportation, buildings, waste and industrial sectors at low prices for carbon (USD20/Mg CO_2) and exceeding all sectors at high carbon prices (USD100/Mg CO_2) (IPCC, 2007b). The Intergovernmental Panel on Climate Change (IPCC) (2007b) estimated that grasslands, forestry and agriculture would sequester approximately 8 Gt CO_2 yr^{-1} given carbon prices of USD100/Mg CO_2; including reduced emissions from deforestation and degradation would maintain an additional 4 Gt CO_2 yr^{-1} in the soil, raising total contribution of the land sectors to about one-third of total annual global emissions (i.e. 12 Gt CO_2 yr^{-1} out of 30 Gt CO_2 yr^{-1}; Figure 5). Substantial amounts of CO_2 emission from the land sector and large potential for sequestration with changes in land management are among the most important arguments in favour of terrestrial sequestration.

Some practices that sequester carbon require land managers to forego optimal harvest (e.g. reducing forage offtake), tolerate reduced yields (e.g. reduced stocking rates) or change land use (e.g. cessation of grazing of vulnerable soils). Others require investments in new equipment that could be substantial (e.g. for seeding, irrigation or fertilization). However, the primary investments necessary for successful widespread adoption of many of the land management practices that enhance ecosystem carbon

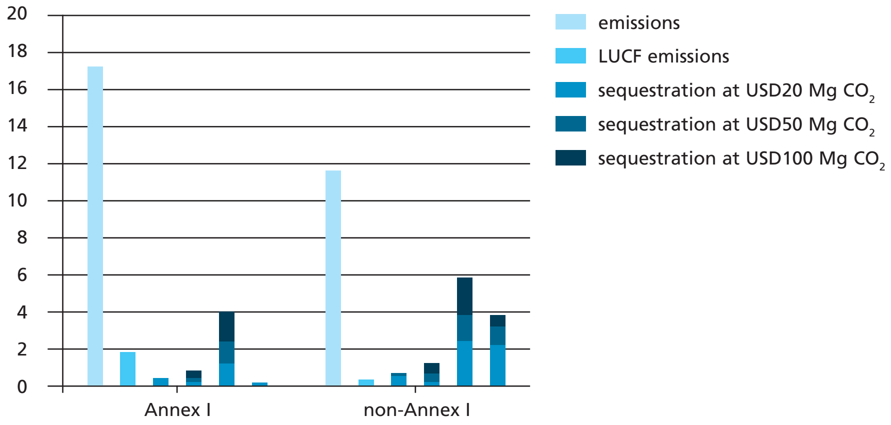

FIGURE 5: **Emissions, emissions from land-use change/forestry (LUCF) and sequestration potential at USD20, 50 and 100 per Mg CO$_2$ for agricultural, grassland, forest and REDD activities**

Source: IPCC, 2007b

storage are knowledge, education and information. Most of the materials required for the implementation of many practices that sequester carbon (e.g. improved species, legumes, grazing management, fire management, etc.) are often no different than those required for degradative land management practices – they differ primarily in their implementation. Technical requirements are often modest and marginal abatement costs are estimated to be negative in some cases (such as adoption of no-tillage in the United States of America and the United Kingdom) (Kelly, Redmond and King, 2009; Creyts *et al.*, 2007).

Carbon emissions from land-use change arise primarily from countries that are exempt from emission reductions under the Kyoto Protocol. Widespread disturbance and degradation (Oldeman, 1994) and continuing deforestation make carbon sequestration and preservation (i.e. United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation [UN-REDD]) substantial sequestration opportunities in these developing countries (Conant and Paustian, 2002a; Benitez *et al.*, 2007; Lal, 2000). Engagement of developing countries in emission reduction activities that simultaneously enhance adaptive strategies is another argument in favour of grassland carbon sequestration (Jung, 2005). Given modest costs and the use of existing technologies, grassland carbon sequestration in developing countries could be enacted in the near term, offsetting emissions from other sectors now, allowing time for the larger investments required to reduce directly emissions from burning fossil fuels (Ellis *et al.*, 2007). Investments in carbon sequestering practices in developing countries that increase grassland/livestock efficiency or productivity and reduce vulnerability to impacts of climate change (i.e. enhancing adaptation) are likely to promote relatively immediate sustainable returns. The economic, environmental and social costs of land degradation are substantial (FAO, 2008b) and investments in sustainable grassland management tend to be an efficient use of limited development resources (The World Bank, 2007). New knowledge about best practices is likely to be required in order to have a meaningful impact in much of the developing world.