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SUSTAINABLE LAND MANAGEMENT FOR MITIGATION OF AND ADAPTATION TO CLIMATE CHANGE

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Executive Summary

1. Increase in atmospheric abundance of carbon dioxide (CO_2) and other greenhouse gases or GHGs (e.g., CH_4, N_2O) is caused largely by anthropogenic activities such as land use conversion for agricultural and silvopastoral purposes, and fossil fuel combustion for energy production. Elevated levels of these GHGs have various effects such as global warming and climate change; however the potential to cause global warming varies among the different GHGs. Indeed the global warming potential (GWP) is 1 for CO_2, 21 for CH_4 and 310 for N_2O. Land use conversion, transformation of forests/savannahs and prairies/steppes via deforestation and biomass burning, started with the dawn of settled agriculture about 8 to 10 millennia ago. Cultivation of rice paddies and domestication of livestock about 5 millennia ago started anthropogenic emission of CH_4. As much as 320 Gt C (see Glossary for details: 1 Gt = 1 billion tons) may have been emitted from terrestrial ecosystems until 1850 and another 158 Gt C thereafter. In comparison, emissions from fossil fuel combustion are estimated at 292 Gt C from 1750 to 2002, and additional 200 Gt C emissions are projected between 2003 and 2030. Conversion of natural to managed ecosystems causes depletion of the terrestrial (soil and biota) C pools because of removal of the vegetation cover, biomass burning, and depletion of the soil organic C (SOC) pool. Removal of the vegetation cover exacerbates losses by soil erosion, increases in the rate of decomposition due to changes in soil temperature and moisture regimes, and reduction in biomass addition to the soil through root biomass and detritus material, and creates a negative C budget. Thus, most agricultural soils have lost between 25% to 75% of their original SOC pool. This deficit has created a C sink (capture) capacity which can be filled through conversion to a restorative land use and adoption of sustainable land management (SLM) technologies. The latter include options which create positive C, elemental (nutrients) and water budgets, enhance net primary productivity and agronomic yield, and increase farm income.

2. The climate change (CC) caused by increase in atmospheric concentration of CO_2 and other GHGs, can be addressed through adaptation and mitigation strategies. Adaptation consists of strategies which minimize vulnerability to CC. The objective is to increase resilience of the ecosystems and communities through adoption of specific SLM techniques that have adaptive benefits. On the other hand, the goal of mitigation strategies is to enhance soil and vegetation (land) sinks for absorbing atmospheric CO_2 and to minimize net emissions. In the context of the resource-poor and small landholders of the developing countries, adaptation to CC is essential. Adaptation strategies are needed to enhance the positive and reduce the negative effects of CC. Adaptation is also needed because complete mitigation of CC may never occur. The strategy is to adopt those SLM technologies which have both adaptation and mitigation impacts at multiple scales (household, community, watershed, national, global).

3. There are four major areas in the tropics and sub-tropics where adoption of SLM technologies can help to both adapt to and mitigate CC: (i) tropical forest ecosystems (TFEs), (ii) tropical savannah and rangeland ecosystems (TSREs), (iii) world cropland soils, and (iv) salinized and degraded/desertified lands. Nonetheless, adoption of SLM technologies in the temperate regions (North America, Europe, Australia, Japan) is also important to adapting to CC. However, this report focuses on SLM options for developing countries of the tropics and sub-tropics.

4. An important strategy in addressing CC comprehensively is to ensure that removal and/or degradation of primary forests is avoided wherever possible. In other words, avoided

deforestation is the best and most cost effective strategy to retain the ecosystem C pool and contribute directly to CC mitigation. Such standing forests (e.g., mangrove forests along coatal zones, catchment forests, etc) are also important in minimizing the impact of climate related hazards such as storms and droughts and helping communities adjust and adapt to changing climate. While forest plantations established on degraded agricultural soils (e.g., croplands, pastures) can increase the ecosystem C pool (soil, litter, biomass), plantations established after removing primary forest cause net emissions and deplete ecosystems C pool. The TFEs have an estimated technical potential of C sequestration of 0.8-1.0 Gt C/yr through afforestation, forest succession and regrowth and establishment of plantations (0.2-0.5 Gt C/yr) involving fast growing species. But it is important to note that such plantations do have important tradeoffs that may affect ecosystem services (eg, tree species such as eucalypts can affect the local water balance, become invasives, lead to biodiversity loss, and as monocultures they are vulnerable to pests/disease, etc). Furthermore, establishment of forest plantations may also require additional land, water and nutrients and compete for these limited resources with those required for food production.

5. The adoption of SLM technologies in TSREs, such as management of tropical savannas and rangelands/pastures, has a technical potential of C sequestration estimated at 0.3-0.5 Gt C/yr. Restoration of grazing lands is an important component, especially in semi-arid and arid regions. More importantly, overgrazing must be avoided since chronically overgrazed lands are most prone to degradation and loss of soil C pool.

6. World cropland soils, (~1500 million hectares) have a large C sink capacity.Most cropland soils have lost 30 to 50% of their original soil C pool. The loss is comparatively more in degraded and depleted soils managed by resource-poor farmers of Sub-Saharan Africa (SSA), South Asia (SA), Caribbean and the Andean regions. Eroded and degraded soils managed by extractive farming practices have lost upto 75% or more of their original C pool, and thus have a high technical C sink capacity. The SLM options include adoption of no-till (NT) farming in conjunction with cover cropping and complex rotations (conservation agriculture), integrated nutrient management (INM) involving biofertilizers and inorganic fertilizers to create the positive nutrient budget, and water conservation (water harvesting and recycling) including supplemental irrigation using drip sub-irrigation. The technical potential of world cropland soils is estimated at 0.6-1.2 Gt C/yr.

7. Restoration of degraded soils and ecosystems is an essential strategy to recarbonize the planet. Large areas of once biologically productive soils have been degraded by physical (erosion, compaction, crusting), chemical (nutrient depletion, salinization, acidification) and biological processes (depletion of SOC pool, reduction in soil biota) leading to a severe depletion of the soil and the biotic C pools. Restoration of such degraded soils and desertified ecosystems can restore the SOC and terrestrial C pools. The estimated technical potential of restoring salt-affected soils is 0.4-1.0 Gt C/yr, and that of desertification control is 0.6-1.7 Gt C/yr. Thus, global potential of C sequestration through adoption of SLM technologies is 2.8-5.3 Gt C/yr (4 Gt C/yr). This potential applies to soils of all biomes (e.g., croplands, grazing lands, forest lands, wetlands and peat soils and degraded and desertified lands), and is the maximum or technical potential of restoring all ecosystems. Even if the economic potential is about 50%-75% of the technical potential, C sequestration through SLM can offset fossil fuel emissions at the rate of about 2 to 3 Gt C/yr. With 1 Gt of soil C being equivalent to 0.47 ppm of atmospheric CO_2, adoption of SLM technologies have a possibility of draw down of atmospheric CO_2 by 120 to 150 ppm over the 21^{st} century. Adoption of SLM technologies, especially by the resource-poor farmers and small landholders of the developing countries, can be promoted through,

among other things, payments for ecosystems services. Trading of C and green water credits though CDM and other voluntary mechanisms are an option which can be pursued through a transparent payment system based on location-specific and area-based SLM interventions in targeted areas.

8. In addition to and contributing to CC adaptation and mitigation, there are numerous co-benefits of various SLM practices and technologies. Important among these are improvement in soil quality, increase in use efficiency of input and agronomic productivity, enhancement in quality and quantity of fresh water resources, and increase in biodiversity. Improvement in soil quality is essential to alleviating food insecurity that affects ~1 billion people worldwide. Widespread use of SLM technologies can increase the SOC pool and improve use efficiency of inputs. Increase in agronomic yield through increase in SOC pool by 1 t C/ha/yr with adoption of SLM technologies is about 300-400 kg/ha for maize, 40-60 kg/ha for soybeans, 20-30 kg/ha for cowpeas, 30-50 kg/ha for wheat, and 10-50 kg/ha for rice (Lal, 2006a). Therefore, annual increase in food production in developing countries can be 24-50 million t/yr of cereals and 8-10 million t/yr of root crops (Lal, 2006b), hence restoration of degraded soils and ecosystems through scaling up SLM options is a truly win-win strategy. It helps support adaptation to and mitigation of CC, advances food security, improves the environment, enhances farm income, and contributes to reduction of rural poverty in many developing countries.

I. Introduction

1. Land refers to the combined soil, water, air, and biotic resources, as well as current land uses that are the basis for rural land use systems. It comprises of soil used for cropland, meadows, pastures, woods, wetlands, marshes, furze, heath, urban and industrial principles. Rural (non-urban) refers to the combined physical, economic and social landscapes that constitute the rural ecumen (space), including managed (agricultural, forest, grasslands, conservation) and natural areas (wilderness, wetlands, etc), but not protected areas, such as national parks, etc.

2. Land is a principal source of livelihood for the majority of poor people in many countries. Besides providing people's livelihoods, land-based activities (such as agriculture and livestock) account for much of the export earnings of many developing countries. Indeed the most important source of environmental income in the world is agriculture, with the small-scale farming being the main pillar that supports the majority of the rural populations in most developing countries (WRI et al., 2005). However, there is evidence of declining land productivity and studies show that significant losses may result if land degradation, among other environmental problems, is not abated. Evidence has shown that areas with good land management also have low incidence of rural poverty.

3. Land degradation (LD) is both a global environment and local development issue that affects all ecosystems and continents. It affects nearly a quarter of cultivable land and creates pressures on the livelihoods of over 1 billion people who depend on land-based activities for their survival. Especially in dryland ecosystems, land degradation, also known as desertification (i.e., persistent degradation of dryland ecosystems due to variations in climatic and

anthropogenic factors), affects the livelihoods of millions of people who depend heavily on ecosystem services for their basic needs (MEA, 2005). Indeed in drylands, more (poor) people depend on ecosystem services than in any other ecosystem. Given this dependence, poverty and land degradation are intertwined. Measures to address LD have strong implications for poverty reduction. Attempts to address rural poverty must therefore include measures to arrest land degradation through sustainable land management. This is especially true for areas such as Sub-Saharan Africa (SSA) where 60% of of the population still live in rural areas and about 70% of cultivated land is affected by some form of degradation (Sanchez, 2002).

4. Climate change (CC) is one of the most pressing global problems of the 21st century. There is widespread recognition and evidence which suggests that global climate change is a reality, and it is likely to influence future patterns of land use and land productivity. However, most countries, especially developing countries, cannot address CC in isolation of their most immediate needs, the food security. This reality calls for linking/operationalizing CC action on existing platforms for poverty reduction in developing countries.

5. Sustainable Land Management (SLM) is defined as a knowledge based combination of technologies, policies and practices that integrate land, water, biodiversity, and environmental concerns (including input and output externalities) to meet rising food and fiber demands while sustaining ecosystem services and livelihoods (World Bank, 2006). SLM aims to simultaneously: (i) maintain or enhance production and services, (ii) reduce the level of production risks, (iii) protect the potential of natural resources and prevent degradation of soil and water quality, and (iv) enhance economic viability and social acceptability (Wood and Dumanski, 1994). In the context of this report, SLM options are defined as those land use and soil/vegetation management practices which create a positive carbon (C), water (H_2O), and elemental balance in

the terrestrial biosphere, enhance net primary productivity (NPP), mitigate climate change (CC) by creating negative CO_2 emissions and improving the environment, and adapting to CC through adjustments in timings of farm operations and alleviation of biotic and abiotic stresses. Such SLM technologies have evolved since 1960s from no-till (NT) farming in 1960s, to conservation agriculture in the 1990s, and SLM systems during 2000s (Figure 1).

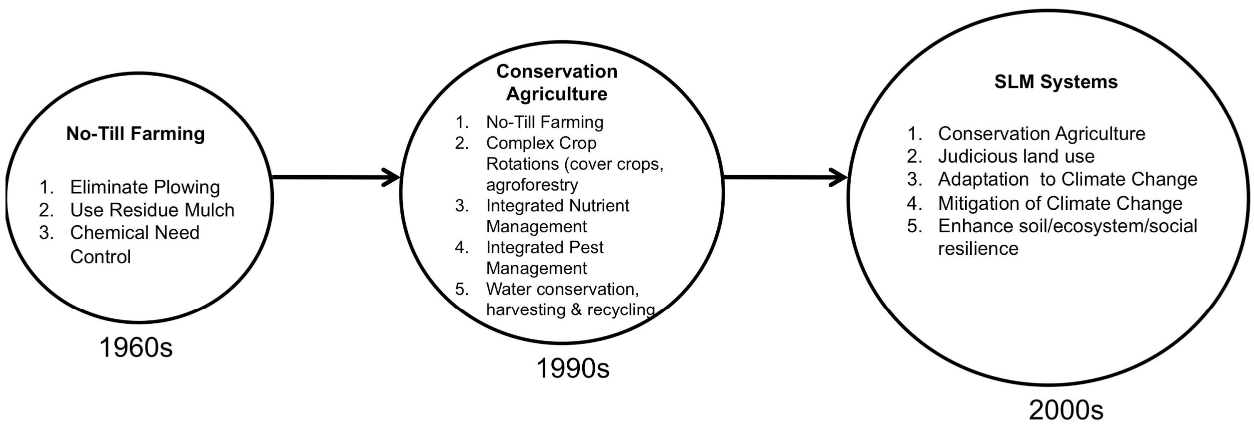


Fig 1. Evolution of sustainable land management (SLM) systems.

6. There are a wide range of SLM options, and no single technological option is suitable for all biophysical, social, economic and ethnic/gender-related situations. Some of the proven SLM technologies include no-till (NT) farming with use of crop residue mulch and incorporation of cover crops in the rotation cycle, integrated nutrient management (INM) technologies including liberal use of compost and biochar[1] as soil amendment, complex cropping systems including agroforestry, water harvesting and recycling using drip irrigation, improved pasture management, and use of innovations such as zeolites and nano enhancement fertilizers (Wild 2003). The choice of an appropriate SLM option depends on site-specific situations. Indicators of SLM for croplands include: (i) agronomic such as crop yields, nutrient balance, soil cover, (ii)

[1] Biochar is a charcoal produced from biomass and is largely inert, highly porous (hence good for drainage and microbial activity), can be used for soil improvement including C sequestration. Biochar is a key ingredient in the formation of anthropogenic Amazonian dark earth (soils).

ecological including soil quality, soil C pool and flux, soil degradation, water quality, weather trends and micro/mesoclimate, erosion, non-point source pollution, emissions of GHGs, (iii) economic such as farm income, profitability, proportion of income spent on food, and (iv) social comprising of the adoption rate of a SLM technology, institutional support available to farmers, age distribution, gender/social equity, land tenure, literacy, human health, etc. Similar sets of SLM indicators for grazing lands include forage quality, maintenance of riparian areas, soil erosion and water quality, stocking rate, etc.

II. Rationale and Context

7. While 75% of the global poor are rural and mainly agrarian, it is also clear that agriculture is and will remain the driver of economic growth in many developing countries, where it often represents at least 25% of GDP. But the quality and productivity of the land depends on the way agriculture is practiced. Better agricultural techniques will necessarily include SLM. And appropriate SLM practices can contribute to agriculture productivity improvements. Combating LD via SLM can lead to increase in land productivity while also improving the environment and mitigating CC. These improvements and ancillary benefits are a direct consequence of increase in quantity and quality of Soil Organic Matter (SOM), as a result of: a) increase in accumulation of organic residues above and below (roots) the soil surface, and b) decrease in oxidation/decomposition rate of organic residues and of inherent SOM content (due to lower surface temperature, more CO_2 and less O_2 in the soil pores, no incorporation of residues), and decline in losses of SOM because of decline in risks of soil erosion by water and wind.

8. The value of SLM can be enhanced to accentuate both local and global benefits by harnessing its potential to sequester carbon (C) in the terrestrial ecosystems including soil and

above ground biomass, and hence directly contributing to CC mitigation (Lal 2006). Other SLM practices such as perennial cover-cropping (e.g., with drought tolerant shrubs and trees) can enhance the ability of areas to be more resilient to extreme climate variability and change (e.g., droughts) while also sequestering C. Hence, investments in SLM can yield livelihood, development, environmental and climate benefits. Therefore, SLM and agricultural growth are not and should not be just about farming and food commodities. Producers will only practice SLM if it pays to do so; hence land degradation mitigation strategies must be designed and implemented as part of the broad and specific development agenda, with the needs of the local communities as their primary focus. Producers (especially poor farmers) would increasingly need to be facilitated into non-traditional and often value-added opportunities such as payments for ecosystem services (PES) and C markets.

9. The objectives of SLM are consistent with many core World Bank policies and strategies that address poverty reduction, rural development and environmental management. The World Bank is already one of the leading financiers of SLM globally. The 2008 WDR advocates improved livelihoods in sustainable agriculture as one of the pathways out of poverty. Improving the livelihoods of subsistence farmers includes improving land productivity and increasing the resilience of farming systems to reduce risk and food insecurity through better natural resource management (NRM). Given its commitment to addressing CC in its operations, the World Bank Group has recently developed the **Strategic Framework on Development and Climate and Change (SFDCC)** which puts priority on strengthening the resilience of communities and economies to climate risks. This, together with other strategies (e.g., Environment Strategy, Reaching the Rural Poor: a Renewed Strategy for Rural Development**,** etc**)** set the framework for

investments in SLM (World Bank, 2001, 2003, 2008). In order to achieve the objectives set out in the strategies, it is important for the World Bank to ensure that its SLM investments capture the synergies and trade-offs between poverty alleviation and climate change action in a targeted and sustainable manner.

SLM-based Carbon Sequestration contributes to Mitigating Climate Change and Greenhouse Gases

10. The two principal sources of the increase in atmospheric carbon (C) pool are fossil fuel combustion and deforestation/land use change (Broecker 2007; IPCC 2007). In the tropics and sub-tropics, deforestation and land use change constitute the principal sources. Whereas nutrients (e.g., N, P, K, S) released by decomposition and burning of biomass are absorbed by crops, C is released into the atmosphere as CO_2 and CH_4 along with nitrogen as N_2O and NO_x. Hence, agricultural practices can render a soil either a sink or a source of greenhouse gases (GHGs, particularly CO_2), with direct influence on the greenhouse effect and the attendant CC (Lal 2004; Lal 2005). Agricultural practices that lead to emissions of GHGs from the soil to the atmosphere include: deforestation (CO_2, CH_4, N_2O), biomass burning (CO_2, CH_4, N_2O), plowing and soil disturbance (CO2), draining of wetlands (CO_2, N_2O), and uncontrolled grazing (CO_2, N_2O). Emission of these gases from agricultural ecosystems is enhanced by subsistence agricultural practices which do not invest in soil quality improvement practices such as erosion control, water management, and application of fertilizers and other amendments.

11. Sequestration of C in terrestrial ecosystems (soils and trees) is widely recognized as a viable strategy to mitigate CC while providing numerous ancillary benefits by also enhancing ecosystem services (such as increased soil productivity, enhanced rainfall infiltration, aquifer recharge, etc). The available data on C sequestration from diverse soils and ecoregions show the

significant contribution that improved soil management can play in C sequestration and mitigation of the greenhouse effect (Lal 2006). Technological options for C sequestration in soil include conservation tillage, mulch farming, integrated nutrient management (INM) including use of manure and biochar, restoration of degraded soils, composting, integrated pest management (IPM), landscape reclamation through afforestation, elimination of bare fallow, and improved pasture management (Lal 2004). Conservation tillage offers the best option for C sequestration in: (a) temperate humid and semi-arid areas, and (b) tropical and sub-tropical humid areas.

SLM and Adaptation to Climate Change is crucial for most developing countries

12. While much work on CC has focused on mitigation, there is an urgent need to balance the approach with strong focus on adaptation, and especially so for SSA. The rationale for increase in focus on adaptation includes the following:

- Least preparedness of stakeholders in many developing countries, especially in terms of institutional resources and capacity, to address the consequences of CC (the challenge of "adaptation") or to tap into the numerous benefits of climate-friendly technologies (the "mitigation" challenge).
- Widespread adoption of those land management practices (e.g., deforestation, biomass burning, land use conversion, soil degradation and desertification) which contribute to CC in most developing countries (especially in sub-Saharan Africa), even more so than emissions from fossil fuel. Thus, action on mitigation in such countries must necessarily concentrate on land use changes and avoided deforestation. Such a strategy will also have positive livelihood and development impact.

- Furthermore, even if global C emissions were reduced in the near future, developing countries such as those in SSA would still be faced with the massive challenge of adapting to CC. Therefore**,** a broader approach is needed to tackle the challenges linked to CC, through responsive measures that prioritize adaptation via mainstream development programs including investments in SLM. Investing in SLM practices such as agro-forestry and perennial cover-cropping can improve the micro-climate, prevent soil erosion, sequester C and help strengthen the resilience of local environments to climate change risks (e.g., droughts).

III. Objectives

13. Investments in SLM can generate appreciable benefits for developing countries by helping to increase agronomic productivity, enhance food security, strengthen NRM, and contribute to effective grass-roots level climate adaptation and mitigation measures. The objective of this report is to show that sustained investment in SLM practices is good business for adaptation and mitigation to CC. SLM is local and efforts to adapt to CC must necessarily also be local and site specific to be successful. Hence this report highlights SLM potential contribution to CC adaptation and mitigation in various parts (ecoregions) of the world. Indeed the need to scale up SLM investments is good not just for land, but for climate action too. Many investments and international policy debates, however, have under-played, missed or lacked appreciation of the potential contribution of SLM to climate action at country level. Consequently, this report contributes to elevating awareness by:

- Presenting practical analysis that can inform policy makers and practitioners to encourage investments in scaled-up SLM activities that contribute to CC adaptation and mitigation especially in developing countries, and,

- Synthesizing the SLM related adaptation-mitigation win-wins (e.g., planting mangroves sequesters carbon and buffers the effects of storm surges on infrastructure near the coast), while noting the crucial operational trade-offs (e.g., tree species such as eucalyptus that are good for carbon sequestration may not be best for biodiversity conservation).

IV. Methodology and Scope

14. This report is based on collation and critical review of the relevant information on SLM practices and technologies in relation to their potential to offset anthropogenic GHG emissions, enhance resilience to climate change and advance food security. While the scope of the report is global, emphasis is placed on the resource-poor small size land holders in developing countries. The report: (a) presents the inter-play of exposure to climate variability and climate change and elevated risk of food insecurity (Schimel 2006; Shapouri and Rosen 2006), (b) describes a range of operationally-relevant SLM technologies and practices for soil restoration and C sequestration for diverse soils and ecoregions, (c) identifies and describes a range of SLM practices that directly contribute to measurable CC mitigation and adaptation benefits, and (d) considers the constraints to adoption of SLM and the potential for scaling up such activities in developing countries.

V. Climate Variability and risks of global food insecurity

15. Some of the key global issues of the 21st century which necessitate that humans be responsive to the attendant changes are: (i) atmospheric concentration of CO_2 increasing from 280 ppm in pre-industrial era to 385 ppm in 2008 (+ 37.5%), and presently increasing at the rate of ~2 ppm/yr, (ii) soil degradation affecting 2 billion hectares (ha) globally and increasing at the rate of 5 to 10 million ha/yr and desertification affecting 3-4 billion hectares especially in

developing countries, (iii) food insecure population of ~1 billion and increasing, and the per capita grain consumption of 300 kg/yr and decreasing, (iv) water scarcity (< 1000 m^3/person/yr) affecting population in 30 countries and increasing to 58 countries by 2050, (v) per capita cropland area of 0.22 ha and decreasing to < 0.07 ha by 2025 for at least 30 densely populated countries, and (vi) global energy demand of 475 quads (1 quad = 1 x 10^{15} BTU) and increasing at the rate of 2.5%/yr. These issues are intertwined at global-scale and are accentuated by human activity (Walker et al., 2009), especially by the increase in world population. It was 6.7 billion in 2008, increasing at the rate of 1.15%/yr or by 70-80 million person/yr, and projected to be 9.2 billion by 2050. Almost all of the increase in world population will occur in developing countries where soils are fragile and under great stress, climate is harsh and changing, and water resources are scarce and getting severely polluted. Addressing the interrelated issues of soil degradation, food insecurity, water scarcity and climate change (CC), necessitates identification and implementation of specific sustainable land management (SLM) options.

VI. Food Security, Climate Change and Sustainable Land Management

16. The number of food-insecure people in the world, about 1 billion mostly concentrated in South Asia and sub-Saharan Africa, is increasing partly due to the rapid increases in prices of wheat, rice and other food staples. Global risks of food insecurity are likely to be exacerbated by the projected CC because of its direct and indirect effects (Figure 2). The principal constraint is the low crop yields obtained by predominantly resource-poor and small size landholders (<2 ha) in developing countries. Low crop yields are caused by the severe problem of soil degradation exacerbated by the widespread use of extractive farming practices, without adoption of any soil restorative measures. Soils in developing countries of the tropics and sub-tropics are severely degraded by accelerated erosion, depletion of SOM and nutrient pools (Muchena et al., 2005;

Anonymous, 2006), salinization, compaction and crusting because of decline in soil structure and water imbalance (too little or too much). Restoration of such degraded/desertified soils is essential to enhancing NPP, improving agronomic yields, and advancing food security. It is estimated that restoring SOM pool by 1 t C/ha/yr, through adoption of SLM practices, can increase food production in developing countries by 24 to 40 Mt/yr for food grains (e.g., wheat, maize, rice, sorghum, millet, cowpeas and soybeans), and by 8 to 10 Mt/yr for roots and tubers (e.g., yam, cassava, and sweet potatoes) (Lal, 2006a; b). The rate of grain production with increase in SOC pool varies among crops (Table 1). This process of improving productivity is an important strategy to increase food production in developing countries.

Table 1. Soil organic carbon impacts on crop yields in the tropics and subtropics (Lal, 2006).

Country	Crop	Soil/region	Yield Increase (Kg/ha/yr/t of SOC)
Kenya	Maize	Kikuyu red clay	243
Kenya	Beans	Kikuyu red clay	50
Nigeria	Maize	Egbeda/Alfisol	254
Nigeria	Cowpea	Egbeda/Alfisol	20
Argentina	Wheat	*Haplundolls/Haplustoll*	64
Thailand	Maize	Northeastern	408
India	Mustard	Inceptisol/UP	360
India	Maize	Inceptisol/Haryana	210
India	Wheat	Inceptisol/Haryana	38
Sri Lanka	Rubber	Alfisol/Ultisol	66

18. Adopting SLM necessitates a practical understanding of the ecosystem functions influenced by land use and management, as moderated by soil quality (Herrick, 2000). Ecosystem C pool and its dynamics are closely linked with SLM (Yin et al., 2007). Such a linkage is especially important because CC may impact sustainability of agricultural land without the implementation of adaptation measures (Romanenko et al., 2007). CC affects ecosystem functions through changes in temperature and precipitation which may in turn considerably alter

agricultural production especially in the tropics with predominantly resource-constrained farmers. Therefore, adaptation to CC implies judicious management of soil quality, appropriate management of landscape units within watersheds, and soil carbon sequestration through management of pool and flux of ecosystem C (Figure 2).

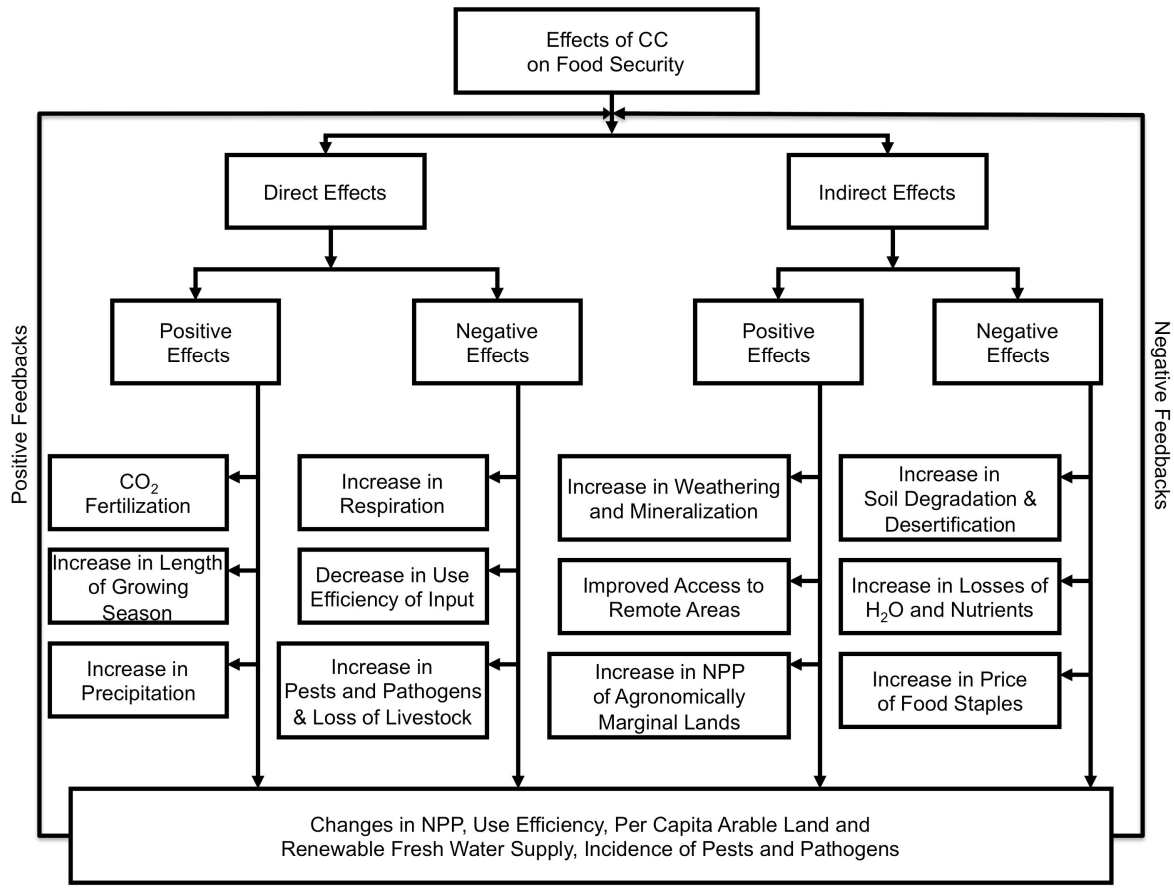


Fig. 2 Direct and indirect effects of climate change on food security in developing countries.

A. Adaptation Versus Mitigation: conceptual issues

19. The urgency to reduce net emission of GHGs into the atmosphere is necessitated by the threat of CC (Schellnhuber, 2005; IPCC, 2007; Hansen et al., 2006). Anthropogenic emissions

can be reduced by identifying non-C or low-C fuel sources, and improving the energy use efficiency. Furthermore, emissions (especially of CO_2) can be sequestered, or transformed into long-lived C pools. Sequestration can be through engineering or abiotic techniques (Chu, 2009; Haszeldine, 2009; Rochelle, 2009; Keith, 2009; Schrag, 2009; Orr, 2009; Normile, 2009) or through biotic measures involving the natural process based on the SLM principles. The need for biotic sequestration and adaptation is re-emphasized by the realization that oceanic uptake of CO_2 is decreasing over time (Que're et al., 2007), and that engineering techniques are expensive (McKinsey & Co., 2009), and still work in progress. Reducing and offsetting anthropogenic emissions require SLM strategies both for adaptation and mitigation. Adaptation to climate change involves any activity that reduces the negative impacts of climate change and/or takes advantage of new opportunities that may be presented (Lemmen et al., 2008). IPCC defines adaptation as an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits benefitical opportunities. Adaptation consists of strategies, which may be either anticipatory or reactive, and by which crops, forages, trees and domestic livestock can become better suited to CC by minimizing their vulnerability to alterations in temperature, effective precipitation and seasonality. Adaptation strategies are synonymous with sustainable development objectives, which is to increase resilience of the cropping/farming systems. In contrast, mitigation involves specific soil and vegetation (land) management activities to reduce the extent and severity of CC. The goal of mitigation strategies is adopt those SLM techniques which enhance soil and vegetation (land) sinks for absorbing atmospheric CO_2 (Scherr and Sthapit, 2009). Conceptual differences among mitigation and adaptation strategies are outlined in Figures 3 and 4. Adaptation strategies may be technological, such as SLM options and practices, policy-based for improved risk management, or managerial such as conversion of cropland to forestry or pastoral land use. The goal is to reduce vulnerability to CC. There is strong value addition in linking adaptation and mitigation actions (Aylis and Huq, 2009). Indeed various SLM technologies and practices can be chosen to help communities to both adapt to and mitigate CC. In the context of the resource-poor and small land holders in developing countries, adaptation to CC is essential because of their vulnerability to harsh environments especially with regard to food-insecurity, water scarcity, climate related harzards (floods, droughts) and degradation of soils and other natural resources. Therefore speficic adaptation strategies are needed to both enhance the positive and reduce the negative effects of CC on communities. Adaptation is also essential because complete mitigation of CC may not happen for a longtime of decades to centuries, if ever. Yet, the choice of SLM options must be such that adaptation and mitigation strategies complement one another and harness the synergistic interactions among them.

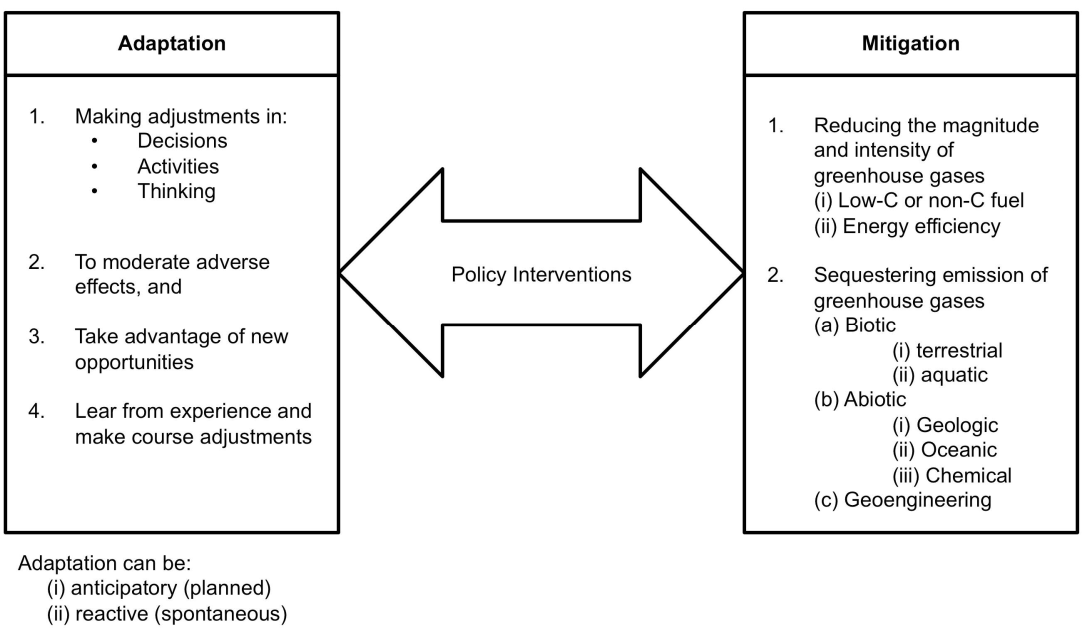


Fig 3. Adaptation vs. mitigation of climate change.

20. The overall goal is to adopt SLM technologies that promote adaptation by helping to buffer against increase in risks of CC (Figure 5). The strategy is to adjust to alternations in effective precipitation (rainfall minus evaporation and runoff losses reflecting the crop-available water reserves which may decrease with CC), increase in temperature, and change in growing season duration through: (i) soil quality improvement and watershed management, and (ii) ecosystem C enhancement and soil restoration (Figure 6). In the context of synergistic interactions, it is important to identify those SLM options which are relevant to adaptation, but are also effective in mitigation of CC. While site-specific SLM technologies have to be fine-tuned with due consideration to biophysical (e.g., soil, terrain, climate, vegetation) and human dimensions issues (e.g., farm size, farm income, institutional support, infra-structure, land tenure, social and gender equity), generic SLM options must address constraints related to soil (erosion, compaction, crusting, salinization, acidity), nutrients (macro and micro elements), water (drought, waterlogging, water quality) and vegetation (weeds, cropping systems, pastures). The long-term objective is to enhance production per unit use of energy–based input by minimizing losses and increasing resilience.

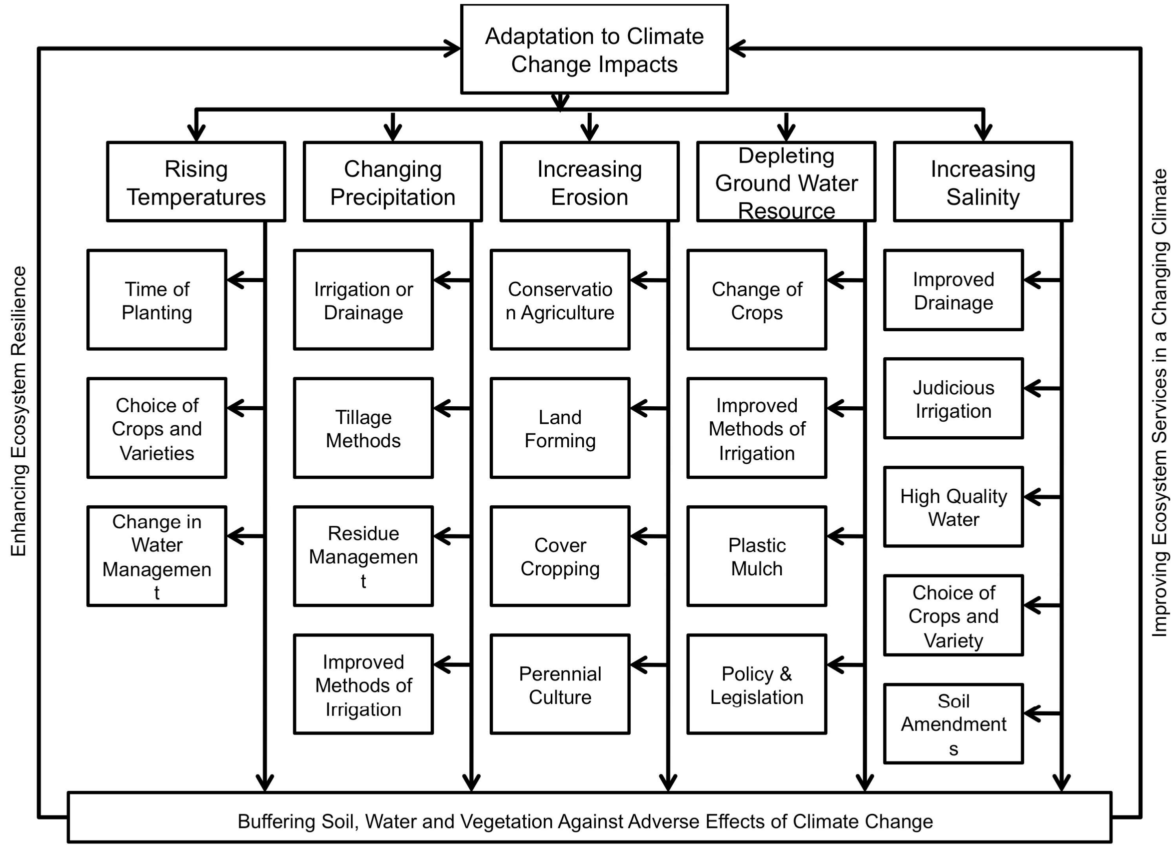


Fig. 5. Reducing risks of climate change through adaptive measures.

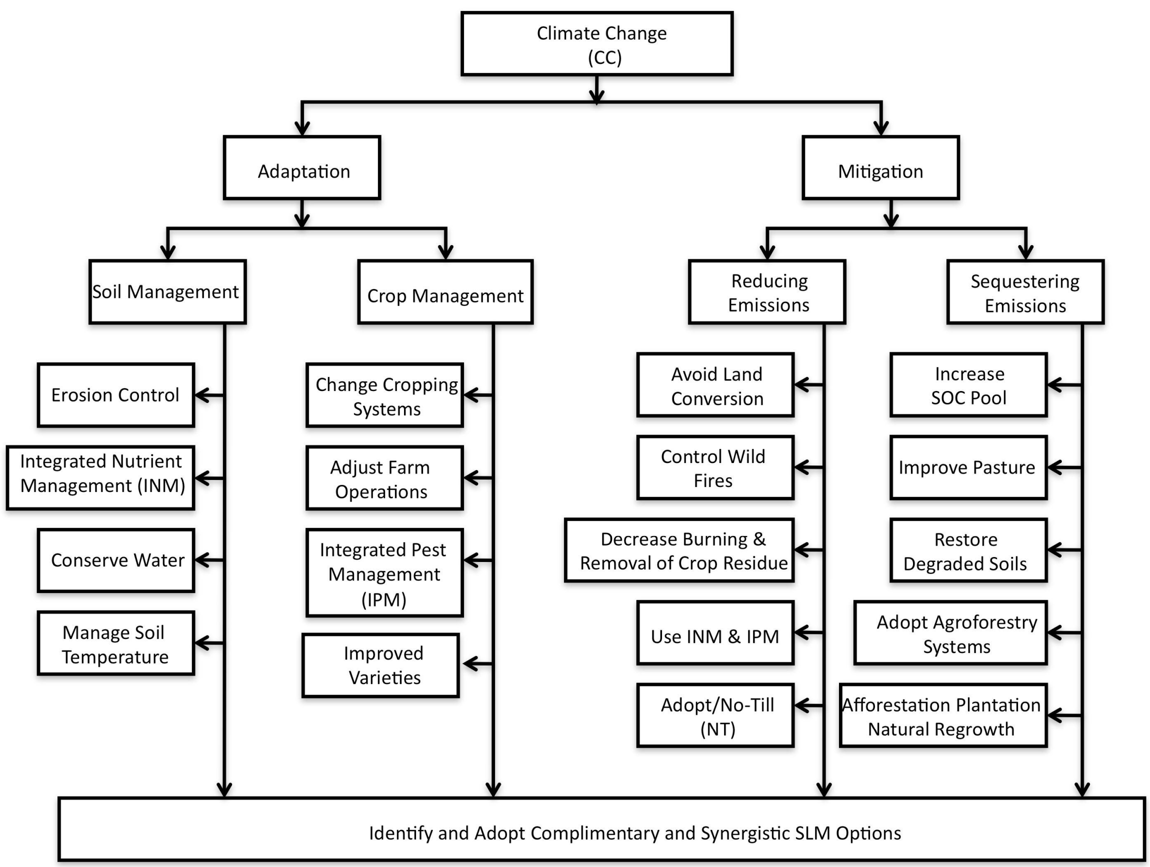


Fig. 6 Strategies for adaptation to and mitigation of the climate change.

B. Soils as a source of atmospheric carbon dioxide

21. World soils constitute the third largest global C pool, comprising of two distinct components: (i) soil organic C (SOC) pool estimated at 1550 Gt, and (ii) soil inorganic C (SIC) pool of 950 Gt, both to 1-m depth (Figure 7). Thus, the soil C pool of 2500 Gt is 3.1 times the atmospheric pool of 800 Gt, (Lal, 2005; IPCC, 2007) with the latter increasing at the rate of 4 Gt/yr. The soil C pool is also 4.03 times the biotic pool (620 Gt), with the latter decreasing at the rate of 1.6-2.0 Gt/yr. All global C pools (oceanic, geologic, pedologic, atmospheric and biotic) are interlinked, and C circulates among these pools. The rate of circulation or flux among pools depends on both natural and anthropogenic factors. For example, emission of 4 Gt of C from the geologic pool (fossil fuel combustion) increases the atmospheric pool by about 1 ppm. Similarly, transfer of about 0.5 ppm of C from the atmospheric pool into soil increases soil C pool by 1 Gt. The projected climate change may drastically alter the global soil C pool, through both positive and negative feedback mechanisms. Increase in global temperature may have a positive feedback due to increase in mineralization of the soil organic matter (SOM), and increase in soil erosion hazard. The largest impact of CC on soil C pool is likely to be in the soils of Tundra and Boreal regions. The permafrost soils, presently a sink of atmospheric C and containing as much as 40% of the global SOC pool, may thaw and become a major source with projected CC (especially global warming).

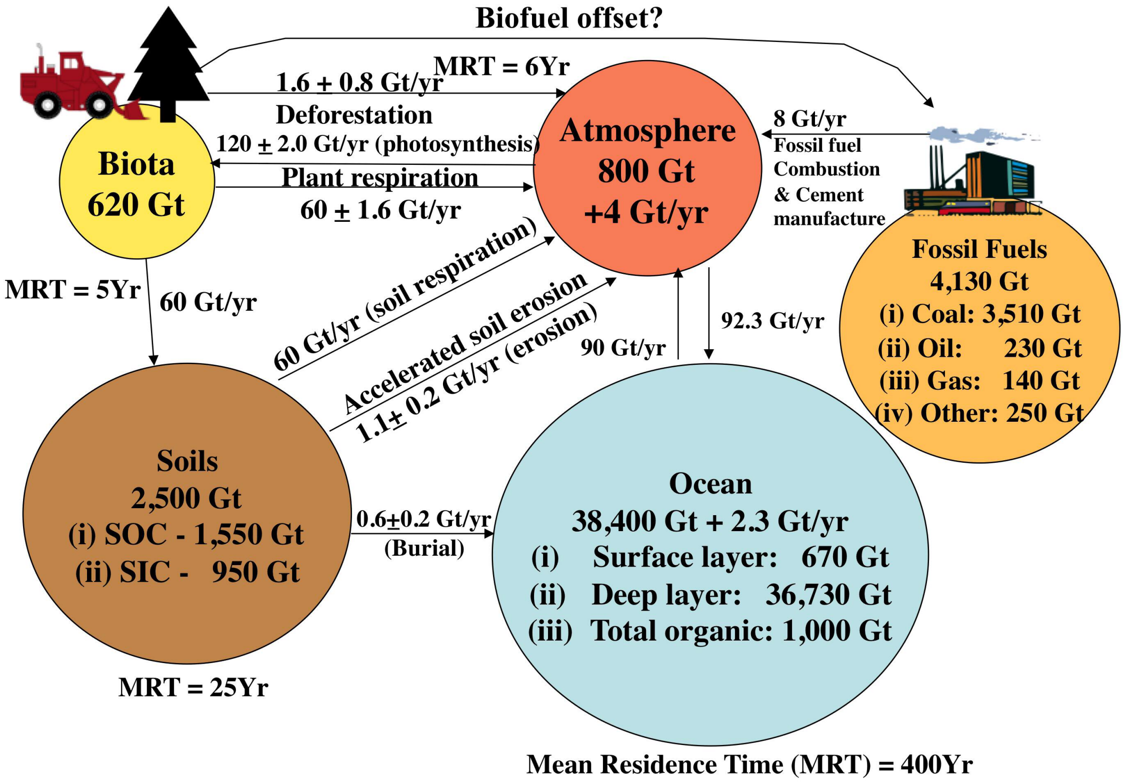


Fig. 7 Global carbon pool and fluxes (Updated from Lal, 2004b).

22. The terrestrial C pool (comprising of soils and trees) has been a source of atmospheric CO_2 ever since the dawn of settled agriculture since about 10,000 years. The amount of C emitted from the terrestrial pool from ~10,000 yrs to 1850 is estimated at 320 Gt. Another 156 Gt of C has been emitted since 1850 because of expansion of anthropogenic activitiesduring the 20th century which drastically depleted the terrestrial C pool. Thus, total emission from the terrestrial sources may be as much as 478 Gt C (Ruddiman, 2003; 2005). Until 1940s and 1950s, more C was emitted into the atmosphere from terrestrial ecosystems due to land use conversion and soil cultivation than from fossil fuel combustion. In comparison, emissions from fossil fuel combustion are estimated at 292 Gt C between 1750 and 2002, and additional emissions of 200

Gt C are projected between 2003 and 2030 (Holdren, 2008). In addtion to CO_2, terrestrial ecosytems are also a source of CH_4 and N_2O.

23. Similar to the estimates of the loss of C pool from terrestrial ecosystems at global scale, regional and national estimates are also available. For example, the loss of C pool in China over the last 300 years is estimated at 3.7 Gt from vegetation and 0.8-5.84 Gt from the soil. Thus, the total loss of terrestrial C pool from the terrestrial ecosystems in China is 4.5 to 9.54 Gt (6.18 Gt) (Quan Sheng et al., 2008). In arid regions of Tanzania, Birch-Thomsen et al. (2007) observed that soils cultivated for 50 years lost 50% of the original SOC pool equivalent to 1.7 kg/m^2 (17 t C/ha). However, reduction in SOC pool was negligible for sites near present or former villages which received substantial amounts of manure despite a long-cultivation history. Similarly, the SOC pool also did not decline in chronosequences representing wetter and fine-textured soils. In the Ethiopian Rift Valley, Nyssen et al. (2008) reported that land use and cover changes lead to the loss of vegetation cover and SOC pool. The SOC pool was 33.0 t C/ha in cropland, 26.3 t C/ha in grazing land and 45.9 t C/ha in woodland. The SOC pool increased from 20 t/ha on depleted coarse-textured soils to 45 t/ha under *Acacia-Balanites* woodland. Also, in Ethiopia, Girmay et al. (2008) reported that conversion of natural to agricultural ecosystems reduced SOC pool by 17% to 83%, while conversion from agricultural to perennial land use (e.g., tree crops) increased it by 1% to 30% over 10 years. Estimates of historic losses of SOC pool, which provide a reference line with regards to the technical potential of C sequestration or the soil C sink capacity have been made for the U.S. (Lal, et al., 1998; Lal and Follet, 2009), China (Lal, 2004b), India (Lal, 2004c), tropics (Lal, 2002a), Latin America (Lal et al., 2006), Central America (Lal et al., 2008) South Asia (Lal et al., 2009), dry land ecosystems (Lal, 2003a; 2004c; Lal et al., 2002b), and the World (Lal, 2003b). Such estimates of the historic C loss, are

important baselines and provide the reference point with regards to the technical potential of C sequestration, and are needed at the regional, national, continental and global scale. It is only with such baselines that various SLM options become key considerations in local livelihood activities that also contribute directly to local climate action in terms of mitigation and adaptation.

24. Conversion of natural to agricultural ecosystems leads to depletion of the SOC pool because C input into the system (through addition of root and shoot biomass and other detritus material) is less than the C loss from the system (e.g., crop harvests, burning, erosion, mineralization, leaching). The rate of mineralization of SOM under agricultural ecosystems is more than that under natural ecosystems because of changes in soil temperature and moisture regimes (Figure 8). Consequently, most agricultural soils have lost 30% to 50% of their original SOC pool in temperate climates and 50% to 75% or more in tropical ecoregions (Lal, 2004b). The magnitude of the depletion of SOC pool is severe in soils prone to degradation by erosion, and those managed by resource-poor farmers and small-size land holders who use extractive farming practices and are unable to adopt SLM options. It should also be noted that many resource-rich farmers are engaged in unsustainable land management practices due to existing distorted incentive systems. Therefore, most agricultural soils contain lower SOC pool than their potential capacity. This deficit in SOC pool, of agricultural and degraded/desertified vis-à-vis the soils under natural ecosystems, has created the so called “soil C sink capacity”. The latter is also determined by the climate, parent material, soil profile, internal drainage, slope gradient and aspect, landscape position, and soil properties (e.g., texture, clay mineralogy). The depleted SOC pool can be restored and the soil C sink capacity filled through soil C sequestration (SCS) by adoption of specific SLM practices.

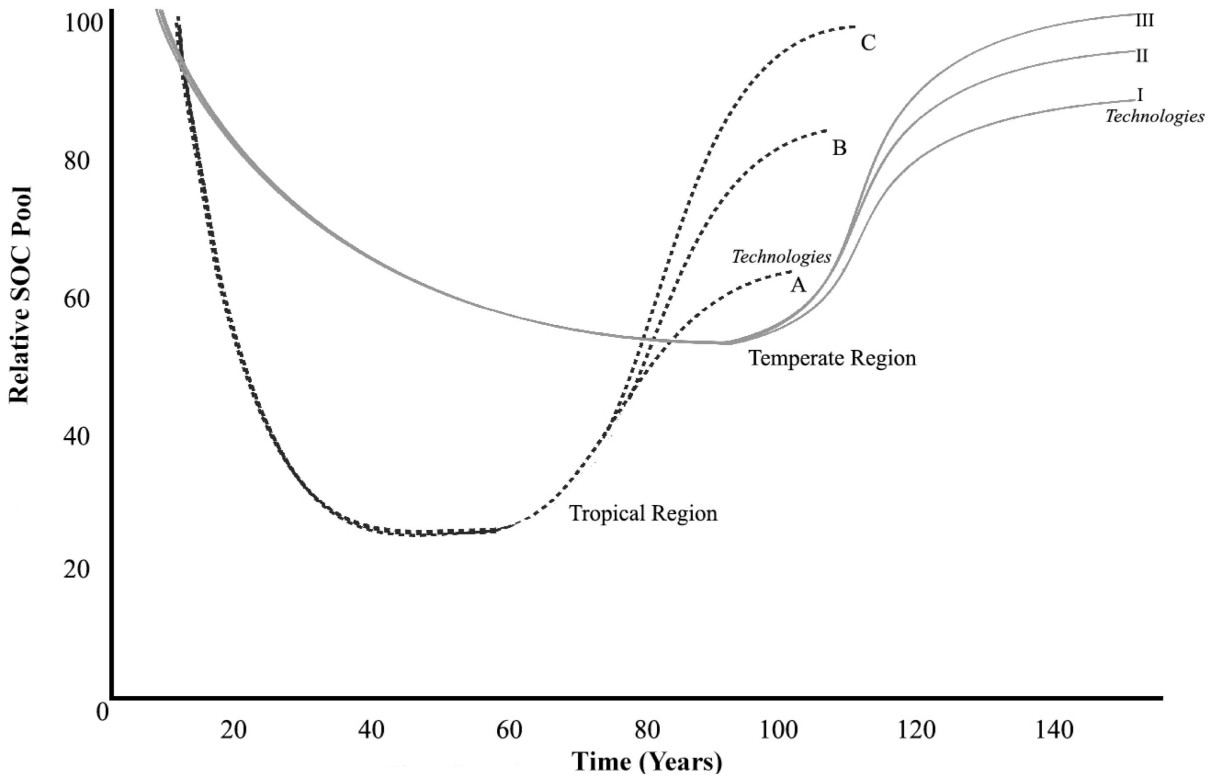


Fig. 8. Soil organic carbon dynamics upon conversion to a restorative land use and adoption of SLM technologies (A, B, C, and I, II, III refer to different SLM options).

C. Soil Carbon Sequestration (SCS)

25. The term ‘C sequestration’ implies capture and secure storage of atmospheric CO_2 into other pools such as biotic, pedologic/soil (together called terrestrial), geologic and oceanic so that it is not re-emitted into the atmosphere. In comparison, SCS occurs through humification of biomass and its stabilization through physical, chemical and biological processes. These processes are described briefly in this report along with techniques for measurement and modeling of the SOC pool for the purpose of trading soil C credits. The strategy of C sequestration is important because: (i) there are not yet viable non-C fuel sources, (ii) there is a strong need to stabilize atmospheric abundance of CO_2, (iii) it is essential to restore and enhance ecosystem services through restoration of degraded/desertified soils by increasing the SOC pool,

and (iv) it is essential to harness the numerous advantages of SCS over the engineering techniques of C capture and storage (CCS) into geologic/oceanic strata. The important point is that most SLM technologies and practices for SCS are proven and in use in many parts of the world. However, what is lacking is the adoption of these practices at scale. On the other hand, technologies such as carbon capture and storage show promise but are yet to be fully proven and applied widely. But there is no time to lose in dealing with the CC challenge: urgency is the key in reducing accumulation of C in the atmosphere. And the SLM practices presented in this report can be put to immediate use for SCS in a cost-effective manner. In addition to being cost-effective, other benefits of SCS include: (i) improvements in soil quality and agronomic/biomass productivity, (ii) increase in use efficiency of inputs such as fertilizer, irrigation water, energy, (iii) decrease in erosion and non-point source pollution, (iv) reduction in risks of hypoxia in coastal ecosystems, (v) increase in soil biodiversity, (vi) improvement in agronomic production, and (vii) achievement of local, regional and global food security. Despite numerous advantages, there are several concerns of SCS which must also be addressed through SLM options. These are: (i) low soil C sink capacity of 20 to 30 t/ha which can be filled at a modest rate of 0.3 to 1.0 t/ha/yr, (ii) uncertainties about the permanence of SCS which depends on land use, soil management and land tenure, and (iii) need for simple and routine methods of estimating changes in soil C pool for a landscape, region or watershed over a short period of 1 to 2 years. Significant advances have been made since the 1990s in effectively addressing some of these concerns. Land use, land use change, and conversion of degraded/desertified lands to restorative use are important to enhancing the ecosystem C pool. The choice of appropriate SLM practices is important to realizing the economic/technical potential for C sequestration of an ecosystem, because land use is an important means to alter the NPP of a terrestrial ecosystem. SCS is a readily implementable option for both mitigation and adaptation to CC, and it can be undertaken in most parts of the world and at different scales. It is important to point out that in addition to benefits of adaptation, SCS can also provide mitigation comparable in cost to current abatement options in other industries (Bangsund and Leistritz, 2008).

VII. SLM Technologies and Other Greenhouse Gases

26. In addition to CO_2, emissions of methane (CH_4) and nitrous oxide (N_2O) are also influenced by SLM. While CO_2 accounts for 63% of the total radiative forcing by long-lived GHGs (WMO, 2008), SLM technologies also play an important role in mitigation of and adaptation to the effects of other GHGs. The data in Table 2 show increase in atmospheric abundance of 3 GHGs due to anthropogenic activities. Methane contributes 18.5% of the direct radiative forcing. Principal sources of CH_4 are wetlands, termites, ruminants, rice paddies, fossil fuel exploitation, biomass burning and landfills. Nitrous oxide contributes 6.2% of the total radiative forcing. Principal sources of N_2O are oceans, soils, biomass burning, fertilizer use and fossil fuel combustion. Various SLM practices have a positive impact on reducing atmospheric abundance of all three GHGs. Good soil structure, through CA/NT and other mulch farming oxidizes atmospheric CH_4 and makes soil a sink. Improving use efficiency of nitrogenous fertilizers reduces N_2O emission. The data on CH_4 and N_2O emission can be converted into CO_2 equivalent by multiplication with the appropriate GWP value of 25 and 298, respectively.

Table 2. Atmospheric abundance and radiative forcing of three greenhouse gases (Adapted from WMO, 2007; IPCC, 2007).

Parameters	Atmospheric Concentration		
	CO_2 (ppm)	CH_4 (ppb)	N_2O (ppb)
Atmospheric concentration (2007)	383	1789	321
Increase since 1750 (%	137	256	119
Absolute Increase in 2006-07	1.9	6	0.8
Relative Increase in 2006-07 (%)	0.05	0.34	0.25
Global Warming Potential (per year)	1	25	298

VIII. Priority Action Themes and Range of SLM Practices

27. The SLM options and related ecological actions can be prioritized on the basis of principal land uses. These land uses are chosen on the basis of their agronomic/economic significance to advancing food security for the growing population, and also their sensitivity to be affected by and/or affect the projected CC. Therefore, this report focuses on four land uses deemed important to SLM for mitigation of and adaptation to CC. These are: (i) tropical forest ecosystems, (ii) savannas, grasslands and rangelands, (iii) croplands, and (iv) degraded and desertified soils including salinized soils. Relevant SLM options for these three land uses are outlined in Figure 9. The SLM strategy outlined in Figure 9 is part of a farming system approach that presents an innovative way of exploiting the land resources in rural and periurban areas in ways that maintain the integrity of the land while enhancing the livelihood of the producers. The value of SLM options listed in Figure 9 can be enhanced to accentuate both local and global benefits by harnessing their potential to sequester C in soils and biota, and accrue other co-benefits.

28. Priority action strategies listed in Figure 9 are based on the following criteria: (i) wherever possible, avoid deforestation and conversion of other natural ecosystems (e.g., savannahs, cerrado, pampas, llanos, steppes, peatlands) to agricultural land use, (ii) intensify

agricultural production on existing crop lands, (iii) increase use efficiency of inputs by enhancing production per unit input of fertilizer, irrigation water and other energy-based components of farming systems, (iv) take marginal lands out of production and convert these to restorative/perennial land use (e.g., tree crops, afforestation), (v) provide incentives to resource-poor farmers in developing countries through payment for ecosystem services rather than subsidies or emergency handouts, and (vi) commodify C sequestered in the soil by developing transparent mechanisms for trading such C credits.

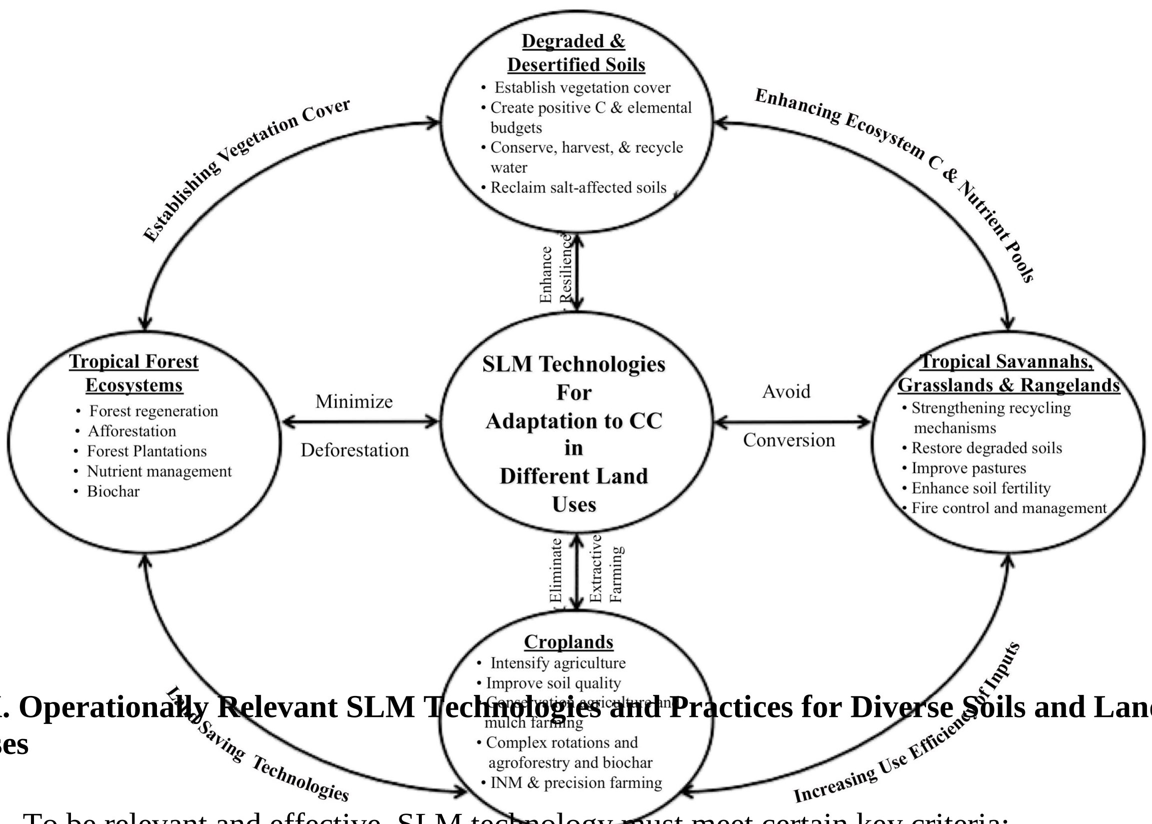


Fig. 9. Strategies for adaptation to climate change in different land uses.

IX. Operationally Relevant SLM Technologies and Practices for Diverse Soils and Land Uses

29. To be relevant and effective, SLM technology must meet certain key criteria:

(i) Technology must be scientifically proven through reliable and data-driven information, repeatable and measureable results, soil-specific agronomic yields, and objectivity-based conclusions. In addition, the choice of SLM technology must be based on local validation through participatory on-farm research.

(ii) The benefits (agronomic and economic) must be concrete, highly visible, and substantial and must accrue directly to the local producers. In situations where crop yields are extremely low (1 t/ha in rainfed farming in SSA, and SA), a technology which increases yield by 10 to 15% may not be sufficient. In view of the increasing population and rising food demand, SLM technology may need to triple or quadruple crop yields over a short period of 5 to 10 years. Therefore, productivity, efficiency, cost-effectiveness, and profitability are important considerations.

(iii) The SLM technology must be ecologically compatible, especially with regards to the current and projected CC. Important ecological factors are drought stress, unfavorable temperatures, high incidence of pests and pathogens, and increase in risks of erosion and other extreme events.

(iv) The SLM technologies must be socially acceptable and ethically grounded. The severe problem of soil degradation can be reversed by creating awareness about the stewardship of land resources. Faith-based and cultural organizations must be involved to teach responsibility, respect, generational/gender/social equity, fairness, and societal values of natural resources through SLM.

(v) Political support and acceptibility is extremely important to any SLM technology and strategy. The Green Revolution largely by-passed SSA partly due to lack of political support. It is now taking root in some countries of SSA (e.g., Malawi, Ghana) maily because of political support. Visionary leadership, committed to national progress and economic growth (rather than personal), is essential to relevance and effectiveness of SLM options.

(vi) SLM adaptation technologies must be considered as an integral component of the mitigation options. These should be considered neither as policy alternatives, nor as opposite to mitigation. In addition, SLM technologies that have appreciable mitigation benefits should be given the prominence they deserve, relative to other industrial mitigation technologies (e.g., clean coal, CCS).

(vii) There must by a minimal of trade-offs in terms of competition for land, water, nutrients, energy, etc. SLM technologies requiring additional inputs, are essential to advancing food security, restoring ecosystesm services, and improving the environment. In comparison, forest plantations would require additional water, nutrients and lands. Increasing food crop productivity through SLM is potentially important to limiting atmospheric CO_2 concentrations (Wise et al., 2009). In view of these considerations, SLM technologies for four prominent ecoregions are described in the following sections.

X. Tropical Forest Ecosystems (TFEs)

30. Forest land uses are important buffers against sudden environmental (e.g., climate) change. Indeed, geographical ranges of tree species have expanded and contracted several times since the last glacial epoch (Hamrick, 2004). Yet, the impact of change of TFEs on the environment and vice versa is an important factor in identifying appriopriate SLM strategies. The large land area and high biodiversity of TFEs warrant a detailed examination of their importance in the global C cycle. Tropical forests store 40-50% of C in terrestrial vegetation (Lewis et al., 2009). The TFEs occur within the humid tropics or the bioclimates characterized by consistently high temperatures and high relative humidity. Total annual rainfall of these regions ranges from 1500 mm to 4500 mm received over 8-12 months. The TFE biome occupies a total area of 1.8 billion hectares (Bha); the vegetation of the humid tropics is dominated by rainforest, covering 1.1 Bha to 1.5 Bha, or about 30% of the land area within the tropics (Table 3). But the available estimates of area of TFE vary widely. For example, Bruenig (1996) estimated the area of rainforest at 1.64 Bha in 1985 and 1.5 Bha in 1995. Knowledge about the major soil types and

their distribution is essential to understanding soil-related constraints and making a rational choice of the appropriate SLM options.The available information indicates that the predominant soils of these ecoregions are Oxisols, Ultisols, Alfisols, and Inceptisols. Of the total land area of TFEs of 1.8 Bha, 35% are Oxisols, 28% are Ultisols, 15% are Inceptisols, 14% are Entisols, 4% are Alfisols, 2% are Histosols, and 2% comprises Spodosols, Mollisols, Vertisols and Andisols (NRC, 1993). Soil-related constraints to crop production include nutrient imbalance characterized by low availability of N, P, Ca and Mg; low pH, and toxic concentrations of Al and Mn. Rather than attaining the steady state condition of the ecosystem C budget, even mature TFEs are natural C sinks because of the recovery of landscapes following disturbances (e.g., storms, fire, wind damage). Lugo and Brown (1992) estimated that TFEs removed from the atmosphere 2.0 to 3.8 Gt C/yr during 1980s.

Table 3. Estimates of area under tropical rainforest (Adapted from NRC, 1993; FAO, 2003).

	Tropical Rainforest Area (Mha)		
Region	**1980**	**1990**	**2000**
Africa	289.7	241.8	224.8
Latin America	825.9	753.0	718.8
Asia	334.5	287.5	187.0
Total	1450.1	1282.3	1130.6

31. Conversion of natural TFEs to agricultural land use leads to a rapid decline in the SOC pool which, in severely degraded soils, may decrease to 20% of the antecedent pool (Figure 10). Adoption of recommended SLM practices and technologies on degraded soils of TFEs can help sequester more SOC (mitigation) and adapt to CC. These practices include: no-till (NT) cropping of root or grain crops with crop residue mulch and integrated nutrient management (INM) for soil fertility improvement, adoption of agroforestry measures, establishing tree crop plantations (cocoa, coffee) with companion shade crops, and afforestation with rapidly growing and site-adapted plantations (Lal, 2005a, b). The rate of SOC sequestration under these SLM strategies

depends on the amount and quality (C:N ratio, lignin content, etc.) of biomass added, depth and proliferation of the root system, conservation-effectiveness of these measures for erosion control and change in soil moisture and temperature regimes that decreases the rate of decomposition of the biomass. The key is to select SLM practices that increase biomass addition to the soil, decrease the rate of its decomposition, and create a positive ecosystem C budget. Restoration of degraded soils and agriculturally marginal lands through afforestation and establishment of perennial vegetation cover (plantations) is an important strategy. Afforestation is also important for water conservation and reducing risks of soil erosion and sedimentation. Establishment of deep-rooted species helps transfer biomass C into the sub-soil where it is away from the zone of frequent perturbations (e.g. farm operations, erosion), and is sequestered for a long time.

A. Natural Regrowth and Forest Succession

32. Restoration of tropical forests is important to improving the environment while adapting to and mitigating CC. The strategy is to let the forest regrowth happen on degraded soils and agriculturally marginal land through natural succession. Yet, sustainable forestry in the tropics is not a panacea (Pearce et al., 2003), and must be objectively and critically assessed.

33. Reforestation has a large potential to fix atmospheric CO_2 through photosynthesis into biomass (Yokoyama, 1997), and humification of a part of the biomass (Lal, 2005a; b). Potential land area for reforestation may be 293 Mha in South America and Africa, and 47 Mha in Asia (Yokoyama, 1997). Globally, land area available for afforestation was estimated at 865 Mha by Houghton (1990), 952 Mha by Depert et al. (1992) and 600-1200 Mha by Winjum et al. (1992). In tropical dry forests of Jamaica, McLaren and McDonald (2003) evaluated several ecological factors (e.g., soil moisture and shade) that affect ecosystem C pool including seed germination

and seedling survival. Also in Jamaica, McDonald and Healey (2000) concluded that soil fertility and elemental cycling (C, N) are fully restored during 20 years of secondary succession.

34. The impacts of forest ecosystems on C sequestration have also been studied at a national scale such as in Spain (Bravo et al., 2008). A regional study conducted across 10 countries in Africa by Lewis et al. (2009) indicated that between 1968 and 2007, above ground C storage in live trees increased by 0.63 t C/ha/yr. Lewis and colleagues estimated the C sequestration potential of African tropical forest to be 0.34 Gt C/yr, and also synthesized the available data across tropical Asia, Africa and Latin America. They observed the mean rate of C sequestration in the above ground biomass at the rate of 0.49 t C/ha/yr which indicates a C sink capacity across all tropical forests of 1.3 Gt C/yr (Table 5). The data in Table 5 from Costa Rica show that forest regeneration is extremely effective in restoring the SOC pool. Lal (2005a;b) assessed the technical potential of forest ecosystems on C sequestration. While various strategies are useful in enhancing SOC, Figure 10 shows that tropical plantations are extremely effective in enhancing the biomass and SOC pool. However, forest ecosystems can also enhance emisson of methane (Sanhuwza, 2006).

Table 4. Estimated annual increase in tropical forest carbon pool (Lewis et al., 2009).

Continent	Area	Rate of C sequestration (Gt C/yr)	
		Mean	Range
Central and South America	786.8	0.62	0.39-0.73
Africa	632.3	0.44	0.26-0.53
Asia	358.3	0.25	0.15-0.30
Total	1777.3	1.31	0.79-1.56

Table 5. SOC pool (t C/ha) to 60-cm depth 4 years after planting (calculated from Montagnini and Porras, 1998).

Site 1		Site 2		Site 3	
Species	**SOC Pool**	**Species**	**SOC Pool**	**Species**	**SOC Pool**

Jacaranda copaia	90.4	*Albizia guachapele*	75.3	*Genipa Americana*	61.1
Calophyllum brasiliense	73.7	*Dipteryx Panamensis*	73.1	*Hieroyma alchorneoides*	64.4
Styrphnodendron microstachyum	74.8	*Terminalia Amazonia*	70.6	*Balizia elegans*	85.9
Vochysia guatemalensis	76.1	*Virola koschnyi*	71.9	*Vochysia ferruginea*	66.9
Mixed	74.9	Mixed	73.2	Mixed	68.5
Regeneration	85.1	Regeneration	95.4	Regeneration	76.8

Assumptions: Organic matter comprised 58% C, and soil bulk density equals 0.6 T/m^3 (Fisher, 1995) for all depths and under all species.

B. Forest Plantations

35. Sustainable forestry in the tropics is an important issue (Pearce et al., 2003), and establishing forest plantations on degraded agricultural lands is an important step in that direction**.** Fast growing woody species grown in dense, short-rotation plantations are important to C sequestration on degraded soils previously under agriculture, or on agriculturally marginal soils (Figure 10). Such plantations provide numerous benefits in products such as timber, boiler fuel, biofuel feedstock and other C-based products. Some species have a high rate of biomass production. For example, some *Populus* clones can produce 70 t/ha over 5 years. Dowell et al. (2008) reported that in Missouri, *P. deltoides* clones yielded almost twice as much as hybrids (66.3 vs. 36.9 t/ha). Net C sequestered in measured C pools ranged from 11.4 to 33.5 t/ha over 5 years. In the Pacific northwestern region of the U.S.A., Case and Peterson (2007) reported that lodgepole pine plantations can be effectively managed to adapt to CC.

Table 6. Effects of plantations of 27-41 years duration on organic carbon pool at 0-20 depth for a soil in Curua-Una Forest Reserve, Para, Brazil (adapted from Smith et al., 2002).

Treatment	**Soil bulk density (t/m^3)**	**Soil Organic Carbon**	
		Concentration (g/kg)	**Pool (t/ha)**
Forest	0.77a	63.9ab	98.4ab
Pinus caribaea	0.84a	42.8c	71.9c
Carapa guianensis	0.80a	49.4bc	79.0bc
Leguminosae	0.81a	51.4bc	83.3bc
Euxylophora paraensis	0.82a	69.9a	114.6a

36. Leguminosae comprised a combination of *Parka multijuga, Dinizia excelsa* and *Dalbergia nigra*.

Tropical plantations are just as much as or even more productive than those in the temperate regions. However, there are important trade offs of tree monocultures: some species become invasives (e.g., eucalyptus in Africa, leucaena in India), others are vulnerable to pests and diseases when grown as monocultures, and some require additional water and nutrients and compete for scarce land resources. In Colombia, South America, Torres Ve'lez and Del Valle (2007) studied the growth and yield of *Acacia mangium.* They observed that trees could reach 15-m height in 3 years. In the humid region of Costa Rica, Redondo-Brenes (2007) studied C sequestration under 7 native tree species grown as plantations. He observed that fast-growing species accumulate more C before they are 10 yr old than slower growing species, and the rate of C storage in the above ground biomass ranged from 12 to 79 t C/ha over 9 to 14 year period. In addition to biomass, tree plantations also enhance soil C. In southwestern Ethiopia, Lemma et al. (2007) observed that SCS at age 20 was 32.7, 26.3 and 18.1 t/ha under *Cupressus*, *Pinus,* and *Eucalyptus*, with an average rate of 1.6, 1.3, and 0.9 t C/ha/yr, respectively. Establishing ecological networks to restore degraded soils through afforestation is important to C sequestration (Armesto et al., 2007). Van Minnen et al. (2008) assessed the importance of establishing tree plantations on reducing net CO_2 emissions. Plantation species found important to C sequestration were river red gum (*Eucalyptus camaldulensis*), rose gum (*E. Grandis*), radiata pine (*Pinus Radiata*), black poplar (*Populus nigra*), Norway spruce (*Picea abies*), and Japanese larch (*Larix kaempferi*). The data in Table 5 from Brazil show that SOC pool under fast growing plantations exceeded that under the natural forest (114.6 t/ha vs. 98.4 C/ha). In Puerto Rico, Parratta (1992) observed that rate of SOC sequestration under plantation was 1022 kg C/ha/yr (Table 7). In the lowland Amazonia of Para, Brazil, Smith et al. (2002) assessed changes of forest floor and surface soil C storage caused by converting primary forest to tree plantations.

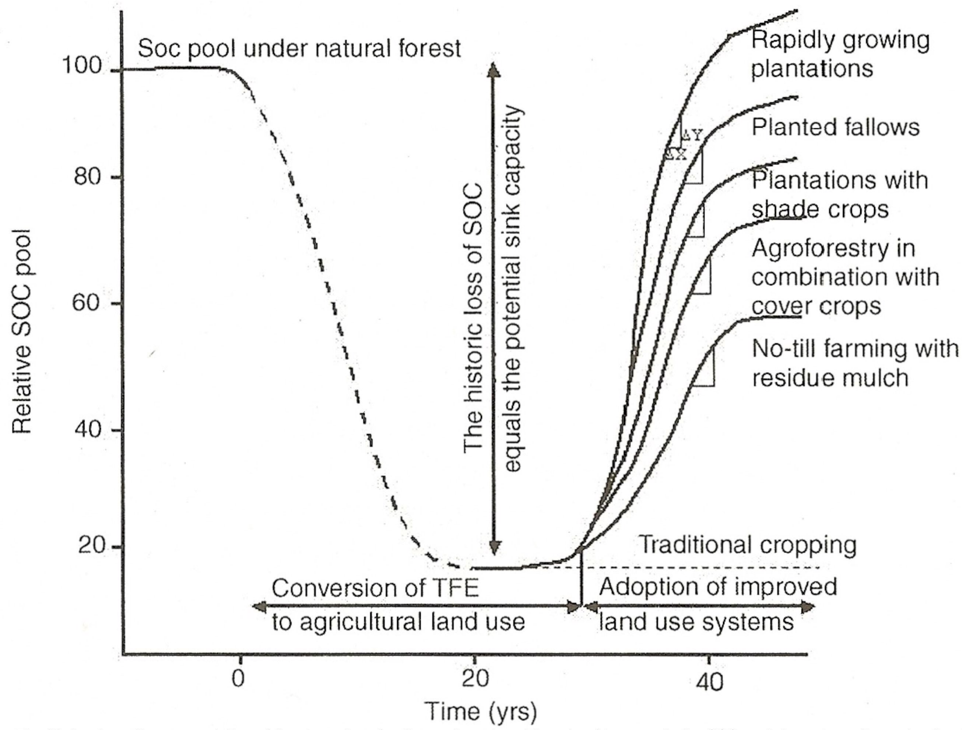


Fig. 10. A schematic representation of the dynamics of soil organic carbon. The rate of increase in the SOC pool depends on the restorative land use. The symbol Δ on each curve denotes the rate (ΔY/ΔX) of SOC sequestration, and it depends on the reference point or base line. The rate may be high and positive when degraded cropland is used as a reference point, and slow or negative when natural system is chosen as reference. Afforestation of degraded agricultural soils with rapidly growing plantations may have SOC sequestration rate of 1 Mg C/ha/yr (Lal, 2005b).

After 30 to 40 years of establishing plantations, SOC pool decreased under *P. Caribbean* (-12%), *C. guineensis* (-13%), *leguminous* (-10%) but increased under *E. paraensis* (+10%). In the sub-humid region of Nigeria, Juo et al. (1995) estimated that SOC pool was more under pure stand of *Leucena* than that under other land uses (Table 8). Lewis et al. (2009) estimated that tropical forests have a C sink capacity of 0.49 t/ha/yr, with a global C sink capacity of 1.3 Gt C/yr. Of this total C (including biomass C and soil C) Lal (2005a, b) estimated that total potential of SOC sequestration in TFEs was 0.2-0.51 Gt C/yr (Table 9). All these field verified data demonstrate the potential of forest plantations to enhance C sequestration on degraded lands. But one must always be cognizant of the **trade-offs** involved in such tree-plantation strategies (e.g., tree species such as eucalyptus that are good for carbon sequestration may not be well suited for local livelihoods and may in fact present ecological problems in some areas particularly if they have potential to become invasives). Soil C concentration, fine root biomass, and soil microbial C concentration have been observed to be significantly lower in forest plantations relative to natural forests irrespective of biomes, geographic regions or other factors (Liao et al. 2010). Such decrease in ecosystem C stock in plantations is likely due to: (a) inappropriate site preparation (e.g., burnt treatment increases soil C loss), (b) increased output due to harvesting of wood products, (c) decreased NPP and litterfall, and (d) the length of time since establishment of the plantation. Soil bulk density, representing the degree of soil compaction, tends to be higher in plantations than in natural forests; increased soil compaction reduces litter decomposition in plantations, limits access to water and nutrients and increases run-off. Furthermore, Jackson et al. (2005) have estimated that plantations decrease stream flow by 227 millimetres per year globally and that climate feedbacks are unlikely to offset such water losses. Such trade-offs imply that the replacement of natural forests by plantations should be approached cautiously since it may not be an optimal strategy for climate change mitigation and adaptation.

37. Forest plantations also have implications to biofuel production, through co-combustion, second generation (cellulosic) ethanol, and biodiesel. Oil palm plantations are being established in tropical rain forests (TRFs) regions to produce biodiesel. Similar to the disadvantage of removing residues from croplands, deforestation of TRFs and draining of peatlands for establishing biofuel plantations can have a large C footprint because of substantial depletion of

the ecosystem C pool. In addition to competing for land and water (along with fertilizers and other resources), there may be a loss of above-ground and below ground C pools by processes leading to establishment of these plantations. Significant C debts are created by draining and clearing of peatlands for establishment of oil palm plantations (Fargione et al., 2008), and for production of biofuels from croplands (Searchinger et al., 2008). Conversion of degraded croplands and desertified lands to energy plantations, with judicious management of water and nutrients, may create a positive C budget in favor of biofuel plantations.

Table 7. SOC and N pools in the 0-20 cm soil layer of Typic Troposamments in control and 4.5 year old plantations of *Albizia lebbek* in Puerto Rico (calculated from Parratta, 1992).

Treatment	Soil Organic Carbon		Total Nitrogen		Sequestration rate (kg/ha/yr)	
	Concentration (%)	Pool (t C/ha)	Concentration (%)	Pool (t N/ha)	SOC	N
Plantation	1.70 (1.04)	35.4	0.095 (1.04)	1.98	1022	89
Control (grasses)	1.44 (1.07)	30.8	0.074 (1.07)	1.58	-	-

Number in parenthesis is soil bulk density in t/m^3.

Table 8. Temporal changes in SOC stock of 0-15 cm depth of an Alfisol in western Nigeria with cultivation and fallowing treatments (recalculated from Juo et al., 1995).

Years after clearing	Bush fallow	Guinea grass	Leucaena	Pigeon pea	Maize & stover	Maize-stover
	-------------	-------------	-------------t C/ha	-------------	-------------	-------------
0	22.5	28.2	22.9	23.9	29.0	24.1
4	18.0	20.8	19.1	20.0	18.5	14.4
7	15.1	17.1	18.5	16.0	18.2	12.8
10	27.4	31.2	35.1	25.2	27.1	24.8
12	27.4	30.0	33.0	20.8	28.1	27.0
13	30.0	30.9	34.3	25.2	29.8	26.0

Table 9. The potential of soil organic carbon sequestration in the TFE of the humid tropics (Lal, 2005a).

Land use	Area (Mha)	Rate of SOC sequestration (kg C/ha/yr)	Potential of SOC sequestration (Mt C/yr)
Agroforestry	500	100-300	50-150
Plantations	250	500-1,000	125-150
No-till mulch farming	50	100-200	5-10
Improved pastures	200	100-500	20-100
Total	1,000		200-510

XI. Tropical Savanna and Rangelands Ecosystems (TSREs)

38. The savanna and rangelands cover 29 x 10^6 km^2 globally, including 20 x 10^6 km^2 in the tropics and 9 x 10^6 km^2 in the temperate regions (Scurlock and Hall, 1998; Chen et al., 2003). These land uses account for 20% to 30% of the global primary production (IPCC, 2000; Grace et al., 2006). Savannas are a highly diverse ecosystem comprising tropical savanna rangeland ecosystems (TSREs) and temperate prairies and grasslands (TPGs). The TSREs include large areas in Africa, South America and the Pacific. The TPG regions comprise prairies and steppes of North America and Russia and derived savannas of Europe, and are characterized by climate with distinct wet and dry seasons leading to strong patterns of physiological and ecophysiological processes. The TSREs are among the most seasonal of the world's major biomes with strong and contrasting climatic conditions within a year, as well as high variability between years (Varella et al., 2004). There are three global regions with predominance of TSRE land uses: (1) Africa with an area under TSRE of 15.1 x 10^6 km^2 or 50% of the continental land area (30.1 x 10^6 km^2), and (2) South America with an area under TSRE of 2.1 x 10^6 km^2 or 11.7% of the continental land area (17.8 x 10^6 km^2), and (3) Asia and the Pacific with distinct

TSRE biomes. The Australian TSRE biomes occupy an area of about 2 x 10^6 km^2 or about 12% of the world's savanna.

39. Similar to forests, regrowth of savanna woodlands is also pertinent to adaptation to CC. Savanna woodlands are also subject to disturbances (e.g., fire, land clearance, erosion) which create opportunities for new growth. Williams et al. (2008) studied C sequestration in seasonally dry deciduous woodlands (called miombo) in southern Africa. These open woodlands extend across an area of 2.7 X 10^6 km^2 (270 Mha). Williams and colleagues observed that clearance of woodlands reduced C pool by 19 t/ha. The SOC pool on abandoned land ranged from 21 to 74 t C/ha to 0.3 m depth compared with 18 to 140 t C/ha in uncleared woodlands. The biomass C pool on abandonment increased at the rate of 0.7 t C/ha/yr. The rate of SOC sequestration with regrowth of woodlands was extremely slow, even though the total soil C storage capacity was >100 t C/ha while no soil on re-grown areas exceeded 74 t C/ha, and no woodland pool exceeded 33 t C/ha. Silver et al. (2000) reported that SOC pool increased at the rate of 1.3 t C/ha/yr in the first 20 years after abandonment. However, Post and Kwon (2000) reported annual rates of SOC sequestration as low as 0.03 t C/ha/ yr in arid conditions. Similar low rates of SOC sequestration were reported in Malawi (Walker and Desanker, 2004). Chhabra et al. (2003) estimated SOC pool in savanna soils of India at 4.13 Gt C into op 50 cm-depth and 6.81 Gt C in 1-m depth with reference to 1980 baseline. This historic loss in savanna forest soil C was 4.13 Gt C. Thus, C sink capacity for savanna soils in India through restoration of woodlands is 4.13 Gt C. Management of such woodlands for ecosystem restoration and C sequestration needs the following considerations (Williams et al., 2008): (i) identifying C-rich soils and conserving woodlands to protect soil C (avoiding emission), and (ii) understanding the observed variability

in vegetation and soil C pool in woodlands, and using that understanding to manage existing woodlands and regrowing areas for greater C storage.

40. The Cerrado, the principal TSRE in South America, refers to the common savanna-like vegetation of low trees, scrub brush and grasses. It occurs entirely within Brazil, and covers approximately 2 x 10^6 km^2 (204 Mha) or 23% of Brazil's land area (Bustamante et al., 2006). In the Cerrado, about 127 Mha out of 204 Mha (62%) is suitable for agriculture (Lilienfein and Wilcke, 2003). The annual precipitation in the Cerrados ranges from 600 mm to 2200 mm. It is characterized by a dry season that lasts from 4 to 7 months. The mean annual temperature varies from 22°C to 27°C (Bustamante et al., 2006). Cultivated pastures in the Cerrado region cover about 66 Mha (Sano et al., 2000), but these pastures are also prone to degradation by excessive grazing (da Silva et al., 2004). Total area under arable land use, mostly soybean, is estimated at 18.0 Mha (Jantalia et al., 2007). The land area, NPP, total C pool, C sink capacity and the rate of C sequestration for all the global biomes are shown in Table 10. Both TSRE and TPG land uses have a biomass C pool of 326 Gt out of the global biomass C pool of 2137 Gt (~15%). With NPP of about 20 Gt C/yr, TSRE and TPG have a C sink capacity of about 0.4 Gt C/yr out of the global C sink capacity of 2.55 Gt C/yr (Table 10). Therefore, understanding components of the ecosystem C pool is essential to identifying SLM options to harness this C sink capacity. This information is not available for the site-specific soil, land use and other physiographic characteristics.

41. The ecosystem C pool comprises of three components: (i) above ground biomass and the detritus material, (ii) below ground biomass, and (iii) soil organic carbon (SOC) pool. The principal fluxes consist of gross primary productivity (GPP), soil and plant respiration, erosion and leaching, and humification (Figure 11). The magnitude of the pool and fluxes in natural

ecosystem depends on the soil, climate, physiography, and vegetation. In northern Australia, Chen et al. (2003) reported that total C pool of the natural savanna is 204 ± 53 t C/ha, with approximately 84% below ground and 16% above ground C pools. The SOC pool is 151 ± 33 t C/ha (74% of the ecosystem C pool). The biomass C pool is 53 ± 20 t C/ha of which 39% is in the root and 61% in the shoot (trees, shrubs, grasses). GPP is 20.8 t C/ha, of which 5.6 t C/ha occurs in the above ground components and 15.2 t C/ha in the below ground components. The NPP is 11 t C/ha/yr of which 8.0 t C/ha/yr is below ground and 3.0 t C/ha/yr is above ground. Annual soil C efflux is 14.3 t C/ha/yr of which about 75% occurs during the wet season. The natural ecosystem is a net C sink during the wet season and a weak source during the dry season. The residence time of C, calculated as ratio of total biomass C to NPP from the studies conducted in Australia and similar ecosystems elsewhere, is 3.4 to 5 yr in the natural savanna (Chen et al., 2003; Scholes and Hall, 1996), 8.6 yr in woodlands (Whittaker and Likens, 1973) and 10-16 yr in tropical rainforest (TRF) land uses (Malhi et al., 1999). Together with the concentration and radiative forcing, the residence time is an important determinant of the global warming potential (GWP) of greenhouse gases (GHGs).

42. Similar to the Australian savannas, ecosystem C pool has also been measured for the Brazillian Cerrado. The average pool in the Cerrado is estimated at 29 t/ha in vegetation and 117 t/ha in soil (1-m depth), or a total of 5.9 Gt in the entire vegetation and 23.8 Gt in all soils (IPCC, 2000). Because of a large variability, the site-specific pool varies widely among soils and local conditions. The SOC pool ranges from 87 to 210 t C/ha (Bustamante et al., 2006). Abdala (1993) estimated the total C pool of a Cerrado in central Brazil at 265 t/ha. It comprises of 28.5 t/ha of arboreal, 4 t/ha of herbaceous, 5 t/ha of litter, 42.5 t/ha of roots and detritus and 185 t/ha of SOC pools to 1-m depth. The role of soil nutrients (e.g., N, P) can be important in recovery of savanna

woodlands in dry regions. In the Yucatan Peninsula of Mexico, Solis and Campo (2004) observed that response to N and P inputs on recovery of tropical dry forests depends on the successional stage of the vegetation. Water deficit can also limit the recovery process in dry regions. Because TSREs are key agricultural zones, some SLM options are briefly outlined in Figure 6.

A. Fire and Emission of Greenhouse Gases

43. In view of the interest in sources and sinks of GHGs, it is important to understand the magnitude and determinants of gaseous fluxes caused by natural and managed fires in TSREs. Biomass burning is a major source of emission of large amounts of GHGs (Crutzen and Andrae, 1990). Fires affect CC by influencing the emission of soot and aerosols (Kaufman and Fraser, 1997); altering vegetation cover along with re-growth of grasses and trees; changing albedo and soil moisture and temperature regimes, and perturbing cycling of elements and water. Mortality of trees and seedlings by fires can reduce presence of trees and woody species while promoting dominance of grasses and herbaceous vegetation (Cardoso et al., 2008). This process creates man-made savannas (Hoffmann et al., 2000). Such environmental degradation on a large scale may weaken the hydrological and C cycles with large-scale changes in ambient temperature and precipitation patterns (Hoffmann and Jackson, 2000).

44. The TSRE land uses can be either fire-prone or fire-dependent ecosystems. Frequency and intensity of fire, depending upon the quantity of biomass available for burning, affect species composition, soil properties and processes, sediment and elemental transport in water runoff, and emission of GHGs, particulate organic matter (POM), and soot/black C into the atmosphere. Mouillot and Field (2005) estimated that an average of 608 Mha/yr were burned every year during the 20th century, and 86% of this occurred in the TSRE biomes. In comparison, fire in the

forest biomes consumed 70.7 Mha/yr at the beginning of the 20th century, mostly in boreal and temperate forests of the northern hemisphere. The occurrence of fire in the northern hemisphere decreased to 15.2 Mha/yr in the 1960s and to 11.2 Mha/yr by the end of the 20th century. During the same period, burnt areas increased to 54 Mha/yr in the tropical rain forest (TRF) biome (Mouillet and Field, 2005).

45. Globally, natural and anthropogenic fires consume ~ 3 Gt C/yr with direct impact on the gaseous composition of the atmosphere and air quality (Grace et al., 2006; Freitas et al., 2005). Biomass burning in South America emits 30 Mt/yr of aerosol particles to the atmosphere (Andreae, 1991). Because of the small size, the aerosol particles and black C (soot) have a long residence time in the atmosphere (Kaufman, 1995). Smoke plumes in South America tend to cover an area of about 4-5 x 10^6 km^2 during the fire season (Prins et al., 1998). Persistence of aerosol can affect the radiation budget and regional climate due to high concentration of black C (BC) in the atmosphere (Andreae, 2001). Biomass burning is also a source of CH_4 and NO_x (N_2O, NO, NO_2). It is estimated that annually, 6.7 Mt N/yr is emitted as NO_x by biomass burning (Davidson and Kingerlee, 1997).

46. Fire-derived charcoal contributes to recalcitrant SOC pool (Czimczik and Masielle, 2007). Of the 3 Gt of biomass C burnt annually, 1.1 Gt is emitted into the atmosphere (CO_2, soot, POM, aerosol, etc.) and about 50 Mt is converted into charcoal of which 26-31 Mt is BC (Fearnside, 2000). The BC is an important component of the global C cycle. Dai et al. (2005) estimated the concentration of BC in temperate mixed-grass savanna ranging from 50 to 130 g (BC) kg^{-1} of SOC (equivalent to 0.55 to 1.07 g BC kg^{-1} of soil). Contribution of BC to SOC pool increases with increase in soil depth. Ansley et al. (2006) observed that BC comprised 13 to 17 % of SOC pool in temperate-mixed grass savannas. In general, studies of natural fire dynamics

are rare. Experiments conducted on grassland fires under natural ecosystems in Tanzania showed that proportions of mass and N volatilized are substantially less than 100%, and that combustion and volatilization losses are strongly influenced by the mass burned and the fire intensity. The studies also showed that relatively more of N than mass is volatilized with increase in fire intensity, and much less mass and N are volatilized in natural fires than laboratory studies indicate (McNaughton et al., 1998).

B. Conversion of TSREs to Agriculture

47. Soils and climates of TSREs are suitable for grain crop production and pastures. Therefore, the TSREs have been widely converted to agricultural production systems (e.g., corn, soybean, sorghum, millet, pasture) since the second half of the 20th century. Harvesting for firewood is another important economic factor of deforestation of TSREs particularly in Africa. Conversion to agricultural systems and susceptibility to fire have resulted in strong changes in vegetation, soil properties and processes, and in disruption of the cycles of elements (C, N, P, S) and water. The large-scale conversion affects local and regional climate. It reduces precipitation by about 10%, increases frequency of dry periods during the rainy season, increases albedo and evaporation, and increases mean air temperature by 0.5°C due to reduction in surface roughness (Hoffman and Jackson, 2000). Increase in air and soil temperatures, reduction in water infiltration rate with an attendant increase in runoff, and increase in evaporation decrease effective (green water) precipitation. In addition, conversion of natural TSREs to agricultural ecosystems decreases C pool in the above ground and below ground biomass. There is also loss of SOC pool due to decrease in impact of biomass C and probably higher losses caused by decomposition, erosion and leaching. Dominant land uses in managed TSREs range from beef cattle production in northern Australia, cattle production and large-scale agriculture in Brazil, to

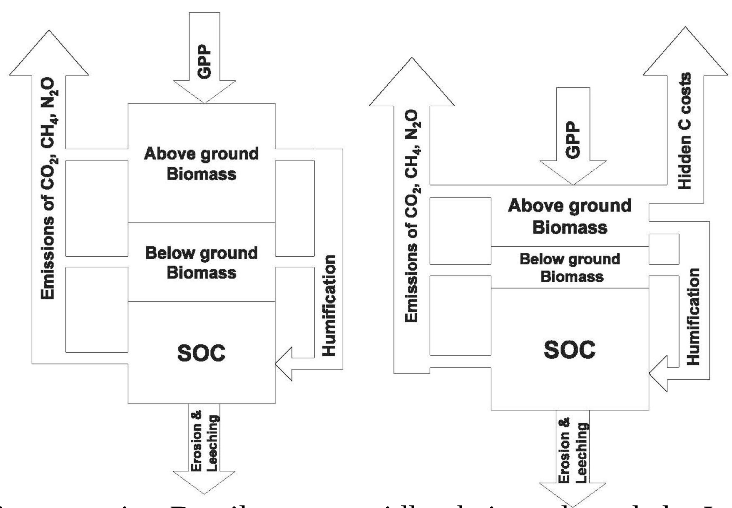
mixed grazing and shifting/traditional agriculture in Africa (Winter, 1990; Klink and Cahado, 2005; Hoffman and Jackson, 2000). About 40% of the Brazilian Cerrado was already converted to agricultural land use by 1995, and the remainder is being converted at the rate of 1.7%/yr (Klink and Cahado, 2005). Large-scale conversion of the Cerrado is a threat to this important ecosystem that cannot be ignored (Scariot et al., 2005). There are four predominant land uses in Brazilian Cerrado: (i) native Cerrado to pasture, (ii) native Cerrado to cropland under conventional tillage, (iii) plow tillage (PT) to no-till (NT), and (iv) native Cerrado to forestry (Bustamante et al., 2006). It is important to note that most croplands in Brazil are rapidly being converted from PT to no-till (NT). The land area under NT is Brazil increased from 1 Mha in 1992 to 24 Mha in 2005 (FEBRADPD, 2005), of which 8 Mha are in the Cerrado region. Jantalia et al. (2007) reported that loss in SOC pool upon conversion from native Cerrado to cropland over a 20 year period was 10 t C/ha with NT compared with 30 t C/ha with PT. Conversion of PT to NT can positively impact the soil C pool, with rate of SOC sequestration of 0.4-1.2 t C/ha/yr depending on the soil depth (Table 11). Corbeels et al. (2007) estimated that conversion of 6 Mha of PT soybean to NT system of seedbed preparation can enhance soil C storage by 4.9 Mt C yr^{-1}. Positive impacts of NT systems on SOC sequestration in Cerrado soils have been reported widely (Corraze et al., 1999; Leite et al., 2004; de Oliveira et al., 2004). However, the NT system adopted in degraded soils may cause decline in SOC pool especially over a short time period (Table 12; Lilienfein and Wilcke, 2003). The rate of C sequestration in NT management also depends on the cropping systems, soil textures, and availability of N. Adoption of NT with double cropping sequesters more C than that with single crops.

48. About 80% of the ecosystem C pool in TSREs biomes is in the soil (Figure 11). Thus degradation affects the ecosystem C pool both in biomass and soil. The removal of protective

tree cover from TSREs also depletes the SOC pool. The principal determinants of the ecosystem C balance following land use conversion are changes in GPP and NPP, rooting depth, erosion, leaching, and temperature-induced decomposition of SOC pool. More importantly, the magnitude of the change in C pool depends on the specific land use to which TSREs are converted to.

(i) Native Savannahs to Pastures

49. Similar to cropland, restoration of degraded pastures is an important SLM option for adaptation to and mitigation of CC. With total land area of 66 Mha, the potential of SOC sequestration in pastures is 15 to 30 Mt C/yr. Brazil alone has more than 167 million cattle (FAO, 2000), raised mostly on grazed pastures. Cultivated pastures, covering 50 Mha in the Cerrado region, out of a total of 80



(A) Natural sources (B) Agricultural ecosystem

Fig.11 Ecosystem carbon pool and fluxes in natural and managed land use in the savanna ecosystem (Lal, 2008; Chen et al., 2003).

Mha under *Brachiaria* spp. in Brazil, are rapidly being degraded. Immediately after establishment, these pastures can support 1-2 animal units (AU)/ha. With severe degradation and appearance of termite hills (termitaria) within a short period, pastures can support only 0.5 AU/ha (de Oliveira et al., 2004). In addition to compaction and decline in soil structure, nutrient depletion and loss of SOC pool are also important factors (Boddey et al., 2004). But restoration of degraded pastures can enhance the SOC pool. da Silva et al. (2004) reported that the SOC pool to 1-m depth in managed pastures was about 100 t C/ha, compared with 200 t C/ha in the Colombian Llanos. Evidence shows that degraded pastures and poor grazing management are a source rather than a sink for atmospheric CO_2 (da Silva et al., 2004). It is therefore important to undertake SLM measures that improve pasture management; such measures include silvopatoral systems which entail sustainable management of pastures in combination with trees and shrubs such as acacias (e.g., *Leucaena leucocephala*) that have high nutritional value for livestock. Such measures may involve intensive silvopastoral systems (with more than 5,000 trees per hectare), improved pasture with high tree density (i.e., more than 30 trees/ha), improved pasture with low tree density (i.e., less than 30 trees/ha), natural pasture with high tree density, high density fodder bank with trees/shrubs for cutting (i.e., more than 10,000 plants/ha), etc. These practices have been implemented in Latin America (Colombia, Costa Rica, Nicaragua) with measurable and demonstrable multiple benefits such as C sequestration, biodiversity conservation, water retention, improved soil fertility, erosion control, wind breaks, (CIPAV, 2004)

50. The average C sequestration rate upon conversion of native Cerrado to pasture is 1.3 t C/ha/yr with a range of -0.87 t C/ha/yr to +3.0 t C/ha/yr (da Silva et al., 2004). Conversion of native Cerrado to plow tillage (PT) cropland leads to depletion of the SOC pool, mostly due to accelerated soil erosion. The magnitude of loss of the antecedent C pool ranges from 40% to 80% in the 0-15 cm depth depending on the clay content. The magnitude of loss tends to increase with decrease in clay content and with increase in the duration of cultivation (Zinn et al., 2005). Overgrazing has more adverse impacts on the SOC pool than the disturbances by fires (Abril et al., 2005). However, restoration of degraded pastures can enhance the SOC pool significantly. The rate of SOC sequestration in restoring degraded pastures is about 1.5 t/ha/yr (Bustamante et

al., 2006). Experiments conducted in the Llanos (Colombian savannas) show that SOC pool can be greatly enhanced through the introduction of deep-rooted African pasture species and legumes into native savannas (Fisher et al., 1994; 1995; Trujillo et al., 2006; Rondon et al., 2006).

(ii) Native Savannahs to Forest Plantations

51. Replacement of savannas to short rotation woody perennials and other tree plantations can also enhance the ecosystem C pool, and make TSRE biomes a net C sink (Scurlock and Hall, 1998; Corazza et al., 1999; Zinn et al., 2002; 2005). Furthermore, increase in the atmospheric CO_2 concentration can also enhance the terrestrial C pool of the plantations through the CO_2 fertilization effect (Parton et al., 1995). Establishment of tree plantations can increase the ecosystem C pool from a mean value of 67 t C/ha under native savanna to a mean value of 150 t C/ha under tree plantations (Scurlock and Hall, 1998). Thus, conversion of 11.5 x 10^6 km^2 of native savannas to these plantations has a potential of sequestering 95.5 Gt C over 50 years, with a mean sequestration rate of ~2 Gt C/yr. San Jose and Montes (2001) estimated the potential of Orinoco Llanos of Colombia for storing C at 8.3 Gt over a 50 year period. In addition, the soil management practices (tillage, residue management, nutrient management), cropping systems (rotation, cover crops), weed and pest control also affect the soil C budget.

Table 10. Land area and total net primary productivity of tropical savannas and other ecosystem (Adapted from Grace et al., 2006).

Ecosystem	Area (10^6 km^2)	Total Pool (Gt C)	NPP (Gt C/yr)	C Sink Capacity (Gt C/yr)	C Sequestration (t C/ha/yr)
Tropical savannas & grasslands	27.6	326	19.9	0.39	0.14
Temperate grasslands	15.0	182	5.6	0.21	0.14
Tropical forests	17.5	553	21.9	0.66	0.37
Temperate forests	10.4	292	8.1	0.35	0.34
Boreal forests	13.7	395	2.6	0.47	0.34
Crops	13.5	15	4.1	0.02	0.01
World	149.1	2137	67.6	2.55	2.0-3.0

Table 11. Rate of soil carbon sequestration by no-till farming in the Brazilian Cerrados.

Cropping System	Duration (yrs)	Soil Depth (cm)	C Sequestration (t C/ha/yr)	Reference
Soybean	12	20	0.83	Corbeels et al. (2006)
Soybean	12	40	0.7-1.15	Corbeels et al. (2006)
Corn-Soybean	2	30	-1.5	San José and Montes (2001)
Rice (upland)	5	10	0.35	Lilienfein and Wilcke (2003)
Soybean-Maize	8	20	0.3-0.6	Metay et al. (2007a)

Table 12. Soil carbon pool in different land uses in cerrado region of Minas Gerais (Recalculated from Lilienfein and Wilcke, 2003).

Land use	Age (yrs)	Soil Organic Carbon Pool (t/ha)	
		0 – 0.3 m	**0 – 2 m**
Cerrado	-	55 ± 2.3 ab	180 ± 6.8 a
Pinus	20	49 ± 2.9 b	170 ± 9.8 a
Degraded Pasture	14	60 ± 4.7 ab	180 ± 14.0 a
Productive Pasture	14	64 ± 8.1 a	190 ± 26.0 a
No-till	2	58 ± 5.3 ab	190 ± 5.8 a
Plow tillage	12	61 ± 3.2 ab	170 ± 12.0 a

Figures in the column followed by the same letters are statistically similar

52. There are two other factors that determine whether managed TSRE biomes are a source or sink for atmospheric concentration of GHGs. The first factor is the flux of GHGs (CO_2, NO_x, CH_4), and the second factor is the hidden C cost of all inputs. Varella et al. (2004) observed no significant differences in annual CO_2 soil emissions between the Cerrado and the pasture, but the temporal trends differed, with higher fluxes in pastures during the transition from the wet to the dry season. Cropland soils, due to application of nitrogenous fertilizers, have larger NO_x emissions than the undisturbed TSRE soils (Perez et al., 2007). In general, NT soils have a higher efflux of N_2O than conventional tillage (CT) soils because of high soil moisture content and lower gas diffusivity (Metay et al. 2007b). With regards to the hidden C costs, fuel consumption in NT was estimated at 14 L/ha compared with 34 to 42 L/ha in PT (Sorrenson and Montoya, 1989).

53. It is important that the net SOC sequestration in any agroecosystem be computed with due consideration to the hidden C costs (Table 13). Among fertilizers, hidden C costs are the highest for nitrogenous fertilizers. Pesticides tend to have 4 to 5 times higher hidden C costs than fertilizers. Lifting ground water for supplemental irrigation has additional costs, which increase with the continuing decline in the water table such as in the Indo-Gangetic Basin of South Asia. It is the high hidden C costs that necessitate judicious use of the C-based inputs through adoption of specific SLM practices such as: (i) NT farming which reduces or eliminates pre-planting seedbed preparation, (ii) integrated nutrient management (INM) that reduces the rate of application of fertilizers, (iii) integrated pest management (IPM) that minimizes dependence on pesticides, and (iv) water harvesting, recycling and conservation in the root zone that reduces the need for supplementary irrigation. Hence the choice of SLM practices must be informed by the

need to increase the use-efficiency of all C-based input by reducing losses caused by erosion, leaching, volatilization, etc. It is in this regard that the importance of scaling-up proven and available SLM technologies and good practices cannot be over-emphasized.

C. Carbon Budget of Savanna Ecosystems

54. It is vital to note that native savannas, under undisturbed and natural conditions, are a relatively small sink of atmospheric CO_2. Grace et al. (2006) reported that NPP of 20 Gt/yr, supports a SOC pool of about 480 Gt out of the global SOC pool (1-m depth) of 1550 Gt (~31%). Whether managed savannas are a source or sink for CO_2 and other GHGs depends on the degree and scale of adoption of SLM technologies. It is estimated that savanna biomes sequester as much as 0.5 Gt C/yr, which may contribute to the so-called missing sink (Scurlock and Hall, 1998). Lal (2008) estimated that grasslands and rangelands together have a potential SOC sink capacity of 0.5 to 1.7 Gt C/yr. But as has been demonstrated, the actual and attainable C sink capacity can be enhanced through adoption of selected SLM technologies and practices.

55. Realization of this vast potential, however, necessitates detailed life cycle analysis of pool and fluxes under principal land use systems. It is widely recognized that the ecosystem C pool declines with conversion from native to agricultural ecosystems with drastic loss of biomass C (both above and below ground) and also of the SOC pool. Such ecosystem C pool can be restored through conversion to planted forests (*Eucalyptus*, *Pinus*, etc.). Soil and vegetation degradation, such as is the case with degraded pastures, make these ecosystems a source of CO_2 and other GHGs.

56. Conversion of PT to NT can also lead to SCS at the rate of 0.3 to 1.0 t C/yr. There is also a saving in fossil fuel because of elimination of primary and secondary tillage operations. It is possible that adoption of NT system on the 18 Mha of croplands in the Brazilian Cerrados can

lead to sequestration of about 15 Mt C/yr in the SOC pool. However, the net C sequestration must be assessed with due consideration of the hidden C costs and increase in N_2O emission as described earlier. In addition to soybean, cultivation of upland rice (covering 2 Mha) is another option that needs a careful evaluation (Pinheiro et al., 2006). Aerobic rice has lower CH_4 emission and lesser water requirements than continuously flooded rice paddies.

Table 13. Hidden carbon costs of farming practices (Lal, 2004a).

Source/ Practice	Equivalent carbon emission (kg C E)
I. Fuel (kg of fuel)	
1. Diesel	0.94
2. Gasoline	0.59
3. Oil	1.01
4. Natural gas	0.85
II. Tillage (per ha)	
1. Moldboard plowing	15.2
2. Chisel plowing	7.9
3. Disking	8.3
4. Cultivation	4.0
III. Fertilizers (Per kg)	
1. Nitrogen	1.3
2. Phosphorus	0.2
3. Potash	0.15
4. Lime	0.16
IV. Pesticides	
1. Herbicides	6.3
2. Insecticides	5.1
3. Fungicides	3.9

57. Recommended SLM options for managed TSREs that have direct implications for CC include: (i) afforestation and reforestation of degraded ecosystems, (ii) restoration of degraded pastures and judicious management with controlled/rotational grazing, (iii) conversion of PT to

NT farming with mulch, cover crops, integrated nutrients and pest management, and (iv) increasing productivity per unit input of C-based input (e.g., diesel, fertilizers, pesticides, irrigation). The overriding strategy is to (a) scale-up these SLM practices in managed TSREs, and (b) minimize or avoid further conversion of TSREs and adopt land saving options for nature conservancy.

XII. Cropland Management

58. The key SLM options for croplands outlined in Figure 9 are: (i) conversion of degraded/desertified and agriculturally marginal soils to a restorative/perennial land use (e.g., tree crops, afforestation), (ii) adoption of conservation-effective measures to control erosion and conserve water and nutrients in the root zone, (iii) conversion of PT to NT farming with crop residue mulch and incorporation of cover crops in the rotation cycle, (iv) creation of a positive nutrient budget in the soil through INM techniques, and (v) adoption of complex cropping/farming systems including agroforestry (Figure 12).

A. Land Use Conversion

59. Land use affects soil quality and the terrestrial/ecosystem C pool through its impact on both the biomass and SOC pools. Land use affects NPP through alterations in soil moisture and temperature regimes, changes in elemental cycling and nutrient availability. In the Loess Valley of China, for example, Gong et al. (2006) documented significant impacts of land use on soil quality, NPP, and ecosystem C pool. Developing strategies that foster SLM in fragile soils (e.g., Loess Plateau in China) is important to enhancing the ecosystem C pool. In Thailand, Gnanaverajah et al. (2008) assessed the ecosystem C pool for 11 different land use systems. The

biomass C pool was 247.9 t C/ha for rubber, 189.4 t C/ha for mixed orchard, 159.1 for eucalyptus, 139.2 t C/ha for coconut, and 12.9 t C/ha for rice paddy. The data from Minas Gerais, Brazil, show that conversion of degraded to improved pastures and establishment of plantations on degraded lands can enhance the SOC pool (see Table 12). Thus a perennial land use, established on degraded land, is an important option to adapt to CC while enhancing the ecosystem C pool and NPP.

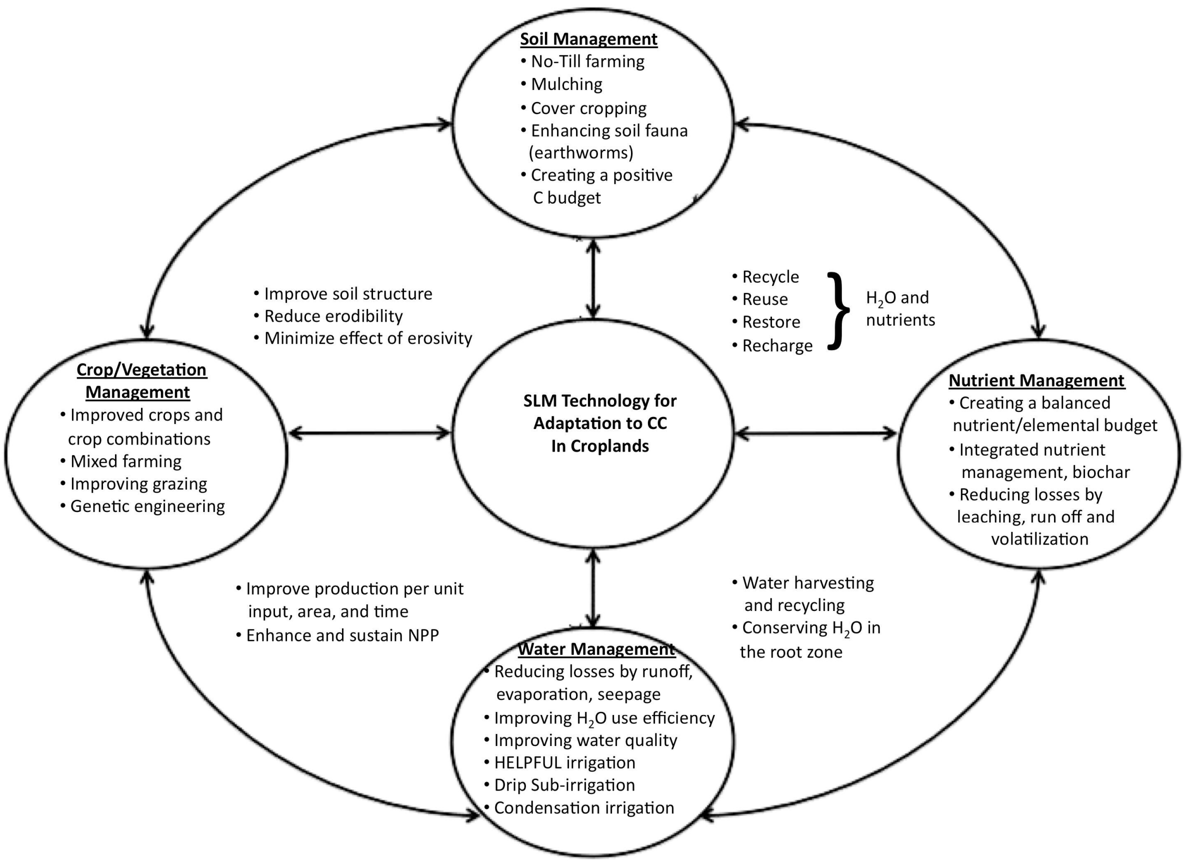


Fig. 12 Cropland management technological options for adaptation to climate changes (Lal, 2009).

B. No-Till Systems

60. The choice of seedbed preparation, of methods and timing of tillage operations, is important to adaptation to and mitigation of CC. Crop residues constitute more that 50% of the

world's agricultural biomass (Smil, 1999), and are important to recycling of C and nutrients. Effectiveness of NT farming on improving soil quality depends on retention of crop residue mulch. It is widely documented that conversion of conventional tillage (CT) to NT farming, with use of crop residue mulch and cover crops in the rotation cycle along with INM, conserve soil and water and improve soil quality. In southwestern Nigeria, Lal (1976) documented a higher SOC pool in NT compared with the CT system of seedbed preparation. In Zimbabwe, Gwenzi et al. (2009) reported that the SOC pool in 0-60 cm depth after 5 years were 27.8-30.9 t C/ha in CT, 32.8-39.9 t C/ha in minimum tillage (MT) and 32.9-41.6 t C/ha in NT system. The rate of SOC sequestration was 0.55-0.77 t C/ha in MT and 0.70-0.78 t C/ha in the NT system. In Sudano-Sahelian West Africa, Bationo and Buerkert (2001) concluded that SOC improvement is critical to sustainable management of soils. Conversion of PT to NT in the Cerrado region of Brazil has increased SOC pool at the rate of 0.3 to 1.5 t C/yr (see Table 10). In the Cerrados of Brazil, Metay et al. (2007a, b) reported that taking into account all three gases (CO_2, CH_4, and N_2O) on CO_2-C equivalent basis, ecosystem C sequestration is more in NT system by 350 kg C/ha/yr in the top 0-10 cm layer. Also in Brazil, Sa et al. (2001) concluded that conversion to NT system with crop residue mulch for a long time attains SOC pool equivalent to or more than natural fallowing. In addition to SOC sequestration, NT farming is also an effective technique for erosion control (Kent, 2002; Lal, 1976). Despite some soils and climatic limitations to adoption of NT farming (Lal, 1976), there is wide spread recognition of the NT concept and practice both for SCS and CC adaptation and mitigation (Xiao-Bin et al., 2006).

61. Research on NT farming in relation to soil, water conservation, and soil quality restoration started in early 1960s in North America, and early 1970s in the tropics. Despite repeated documentation of its usefulness in conserving soil and water, enhancing soil quality,

sequestering C and mitigating CC, the acceptance of this technology is rather low. Global adoption of NT farming is estimated at ~90 Mha or about 6% of the cropland area of the world. It is primarily practiced for large-scale cultivation of row crops (maize, soybeans, wheat) in USA, Brazil, Argentina, Canada, Australia, Paraguay etc. It has not been adopted by the resource-poor farmers and small-size landholders of SSA and SA. Yet, it is in SSA and SA that NT and other SLM technologies are needed the most. Among several reasons identified for the lack of adoption of such SLM technologies include poor infrastructure, low institutional support, land tenure and ownership issues, and non-availability of inputs. Lack of adoption of NT and other SLM practices could also be due to lack of stakeholder sensitization to land management issues and NT opportunities so as to create the requisite awareness and willingness to change pre-existing practices (Pieri et al. , 2002). Some of the inputs required for adoption of SLM technologies are either not available, are prohibitively expensive that resource-poor farmers cannot afford, or farmers are not sure of their effectiveness because of the uncertainties due to climate, soil degradation, and market fluctuations. Yet, NT has important benefits for CC adaptation and mitigation in these areas.

C. Integrated Nutrient Management

62. Depletion of soil fertility and nutrient imbalance are major constraints in improving productivity in many developing countries, especially in SA and SSA. Most cropland soils in developing countries are affected by negative nutrient balances; in Africa, nitrogen-phosphorus-potassium (NPK) depletion occurs at 20 to 40 kg/ha/yr throughout the continent (Smaling, 1993; Smaling et al., 1993; Sanchez, 2002). African farmers traditionally left lands fallow to restore nutrients and regain fertility, but because of growth in population and food demand, crops now grow continuously with little or no nutrient input. In the Sahelian zone of Sudan, Ayoub (1999)

observed that crop yields were severely reduced by decline in soil fertility. Thus, soil fertility management and fertilizer use could strongly increase crop yield in the Sahel. Fertilizer use in SSA is low (NPK at 8.8 kg/ha/yr) (Henao and Baanante, 2006). This situation is attributable to the inaccessibility and high cost of inorganic fertilizers. In contrast with Africa, fertilizer use in SA is generally high (NPK at 100/kg/ha/yr). Fertilizer consumption in SA increased by a factor of 42 from 1961 to 2003 and accounts for much of the yield gain in the region during the period (Lal, 2007). However, there has been widespread decrease in the responses of crops to agricultural inputs in SA since 2000.

63. One possible reason for the observed decline in agronomic yields in SA is the loss of soil organic matter (SOM). In SA and SSA, crop residues and weeds are used as fodder for animals or for cooking fuel (Eswaran et al., 1999). Without input of organic matter, degraded soils have low water and nutrient capacities, so they often do not respond to the addition of inorganic fertilizer. Numerous studies indicate that there can be strong synergism in the use of both organic and inorganic fertilizers. In SA, manure is used for cooking fuel; in many parts of SSA, the poorest farmers use some crop residues as building material and might not have animals as a source of manure, and they are reluctant to use their small plots to grow crops that yield only green manures. Low SOM leads to a decrease in the abundance of important soil organisms, such as bacteria, fungi, termites, earthworms, insects, and small animals that inhabit the rhizosphere. It is important to note that SOM content can easily be improved by manuring. In the Sudano-Sahelian conditions, Mando et al., (2005a; b) observed that manure application (10 t/ha) increased sorghum yields by 56 to 70%. In Burkina Faso, Ouedraogo et al. (2007) concluded that a combination of organic manures and chemical fertilizers is essential to increasing and sustaining high yield of sorghum and other grain crops. In the Pampas of Argentina, Quiroga et

al. (2006) reported a strong positive correlation between barley grain yield and SOM concentration. Increasing SOM concentration by 1 g/kg led to increased barley grain yield by 130 kg/ha.

64. Soil infertility owing to deficiency of essential plant nutrients, is a major constraint affecting crop yields in developing countries. It is estimated that as much as 50% of the increase in crop yields worldwide during the twentieth century was due to adoption of chemical fertilizers (Borlaug and Dowswell, 1994; Loneragan, 1997). Fertilizers played a major role in increasing agronomic production in SA, where fertilizer input between 1969 and 1995 increased from 20 to 145 kg/ha/yr (Hossain and Singh, 2000). Among macronutrients, N is the most limiting factor to enhancing crop yield (Eickhout et al., 2006). In addition to N, productivity of the rice-wheat system in Asia operates at low yield because of inadequate supply of other nutrients and inappropriate water use. Replacing lowland flooded with aerobic rice is a new development (Bouman et al., 2007; Kreye et al., 2009), which can save water and address the severe concern about rapid depletion of ground water in the Indo-Gangetic Basin (Kerr, 2009; Rodell et al., 2009). Similarly, use of genetically-improved high rise rice can adapt to inundation under extreme conditions of flooding (Voesenek and Bailey-Serres, 2009). Low productivity in SSA is, to a large extent, attributable to soil infertility (Sanchez, 2002). High C and N pools are also related to clay content and type, and other horizon characteristics (Schaefer et al., 2008), along with availability of plant nutrients and cations. In Haiti, Clemont-Dauphin et al. (2005) reported that availability of P, K are essential components of SLM options.

65. Plant nutrients needed to replenish what is annually removed from the soil to meet the global demand for food and fibers are estimated at 230 Mt (Vlek et al., 1997). Thus, it is important to adopt a holistic approach based on SLM practices that enhance INM (Gruhn et al.,

2000). The latter recognizes the importance of nutrient recycling using crop residues and other biosolids such as manure and compost, increasing biological N fixation (BNF) through leguminous cover crops, using mychorrhizal inoculation, and applying chemical fertilizers and organic amendments. In this regard, establishing links between livestock production and cropland management is very important (Naylor et al., 2005).

66. Because of the widespread problems of soil degradation and prevalence of extractive farming, cropping systems in developing countries need to be reinforced with microelements (Zn, Cu, I, Fe, B). These elements must be supplied through the soil, including application of S and N (Soliman et al., 1992) and Zn (Wijesundara et al., 1991). There are several strategies for improving availability of macrominerals and microelements in the soil. These include (Welch and Graham 2004/2005):

(i) Conducting soil tests for assessing fertility status and using appropriate targeted interventions,

(ii) Use of micronutrient fertilizers in appropriate formulations and at desired rates based on soil tests (e.g., Zn, Mo, Ni, Se, Si, Li, I), and supplying others through organic amendments (e.g., Fe, Cu, Mn, B, Cr, V),

(iii) Adopting diversified cropping systems including indigenous food crops, and,

(iv) Growing microelement dense varieties including improved crop varieties to improve bioavailability of essential elements (Hirsh and Sussman, 1999; Yang et al., 2007). Mapping soil micronutrients (White and Zasoski, 199) is essential to choosing appropriate SLM practices since micronutrient status can be used to index soil quality (Erkossa et al., 2007) and to identify strategies for its improvement. In parts of West Africa, where depletion of soil fertility through extractive farming practices creates negative nutrient budgets (Anonymous, 2006), enhancement of soil fertility is essential to improving soil quality and raising NPP, while also addressing CC.

The current low level of SOC pool in the soils of SSA must be increased above the threshold level so that soils can respond to other inputs (e.g., improved varieties) and reduce farmer's vulnerability to CC. Bationo et al. (2005) described several SLM options for soils of SSA including soil and water conservation through watershed management, use of fertilizers and other soil amendments, and crop residue management. These options are outlined in Figure 9.

D. Cropping and Agroforestry Systems

67. The term cropping system implies crop management including rotation and cropping sequences, mixed and relay cropping, agroforestry, and timing of farm operations. In contrast, the term farming system is much broader in scope and also encompasses land use, such as silviculture, silvo-pastoral system, and agro-silvo-pastoral systems. Thus, choice of appropriate cropping systems is extremely important to local CC action and adaptation, through alterations in time of planting, cropping sequences and combinations, INM and other components of improved cropping systems.

68. Rice-based cropping systems are important in Asia. The rice-wheat system has been the basis of the Green Revolution in SA and the sustainable management of rice-based system is essential to meeting the basic needs of 3.7 billion people in Asia (Lal et al., 2004). In the Philippines, Pampolino et al. (2008) reported that balanced fertilization of irrigated rice is essential to maintaining and increasing the SOC pool. Other innovations for rice-based systems include direct seeding with NT system (Lal et al., 2004), and aerobic rice grown under upland rather than submerged conditions.

69. Agroforestry intentionally combines agriculture (crops and animals) and forestry to create integrated and sustainable land use systems. It is also defined as "a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in

landscape, diversifies and sustains production for increased social, economic and environmental benefits for land uses at all levels" (www.icraf.cgiar.org). It involves the use of integrating selected tree species that are intentionally planted and managed in rural landscape and communities (Schoeneberger, 2008).

70. Agroforestry systems that are based on installing contour hedgerows, have several advantages for the small landholders and other producers in developing countries. Notable among these are the following: (i) deep root system loosens the sub-soil, improves water infiltration, and transfers C into the sub-soil, (ii) perennial hedgerows strengthen nutrient cycling, (iii) prunings provide biomass for mulching and improve soil structure and tilth, (iv) contour hedgerows decrease risks of runoff and water erosion, and also serve as windbreaks, (v) trees grown in association with crops and forages increase biodiversity, and (vi) perennials enhance SOC pool, and improve soil fertility and available plant nutrients. An important merit of contour hedgerows is soil erosion control (Lal, 1989a; Pellek, 1992). In Haiti, alley cropping system has been reported as an economic structure for enhancing soil conservation (Bayard et al., 2007), improving N availability and increasing crop yields (Isaac et al., 2003, 2004), and creating another income stream for farmers (Murry and Bannister, 2004). Traditional agroforestry systems provide numerous ecosystem services, especially on steep lands such as in the eastern Himalayan region of India (Sharma et al., 2007). While there may be additional labor needed and some land area is taken out of crop production, hedgerows and agroforestry enhance the SOC pool, and sequester C in the biomass. One of the traditional agroforestry systems is the management of native woody shrub communities in arid climates. In Senegal's Peanut Basin, Lufafa et al. (2008a; b) reported increases in soil and biomass C pools by two native woody shrubs: *Guiera senegalensis* (J.F. Gmel) and *Piliostigma reticulatum* (D.C. Hochst). The SOC

pool to 40 cm depth was ~ 17 t C/ha, of which 57% was in the top 20-cm (Lufafa et al., 2008b); compared with the traditional "pruning-burned" management practice, returning pruning for 50 years would increase soil C sequestration by 200-350% without fertilization, and by 270-483% with low fertilization regime (35 kg N/ha/yr). These SLM practices enhance adaptation to CC through increase in crop yields by improving soil fertility, and would transform these degraded semi-arid agroecosystems from a source to a sink for atmospheric CO_2 (Lufafa et al., 2008a).

71. Agroforestry systems have been widely evaluated for C sequestration in the above ground biomass and soil. Nair et al. (2008) have reviewed the rates of C sequestration in soil and above ground biomass in different ecoregions. The rate of C sequestration in the biomass ranges from 0.29 to 15.2 t C/ha/yr. Similarly, the data on SOC pool also indicated significant improvements under agroforestry system.

72. In Mali, Takimoto et al. (2008) reported C sequestration with *Faidherbia albida* and *Vitellaria paradoxa* under traditional and improved agroforestry systems. The C pool in biomass ranged from 0.7 to 54.0 t C/ha and that in the soil (1-m depth) from 28.7 to 87.3 t C/ha. These data indicated the importance of SCS in the agroforestry system. In Malawi, Makumba et al., (2007) reported that there was a net decrease of SOC pool by 6-7 t C/ha in maize monoculture in 0-200 cm depth compared with SCS of 123-149 t C/ha over 10 years with *Gliricidia*-based agroforestry system. In Zambia, Koanga and Coleman (2008) assessed SOC in N- fixing trees with and without maize. Measured SOC pool to 20-cm depth ranged from 22.2-26.2 t C/ha in maize monoculture, 29.5-30.1 t C/ha in non-cropping fallows, and 32.2-37.8 t C/ha in cropping fallow treatments. Nitrogen fixing trees (*Leucaena* spp. *Gliricidia* spp., *Senna* spp., *Sesbania* spp., *Cajanus* spp.) have more SCS potential than non-nitrogen fixing trees. The SOC pool also increased with increase in tree biomass production and tree rotation. Some long-term

experiments conducted in Nigeria (Juo et al., 1995; Lal, 2005b) showed that natural regeneration (bush fallow system) and *Leucaena* plantation increased SOC pool by 7.5 t C/ha and 11.4 t C/ha in 0-15 cm depth over 13-year period, respectively (see Table 8). However, another study in southwestern Nigeria also showed that alley cropping systems (with *Leucaena* and *Gliricidia*) did not prevent the decrease in SOC pool despite their effectiveness in soil erosion control (Lal, 1989b; c).

73. In view of the potential synergies between existing multilateral environmental agreements in the implementation of land use change and forestry activities (e.g., the overlap among UNCCD, UNFCCC, and UNCBD) (Cowie et al., 2007), there is a need to identify policy options for facilitating beneficial forestry/agroforestry systems and other land use changes. For this, the data on the technical potential of C sequestration is needed for such land use systems. Watson et al. (2000) estimated that 400 Mha of area under agroforestry systems could sequester C at the rate of 0.72 t C/ha/yr. Nair et al. (2008) estimated that the global area under agroforestry systems of 1,023 Mha can be increased to sequester C. Dixon (1995) estimated that 585-1215 Mha of area under agroforestry systems (in Africa, Asia, Americas) has a technical potential for C sequestration of 1.1-2.2 Gt C/yr. Dixon also estimated that an additional 630 Mha of croplands and grasslands that are currently fallow or marginal lands primarily in the tropics could be converted into agroforestry.

E. Biochar

74. Biochar refers to charcoal produced from biomass. Appropriately used, biochar can be applied as soil amendment for improving soil physical and biological properties (Sombroek et al., 2003; Rumpel et al., 2005; Lehman and Joseph, 2009). With high application rates, it can also lead to SCS especially in situations where biochar may be available. Biochar can by

produced from surplus biomass such as those from sawmill, dairy farms, food processing units, rice husking mill, timber yard, etc. Biochar may also be produced as a co-product of a biofuel production system. The rate of application of biochar on cropland soils can be as high as 50-150 t/ha (Lehmann et al., 2006). However, the availability of biochar at such a high rate has logistic challenges. Apart from benefits of SCS and mitigating CC (Morris, 2006; Fowles, 2007), biochar can also improve soil fertility and increase agronomic production (Whitford, 2008). In Laos, Asai et al. (2009) reported that application of biochar improved saturated hydraulic conductivity of topsoil. It also increased grain yields at sites with low P availability and improved the response to N and NP chemical fertilizer treatments. In Colombia's Orientale Savanna Oxisol, Major et al. (2006) reported that biochar application of 8 to 20 t/ha did not have a significant effect on maize yield during the first year, but increased it by 15% and 23%, respectively during the second and third year. In a pot culture experiment conducted on a hard-setting Alfisol in NSW Australia, Chan et al. (2007) reported significant changes in soil quality, SOC concentration, tensile strength at biochar application rates of >50 t/ha. Steiner (2007) also reported the beneficial effects of biochar application on soil fertility. But biochar may not be suitable in every situation. Apart from the logistics with regards to the biomass feedstock for producing biochar, application of fire-derived charcoal may also enhance loss of forest humus (Wardle et al., 2008). Therefore, identification of specific niches for biochar application is crucial to harvesting its benefits.

F. Water Management

75. Rainfall deficit and variability are serious constraints to increasing productivity of rainfed agriculture in places like the Sahel (Ayoub, 1999), and elsewhere. Droughts also aggravate the problem of soil degradation and erosion, vegetation damage, slough and lake deterioration and

wildlife loss (Maybank et al., 1995). Production uncertainty associated with rainfall variability remains a fundamental constraint in SSA, a constraint which will be exacerbated with the projected CC (Cooper et al., 2008). During the 21st century, climate change and the growing imbalance among fresh water supply, consumption and population may alter the water cycle dramatically (Jackson et al., 2001). Thus, addressing drought stress and uncertainties in rainfall amount and seasonal distribution is an essential first step in adapting to current and future CC in many affected developing countries (Esikuri, 2005). About 18% of the world's irrigated cropland area generates 40% of agricultural produce. While irrigation is extensively used in Asia (China, India, Pakistan), it is scarcely used in other areas especially SSA. Currently, only 5% of agricultural land in SSA is irrigated, compared with more that 60% in parts of Asia. It is estimated that crop yields can be increased by a factor of 2 to 4 in many parts of SSA through better water management (NRC, 2009). Rockström et al. (2006, 2007) have emphasized the importance of water harvesting technologies, and increasing water retention with tied-ridges, rock bunds and other simple structures, which conserve, harvest and recycle water. In addition, there are several sustainable irrigation management technologies (Lorenzini and Brebbia, 2006) such as condensation irrigation and sub-surface irrigation by condensation of humid air (Lindblom and Nordell, 2006) which can save water and decrease risks of salinization (Figure 9). Thomas (2008) described several opportunities of water management for reducing the vulnerability of dryland farmers in Central and West Asia and North Africa to CC. Important among these opportunities are supplemental irrigation along with water harvesting and recycling using modern irrigation techniques (e.g., drip sub-irrigation), growing salt-tolerant plant species (see following section), and converting to conservation agriculture. Drip irrigation is a demonstrated water-saving technology, and has the potential to improve crop production in SSA

(Karlberg and de Vries, 2004). Maintaining and enhancing productivity of irrigated land through improvements in water use efficiency is essential to increasing NPP (Hargreaves, 2003), improving ecosystem services, and adapting to CC.

76. Adoption of various SLM options in soils of managed ecosystems has a high technical potential for SCS (Table 14). Rates of SCS in croplands vary widely depending on SLM option, soil type, and climate (Table 14). In most cases, the rates of SCS in intensively managed cropland soils (NT farming, rotations, manuring, etc.) range from 300 to 600 kg/ha/yr. The rates of C sequestration in the biomass (above and below ground) are extremely high in forest ecosystems, and can be as high as 3000 kg/ha/yr in well-managed forest plantations, and especially when degraded soils are converted to perennial land uses.

Table 14. Experimentally measured rate of soil carbon sequestration with adoption of various sustainable land management options (Lal, 2008).

SLM Option	Region	Rate (kg C/ha/yr)
I. Cropland soils		
(i) Conservation tillage	North America	200-1200
	South America	300-600
	Australia	100-1000
(ii) Rotations	North America	200-300
(iii) Nutrient management	North America	300-500
	South Asia	500-1000
	Tropics	100-200
(iv) Intensive farming	North America	500-1000
	Europe	500-1000
II. Grazing land soils		
(i) Rangeland management	North America	20-500
(ii) Pasture management	North America	500-1000
III. Forest land soils		
(i) Stand management	Europe	400-500
	North America	600-800
(ii) Afforestation	Europe	500-3000
	Sub-Saharan Africa	100-3000
(iii) Agroforestry	Central America	500-800
IV. Minesoil Reclamation		
(i) Afforestation	North America	300-3000
	Pacific	1500-2500

XIII. Desertification Control

77. Desertification is the persistent degradation of dryland ecosystems by variations in climate and human activities (UNEP, 1977, 1990; UNCED, 1992; www.unccd.int; MEA, 2005). Desertification is caused by various social, political, economic, and natural factors which vary from place to place and in time (Mortimore, 1994; Mainguet and da Silva, 1998). In drylands, more people depend on ecosystem services for their basic needs than in any other ecosystem. Yet land degradation in these drylands diminishes biological productivity and directly affects ecosystem services (e.g., food and water, climate regulation, soil conservation, recreation) provided to millions of people. The process of desertification has been studied with regards to its impact on production, income and well being of people (Mendoza, 1990; Blaikie, 1989; Verstaete, 1986; MEA, 2005). The effect of global CC on desertification is complex and not fully understood. However various approaches for combating desertification and mitigating CC are directly linked in many ways thus necessitating synergistic implementation of the United Nations conventions on desertification, climate change and biological diversity (MEA, 2005). It is important to point out that various SLM technologies and practices offer crucial, and in many cases the only, options for combating desertification in many parts of the world. Such practices also provide the best practical options for effective local actions to address climate change.

78. However, the process of desertification is not confined to the drylands of the tropics or economically developing regions alone. It also occurs in developed countries (e.g., USA), high latitude humid ecoregion (e.g., Iceland) and even humid regions (tropical rainforest). It results mainly from land misuse and soil mismanagement. The 2005 Millenium Ecosystem Assessment confirmed that desertification is potentially the most threatening ecosystem change impacting

livelihoods of the poor. Land degradation and desertification undermines the long-term development of many nations. The scale of the land degradation challenge calls for sustained and collective action by the international community. But for these efforts to bear sustainable results, the implementation of of measures to combat land degradation and desertification (i.e., UNCCD) must be guided and defined at the country level.

79. Drylands cover 47% of Earth's land area (Table 15). Because of the harsh climate, these regions are prone to desertification. The problem is exacerbated by marked rainfall seasonality and variability, which determine the pulse of biological activity and NPP. Estimates of the extent of desertification range widely and are highly subjective. UNEP estimated 3.97 Bha in 1977, 3.48 Bha in 1984 and 3.59 Bha in 1992 (UNEP, 1977, 1984a; b, 1992). The land area affected by desertification was estimated at 3.25 Bha by Dregne (1983) and 2.0 Bha by Mabbutt (1984). According to the GLASOD methodology (Oldeman and Van Lynden, 1998), the land area affected by desertification is estimated at 1.14 Bha (Table 16). These estimates are similar to those by UNEP (1991) with reference to degradation of soil and vegetation. In addition, UNEP's (1991) estimates include 2.58 Bha of degraded vegetation on rangelands. Estimates of the current rates of desertification also vary widely, and the annual rate is estimated at 5.8 Mha or 0.13% of drylands in the mid latitudes (Table 17). Eswaran et al. (2001) estimated the land area vulnerable to land degradation and the number of impacted people (Table 18). The area vulnerable to degradation is 4324 Mha (33% of Earth's land area) and the impacted population is 2.65 billion (46% of the world's population in 2000). Eswaran and colleagues also estimated land area affected in regions with different population density. Total land area vulnerable to desertification is 1990 Mha for population density of <10 person/km^2, 1160 Mha for 11-40 persons/km^2 and 1170 Mha for population density of >41 persons/km^2 (Table 18). Bai et al. (2008) estimated the

global extent of land degradation on the basis of decline in NPP, and reported that 3506 Mha are degraded (23.5% of the land area), and about 1.54 billion (23.9%) people are affected globally (Table 19).

Table 15. **The extent of global drylands (recalculated from UNEP, 1992). The climatic classification is based on FAO (1993).**

Classification	**Land Area (Bha)** D sub-humid	**Semi-arid**	**Arid**	**Hyper-arid**	**Total**	**% of Global Area**
Köppen (1931)	-	1.91	1.61	-	3.52	26.3
Thornthwaite (1948)	-	2.05	2.05	-	4.10	30.6
Meigs (1953)	-	2.11	2.17	0.58	4.86	36.3
Shantz (1956)	-	0.70	3.32	0.63	4.65	34.8
UN (1977)	-	1.78	1.83	0.78	4.39	32.8
UNEP (1992)	1.32	2.37	1.62	1.00	6.31	47.2

Hyper-arid = <200 mm precipitation annually.
Arid = <200 mm of winter rainfall or <400 mm of summer rainfall.
Semi-arid = 200 – 500 mm of winter rainfall or 400 to 600 mm of summer rainfall.
Dry sub-humid = 500 to 700 mm of winter rainfall or 600 to 800 mm of summer rainfall.
Bha = 10^9 ha.

Table 16. Comparison between Glasod estimates of desertification in dry areas with that of UNEP methodology (Lal, Hassan and Dumanski, 1999).

UNEP (1991)	**Area (10^6 km^2)**	**Oldeman and Van Lynden (1998)**	**Area (10^6 km^2)**
Degraded irrigated land	0.43	**Water erosion**	4.78
Degraded rainfed cropland	2.16	**Wind erosion**	5.13
Degraded rangeland (Soil & vegetation)	7.57	**Chemical degradation**	1.11
Sub-total	10.16	**Physical degradation**	0.35
Degraded rangeland (vegetation only)	25.76	**Total**	11.37
Grand total	35.92	**Light**	4.89
Total arid land area	51.72	**Moderate**	5.09
% degraded	69.5	**Severe and extreme**	1.39
		Total	11.37

These estimated refer to soil degradation only

Table 17. Estimate of annual rate of land degradation in mid latitude drylands (calculated from Mainguet, 1991; UNEP, 1991).

Land use	Total land area (Mha)	Rate of desertification	
		Mha/yr	% of total/yr
Irrigated land	131	0.125	0.095
Rangeland	3700	3.200	0.086
Rainfed cropland	570	2.500	0.439
Total	4410	5.825	0.132

Mha = 10^6 ha

Table 18. Estimates of land area under different vulnerability classes of desertification and the number of impacted people (Eswaran et al., 2001).

Vulnerability Class	Area Affected		Population	
	10^6 km^2	% of Global Land Area	10^6 People	% of Global Population
Low	14.60	11.2	1,085	18.9
Moderate	13.61	10.5	915	15.9
High	7.12	5.5	393	6.8
Very High	7.91	6.1	255	4.4
Total	43.24	33.3	2,648	46.0

Table 19. Estimates of area affected by land degradation (Bai et al., 2008).

Parameter	Value
Area affected (10^6km^2)	35.06
Percent of land area	23.54
Total NPP loss (Mt C/yr)	955
Percent of total population	23.9
Total population affected (billion)	1.54

80. Two principal biophysical processes leading to desertification are erosion and salinization. These processes are also affected by overgrazing and fire. Accelerated soil erosion by wind and water are severe in semi-arid and arid regions (Balba, 1995; Baird, 1997), especially those in Mediterranean climates (Brandt and Thornes, 1996; Conacher and Sala, 1998a, b). In the dry Chaco forest of Argentina, Abril et al. (2005) observed that overgrazing was a major cause of

decline in soil quality and that overgrazing had a more adverse effect than fire. Burned but ungrazed land recovered sooner than chronically overgrazed land. Desertification control through SLM options involves measures such as conserving, harvesting and recycling water, establishing vegetation cover, creating positive C and nutrient budgets, and reclaiming salt-affected soils. The SCS through desertification control can provide another income stream for farmers and land managers. Furthermore, the residence time of C in drylands is much longer and the decomposition rate much slower than that in humid environments (Gifford et al., 1992). The technical potential of SCS to create an income stream for farmers and land managers through desertification control is discussed next.

XIV. Management of Salt-Affected Soils

81. Secondary salinization is a major problem on irrigated lands. The irrigated land area in the world has increased 50 fold during the last three centuries from 5 Mha in 1700, 8 Mha in 1800, 48 Mha in 1900 to 255 Mha in 2000. Risks of secondary salinization are exacerbated by use of poor quality water, poor drainage and excessive irrigation, leakage of water due to defective delivery systems, impeded or slow soil drainage, and other causes. Salinization is a severe problem in China, India, Pakistan, and in the countries of Central Asia (Babaev, 1999). For example, the extent of salinized land area is 89% in Turkmenistan, 51% in Uzbekistan, 15% in Tajikistan, 12% in Kyrgyzstan, and 49% of the entire region (Funakawa et al., 2000; Khakimov, 1989; Pankova and Solovjev, 1995). Salinization is also a problem in southwestern USA, northern Mexico and in some dry regions of Canada (Balba, 1995). High salinity and water logging in South Asia (FAO, 1994), is caused mainly by excessive irrigation and lack of proper drainage (Lal, 2009d).

82. But irrigation is not the only reason for salinization of land; many coastal areas are threatened by climate change in ways that lead to salinization. More importantly, most if not all small island developing nations of the Pacific and Indian Oceans as well as the countries of the Caribbean are among the most vulnerable to global climate change (IPCC, 2007). While the severity of the impacts will vary from country to country, there are various key concerns directly linked to climate change that will affect countries across these regions. Projected sea level rise will combine a number of factors resulting in accelerated coastal erosion, increased flood risk and in some areas permanent loss of land. Any increase in the intensity and destructiveness of tropical storms will further accelerate land degradation along the coasts. The impacts of sea-level rise will be further exacerbated by the loss of protective coastal systems such as coral reefs in areas such as the Caribbean (Oxenford et al., 2007). More immediately, such sea-level rise is also directly associated with saline intrusion into coastal lands and aquifers, affecting the availability of farmland and freshwater. Hence using known SLM practices and technologies for reclamation and management of such salt affected lands is a crucial strategy to adapt to climate change in many areas around the world.

83. Despite the areal extent of salt–affected soils worldwide, the research information on SOC pool and flux under different management systems is rather scant (Wong et al., 2008). There are 3 major SLM strategies to reclaim salt-affected soils (Figure 13): (i) enhance tolerance to high salt concentrations either by choosing salt-tolerant species or by enhancing tolerance to excess salts through selective breeding, (ii) improve SOC concentration because even the slightest increase can have a major positive impact on soil structure aeration, permeability, water retention and microbial/enzymatic reactions, and accelerate soil desalinization by leaching excess salts out of the soil profile, and (iii) leach salts out of the root zone through improved

drainage and irrigation with good quality water. The relative significance of each strategy depends on the soil-specific conditions.

A. Salt Tolerance

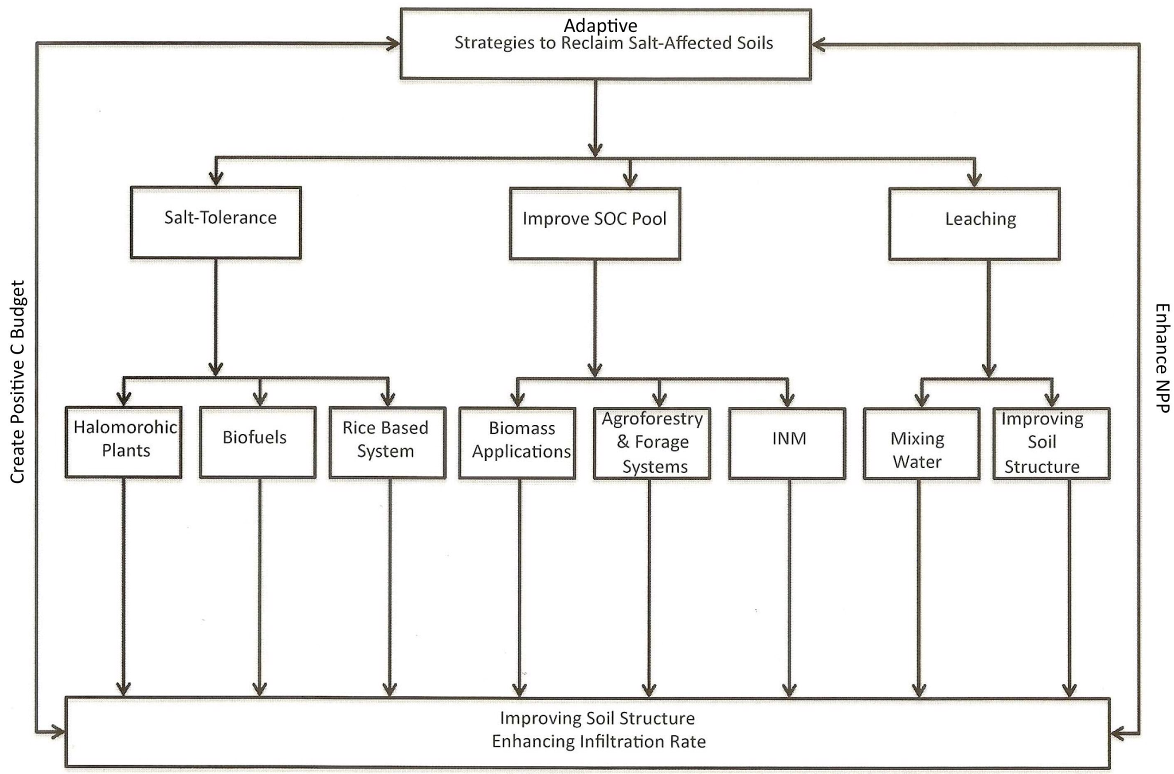


Fig. 13.SLM strategies to reclaim salt-affected soils can reduce vulnerability to CC.

84. Vegetation is essential to enhancing the SOC concentration, which is low in salt-affected soils because of little or no vegetation cover. Establishment of plants increases SOC concentration by: (i) addition of leaf litter, (ii) growth and turnover of root biomass, (iii) addition of root and mucilage exudates, (iv) increase in activity of soil fauna especially microbial biomass. Some plant species are naturally adapted to saline conditions (Table 20) and should be considered for reclamation of salt affected areas. Most terrestrial plants evolved in saline ocean water with high salt concentration of about 500 mmol L^{-1}. However, most species eventually adapted to terrestrial environments with low salt concentrations around 450 million years ago

(Rozema and Flowers, 2008). Yet, about 1% of the species growing under terrestrial environments have retained tolerance to high salt concentrations. These species, called halophytes, have a wide range of phonological characteristics, and include cereals, legumes, annuals, perennials, shrubs, trees, etc. Qadir et al. (1998) reported that there are 16 major halophytic plant families in Iran. These families, in terms of the number of species, are in the order *Chenopodiaceae*> *Poaceae*> *Asteraceae*> *Brassucaceae*> *Plumbaginaceae*> *Cyperaceae*> *Tamar-ciacae*> *Zygophyllaceae*> *Polygonaceae*> other families. The growth rates of halophytes are comparable to those of conventional plants. There are also some useful halophytes which can be used for industrial purposes and biofuel production. Halophytes can also be grown under arid conditions by irrigation with saline water, or mixing saline water with fresh water. In addition to exploration of natural genetic variations, development of transgenic plants is another option to enhance the degree of salt stress tolerance (Yamaguchi and Blumwald, 2005). And in coastal zones affected by saline intrusion partly due to sea level rise, introduction of such halophytes is a practical strategy to adapting to CC. In addition, plants such as coconuts, oil palm, guava, mango, mangroves, casuarina, can be an important addition to local livelihoods while helping to protect coastal lands (from erosion, storms) and adapt to CC.

Table 20. Some salt tolerant plants (Adapted from Lal et al., 1999).

	Plant	Latin Name
I	**Fruit trees**	
	Tamarind	(*Tamarindus indica*)
	Mango	(*Mangifera indica*)
	Loquat	(*Eriobotyra japonica*)
	Jamun	(*Syzygirum cuminii*)
	Coconut	(*Cocos nucifera*)
	Oil Palm	(*Elaeis guineensis*)
	Guava	(*Psidium guajava*)
II	**Halophytes**	
	Pickle weed	(*Salicornia* spp) Turtle weed
	Salt Grass	(*Distichlis palmeri*) Seep weed

	NyPa Forage	(*Distichlis* spp)
	Salt bushes	(*Atriplex numularia*)
	Algae	(*Spirulina geitleri*)
III	**<u>Trees</u>**	
	Gum trees	(*Eucalyptus* spp)
	Acacia	(*Accacia* spp)
	Shisham	(*Dalbergia sissoo*)
	Ye-eb	(*Cordeeauxia edulis*)
	Pine	(*Pinus oocarpa*)
	Mesquite	(*Prosopis juliflora*)
	Jojoba	(*Simmondsia chinensis*)
	Casuarina	(*Casuarina equisetifolia*)
	Albizia	(*Albizia lebbeck*)
	Ber	(*Zizyiphus mauritiana*)
	Arjuna herb	*(Terminalia Arjuna)*
IV	**<u>Grasses and Forages</u>**	
	Karnal Grass	(*Leptochloa fusca*)
	Vetiver	(*Vetiveria* spp)
	Narrow Leaf Lupin	(*Lupinus angustifolius*)
	Wheat grass	*(Thynopyron ponticum)*
V	**<u>Crops</u>**	
	Triticale	(*Secale* spp)
	Bambara groundnut	(*Voandzeia subteranea*)
	Marama bean	(*Tylosema esculentum*)
	Tepary bean	(*Phaseolus acutifolius*)

B. Techniques to Enhance the Quality of Salt-Affected Soils

85. Improving SOC pool is important to reclaiming salt-affected soils. Even at a low concentration, SOC is important to improving soil fertility, increasing water permeability, enhancing aggregation, and accentuating soil biotic activity. Thus, improving SOC pool is an important strategy of reclaiming salt-affected soils. The goal is to create a positive ecosystem C budget (Figure 13). Because many areas may be affected by salinity due in part to CC induced dessication and saline intrusion, this report presents some of the proven SLM practices that could be employed to reclaim such soils. There are several technologies which have proven effective in enhancing the SOC pool of salt-affected soils. Some of these are briefly discussed below:

(i) Manuring

86. Application of manure on salt-affected soils sets in motion the reclamation process. It can enhance the SOC pool in salt-affected soils, increase microbial activity in the rhizosphere, and positively impact cycling of C, N, P, S, and other elements (Liang et al., 2005). Restoration, while reducing salt concentration, leads to improvements in nutrient availability and SOC pool, especially through the addition of the root biomass (Hua et al., 2008). In addition to soil fertility, soil structure is also improved in salt-affected soils amended with manure. Most soils of the arid regions have low SOC concentrations ranging from 0.03 to 3.0 g/kg, compared with SOC concentration in animal manure at >300 g kg^{-1} (Zahoon et al., 2007). Therefore, application of manure and organic amendments can enhance SOC pool significantly in these areas (Garcia-Orenes et al., 2005). In Southern Spain, Garcia-Ornes et al. (2005) observed increases in aggregation and aggregate stability with application of organic amendments. Use of successive applications of poultry manure, however, can increase the risks of secondary salinization (Li-Xian et al., 2007), and the effect is more severe in greenhouse vegetable production (Shi et al., 2009). Salt concentration in animal manure is in the order pigeon manure > chicken manure > pig manure. In general, cattle manure has lower salt concentration.

(ii) Crop Residue Management

87. Adoption of NT systems, mulch farming, and crop residue management are important to reclaiming salt-affected soils, by enhancing water transmission and structural properties, and reversing the desertification process (El-Tayeb and Skujins, 1989). In the Centro Ebro Valley of NE Spain, Badia (2000) reported that application of barley straw at 6 t/ha increased SOC concentration and pool and enhanced soil physical properties over a 2-year period (Table 21). The rate of SOC sequestration over the 2-year period was 0.68 t C/ha/yr in a saline soil and 1.55 t

C/ha/yr in a saline-sodic soil (Table 21). Use of crop residue as mulch is usually practiced in conjunction with NT systems. Mulching and incorporation of cover crops in the rotation cycle can improve soil structure, increase aeration, and enhance soil physical quality especially of the surface layer. Direct seeding of wheat (*Triticum aestivum*) after rice (*Oryza sativa*) is being rapidly adopted throughout the Indo-Gangetic Basin for the rice-wheat system (Hobbs and Gupta, 2003; 2004; Hobbs et al. 2002; 2008) and has ameliorative effects on soil properties and grain yield of wheat. Savings in time and energy needed for conventional seedbed preparation and higher and better quality yield of wheat sown early are important co-benefits of this system to the small-scale farmer of the South Asian region.

(iii) Establishing Tree Plantations

88. Rapid salinization since the World War II (~1940s) has partly resulted from increased recharge following the wide spread clearing of perennial native forests and woodland and their replacement by annuals which use less water. This land use change has significantly raised the water table (Farrinon and Salma, 1996). Thus, establishing trees in salinized and waterlogged soils is important to lowering the water table. Recharge must also be reduced to prevent any further rise in salts. In this regard, planting trees is one of the most favorable SLM options (Farrinon and Salma, 1996). Tree-based or complex cropping systems are important to restoring salt-affected soils. It has been widely documented that reforestation by trees on cleared lands lowers ground water levels compared with adjacent agricultural lands (Bari and Schofield, 1992). Several tree species are suited for establishment in salt-affected soils (see Table 20). Leguminous trees such as *Prosopis juliflora* and *Dalbergia sissoo* are adapted to degraded sodic soils of northwest India (Mishra and Sharma, 2003). *Eucalyptus* spp. grows under diverse conditions, including sodic soils in India (Mishra et al., 2003) and Australia (Lambers, 2003). Evergreen and

deep-rooted trees transpire a large quantity of water, lower the water table, and improve aeration. Furthermore, the deep-rootedness of trees allows access to deep soil moisture whereas the shallow-rooted annuals suffer easily from drought stress. Thus, establishing trees on salt-affected soils provides a long-term solution for managing dryland salinity problem (Ward et al., 2003; Lambers et al., 2003). In Iran, *Tamarix* and *Atriplex* plantations are effective in decreasing salinity. Other trees found suitable for growing on salt-affected soils in Iran are *Haloxylon aphyllum, H. persicum, Petropyrum euphratica* (Qadir et al., 2008). *Atriplex* is also a potential fodder shrub.

Table 21. Effect of crop residue management on the quality of a saline and saline-sodic soil Northeast Spain (Recalculated from Badia, 2000).

Soil	Residue Management	E C (dS/m)	SAR (mmol/L)	Infiltration Rate (mm/h)	Bulk Density (t/m^3)	Aggregate Stability (g/Kg)	Soil Organic Carbon g/Kg	Soil Organic Carbon t/ha	Soil Organic Carbon tC/ha/yr
Saline	Removed	12.1a	6.1a	12.6b	1.44a	242b	4.4b	9.82	-
	Incorporated	4.9b	5.7a	78.0a	1.33b	322a	5.6a	11.17	0.68
Saline-sodic	Removed	12.9a	16.1a	10.2a	1.37a	263a	4.7b	9.66	-
	Incorporated	6.6b	14.7a	15.0a	1.27b	287a	6.7a	12.76	1.55

Straw incorporated at the rate of 6 t/ha
Soil depth = 15 cm

(iv) Agroforestry Systems

89. Tree-based and complex cropping systems with deep-rooted plants (e.g., trees and perennial pastures) in agroforestry systems can be an important strategy to reclaiming salt-affected soils (Stirzaker et al., 2002). Deep-rootedness of trees is important to incorporating the SOC pool in the sub-soil and enhancing soil structure. Perennials with deep root systems also use more water than shallow-rooted annuals and can improve the drainage conditions. The data in Tables 22 and 23 from Uttar Pradesh India, show high rates of SCS in sodic soil planted with *Eucalyptus* with significant increase in SOC pool to 150 cm depth. The rate of SCS was 1.1 to 1.5 t C/ha/yr (Tables 22 and 23). Trees can also be grown in association with crops and pastures through agroforestry systems. The strategy is to restore complexity and resilience through introduction of appropriate agroforestry systems (Hobbs and Cramer, 2003; Lambers, 2003). Because of this potential, agroforestry systems are being proposed at a large scale for reclamation of 8.8 Mha of salt-affected soils in South-western Australia. Harper et al. (2005) estimated that rates of C sequestration in biomass of *E. Globulus* over a 10 year period range from 3.3 to 11.5 t CE ha/yr in Collie catchment, Australia (Table 24). These are extremely high rates of C sequestration, especially on a large scale watershed. Experiments conducted in the Indo-Gangetic plains showed that growing mesquite (*Prosopis juliflora*) and other perennials is also an effective strategy for increasing the SOC pool in salt-affected soils. The data in Table 25 show that establishing mesquite on an alkaline soil in northwestern India increased its SOC concentration over a 74-month period from 0.18% to 0.43% in 0-15cm depth, and from 0.13% to 0.29% in 15-30 cm depth. Establishing mesquite in association with Kallar grass (*Leptochloa fusca*) increased SOC concentration over a 74 month period from 0.19% to 0.58% in 0-15cm depth compared with 0.12% to 0.36% in 15-30 cm depth (Table 25). The data in Figure 14 from

Garg (1998) show increase in SOC pool from about 10 t/ha to > 45 t/ha after an 8 year period under *Acacia nilotica* and about 40 t/ha under *Dilbergia sissoo*. In addition to lowering the water table, enhancing aeration and improving the SOC pool, there are other ecosystem services provided by appropriate agroforestry systems. Other benefits include use of woody biomass as fuel source, increase in biodiversity and provision of fodder. Bioremediation of sodic soils by using silvopastoral systems has proven effective in soils of northwestern India (Kaur et al., 2002). From such field based evidence, it is clear that agroforestry techniques can advance sustainable management of soil resources, especially of salt-affected soils which tend to have numerous physical and chemical/nutritional constraints to high agronomic production.

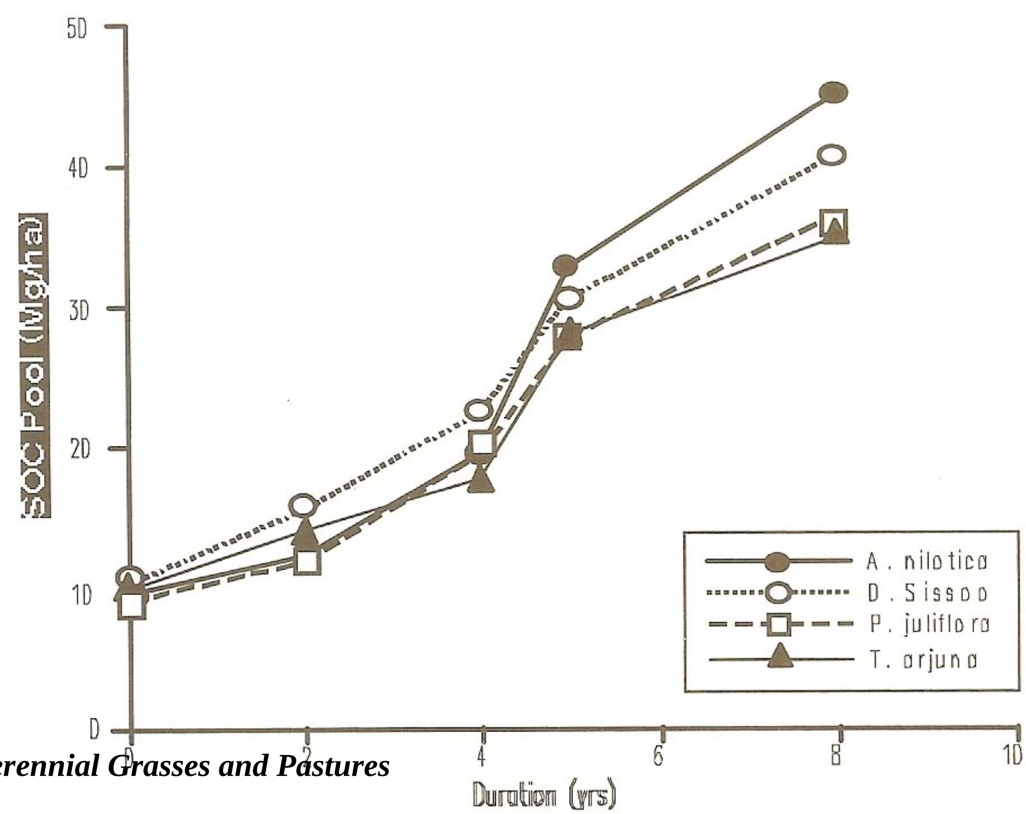


Fig 14: C sequestration through reclamation of salt affected soils in northern India (recalculated from Garg, 1998; Lal et al., 1998)

(v) Perennial Grasses and Pastures

90. Similar to the beneficial effects of trees, establishing deep-rooted grasses also enhances the SOC pool and can reclaim salt-affected soils. In NSW Australia, Wong et al. (2008) reported

that SOC concentration was significantly higher in the profiles that were vegetated with native pastures (1.96-2.71% in the 0-5 cm layer) or re-vegetated with sown pastures (2.35% in the 0-5 cm layer) than in profiles that were scalded (1.52% in 0-5 cm layer). Several studies have shown that growing Kallar grass has strong ameliorative effects. In Pakistan, Akhter et al. (2004) observed strong positive effects of growing Kallar grass for 3 years on soil physical properties, especially the plant-available water capacity, hydraulic conductivity, and structural stability. Improvement in soil physical properties was positively correlated with the SOC concentration. The data in Table 26 from Pakistan indicate increase in duration of establishing Kallar grass decreases soil bulk density linearly up to 100 cm depth. In addition, there was also an increase in plant-available water capacity and saturated hydraulic conductivity with increase in duration of establishing the Kallar grass (Table 26). Wong et al. (2008) reported that profiles that were vegetated with native pastures contained 35.2-53.5 t C/ha to 30 cm depth compared with 42.1 t C/ha in sown pastures, only 19.8 t C/ha in scalded profile, and 7.7 to 11.4 t C/ha in scalded-eroded soils. Regardless of the antecedent concentration, SOC pools in young pastures reach values observed in old pastures with the observed increase persisting for about 40 years (Conant et al., 2001). Wong et al. (2008) observed that SOC pool in re-vegetated pastures increased to a level comparable to that under native pastures. The data in Table 27 from Pampa, Argentina show that conversion of arable (cultivated) land to grass lands can increase SOC and total nitrogen (TN) concentrations and restore salt-affected soils.

Table 22. Changes in bulk density and organic carbon concentration and pool under *Eucalyptus* plantations after 3 and 6 years of growth in a sodic soil of Utta Pradesh, India (Recalculated from Mishra et al., 2003).

Treatment	Soil Depth (cm)	SOC Concentration (g/kg)	Bulk density (t/m^3)	SOC Pool (t/ha)	Rate of SOC sequestration (tC/ha/yr)
1. Control					
	0-10 (10)	2.0	1.66	3.32	
	10-30 (20)	1.6	1.59	5.09	
	30-60 (30)	0.9	1.66	4.48	
	60-90 (30)	0.6	1.72	3.10	
	90-120 (30)	0.6	1.74	3.13	
	120-150 (30)	0.3	1.76	1.58	
	Total			20.70	Baseline
2. Three year old Plantation					
	0-10 (10)	3.2	1.39	4.45	
	10-30 (20)	2.2	1.39	6.12	
	30-60 (30)	1.2	1.48	5.33	
	60-90 (30)	0.8	1.56	3.74	
	90-120 (30)	0.7	1.63	3.42	
	120-150 (30)	0.3	1.67	1.50	
	Total			24.56	1.29
3. Six year old Plantation					
	0-10 (10)	4.2	1.27	5.33	
	10-30 (20)	2.8	1.27	7.11	
	30-60 (30)	1.0	1.38	4.14	
	60-90 (30)	0.6	1.45	2.61	
	90-120 (30)	0.7	1.52	3.19	
	120-150 (30)	1.0	1.57	4.71	
	Total			27.09	1.07

Table 23. Changes in bulk density and organic carbon concentration and pool under *Eucalyptus* plantations after 9 year of growth in a sodic soil of U.P. India (Recalculated from Mishra et al., 2003).

Treatment	Soil Depth (cm)	SOC Concentration (g/kg)	Bulk density (t/m^3)	SOC Pool (t/ha)	Rate of SOC sequestration (t C/ha/yr)
1. Control					
	0-10 (10)	4.2	1.54	6.46	
	10-30 (20)	2.8	1.48	8.29	
	30-60 (30)	1.0	1.45	4.35	
	60-90 (30)	0.6	1.52	2.74	
	90-120 (30)	0.7	1.40	2.94	

	120-150 (30)	1.0	1.50	4.50	
	Total			29.28	Baseline
2. Nine year old Plantation					
	0-10 (10)	12.8	1.01	12.93	
	10-30 (20)	6.6	1.01	13.33	
	30-60 (30)	2.3	1.01	6.97	
	60-90 (30)	0.9	1.07	2.89	
	90-120 (30)	0.8	1.09	2.62	
	120-150 (30)	1.1	1.18	3.89	
	Total			42.63	1.48

Table 24. Estimate of C sequestration rates in salt-affected soils of the Collie Catchment, Australia (Recalculated from Harper et al., 2005).

Sub-catchment	**Carbon sequestration rate (t C/ha/yr)**	
	Low	**High**
Bingham River	3.8	5.2
Collie River Central East/James Well	3.8	5.2
Collie River East	3.3	4.4
Collie River South Branch	4.6	6.0
Harris river	8.5	11.5
Wellinon Reservoir/Collie River Central	6.6	9.0

Table 25. Increase in soil organic carbon (SOC) concentration % of an alkali soil in northwestern India by growing *Prosopis juliflora-Leptochloa fusca* system (Singh et al., 1994).

Time (months)	0-15 cm Depth		15-30 cm depth	
	Prosopis	Prosopis + grass	Prosopis	Prosopis + grass
0	0.18	0.19	0.13	0.12
22	0.20	0.28	0.12	0.16
52	0.30	0.43	0.19	0.21
74	0.43	0.58	0.29	0.36

(vi)

Table 26. Effect of Kallar grass on physical properties of a salt-affected soil in Pakistan (Adapted from Akhter et al., 2004).

Duration (Yr)	Plants Available Water (cm)			Soil Bulk Density (t/m^3)		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
0	5.0	5.2	5.1	1.62	1.73	1.68
1	5.6	6.0	5.4	1.61	1.72	1.60
2	5.8	6.0	5.8	1.58	1.65	1.59
3	6.0	6.1	6.2	1.55	1.59	1.56
4	6.7	6.1	6.5	1.54	1.53	1.55
5	6.5	6.2	6.5	1.53	1.53	1.54

$P_b = 1.672 – 0.031$ D, $R^2 = 0.96$ **, $P_b = t\ m^3$ D = Duration (yr)
$K_s = 2.07\ D^{2.007}$ $R^2 = 0.98$, $K_s = mmd^{-1}$

Integrated Nutrient Management

91. Soil salinity and nutrient deficiencies are the main factors which adversely affect NPP in salt-affected soils. Therefore, balanced application of essential plant nutrients, both macro (N, P, K) and micro (Zn, Cu, B), is essential for good plant growth and development. Further, increased salinity reduces availability and uptake of both water and nutrients, thus reducing NPP. Application of P is especially important to improving plant growth in salt-affected soils (Zahoon et al., 2007), since P increases root growth which in turn enhances the SOC pool.

Table 27. Soil organic carbon and total nitrogen concentration of some salt-affected soils in Pampa, Argentina (Recalculated from Peinemann et al., 2005).

Soil Type	Land Use	Depth (cm)	Salinization	SOC Conc. (g/kg)	TN Conc. (g/kg)	C:N Ratio
I. Chascomu's						
1. Aquic Argiudoll	Natural Grassland	0-3	Non-Saline/ Non-sodic	38a	3.3a	11.5a
		3-6		35b	3.2a	11.1a
		6-9		32b	3.1a	10.4a
2. Typic Natraquoll	Natural Grassland	0-3	Non-Saline/Sodic	25a	2.2a	11.2a
		3-6		16b	1.6b	10.2a
		6-9		13c	1.1c	11.0a
II. Balcarce						
1. Petrocalcic Paleudoll	Arable	0-6	Non-Saline/ Non-sodic	39a	3.3 a	11.8a
		6-21		33b	2.8 a	11.8a
		21-30		34b	2.8a	12.2a
2. Typic Natralboll	Natural Grassland	0-6	Saline/Sodic	46a	4.4a	10.5a
		6-15		20b	1.8b	10.9a
		15-22		13c	1.0b	12.9a

SOC = Soil Organic Carbon TN = Total Nitrogen

Figures in the column for the same soil and land use followed by similar letter are statistically similar.

C. Leaching of Soluble Salts:

92. Leaching with good quality irrigation water is important to reducing/diluting salt concentration in the root zone. Thus, bioirrigation and bioturbation are essential to soil restoration (Canvan et al., 2006). In this context, incorporation of rice in the rotation cycle is a useful practice. Assessment of leaching requirements provides a useful guide to determine the amount of water required for achieving the desired effect. Leaching of the excess salts out of the root zone can enhance crop growth and yield. The data from Iran showed the positive effects of leaching on relative grain yield of barley (*Hordeum vulgare*) by a factor of 4 to 22 and that of straw yield by 3 to 19. Effectiveness of leaching is also enhanced by application of soil amendments (e.g., gypsum), and acidifying *Thiobacilus* microorganism (FAO, 2000). In a mountainous oasis of northern Oman, Luedeling et al. (2005) concluded that sustainability of an irrigated land use system is primarily due to high water quality with low Na^+ but high $CaCO_3$

concentration. It is this high quality irrigation water that is responsible for good soil structure, favorable internal drainage, and lack of salinization. Manuring, rather than heavy use of chemical fertilizers, has also maintained a favorable structure.

D. Potential of SOC Sequestration in Salt-Affected Soils

93. There are approximately 930 Mha of salt-affected soils in arid and semi-arid regions of the world. Adoption of reclaimative measures on these soils can lead to increases in above- and below-ground biomass production and to improvements in SOC concentration and pool. The rate of SCS can be as high as 0.5-2 t C/ha/yr. Even if the rate of biomass production, in arid environments with low availability of water and nutrients, is low at 0.5-1 t C/ha/yr, total ecosystem C pool can be enhanced at 1-3 t C/ha/yr. It is estimated that 100 Mha of reclaimed soils can be used for crop production, of which 56 Mha are irrigated and 44 Mha are rainfed. In addition, 280 Mha can be used for perennial land uses. Thus, the potential of C sequestration in 380 Mha of reclaimed salt affected soils is 0.4-1.0 Gt C/yr (Table 28). If economic and realizable potential is 66% of the technical potential, reclamation of salt-affected soils can offset anthropogenic emissions at the rate of 0.25 to 0.66 Gt C/yr for about 50 years.

Table 28. Technical potential of reclaiming salt-affected soils on SOC sequestration (Lal, 2009d).

Land Use	Area (Mha)	C Sequestration Rate (t/ha/yr)		Technical Potential (Mt C/yr)
		Soil	Biomass	
1. Cropland	100			
a. Irrigated	56	1.0-2.0	-	56-112
b. Rainfed	44	0.5-1.0	-	22-44
2. Perennial Land use	280	0.5-1.0	0.5-2.0	280-840
Total				358-996

E. Growing Halophytes as Biofuel Feedstocks

94. Strongly and extremely salinized soils may need to be taken out of agricultural and pastoral land uses and planted with specific trees, shrubs or grass species that could be used as biofuel feedstocks. Such biomass can also be used as direct fuel for power generation through co-combustion. In addition to salt-affected soils, some water reserves are saline (brackish) with high salt content ranging from 5000 to 40,000 ppm. While common crops cannot tolerate such high salt concentrations, some halophytes can adapt to such conditions. Karlberg and de Vries (2004) collected data on several crops regarding their tolerance to irrigation with saline water. They reported that most cereals (wheat, corn, rice, barley, sorghum, rye grass, and small grains) can be grown in soils with a salinity level of 20-16 dS/m. In contrast, legumes and other crops (e.g., alfalfa, tomato, cotton, oat, choke, beet) can be grown at salinity levels of 2-8 dS/m. A major opportunity in biotechnology lies in designing new germplasm that is tolerant to high salt concentrations in the root zone, and has high NPP in such environments. Examples of some useful halophytes as shown in Table 29 indicate vast potential of producing high-grade fodder, forage, oil, and food. Experiments reported by Glenn et al. (1993) show that halophytes irrigated with seawater can produce biomass yield of 17 to 35 t/ha/yr with a net C sequestration rate of 4-8 t C/ha/yr (Table 29).

Table 29. Mean annual biomass yield and carbon sequestration rate of seawater irrigated halophytes at Puerto Penasco, Sonora, Mexico (Adapted from Glenn et al., 1993).

Species	**Biomass Yield (tC/ha/yr)**	**C Sequestration Rate (tC/ha/yr)**
1. Batis maritime	34.0	8.2
2. Atriplex linearis	24.3	6.7
3. Salicornia bigelovii		
• **Year one**	22.4	5.6
• **Year two**	17.7	4.3
4. Suaeda esteroa	17.2	4.3
5. Sesuvium partulacastrum	16.7	4.2

XV. Potential of Desertification Control to OFFSET Anthropogenic Emissions

95. The total potential of degraded lands restoration and desertification control to sequester C is shown in Table 30. The total potential is 0.6-1.7 Gt C/yr, with a mean of about 1.2 Gt C/yr. The SLM options to achieve this potential include restoration of eroded lands, reclamation of salt-affected soils and production of biofuel feedstock through halophytes. Squires et al. (1995) estimated that management of drylands through desertification control has an overall C sequestration potential of 1.0 Gt C/yr. These high estimates are in contrast to overall low C storage potential of world soils estimated by Schlesinger (1990). Estimates presented in Table 30 are crude, tentative, and merely suggestive of the high potential that exists if judicious land use measures are adopted in the drylands. Uncertainties are high and may be 30 to 50%, as is evidenced by a wide range in the rate of C sequestration in soil and biomass. Further, estimates of potential for different strategies are not additive, and the data need to be used with due consideration of site-specific conditions. The potential of C sequestration in the ecosystem is computed for a 50-year period. Although C sequestration in an ecosystem can continue for up to 150 years (Akala and Lal, 2000), the rate and cumulative amount of sequestration are high only for up to 50 years. Upon conversion to restorative or improved systems, rate of C sequestration may peak within 10 to 15 years. Therefore, for practical purposes, 50 years is an adequate period to estimate the potential (Lal et al., 1998).

Table 30. Potential of desertification control and land restoration to sequester C (Gt C/yr) (Recalculated from Lal, 2001).

Process	Range	Mean	% of Total Potential
Restoration of eroded lands	0.2-0.3	0.25	21
Restoration of physically and chemically degraded soils	<0.01	<0.01	1
Reclamation of salt-affected soils	0.4-1.0	0.7	60
Agricultural intensification on undegraded soils	0.01-0.02	0.015	-
Sequestration as secondary carbonates	0.01-0.4	0.2	17
Total	0.62-1.72	1.17	100

These estimates have large uncertainties, the potentials of different strategies may not be additive, and adoption of recommended measures at global scale remains a major challenge.

96. An important consideration to realization of this biophysical potential is identification and implementation of policies that facilitate adoption of SLM options, assessment of the societal value of soil C, and development of mechanisms that facilitate C trading (e.g., clean development mechanism (CDM)). An important issue is C farming and its commoditization. For some of these SLM practices to be scaled-up, farmers and other land managers would need to be compensated for adopting practices that benefit the local and global environments. Important among the societal benefits of enhancing soil and ecosystem C, for which farmers must be directly compensated, include: (i) reduction in erosion and downstream sedimentation, (ii) decrease in non-point source pollution, (iii) biodegradation of pollutants, (iv) purification of natural waters, (v) enhancement of biodiversity (soil and vegetation), and (vi) reduction in risks of accelerated greenhouse effect.

XVI. Fostering a Conducive Environment for Implementing SLM Practives in Developing Countries

97. Implementation of SLM practices in developing countries necessitates objective analyses of biophysical, economic, social and cultural factors. Choice of SLM options must be based on biophysical factors including soil temperature and moisture regimes, rainfall amount and its distribution, soil texture (clay content and type), internal drainage, slope gradient, etc. Ecological

conditions in low land tropics are in sharp contrast to those in the highlands and temperate regions. Institutional support, land tenure, access to credits and markets, availability of inputs are also important to SLM technology and may also depend on competing uses for inputs. For example, crop residues are needed for cattle feed, fencing and construction, and as household fuel. Similarly, cattle dung is used in many places as cooking fuel rather than as manure. Land tenure rights and gender issues are crucial determinants of land use choices and practices. And as noted earlier, adoption of SLM practices requires a profound change in mindset, perceptions, and behavior of target communities with regard to land use and management. Indeed there is a risk of recommended SLM practices failing if the target producers are poorly-prepared or under-prepared to implement those practices (Pieri et al., 2002).

98. Above all, implementation of SLM options requires sustained political support. Visionary, committed, progressive, and supportive political leadership is an essential pre-requisite to adoption of SLM technologies. Establishing strong and direct channels of communication, between researchers/extension agents, women and youth groups, community leaders, faith-based organizations, and policy makers, is essential. Indeed the important role of religion/cultural groups (faith-based organizations) in promoting sustainable land management practices cannot be over-emphasized. Several laws, charters and resolutions have proven utterly ineffective because of the lack of political support. Local, state, and federal governments can enhance support for SLM by making budgetary provisions for adoption of SLM technologies at scale. Indeed the UNCCD places primary responsibility for action to combat land degradation with affected country governments themselves. Therefore, while international and bilateral support for SLM is crucial, it must be matched by developing country government support. The 2005 Millenium Assessment noted that while desertification must be fought at all levels, it is

clear that the battle must ultimately be won at the local level. And there is clear evidence that with sustained local commitment, success is possible (Reij and Waters-Bayer, 2001). For this reason, sustainable land management should be viewed as a high priority poverty reduction instrument at local, national, regional, and global levels. This implies using existing country strategies and development frameworks (e.g., poverty reduction strategies (PRSPs), country assistance strategies (CASs), community driven development (CDD) etc.) to ensure that promoting sustainable land management is mainstreamed and handled as an on-going development issue rather than as a stand-alone issue requiring ad hoc responses. Finally, gender mainstreaming in land administration and management is critical in many countries. Meeting world food needs in the future will depend increasingly on addressing issues related to gender and on strengthening the capabilities and resources of women. Approximately 98% of rural women classified as economically active are engaged in agriculture and are the primary food producers in many parts of the world. Women make up 60% of the world's 1.2 billion poor. The percentage of women below the poverty line has increased by half since the 1970s. These realities need to be reflected in sustainable land management investments at all levels. It is crucial to urgently strengthen awareness and support with respect to women and vulnerable groups in sustainable land management activities.

XVII. Payments for Ecosystem Services

99. A successful implementation of SLM technologies involves both science and policy (Schneider, 1989). Increasing farm income is important to improving the adoption of SLM practices. Paying farmers for ecosystem services may create the much needed income stream to support households in adopting SLM. Among numerous ecosystem services that adoption of SLM technology can enhance is the soil C sequestration to offset fossil fuel emissions.

Therefore, it is important that soil C be made a commodity that can be traded as any other farm produce. The societal value of soil C as a commodity must be based on ecosystem services that it enhances for the benefit of humanity. These ecosystem services include: (i) off-setting anthropogenic emissions due to fossil fuel combustion, (ii) reduction in erosion and sedimentation, (iii) decline in risks of hypoxia of coastal ecosystems, (iv) increase in biodiversity, and (v) savings in land for nature conservancy by enabling continuous farming on the same land, reducing encroachment pressure, and enhancing/sustaining agronomic production over a longer-time horizon.

A. Trading Soil Carbon and Green Water Credits

100. The current value of soil C ($8 – 15/t of C) is relatively low. It is likely to increase with the possibility of voluntary or regulated imposition of cap and trade systems. Nonetheless, undervaluing of this important resource can lead to its abuse. It is thus important to identify criteria for determining the societal value of soil C through transparent and fair criteria. Soil C is not yet listed under Article 3.3 of the Kyoto Protocol. The omission of SCS in the Kyoto Treaty, a historical oversight on the part of the founding members of the IPCC, has been a missed opportunity for engaging producers in developing countries in gainfully contributing to CC adaptation and mitigation through SLM practices. Furthermore, trading credits of C sequestered in soil, a win-win scenario for improving household income of the 75% of the world's poor who live in rural areas, would be an engine of economic development by enhancing agricultural production through adoption of appropriate SLM technologies and practices. These SLM options would: (i) protect the existing SOC stocks, (ii) reduce emission of GHGs from agroecosystems, and (iii) increase SOC and terrestrial C stocks. Indeed, several studies have indicated that C sequestered in biomass and soils can be traded under the CDM (Garcia-Quijana et al., 2007) and

other voluntary mechanisms to generate another income stream for farmers. In this context, González-Estrada et al. (2008) have identified SLM practices which can increase SOC pool and farm income for smallholder agricultural systems in northern Ghana. Bigsby (2009) proposed a system of banking C stored in forest ecosystems. The “C banking” systems proposed by Bigsby treats sequestered C in the same way that a financial institute treats capital. In this system, forest owners “deposit” C, in exchange for an annual payment, and those who need C offsets “borrow” C by making an annual payment. Therefore, the role of the C bank is to aggregate deposits of C and use these to meet various demands for C. The system allows participants in the C market to receive current value for C (Bigsby, 2009).

101. The adoption of SLM technology is also essential to advancing food security, improving household income, and promoting economic development. Yet, large scale adoption of SLM technology remains a challenge especially in the poorest regions of the world such as SSA and SA. Severe problems of soil degradation and desertification continue to be the major drivers of unsustainable land use and production systems, despite a vast body of scientific knowledge gathered since 1950's. There is also a long history of repeated attempts to solve the perpetual problems of soil degradation, poverty and unproductive land use with modest or little success. It is thus necessary to identify factors that exacerbate land-soil degradation in the regions where scientifically proven technologies exist but have not been adopted.

102. Similar to soil C, green water credits can also be traded. Trading water credits may also be an important solution to the problem of rapid depletion of ground water in the Indo-Gangetic Basin, as reported by Kerr (2009) and Rodell et al. (2009). Adoption of SLM technologies would conserve water by reducing losses through runoff and evaporation. It would also reduce flash floods and sedimentation of streams and waterways. Therefore, farmers adopting SLM could

also be paid for water conservation. Similar to soil C, financial mechanisms can be created whereby downstream water users pay upstream water managers for conserving and improving water quality, quamtity and availability (ISRIC, 2009). Green water credits, while improving use efficiency of limited water resources, create market opportunities and address the incentive gap.

103. There is clearly an urgent need to implement incentive mechanisms which could help address the challenge of promoting adoption of SLM practices at scale. It is in this context that C trading can provide a mechanism to link the science of soil quality improvement through C sequestration with the adoption of SLM practices. It can provide an income stream for resource-poor farmers and small landholders who would otherwise not invest in soil restoration (Antle and Diagana, 2003). Smith et al. (2007) discussed policy and technological constraints to implementation of SLM technologies and showed the importance of identifying policies that provide benefits for climate but also enhance economic, social and environment sustainability. Linked to this, there are several challenges to widespread implementation of CDM in developing countries, especially in Africa. Important among these include:

104. **Measurement, monitoring and verification:** The feasibility of C credits will depend on availability, cost-effectiveness, routine, simple and some surrogate (practice-based) methods of accessing C credits. It is important to aggregate small amounts of C sequestered in a large number of small farms to a scale large enough to be tradable on C markets.

105. **Soil C under Article 3.3:** The CDM is currently offered for afforestation and reforestation projects. Soil C is not yet included under CDM, although there are voluntary markets outside of the Protocol that are trading in soil C (e.g., Chicago Commodities Exchange).

106. **Sink Projects:** Markets for buying and selling C credits are increasing. However there are few projects involving terrestrial C sequestration activities or sink projects. There is limited

funding for sink projects outside of the Work Bank facilitated C projects.

107. Adoption of SLM through Economic Incentives: The strategy of SCS through the deliberate choice of SLM practices for sequestering and trading of C credits to create another income stream for land users is called “farming soil C”. The objective is to grow (increase) soil C pool and trade it as a farm commodity for financial gains. The rate of SCS depends on climate, land use, soil properties and choice of specific SLM technologies. The rate is generally more for cool and humid than warm and dry climates, heavy-textured soils containing predominantly high activity clays (HAC) than light-textured soils with low activity clays (LAC), soils managed with SLM practices than those cultivated with extractive farming, restorative farming systems involving judicious use of crop residues and biosolids (manure, compost) than those where residues are removed and biosolids are rarely used and, degraded and desertified soils with high SOC deficit than those containing relatively high initial SOC pool. Commonly observed rates of SOC sequestration listed (see Table 14) provide general guidelines, but the site-specific rates must be established through local studies. Estimates of regional and global potential of soil carbon sequestration in croplands are shown in Table 31. These estimates are tentative and can be improved with increase in data availability especially for developing countries. In the best case scenario, the global potential of SCS is about 1Gt C/yr (Table 31). There exists an additional potential of 1 Gt C/yr in the forest biomass, and 1 Gt C/yr through the fossil fuel off-set of anthropogenic emissions through establishment of forest plantations. The technical potential of C sequestration in the terrestrial biosphere is much greater, and maybe as much as 6 to 10 Gt C/yr (Table 32).

108. With the current prices, the extra income generated though C trading is rather small (often <1 $/acre). At this price, it is doubtful whether the revenues generated through C

sequestration can substantially increase rural household income in Latin America, Africa and Asia. Thus, the opportunity cost (i.e., trade-offs) of adopting C-enhancing SLM practices must also be taken into account.

Table 31. Regional and global estimates of soil carbon sequestration.

Region/Country	Potential (Mt C/yr)
USA	144-432
European Union	70-200
West Asia, North Africa	200-400
China	100-240
India	40-50
Sub-Saharan Africa	20-40
World	600-1200

Table 32. Potential carbon sink capacity of global ecosystems. (USDOE, 1999).

Ecosystem	Potential Carbon Sink Capacity (GtC/yr)
Grasslands	0.5
Rangelands	1.2
Forests	1.0-3.0
Urban forests and grasslands	-
Deserts and degraded lands	0.8 – 1.3
Agricultural lands	0.85 – 0.9
Biomass croplands	0.5 – 0.8
Terrestrial sediments	0.7 – 1.7
Boreal peatlands and other wetlands	0.1 – 0.7
Total	5.65 – 10.1

109. Establishment of C markets (or C farming) as a mechanism for developed countries to negate some of their CO_2 emissions could help promote at-scale adoption of SLM technologies in developing countries. González-Estrada et al. (2008) evaluated different crop management strategies for Northern Ghana for their capacity to sequester C in agricultural soils and for their contribution to household income. They identified those SLM practices that can simultaneously increase SOC and farm income and also classified them for their cost of investment. Funk and Kerr (2007) observed that C farming is an important strategy to restoring forests on Maori lands in New Zealand. Zomer et al. (2008) argued that afforestation and reforestation through CDM are relevant to improving community livelihood and advancing food security. Unruh (2008) examined the prospects of using tropical forest projects for C sequestration in Africa, and argued that land tenure is a prohibitive obstacle to the implementation of afforestation/reforestation approaches. He identified 5 primary tenure problems: (i) the disconnect between customary and statutory land rights, (ii) legal pluralism, (iii) tree planting as a land claim, (iv) expansion of treed areas in small holder land use systems, and (v) difficulty of using the "abandoned land" category. Similarly to land tenure, the issue of permanence and discounting for land-based C sequestration needs to be resolved (Kim et al. 2008) so that farmers are paid fairly and transparently. Obviously the issue of baselines must be addressed adequately. It is often argued that there is a strong incentive for landholders to participate in the C-sink projects when the previous land use has a continuously decreasing C stock, which is in fact the baseline used to determine the eligible C (Wise et al., 2007). However, such a baseline would exacerbate the problem of mining the soil C pool prior to signing on the C-sink project under CDM. Even if C

payments may increase rural income through the adoption of SLM technology, they may also introduce additional social tensions and institutional issues (Perez et al., 2007a) in an already complex rural setting. In this context, it is important to understand the farmer decision-making process, and how farmers' perceptions of the environment (Ryder, 2003) change in space and time.

XVIII. Co-Benefits and Ecosystem Services through SLM

110. While off-setting anthropogenic emissions, C sequestration in terrestrial ecosystems has numerous co-benefits through enhancement of ecosystem services (Figure 15). Important among these are numerous benefits including increase in NPP with attendant improvement in production of food, feed, fuel, fiber and other materials of industrial importance (e.g., timber). Increase in the terrestrial C pool also buffers ecosystems against drastic perturbations through moderation of climate as influenced by atmospheric chemistry, erosive events and non-point source pollution and sedimentation, desertification control, denaturing and filtering of pollutants and improving water quality. There are also numerous supporting services such as increase in biodiversity, maintenance of landscape, improvement in land quality, and enhancement of cultural and aesthetical values of the land. Increase in ecosystem C pool contributes to production of goods and services of value to humans. Ecosystem indicators, which can be used to assess ecosystem health (Dale and Polasky, 2007) depend on the ecosystem C pool. Monteil (2008) reported that dust travelling from the Sahel across the Atlantic affects human health in the Caribbean. Hence adoption of SLM practices in the Sahel, with an attendant improvement in soil quality and productivity, can reduce the incidence of "Harmattan" and also provide local and global environmental benefits.

111. Improvement in watershed conditions via SLM is a key ingredient to reducing soil

erosion, sedimentation, and non-point source pollution while enhancing water quality and C sequestration in terrestrial ecosystems. Sediment-bound nutrient transport, a principal cause of non-point source pollution, can be mitigated through simple SLM techniques of watershed management such as installation of microdam catchments used in Northern Ethiopia (Haregeweyn et al., 2008). Desertification and transport of dust to South America (McConnell et al., 2007) are linked to poor watershed management. Increasing drought severity, such as linked to Amazonian deforestation (Cox et al., 2008), can also be mitigated through adoption of SLM on a watershed scale. Nutrients transported by rivers for long distances (Subramaniam et al., 2008) are principal causes of eutrophication of coastal waters and strong indicators of poor land management practices in watersheds. Disposal of untreated municipal/urban waste, an important issue in developing countries, especially in large urban centers of South America (Mendez et al., 2008) is an integral component of watershed management. Thus, adoption of SLM options increases C sequestration, enhances watershed resilience, and improves the environment.

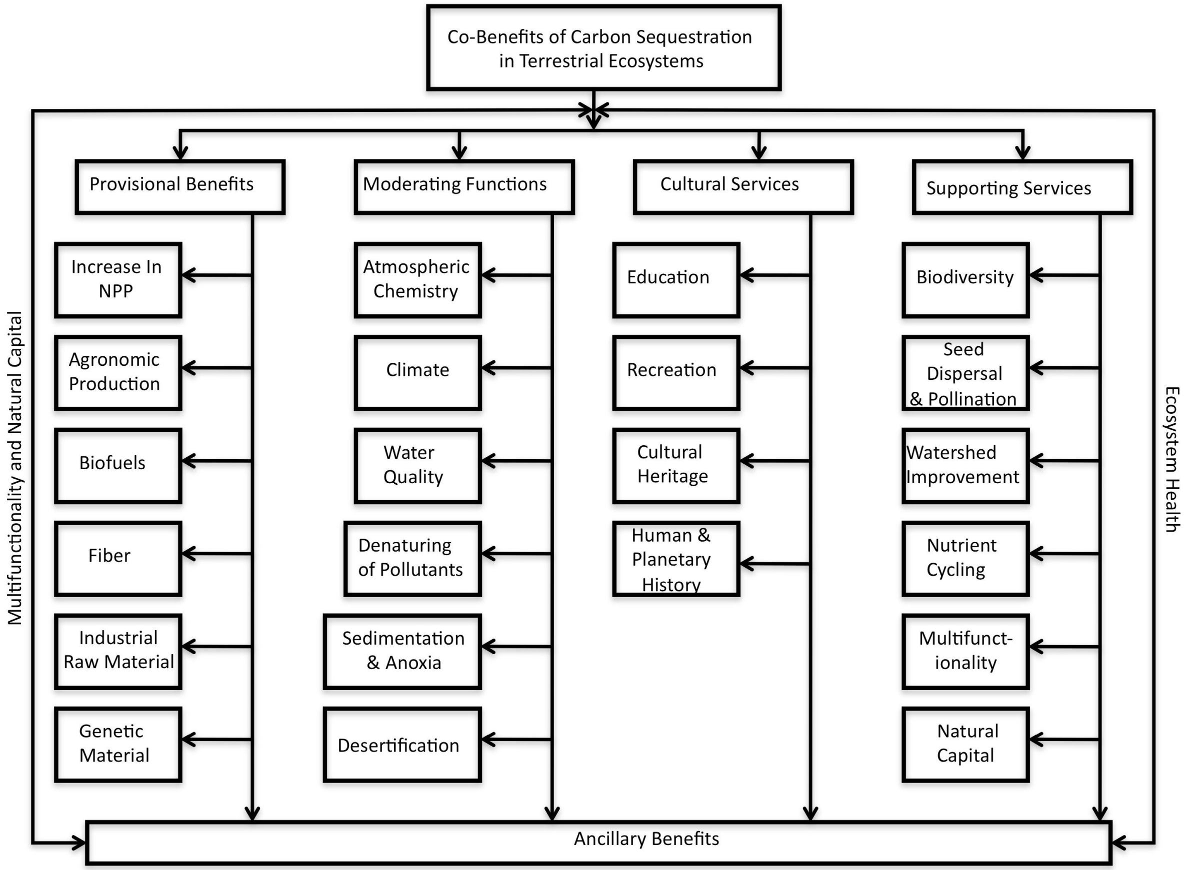


Fig. 15. Co-benefits of carbon sequestration in terrestrial ecosystems.

112. Havstad et al. (2007) identified 5 key elements of landscape dynamics: soils geomorphic characteristics, resource redistribution, transport of matter and water, environmental component, and historical legacies. Such landscape multi-functionality and natural capital are also related to SLM and ecosystem C pool. The multi-functionality of the landscape implies provision of a large number of goods and functions relating to social, economic and environmental prosperity and sustainability (Crossman and Bryan, 2009). Another important issue of SLM is that related to the **natural capital**. It is defined as the stock of assets provided by natural systems and the benefits that flow especially to humans (Costanza et al., 1997). There exists a strong inter-relationship between SLM for ecosystem C enhancement and the natural capital through strong linkage between environmental, economic and social factors. Both concepts of multi-functionality and

natural capital can be linked through ecosystem C pool and SLM. An optimal ecosystem C pool is essential for the landscape to be multi-functional and have a high stock of natural capital. Increase in biodiversity is an example of multi-functionality of a landscape, because there exists spatial consequences between biodiversity and ecosystem services (Egoh et al., 2009).

113. Adoption of SLM is essential to soil quality and improvement in ecosystem C pool. Soil quality is defined as the "degree of fitness of a soil for specific use" –its ability or capacity to function for a specific purpose (Doran and Jones, 1996; Gregorich and Carter, 1997). Maintaining the natural resource base and soil quality through improvement in SOC is essential to achieving SLM (Lal, 1997). Rotations and cropping systems which return large quantities of biomass into the landscape generally improve soil quality (Hulugalle and Scott, 2008). Indeed soil quality is an ideal indication of SLM (Herrick, 2000).

XIX. Deepening and Scaling Up of SLM-Related C Sequestration Activities

114. Until the 1990s, the principal objectives of managing SOM in agricultural production systems were those related to improving soil fertility for increasing agronomic productivity. Therefore, SOM (SOC) concentrations and temporal changes were measured in the plow layer or the zone where roots of seasonal crops are concentrated. In this regard, SLM included cropping systems (rotations, sequences, combination, agroforestry measures), tillage methods (NT, reduced tillage, conservation tillage), surface cover (residue mulching, cover cropping), and nutrient management (compost, manure, biological N fixation, mycorrhizae, fertilizer) options which enhanced and sustained SOC concentration in the root zone. The latter has been measured in the units of percentage or weight basis (g/kg, mg/kg). With growing interest since 1990s in using soils as a sink for atmospheric CO_2, SOM enhancement has acquired multi-functional considerations. As a C sink, soil depth of interest is 1-2 m rather that just the root zone. The

labile SOC fractions and their dynamics (mineralization to release plant nutrients) are important to plant growth and agronomic productivity. In contrast, recalcitrant fractions and their permanence (long residence time without leakage) are important to addressing CC. Rather than the narrow interest in the plot-scale data to manage soil fertility using precision farming for crop production, it is the changes in the SOC pool at the watershed, regional or national scale which are relevant to off-setting anthropogenic emissions for mitigating CC. Thus, appropriate units of measurement are kg/ha, kg/ha/yr, Gt C/yr, etc. In addition to adoption of SLM options at farm scale, the goal is to accrue benefits by adoption at regional, watershed or national scale. It is important, therefore to scale up SLM options to regional and national scales for C sequestration. The need for upscaling of C sequestration activities, however, necessitates understanding and improving: (i) the process of SCS in relation to soil quality, (ii) methods for assessment of soil C at landscape scale in a cost-effective and credible manner, and (iii) predicting soil C pool at different scales. Indeed, improving soil quality through increase in SOC pool is an appropriate adaptation-mitigation win-win strategy, because it affects one of the largest terms of the global C balance through exchange of C between soils and the atmosphere (Gardi and Sconosciuto, 2007) while enhancing food/fiber production. Successful synergetic adaptation-mitigation SLM strategies are those which improve local livelihoods and strengthen resilience of target communities while making soils/ecosystem a net sink for atmospheric CO_2 (Cerri et al., 2007a, b; Mauere et al., 2008).

A. Processes of Soil C Sequestration and Improvements in Soil Quality

115. There are distinct physical, chemical and biological processes that enhance and protect C sequestration in the soil (Figure 16). The net effect of these processes is the slow turnover and prolonged mean residence time (MRT). In Madagascar, for example, Coq et al. (2007) reported

that increase in earthworm activity enhanced soil aggregation, improved soil quality and increased SOC pool. In tropical soils of Brazil and Sub-Saharan Africa, Barthes et al. (2008) reported that both total soil C and fine SOM increased with increase in silt and clay contents. Barthes and colleagues also observed that aggregate stability depended closely on Al-containing sesquioxides. Residue management experiments in sugarcane plantations in Brazil showed that leaving cane residues on the soil surface rather than burning increased SOC concentration at the rate of 2.0 to 2.6 t C/ha/yr, and the increase in SOC pool was strongly correlated with increase in soil aggregation (Luca et al., 2008). According to the hierarchical model, three different classes of SOM, persistent, transient and temporary, are associated with three different physical soil fractions i.e., > 250 µm macro-aggregates, 53-250 µm micro-aggregates and < 53 µm silt-and-clay content, respectively (Tisdale and Oades, 1982). Plante et al. (2006) concluded that micro-aggregate-level-silt-sized fractions best preserved C upon cultivation. Indeed, increases in total SOC under NT over PT management are attributed to both a greater amount of C-rich macro-aggregates (>250 µm) but also to reduced rate of macro-aggregate turnover under NT due to formation of highly stable micro-aggregates within macro-aggregates in which SOC is stabilized and sequestered over the long-term (Six et al., 2000; Denef et al., 2004, 2007). Gillabel et al. (2007) also concluded that increase in SOC pool in irrigated compared with unirrigated land was due to the increase in micro-aggregate-associated C storage since irrigation increased the micro-aggregation. Therefore, irrigation management combined with NT and mulch farming could greatly enhance SCS in arid regions. In California, USA, Kong et al. (2005) concluded that a strong linear relationship between SCS and cumulative C input indicated that these soils had not yet reached an upper limit of C sequestration. Kong and colleagues also observed that C shifted from < 53 µm fraction in low C-input systems to the large and small macro-aggregates in high C-input systems. A majority of the SCS through additional C-input was sequestered in the micro-aggregates-within-small-macro aggregates (Kong et al., 2005). In general, the rate of SCS, at global scale, is estimated at 220 kg/ha/yr (Paustian et al., 1997) to 480 kg/ha/yr (West and Post, 2002). These rates are low in comparison with soil-specific observations made for a wide range of cropping and land use management systems. Thus, the rates of SCS may be increased through adoption of specific SLM technologies for specific soils.

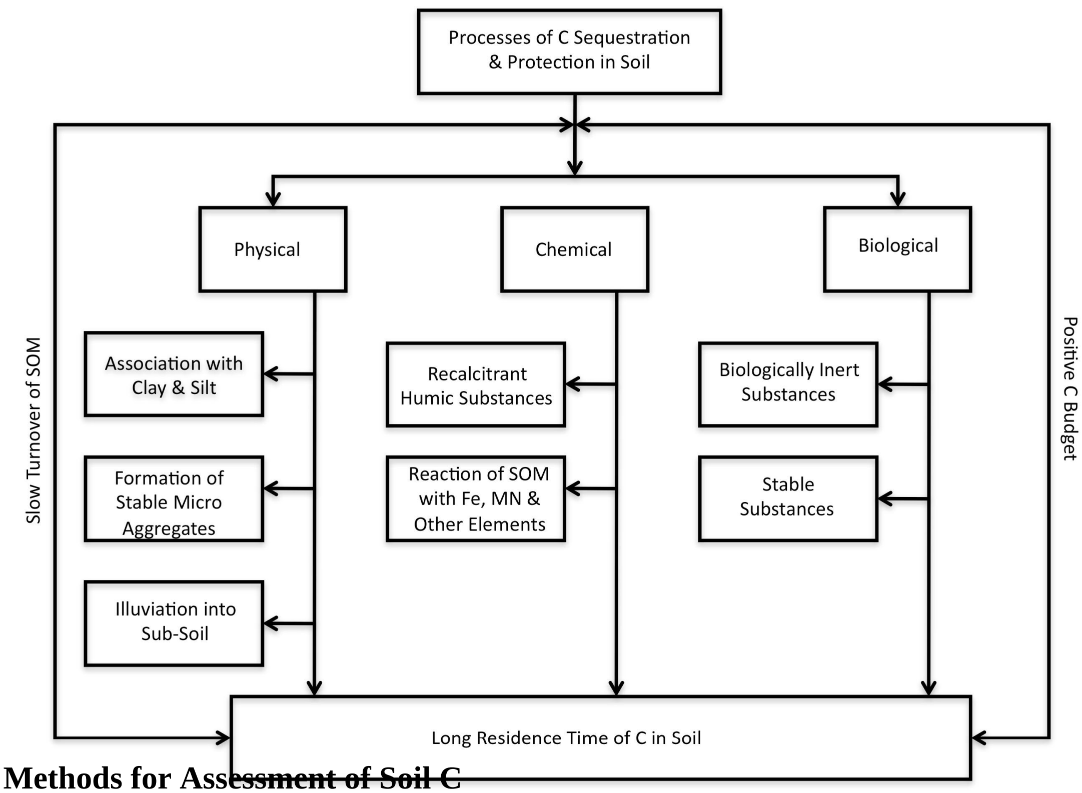


Fig. 16 Mechanisms of SOC sequestration and protection.

B. Methods for Assessment of Soil C

116. Two major concerns regarding land-based C sequestration are the issues of: (i) measuring C pool and flux over the landscape and regional scales, and (ii) permanence. It is argued that data on soil C based on point-scale measurements are expensive and highly variable, and that sequestration may not last forever because the C may either be re-emitted or require additional inputs to maintain the practices that keep it sequestered. These are relevant concerns which must be addressed objectively. Several innovative techniques have been developed to assess soil C

through field (in situ) measurements by using laser-induced breakdown spectroscopy (LIBS) (Ebinger et al., 2006), rapid analyses of soil samples by spectroscopic methods (Reeves et al., 2002), and by non-invasive and tractor-mounted techniques used over a landscape based on inelastic neutron scattering (INS) principles (Wielopolski et al. 2000). Increasing attention is also being paid to near-infrared reflectance (NIR) spectroscopy for the rapid and cost-effective determination of soil C and N concentrations (Shephard and Walsh, 2002; Brunet et al., 2008). West et al. (2007) described a C accounting framework that can estimate C dynamics and net emissions associated with changes in land management on a regional scale (i.e., Midwest U.S.A). This technique integrates field measurements, inventory data and remote sensing products to estimate changes in soil C and estimates where these changes are likely to occur at a sub-county resolution. Credible techniques based on □^{13}C analyses are also available to determine SOC stability (permanence), turnover and source of C (Clay et al., 2007). There are also thermi-gravimetry methods to distinguish between fossil C (coal-derived C) and recent organic C (Maharaj et al., 2007).

C. Modeling Soil C Pool At Different Scales

117. The SOC turnover and agronomic productivity are strongly influenced by climatic factors and a range of environmental variables. Therefore, several models have been developed to assess SOC sequestration under different land uses and management scenarios. Two widely used SOC prediction models are CENTURY 4.0 (Parton et al., 1987; 1988) and Roth C-26.3 (Coleman and Jenkinson, 1995; Jenkinson and Rayner, 1977). These models have been extensively used to assess the effects of modifying agricultural practices to increase soil C pool in Africa and Latin America (Farage et al. 2007), in the Brazilian Amazon region (Cerri et al., 2007) and Asia. Traore et al. (2008) used Roth C 26.3 in subhumid West Africa to estimate the SOC pool for

community level C contracts. The Soil and Terrain (SOTER) model (FAO et al., 2007) is based on land resource information system in which each map unit represents a unique, relatively uniform combination of landform/terrain, parent material and soil characteristics (Van Engelen and Wen, 1995). Batjes (2008) mapped SOC pool in Central Africa using SOTER. The Global Environment Facility (GEF) co-financed a project to develop and demonstrate a system for producing spatially explicit estimates of SOC pool and changes at the national and sub-national scales. This project used Century, Roth C, and other models to develop the GEFSOC Modeling System (Milne et al., 2007). The model has been used to estimate SOC pool in the Brazilian Amazon, the Indo-Gangetic Plains of India, and for Kenya and Jordan (Falloon et al., 2007).

118. A bottom-up modeling approach can also be useful in assessing the regional C budgets using field data. Pascala et al. (2001) estimated the C budget in the U.S. using a variety of inventory data on the basis of a bottom-up approach. Janssens et al. (2003) used top-down and bottom-up approaches to estimate Europe's current C sink capacity. There are numerous uncertainties in such estimates because of the complex nature of C uptake and heterogeneity of land surfaces. Therefore, the net ecosystem carbon exchange (NEE) technique, a bottom-up approach, is used to measure the ecosystem C budget. This procedure is based on the flux measurements using micro-meteorological methods called FLUXNET (Baldocchi et al., 2001). Ito (2008) has applied the FLUXNET technique using AsiaFlux data to estimate the regional C budget of East Asia. Ratification of the Kyoto Protocol has indeed encouraged development of a range of modeling techniques to assess the potential of C sequestration in cultivated soils under different climate change scenarios. Using this technique, Lugo and Berti (2008) identified SLM practices for North-East Italy as follows: (i) conversion of cropland to grassland with sequestration rate of 2.5 to 13.8 t C/ha by the end of the first commitment period, and (ii)

business as usual was a source of C by 20.8 t C/ha.

XX. Some Constraints to Adoption of SLM in Developing Countries

119. Despite the availability of research information about SLM options, there is limited adoption of SLM practices at scale by producers in developing countries. For examples, NT farming is only adopted on about 90 Mha of cropland in North and South America and Australia. It is not adopted in developing countries of SSA and SA, where it is needed the most to control erosion, conserve water, sequester C and recycle plant nutrients. There is also a limited adoption of INM, drip irrigation and other SLM practices described in this report. Constraints to SLM adoption can be physical (soil, rainfall, temperature, drought, terrain), economic (lack of resources availability for input, low income, poor terms of trade), social (gender, etc), environmental (climate change, pests and pathogens, dust storms) and institutional (land tenure, access to market, extension services).

120. Land degradation tends to be an inherently complex problem to analyze since conditions vary tremendously not only from region to region, but also from plot to plot within a farm. This makes a complete understanding of farmers' decision-making processes difficult. Consequently, this complexity may affect the rate and scale of adoption of recommended SLM practices and the associated C sequestration. For example, it might make sense for a household to find it in their interest to conserve one of their plots and not another. Moreover, there are substantial non-linearities, both in the underlying physical relationships (e.g., yield may be insensitive to land degradation over a range of degradation, then respond quickly once a threshold is reached, then again be insensitive), and in the farmers' decision-making process (e.g., various factors may not be binding unless other factors are not binding as in the case of tenure only becoming a potential constraint to adoption of a recommended SLM practice if the practice is profitable; but if the

practice is not profitable, it might appear that tenure does not matter, but it might begin to matter if a new, profitable, SLM practice is introduced).

121. Poverty is obviously one of the factors that determine whether or not land users adopt SLM and conserve land. However, the relationship between poverty on one hand and land degradation/ land conservation on the other, is unlikely to be un-ambiguous. It is true that poor households that depend entirely on their land may mine the soil for their sustenance, but there is no general rule that the poor tend to conserve less and degrade more. Indeed the impact of poverty on SLM/land conservation decisions is unlikely to be as simple as is often assumed. What is clear is that those SLM practices that enhance livelihoods and reduce poverty may have a higher chance of being adopted widely.

122. Whether SLM practices are adopted or not depends on their expected returns and profitability relative to the other options available to the producers/farmers. Thus introduction of cash crops (such as orchards and fruit trees) can be an important incentive to scale up SLM practices (Scoones and Toulmin, 1999). The profitability of SLM depends, like the profitability of all other investments, on the whole range of product and factor prices that farmers face. The relationship is certainly not unambiguous. Increasing output prices might lead to more degradation (intensive production becomes more profitable) or to more conservation (if production is more valuable, it makes more sense to try to protect it), or to both, depending on specific local circumstances. Even if a particular SLM practice is profitable, farmers may be unable or unwilling to adopt it because of particular constraints such as insecure tenure or lack of credit. Removal of such barriers may in fact allow the wide scale adoption of SLM practices especially if they are profitable to the producers/farmers.

123. Of course, when there are SLM externalities, there is no reason to assume that privately optimal land conservation decisions will also be socially optimal. But if SLM externalities are the main concern, an intensive effort to persuade farmers to adopt SLM practices may not be helpful since conservation generally tends to be under-adopted from a social perspective, especially when it produces positive externalities. The key in such cases is to develop processes to get farmers to internalize the externalities through mechanisms such as Payments for Ecosystem Services. Such payments may help speed the scaling up of SLM in various parts of the world. To this end, the Latin America and the Caribbean region has pioneered systems of payments for ecosystem services that are aimed at promoting and scaling up specific SLM practices (CIPAV, 2004). Indeed there are on-going payments for ecosystem services (e.g., carbon sequestration, water retention, improved soil productivity, prevention of landslides and erosion, biodiversity conservation, etc) based on specific SLM practices (e.g., improved pastures with more than 5-30 trees/ha, riparian zone rehabilitation, shade grown coffee, diversified fruit tree plantation, fodder trees and shrubs, etc) that are being scaled up in the region (e.g., Costa Rica, Colombia, Nicaragua), and in fact these experiences provide a good model for learning and replication in other parts of the world.

124. In addition to the factors discussed above, several specific reasons for slow or low adoption of SLM options include: (i) lack of identification of soil-specific or site-specific technologies, (ii) little awareness of the commonsense based fundamental principles governing sustainable management of soils, (iii) inadequate consideration of SLM synergies and trade-offs, (iv) inappropriate policies, and (iv) lack of specific action plans. These reasons are elaborated below.

A. Choice of Site-Specific Technologies

125. Identification of site-specific SLM options must be based on the following considerations:

(i) The extent and severity of land degradation and climate change differ among ecoregions, and their effects vary among soil types, terrains, physiographies, land use, farming systems and the economic status of the farming communities.

(ii) Climate change may also create some opportunities for land users such as new crops that may now be grown where previously impossible (e.g., long duration or warm season crops).

(iii) The effectiveness of SLM technologies also differs among ecoregions, and there is no one size that fits all. Identification of site-specific technologies through validation and appropriate adjustment is essential.There are trade offs among SLM options, and relative cost effectiveness may also vary among ecoregions. None of the SLM options are cost free, and most may have hidden economic and environmental costs. What is important is to reduce the negative trade-offs by addressing loss of land productivity via SLM practices that enhance ecosystem integrity by restoring watershed functions (e.g., reduced siltation of waterways), stabilizing soil loss (upland/lowland sediment storage and release), protecting transboundary rivers, enhancing riverbank protection, sequestration of C, etc. In other words, choosing SLM practices that have multiple co-benefits will tend to reduce certain key trade-offs.

(iv) The choice of SLM options without consideration of certain key factors may also result in some negative effects. For example, NT may not work if crop residues are removed, herbicides are not effective in controlling weeds, and a seed drill is not available. Excessive, flood-based, and improper irrigation (without drainage) may cause secondary salinization and imbalance of the ground water. Thus, the use of “technology without wisdom” can create serious collateral problems.

(v) It is vital to provide some economic rationale for the SLM approaches that are to be introduced. The sustainability of any SLM practices at local level depends on opportunities to increase the income of the local community. Therefore, it is crucial to consider and estimate the market potential of the selected SLM practices (e.g., hillside rehabilitation with perennial fruit trees and horticultural crops) at local, regional and even international levels. If SLM practices are to be scaled-up, then their economic and financial benefits and impacts on communities' livelihoods will need to be assessed and demonstrated. In this regard, SLM interventions should explicitly build-in economic and financial indicators for monitoring the performance of interventions, and relate these to an overall livelihoods impact analysis in the targeted communities.

B. Principles of Sustainable Soil Management

126. There are specific principles of sustainable management of soil resources (Lal, 2009b) that are relevant to the choice of SLM options for site-specific situations (Figure 17).

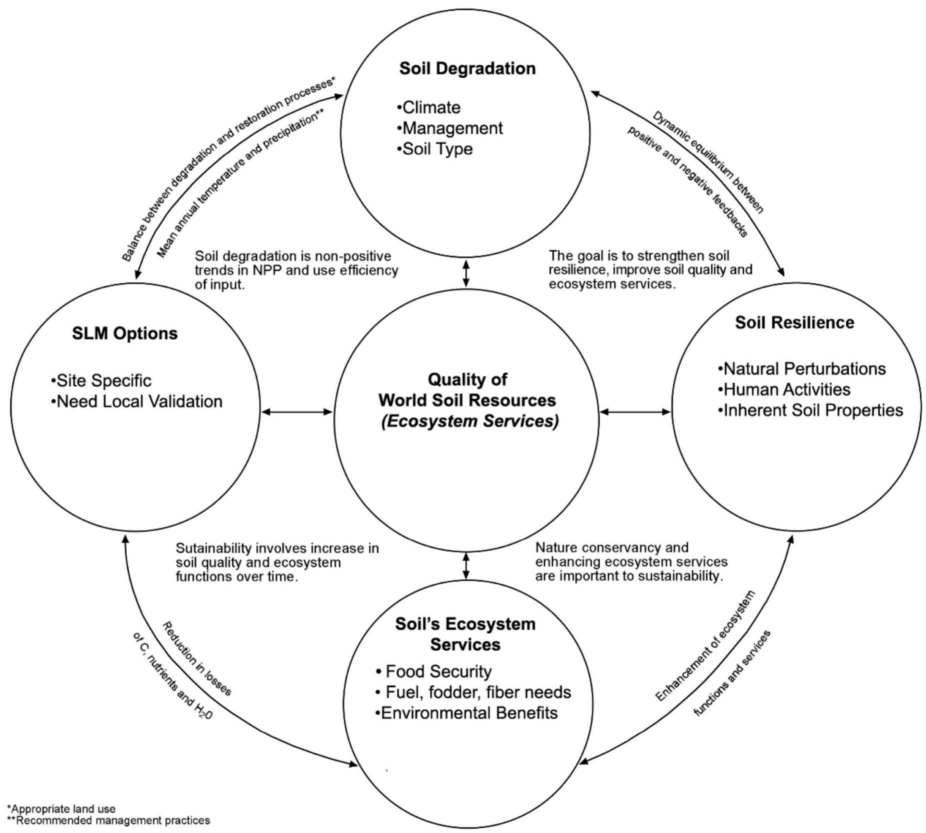


Fig. 17. Properties, processes and practices which govern soil degradation and resilience, and sustainable management. (Adapted from Lal, 2009b).

(i) <u>Soil Resources Are Finite, Fragile and Unequally Distributed</u>: Soil resources are unequally distributed among biomes and geographic regions. Highly productive soils in favorable climates are finite and often located in regions of high population density, and have already been converted to managed ecosystems (e.g., cropland, grazing land and pasture, forest and energy plantations).

(ii) <u>Soil Degradation is Caused by Land Misuse and Soil Mismanagement</u>: Most soils are prone to degradation through inappropriate land use. Anthropogenic factors leading to soil degradation are driven by desperate situations and helplessness in the case of resource-poor farmers and smaller landholders; and greed, short sightedness, poor planning/policies and inappropriate incentives for quick economic returns in the case of large scale farmers and commercial farming enterprises.

(iii) <u>Soil Degradation Depends on "How" Rather Than "What" is the "Land Use</u>:" Accelerated soil erosion and decline in soil quality by other degradation processes depend more on "how" rather than on "what" crops are grown. The productive potential of farming systems can only be realized when implemented in conjunction with restorative and recommended soil and water management practices. Sustainable use of soil depends on the judicious management of both on-site and off-site inputs. Indiscriminate and excessive use of tillage, irrigation and fertilizers can lead to as much as or even more degradation than none or minimal use of these technologies.

(iv) <u>Harsh Climate Plays an Important Role in Soil Degradation</u>: The rate and susceptibility of soil to degradation processes increases with the increase in mean annual temperature and the decrease in mean annual precipitation. All other factors remaining constant, soils in hot and arid climates are more prone to degradation and desertification than those in cool and humid ecoregions. However, mismanagement can lead to desertification even in arctic climates (e.g., some parts of Iceland).

(v) <u>Soils and Terrestrial Ecosystems Can Be Either a Source or Sink of Greenhouse Gases</u>: Soil can be a source or sink of greenhouse gases (e.g., CO_2, CH_4, and N_2O) depending on land use and management. Soils are a source of radiatively-active gases with extractive farming practices which create a negative nutrient budget and degrade soil quality, and a sink with restorative SLM practices which create positive C and nutrient budgets and conserve soil and water while improving soil structure and tilth.

(vi) <u>Rate of New Soil Formation is Extremely Slow</u>: While soils are non-renewable resources over a human time frame of decadal or generational scales, they are renewable on a geological time scale (centennial/millennial). This implies that with the increase in human population of 70 to 80 millions per year and projected to be 10 billion by 2100, restoring degraded and desertified soils over a centennial-millennial scale is not an option. Hence, because of the heavy demands on finite resources, soils are essentially a non-renewable resource, and must not be taken for granted.

(vii) <u>Soil Resilience Depends on Land Use and Management</u>: Soil's resilience to natural and anthropogenic perturbations depends on its physical, chemical and biological processes. Favorable chemical and biological processes enhance resilience only under optimal soil physical properties (e.g., soil structure and tilth), processes (e.g., aeration, water retention and transmission), and edaphological environments (e.g., soil temperature).

(viii) <u>Build up of Soil C Pool is a slow Process</u>: The rate of restoration of the SOM pool is extremely slow, while that of its depletion through extractive farming and soil degradation is often very rapid. The rate of restoration and degradation processes may differ by an order of magnitude.

(ix) <u>Soil Structure, like Photosynthesis is Nature's Gift:</u> Processes governing soil structure are as important to NPP as those affecting photosynthesis, but are much less understood. Soil structure, similar to an architectural design of a functional building, depends on stability and continuity of macro-, meso- and micropores which are the sites of physical, chemical and biological processes that support the soil's life support functions. Site-specific sustainable land management practices tend to enhance stability and continuity of pores and voids over time and under diverse land uses.

(x) **<u>Sustainability implies Positive Trends</u>:** Sustainable land management implies an increasing trend in NPP per unit input of off-farm resources along with improvement in soil quality and ancillary ecosystem services such as increase in the ecosystem C pool, improvement in quality and quantity of renewable fresh water resources, and an increase in biodiversity. However, positive trends cannot be maintained indefinitely (Bartlett, 2005), and emphasis must be given to ecosystem resilience.

127. The importance of SLM is appropriately highlighted by the fact that if soils are not restored, crops will fail even when rains do not (Lal, 2008). Hence knowledge and information on land management is essential to the well-being of societies. But understanding the significance of land degradation is constrained by many uncertainties. It is therefore critical for all stakeholders to deepen, better coordinate and integrate ongoing efforts aimed at gathering policy relevant and action-oriented data on various aspects of land management. Only then can there be effective SLM interventions that demonstrate impact at large scales.

C. SLM Synergies and Trade-offs

While many SLM practices do indeed provide multiple livelihood and environment synergetic benefits, it is important that such multi-functionality be reflected in the performance indicators chosen and that the issue of trade-offs be clearly defined, discussed and measured. The definition of synergies and trade-offs that are inherent in many SLM practices would not only help to enhance the design, implementation, and scale-up of SLM investments, but would also be key in enhancing sustainability of interventions. While clearly elaborating what is meant by synergies and trade-offs in the context of specific SLM investments, such work should: (a) prepare an empirical assessment of the synergies between SLM, climate change action, etc, and (b) provide location-specific multi-dimensional (e.g., financial, environmental, social, etc.) analysis of the inherent trade-offs between local livelihood-related activities and recommended SLM measures supported by any given investment.

D. Inappropriate Policies

One of the main barriers to scaling-up of SLM in many parts of the world is the existence of national policies that encourage poor stewardship of the land. To promote scaling up of SLM, countries may need to put in place policies that encourage good stewardship of the land while also fostering climate change adaptation and mitigation. Examples include: policies that improve efficiency of irrigation and water use especially in agriculture (e.g., improved pricing schemes for irrigation water), policies to prevent and combat land degradation (e.g., reforms in tenure practices, schemes to promote contour farming and cover cropping), policies for improved livestock management (e.g., schemes to improve pasture quality and prevent degradation of pastures), policies for cropland management (e.g., promoting use of improved crop varieties, agroforestry schemes, perennial cover cropping, rainwater harvesting schemes) (Mani et al., 2008).

E. Elements of a strategy that twins SLM and local climate action

128. General SLM options for adaptation to climate change are outlined in Figure 9. Site specific SLM options must be chosen with regard to soil type, climate, physiography, and social/economic/cultural factors following a well thought out action plan. The specific action plan needed for addressing food security and climate change may involve a series of steps as outlined in Figure 18.

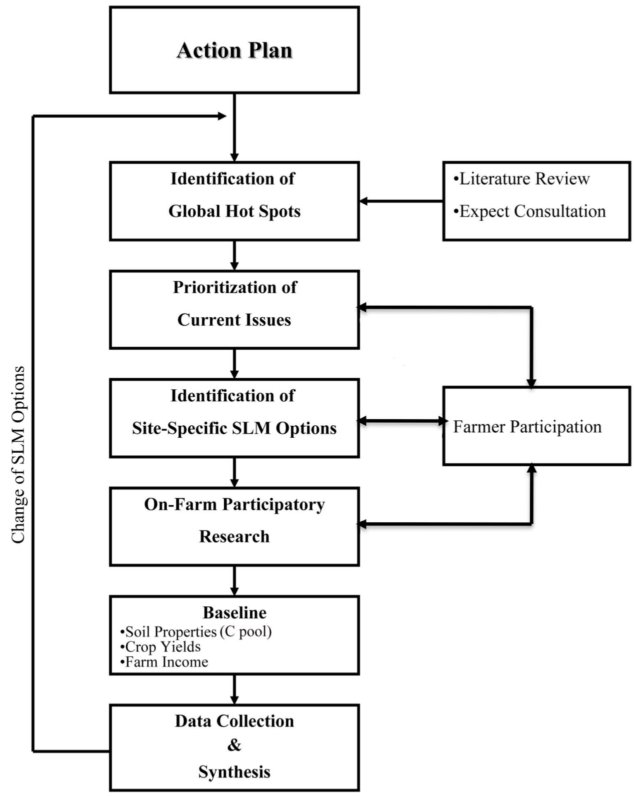


Fig. 18. Flow chart of an action plan for a specific region.

(i) **Identify Global Hot Spots:** It is appropriate to identify global hot spots where the issues of food insecurity, degradation of soil and natural resources, and vulnerability to CC are serious concerns. These regions include SSA, SA, Central America and the Caribbean, acid soil savannas of South America including Cerrados and Llanos, the Andean regions, the Himalayan-Tibetan ecosystems, and other ecologically sensitive regions.

(ii) **Prioritize Specific Issues:** For the specific region (see above), it is important to identify important issues of major concern with the current and anticipated CC. These issues may include risks of soil erosion, severity of drought stress, nutrient deficiency, vulnerability to salinization, wild fires etc. Such a prioritization may be done in consultation with the farmers and other stakeholders.

(iii) **Identify SLM Options:** Site specific SLM options must be identified to address these priority issues. Examples of SLM options may include: conservation agriculture, drought-tolerant crop varieties, efficient irrigation methods, water harvesting and recycling, INM, agroforestry, etc. Similar to prioritization of issues, identification of SLM options must also be done with full participation of the target communities.

(iv) **Establish On-Farm Demonstrations/Research:** There is evidence from various parts of the world that farmers not only have a very good knowledge of the land degradation/soil dynamics in their localities, but they are in fact taking measures to innovate and conserve their lands (Pagiola and Dixon, 1997; Reij and Waters-Bayer, 2001). Hence validation of SLM vis-à-vis traditional methods of soil and water management must be done under on-farm conditions using a farmer participatory approach. Most farmers in regions of global hot spots (see above) are small land holders (1-2 ha). Thus, on-farm demonstrations may involve 50 to 100 farms. It is important that SLM research questions are formulated to be practically relevant to producers/farmers and policy makers by identifying which problems are important under what conditions and in what locations (e.g., what is needed on a steep slope is not the same as what is needed on a shallower one in the same general location). Hence research should avoid generic questions such as estimating returns to soil conservation in a given area or assessing the cost of land degradation to a country. While such studies may be difficult and interesting, they have limited operational relevance since (a) results tend to be incredibly site-specific meaning wide differences in what farmers can realistically do depending on their access to land, credit, markets, labor and knowledge (Scoones and Toulmin, 1999), (b) farmers/producers in study areas are usually already aware of the key issues, (c) data needs make it is easy to get the concept and assumptions wrong, and (d) apart from showing how big the problem is, such studies tend to have limited value in addressing the problem. Therefore, research questions should attempt to understand how land degradation relates to poverty in any given area, and how SLM can contribute to improving farmers'/producers' livelihoods while reducing land degrataion and contributing to local climate action.

(v) **Baseline:** Prior to implementation of recommended SLM technologies, it is necessary to establish baselines with regards to soil quality (SOC pool, aggregation, bulk density, erosion, vulnerability, poverty levels, land tenure, existing land use practices, etc), agronomic yields and profitability. Impact assessment of SLM options cannot be credibly accomplished without the baseline information on critical indicators of sustainability. Indeed, few existing SCS projects have paid careful attention to establishment of such baselines. Thus, the concerns about erroneous data in SCS and other indicators can be addressed if most SLM projects established solid baselines.

(vi) **Knowledge exchange, Farmer fied visits, and Evaluation of SLM Options:** Farmer evaluation of SLM options is important to assess acceptability of new technology. Appropriate modifications and fine tuning is needed before implementing at scale.

129. **Project vs. Programmatic Approaches:** Beyond specific individual projects, the best way to scale-up SLM is through existing country development frameworks and strategies (e.g., poverty reduction strategies, country partnership strategies). In addition, such country frameworks and strategies provide an opportunity for the various national government agencies, community organizations and funding agencies to work together**.** Many countries face the challenge of multiple donors and agencies attempting to implement SLM and reduce land degradation. Coordination of these efforts, agencies and organizations is important for effective

and efficient use of limited financial resources, strengthening of institutional capacity and delivering long-term socioeconomic and environmental benefits.

XXI. Conclusions

130. This report has provided empirical examples from different parts of the world of SLM practices and technologies that have multiple benefits for communities and CC adaptation and mitigation. An important attribute of many SLM practices is the fact that similar practices/technologies are effective both for adaptation to and mitigation of CC. But for these SLM practices to have appreciable and visible CC benefits, they have to be adopted at scale in various parts of the world. Indeed various SLM practices present win-win options for mitigating and adapting to CC. Such practices reduce vulnerability to climate change by improving agronomic yields under adverse conditions, enhancing soil quality, and increasing farm income. But they also mitigate CC by sequestering C and reducing emission of other GHGs from agroecosystems. Such dual-impact SLM technologies include no-till farming with crop residue mulch, use of complex crop rotations including leguminous cover crops and agroforestry systems, perennial tree crops, integrated nutrient management involving elemental recycling and use of compost and biochar, water harvesting and recycling, and restoration of degraded and desertified soils.

131. Many SLM technologies are readily accessible to resource-poor farmers in developing countries, doable and have tangible and visible impacts in terms of economic, ecologic, social and cultural benefits. However, experiences from Latin America and the Caribbean, sub-Saharan Africa, East Asia and the Pacific, Middle-East and North Africa, Europe and Central Asia, and South Asia regions highlight the need for multi-pronged approaches to SLM that would tackle and address the issues of land tenure and property rights, confusion over institutional/agency

collaboration and coordination, watershed management (upstream vs downstream linkages), payments for ecosystem services, the costs associated with land degradation and how to make the 'business case' for investments, chemical pollution from agricultural lands, and the unavoidable linkages between SLM and climate change actions. What is clear from these experiences is that for SLM practices to be adopted, the benefits of such practices must (i) accrue directly to the local land users, and (ii) ensure a dynamic upstream-downstream linkage between the affected stakeholders. Hence the operational focus of SLM interventions should not be on combating land degradation/ or desertification per se, but on sustainable land management practices that promote sound stewardship of the land resources while improving the food security and livelihoods of the affected households and communities.

132. A new generation of fertilizers, slow release formulations based on nano-enhanced materials and zeolites, are available to decrease losses and increase use efficiency. Bio-engineered and improved crops can be grown to adjust to high temperatures and extreme events. Innovative tillage methods, facilitated by the availability of improved crops, are available to reduce risks of high temperature, drought, inundation, runoff and soil erosion. Cost-effective SLM technologies exist to reduce water pollution, increase soil water reserves and improve water use efficiency.

133. Enhancing the ecosystem C pool through SLM practices has numerous co-benefits. In fact adoption of SLM technologies has a technical potential to off-set CO_2 emissions by as much as 4 Gt C/yr (2.8-5.3 Gt C/yr) through SCS, tree biomass, and biofuel substitutes (Table 33). And tapping the Carbon Market can help in scaling up SLM interventions. Targeted land rehabilitation measures can contribute to climate change (CC) management while tapping the carbon market. The World Bank's Carbon Finance Program has demonstrated the potential of

market-based public/private initiatives to invest significantly in sustainable land management interventions that provide measurable local and global benefits. Indeed the current portfolio has projects in various countries (e.g., Moldova Soil Conservation; Philippines Watershed Rehabilitation; Romania Afforestation; etc) that respond directly to the challenge of capturing and implementing the synergies among the three major global environmental conventions (i.e., UNCCD, UNFCCC, UNCBD).

Table 33. Technical potential of C sequestration in terrestrial biosphere through adoption of SLM technologies.

Biome/Activity	Technical Potential (Gt C/yr)
1. Afforestation and forest succession in the TFE biome	1.2-1.4
2. Forest Plantation	0.2-0.51
3. Tropical Savannah Ecosystem	0.3-0.5
4. Cropland Management	0.6-1.2
5. Agroforestry	1.1-2.2
6. Restoration of salt-affected soils	0.4-1.0
7. Desertification Control	0.6-1.7
8. Biofuel off-set	0.3-0.5
Total	2.8-5.3

134. Another co-benefit is the improvement in soil quality and increase in agronomic productivity. Appropriate SLM practices are available to enhance production and advance food security. Increase in soil C pool by 1 t/ha/yr can improve agronomic yield in developing countries by 24 to 40 million t/yr of food grains and 8 to 10 million t/yr of roots and tubers. But such increases in agronomic production can be sustainable only if long-term improvement in soil quality is maintained through specific SLM practices.

135. The large scale adoption of proven SLM technologies has been slow partly because resource-poor farmers cannot afford the needed inputs and land tenure systems are not conducive to the use of long-term restorative management. On the other hand, distorted policies and incentives continue to encourage richer farmers to use inappropriate land management practices.

In the context of most developing countries, it is important to emphasize that the most prevalent nature-based livelihood of the poor and source of environmental income is small-holder agriculture (WRI et al., 2008). And the way such agriculture is practiced determines not only the quantity and sustainability of environmental income, but also the ability of the poor to enhance their resilience to environmental and socio-economic challenges. To a large degree, the sustainability of agriculture in most countries will depend on the large scale adoption of SLM practices and technologies, some of which are described in this report. But farmers and other producers will not green the land for the aesthetics; successful scaling up of SLM requires that land users (i) have secure tenure arrangements to enable longer term investments in land conservation measures, (ii) have the capacity to implement the recommended practices, and (iii) derive direct benefits from implementing the said practices on their lands. Therefore, realignment of policies and incentives, removal or lowering of institutional barriers, and access to markets including payments to farmers for providing ecosystem services, may be essential to create the much needed enabling environment to promote the adoption of proven SLM practices at scale.

136. Adaptation to and mitigation of climate variability and change provides an opportunity to scale up SLM practices in the most vulnerable countries**.** Climate variability and change can and does exacerbate land degradation. Many countries, especially in Africa and particularly the poorest communities living in coastal areas and drylands are most vulnerable to extreme weather events such as droughts, sea level rise, floods, and heat waves. The risks to development are greater in these poorer countries and the ability to adapt smaller. While the effects of droughts are exacerbated by armed conflicts and the pre-existence of major diseases, increased water stress will put further pressure on these triggers. The current global focus on climate change and the availability of additional funds for adaptation and mitigation thus provide an opportunity to

improve the strategies and action plans for more coordinated effort at the national level on scaling up SLM practices.

137. In order to minimize the strong disconnect between research and application, there is a need to build the knowledge base and capacity to analyze the sustainable land management-growth linkages on one hand, and the SLM-climate change linkages on the other. In this context, it is crucial to support developing countries in accessing climate data and investing in transfer of technologies for SLM and climate action in key sectors (e.g., forestry, livestock, agriculture, water).

XXII. References

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XXIII. Acronyms

~	=	About
AU	=	Animal unit
BC	=	Black carbon
Bha	=	Billion hectares
BMPs	=	Best management practices
BNF	=	Biological nitrogen fixation
BTU	=	British thermal unit
C	=	Carbon
C:N	=	Carbon : nitrogen ratio
CC	=	Climate change
CCS	=	Carbon capture and storage
CCX	=	Chicago Climate Exchange
CDM	=	Clean Development Mechanism
CE	=	Carbon equivalent
CH_4	=	Methane
CO_2	=	Carbon dioxide
CT	=	Conventional tillage
DDA	=	Developing and disadvantaged countries
dS	=	Deci Siemen (unit of electrical conductivity)
FAO	=	Food and Agric. Organization
GEF	=	Global Environment Facility
GHG	=	Greenhouse gas
GLASOD	=	Global land assessment of soil degradation
GPP	=	Gross primary productivity
Gt	=	Gigaton, 1 billion ton
GWP	=	Global warming potential
ha	=	Hectare (2.47 acres)
HAC	=	High activity clays (e.g., Montmorillonite)
INM	=	Integrated nutrient management
INS	=	Inelastic neutron scattering
IPCC	=	Inter-governmental Panel on Climate Change
JI	=	Joint Implementation
Kg	=	Kilogram
Km	=	Kilometer
L	=	Liter
LAC	=	Low activity clays (e.g., Kaolinite)
LIBS	=	Laser induced breakdown spectroscopy
Mha	=	Million hectare
mm	=	Millimeter
Mt	=	Million ton
N	=	Nitrogen
N_2O	=	Nitrous oxide
NEE	=	Net ecosystem exchange

NIR	=	Near infrared spectroscopy
NO_x	=	Oxides of nitrogen (N_2O, NO, NO_x)
NPK	=	Nitrogen, phosphorus, potassium
NPP	=	Net primary productivity
NT	=	No-till
P	=	Phosphorus
POM	=	Particulate organic matter
ppm	=	Parts per million
PT	=	Plow tillage
Quad	=	Quadrillion BTU (10^{15} BTU)
RMPs	=	Recommended management practices
SA	=	South Asia
SCS	=	Soil carbon sequestration
SIC	=	Soil inorganic carbon
SLM	=	Sustainable land management
SOC	=	Soil organic carbon
SOM	=	Soil organic matter
Spp	=	Species
SSA	=	Sub-Saharan Africa
t	=	Ton (metric ton)
TFE	=	Tropical rainforest ecosystem
TN	=	Total nitrogen
TPG	=	Temperate prairies and grasslands
TRF	=	Tropical rainforest
TSE	=	Tropical savannah ecosystem
U.P.	=	Uttar Pradesh, India
UNEP	=	United Nations Environment Program
UNCCD	=	United Nation Convention to Control Desertification
UNFCC	=	United Nations Framework Convention on Climate Change
yr	=	Year

XXIV. Glossary

Aggregate A group of primary soil particles that cohere to each other more strongly than to other surrounding particles. A structural unit.

Aggregation The process whereby primary soil particles (sand, silt, clay) are bound together, usually by natural forces and substances derived from root exudates and microbial activity.

Agro-ecosystem Ecosystem under agricultural management; an open, dynamic system that is connected to other ecosystems through the transfer of energy and materials.

Agroforestry Any type of multiple cropping land-use that entails complementary relations between tree and agricultural crops and produces some combination of food, fruit, fodder, fuel, wood, mulches, or other products.

Amendment Substance, such as manure and compost, that is added to soil to make it more productive.

Anaerobic The absence of molecular oxygen or a process occurring in the absence of oxygen.

Anthropogenic Of human origin.

Arable land Land so located that production of cultivated crops is economical and practical.

Aridic A soil moisture regime that has limited water available for a long time.

Available nutrients The amount of soil nutrient in chemical forms accessible to plant roots or compounds likely to be convertible to such forms during the growing season, and the contents of legally designated "available" nutrients in fertilizers.

Available water (capacity) The amount of water that a plant can absorb, and is released between in situ field capacity and the permanent wilting point.

Baseline data set First set of measurements made at a site.

Biochar Charcoal produced from biomass and used as a soil amendment.

Biomass Refers to living plant or animal matter.

Biota A group term for living organisms, including both plants and animals.

Black carbon Refers to soot aerosol – an aerosol consisting of highly absorbing carbon compounds that are produced as a result of the incomplete combustion of fossil fuels or biomass.

Carbon cycle Route by which carbon is fixed by photosynthesis, added to soil as plant and animal remains, then released from soil through decomposition and mineralization.

Carbon-organic nitrogen ratio The ratio of the mass of organic carbon to the mass of organic nitrogen in soil, organic material, plants, or microbial cells.

Catchment The area of a drainage basin delimited by the watershed.

Clay A mineral particle < 2 μm equivalent diameter.

Climatic index A simple, single numerical value that expresses climatic relationships, such as precipitation-evaporation, or aridity index.

CO_2 fertilization Refers to the tendency for higher atmospheric CO_2 concentrations to simulate plant growth. This can occur as a result of the direct stimulation of photosynthesis, or an improvement in the efficiency of water use, which allows more plant growth for a given supply of water.

Composting A controlled biological process which converts organic constituents, usually wastes, in to humus-like material suitable for use as a soil amendment or organic fertilizer.

Conservation tillage Any tillage sequence, the object of which is to minimize or reduce loss of soil and water; operationally, a tillage or tillage and planting combination which leaves a 30% or greater cover of crop residue on the surface.

Cover crop Close-growing crop, that provides soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When plowed under and incorporated into the soil, cover crops may be referred to as green manure crops.

Crop residue Plant material remaining after harvesting, including leaves, stalks, roots.

Crop residue management Disposition of stubble, stalks, and other crop residues by tillage operations.

Crop rotation A planned sequence of crops growing in a regularly recurring succession on the same area of land, as contrasted to continuous culture of one crop or growing variable sequences of crops.

Cropland Total area on which field crops, fruits, vegetables, nursery products, and sod are grown.

Cropping intensity Share of farmland devoted to cultivation.

Cultivated land Land used to produce crops; includes land left fallow for a part of the year.

Dentrification The process whereby nitrate (NO_3^-) or ammonium (NH_4^+) is converted to gaseous N_2 or N_2O.

Drip irrigation Irrigation whereby water is slowly applied to the soil surface through small emitters having low-discharge orifices.

Dryland farming Crop production without irrigation (rainfed agriculture).

Ecosystem A system which involves the interaction of organisms, causing energy flows and the exchange of materials between living and nonliving parts of the system.

Ecozone Area having distinct climate, vegetation, geology, and soils.

Equivalent CO_2 increase The increase in CO_2 concentration alone that has the same global mean radiative forcing as that arising from increases in a variety of well-mixed greenhouse gases.

Erodibility Measure of a soil's susceptibility to erosion.

Erosion Movement of soil from one location to another mainly by wind and water, and also by tillage.

Evapotranspiration The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants.

Farming system Overall plan to manage cropping and soils that combines a variety of management practices.

Fertility, soil The relative ability of a soil to supply the nutrients essential to plant growth.

Fertilization Application of plant nutrients to the soil in the form of commercial fertilizers, animal manure, green manure, and other amendments.

Field capacity The water content of a soil after drainage under gravity is more or less complete over soil 2 or 3 days after having been wetted with water and after free drainage is negligible.

Flux A rate of flow of a quantity such as mass or volume of a fluid, electromagnetic energy, number of particles, or energy across a given area.

Fragile land Land that is sensitive to degradation when disturbed; such as with highly erodible soils, soils where salts can and do accumulate, and soils at high elevations.

Global warming potential A single index that attempts to quantify the climatic impact of the same emission of a given greenhouse gas relative to that of a reference gas (usually CO_2), by taking into account the different heat-trapping abilities on a molecule-by-molecule basis and the different rates of removal of the two gases.

Green manure Plant material incorporated into soil while green or at maturity, for soil improvement.

Greenhouse gas Any gas that emits and absorbs radiation in the infrared part of the electromagnetic spectrum, thereby tending to make the climate warmer than it would be in its absence (CO_2, CH_4, N_2O).

Humification The process of humus formation via organic matter decomposition.

Humus Total of the organic compounds in soil exclusive of undecayed plant and animal tissues, their "partial decomposition" products, and the soil biomass. It is well decomposed organic portion of the soil forming a dark brown, porous, spongy material with a pleasant, earthy smell.

Hydrologic Relating to water.

Hydrologic cycle Route by which water passes naturally from water vapor in the atmosphere through precipitation onto land or water and back into the atmosphere by means of evaporation and transpiration.

Immobilization The process whereby nutrients that are released by mineralization are taken up by microbes and become unavailable for use by plants.

Improved pasture Area improved by seeding, draining, irrigating, fertilizing, brush or weed control, not including areas where hay, silage, or seeds are harvested.

Infiltration The entry of water in to soil.

Irrigation The intentional application of water to the soil, usually for the purpose of crop production.

Kyoto Protocol The agreement reached in Kyoto, Japan, on 10 December 1997 to limit emission of greenhouse gas by industrialized countries.

Land use Way in which land is used, such as for pasture, orchards, and producing field crops.

Macronutrient A plant nutrient found at relatively high concentrations (>500 mg kg^{-1} or ppm) in plants. Usually refers to N, P, and K, but may include Ca, Mg, and S.

Manure The excreta of animals, with or without an admixture of bedding or litter, fresh or at various stages of further decomposition or composting. In some countries may denote any fertilizer material.

Microirrigation The frequent application of small quantities of water and drops, tiny, streams, or miniature spray through emitters or applicators placed along a water delivery line. Microirrigation encompasses a number of methods or concepts such as bubbler, drip, trickle, mist, or spray.

Micronutrient A plant nutrient found in relatively small amounts (<100 mg kg^{-1} or ppm) in plants. These are usually B, Cl, Cu, Fe, Mn, Mo, Ni, Co, and Zn.

Mineralization The processes whereby nutrients in organic matter are converted back to forms that can be readily used by plants or micro-organisms as a result of decomposition.

Monsoon The seasonal shift in wind patterns over south Asia and west Africa, whereby air flows from ocean to continent in summer and the reverse in winter. The summer monsoon brings rainfall to the affected regions.

Mulch farming A system of tillage and planting operations which maintains a substantial amount of plant residues or other mulch on the soil surface.

Mycorrhiza (pl. **micorrhizae**) Literally "fungus root". The association, usually symbiotic, of specific fungi with roots of higher plants to increase P uptake.

Net Primary Production (NPP) The rate of photosynthesis by a plant minus the rate of growth and maintenance respiration.

Nitrification The process that converts NH_3 or NH_4^+ into NO_2^- or NO_3^-.

Nitrogen fixation The process that converts atmospheric N_2 into NH_3 or NH_4^+.

No-till Tillage practice involving direct seeding, which does not break the soil surface. It implies seeding crops without plowing directly into the soil with no primary or secondary tillage since harvest of the previous crop.

Nutrient balance An undefined theoretical ratio of two or more plant nutrient concentrations for an optimum growth rate and yield.

Nutrient cycle The movement of nutrients within ecosystems.

Nutrient retention Holding onto nutrients.

Nutrient Utilization Efficiency (NUE) An increase in the C:nutrient ratio in plant organic matter, such that less nutrients are required per unit of assimilated carbon. This can occur as a consequence of the biochemical downregulation of the photosynthetic response to higher CO_2, in which the concentration of rubisco enzyme decreases.

Organic fertilizer Byproduct from the processing of animals or vegetable substances that contain sufficient plant nutrients to be of value as fertilizers.

Organic matter Decomposed plant and animal residues.

Permanent crop cover Perennial crop, such as forage, that protects the soil throughout the year.

Pollution The presence or introduction of a pollutant in to the environment.

Positive feedback A feedback in which the initial change (ΔA) provokes a change in some intermediate quantity (ΔB), and the change ΔB acting alone tends to provoke further change in A that is in the same direction as the initial change. A positive feedback has a destabilizing effect.

Productivity The output of a specified plant or group of plants under a defined set of management practices.

Radiative forcing The perturbation in the radiative balance at the tropopause in response to some externally applied perturbation (such as an increase in greenhouse gas concentrations other than water vapor).

Remote sensing The recording of images of the ground from aircraft or satellites.

Residence time The average length of time that a molecule spends in a reservoir before being removed (such as C or N in soil).

Residue management Maintaining a cover of crop residues on the soil surface.

Runoff Portion of total precipitation that enters surface streams rather than infiltrating the soil. It is the water that runs over the soil surface, laterally through the soil, or in stream channels.

Salinity Amount of soluble salts in a soil.

Salinization The process by which soluble salts accumulate in the soil.

Salt-affected soil Soil that has been adversely modified for the growth of most crop plants by the presence of soluble salts, with or without high amounts of exchangeable sodium.

Seedbed Soil prepared for seeding.

Sink A reservoir into which a gas is absorbed and stored for a long period of time, such as soil or trees.

Soil compaction Pressing together of soil particles, reducing the pore space between them, and increasing its strength.

Soil conditioner A material which measurably improves specific soil physical characteristics or physical processes for a given use or as a plant growth medium. Examples include sawdust, peat, compost, synthetic polymers, various inert materials and biochar.

Soil conservation Protection of the soil against physical loss by erosion or against chemical deterioration; that is, excessive loss of fertility by either natural or artificial means. A combination of all management and land use methods that safeguard the soil against depletion or deterioration by natural or by human-induced factors.

Soil degradation General process by which soil declines in quality and is thus made less fit for a specific purpose, such as crop production.

Soil fertility The quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops.

Soil health Soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment.

Soil organic matter Constituent of soil that includes plant and animal remains in various stages of decomposition, cells and tissues of soil organisms, and substances produced by the soil microbes. It comprises organic fraction of the soil exclusive of undecayed plant and animal residues.

Soil quality indicator Property, function, or condition of soil that is useful in describing soil quality.

Soil quality Soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment; *also* **soil health**.

Soil structure Physical properties of a soil relating to the arrangement and stability of soil particles and pores.

Soil structure The combination or arrangement of primary soil particles into secondary units.

Stubble mulch The stubble of crops and crop residues left essentially in place on the land as a surface cover before and during the preparation of the seedbed and at least partly during the growing of a succeeding crop.

Sustainable agriculture Way of farming that maintains the land's ability to produce over time.

Symbiotic A mutually beneficial relationship between two different species.

Threshold values Points at which a change in soil quality is likely to occur.

Tillage The mechanical manipulation of the soil profile.

Tilth Physical characteristics of the seedbed following tillage.

Water table The upper surface of ground water or in the soil.

Water use efficiency (WUE) The ratio of carbon assimilation by photosynthesis to water lass through transpiration.

Waterlogged Saturated or nearly saturated soil when all pores are full of water.

Wilting point The point at which plants wilt because of lack of water in the soil.

Yield The amount of a specified substance produced (e.g., grain, straw, total dry matter) per unit area (t/ha, kg/ha).

XXV. Units and Conversions

Length

1 inch	=	25.4 mm
1 foot	=	0.3048 m
1 yard	=	0.9144 m
1 chain	=	20.12 m
1 mile	=	1.609 km

Area

1 in^2	=	645 mm^2
1 ft^2	=	0.0929 m^2
1 yd^2	=	0.8361 m^2
1 acre	=	4047 m^2
	=	0.4047 ha
1 $mile^2$	=	259.0 ha
	=	2.59 km^2

Volume

1 ft^3	=	0.02832 m^3
1 yd^3	=	0.7645 m^3
1 gal (UK)	=	4.546 litres
	=	0.004546 m^3
1 gal (US)	=	3.785 litres
	=	0.003785 m^3
1 $mile^3$	=	4.166 km^3
1 acre-ft	=	271,400 gal (UK)
	=	1613 yd^3
	=	1233.5 m^3
1 mill gal (UK)	=	3.7 acre-ft
	=	4564 m^3

Mass

1 ton (US)	=	0.9072 ton (metric)
1 bushel of corn	=	56 lbs
1 cwt (hundredweight, short)	=	0.454
quintal	=	45.4 kg
1 pound (lb)	=	0.454 kilogram (kg)
1 ounce (oz)	=	28.35 gram (g)
1 ton (US)/acre	=	2.2417 Mg/ha
1 gigaton	=	1 billion metric ton (1 Pg)
I million ton	=	I terragram (1Tg)

Flow

1 cusec (ft^3/second)	=	0.2832 m^3/sec	=	1.0194 hectare-centimeters/hour
			=	101.94 m^3/hr
1 mill gal (UK)/day	=	3.7 acre-ft/day	=	4564 m^3/d (cmd)
			=	1.867 cusec = 0.0531 m^3/sec
1 cusec for 24 hour	=	1.983 acre-ft	=	2447 m^2
1 acre-foot	=	0.1233 hectare-meter, ha-m	=	12.33 hectare-centimeters
1 acre-inch	=	0.01028 hectare-meter, ha-m		
	=	1.028 hectare-centimeters	=	102.8 m^3
1 gal (US)/min	=	0.00227 hectare-centimeter/hour		
	=	0.227 m^3/hr		

Force

1 Newton	=	10^5 dynes cm^{-2}

Energy and Power

1 erg	=	10^{-7} J
1 watt	=	1 J sec^{-1}
1 H.P.	=	746 watts