ECONOMIC AND SECTOR WORK

# CARBON SEQUESTRATION IN AGRICULTURAL SOILS

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THE WORLD BANK

ARD
AGRICULTURE AND RURAL DEVELOPMENT

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# PREFACE

Agriculture's direct reliance on the natural resource base has always been a defining characteristic of the sector. Production relies directly on soil, water, and a variety of biological processes. And it also relies on the climate at the same time that its role in the global carbon cycle makes it a major contributing factor to climate change. Today, more than ever before, we understand not only the significance that climate has for agriculture, but also the enormous significance that agriculture has for the climate.

The growing consensus on the need for a *climate-smart agriculture* emerged largely out of international awareness of the sector's negative impacts—its ecological footprint. It also grew out of the recognition that conventional forms of agricultural production are often unsustainable and deplete or "mine" the natural resources on which production relies over time. Agriculture is the world's leading source of methane and nitrous oxide emissions, a substantial source of carbon emissions, and the principal driver behind deforestation worldwide. Some 30 percent of global greenhouse gas emissions are attributable to agriculture and deforestation driven by the expansion of crop and livestock production for food, fiber and fuel.

More recently, this perspective of agriculture as a source of greenhouse gas emissions and pollution has become more balanced, with a growing understanding of the environmental services the sector can provide if production is well-managed. While agriculture emits a large volume of greenhouse gases, its biomass and especially its soils also sequester carbon out of the atmosphere, and this role as a carbon sink and as a carbon store can be strategically optimized through proven farming techniques and methods that simultaneously reduce emissions. These technical elements of climate-smart agriculture are by now well understood, and in addition to their technical feasibility, they can be highly productive and profitable.

As this document will discuss, this new and more sustainable pattern of agricultural development can make the sector an active agent in climate change mitigation at the same time that it improves and builds upon the sector's capacity to adapt to the increasing temperatures and declining precipitation that are already reducing yields of grains and other primary crops in many parts of the vast semi-arid tropics where so many of the poorest reside. This trend is projected to intensify in the coming decades and have serious ramifications for global food security, and for the food security of vulnerable populations in particular.

Agricultural production operates under intensifying pressures. Food production will need to effectively double in many developing countries by 2050 to feed a growing and increasingly urban global population. The agriculture systems that supply this food play a pivotal role in these countries' economies. Agriculture employs up to two-thirds of their workforce and accounts for between 10 and 30 percent of their gross domestic product. Increasing productivity is agriculture's most pressing priority, but it is not its only priority.

Perhaps the most important point conveyed in this document is that the dual roles of agriculture as a source of food security and as a source of environmental services converge in fundamental ways. Too often the relationship between these roles is viewed as a series of painful trade-offs. Yet the same carbon that is sequestered through sustainable practices makes those practices more productive. The carbon that is removed from the atmosphere and captured in soils and plant biomass is the same carbon that makes agricultural soils more fertile, and that leads to higher profit margins for producers. Higher carbon content enables the soil to make more water and nutrients available to support crop growth, and increases the resilience of farmland, reducing both the need for fertilizer applications and susceptibility to land degradation. The Intercontinental Panel on Climate Change (IPCC) indicates that carbon sequestration accounts for about 90 percent of global agricultural mitigation potential by 2030.

While technical progress in the area of integrated “landscape” approaches to managing natural and economic resources has been very promising, the adoption of these approaches still faces serious constraints in many developing countries. Among the most important of these constraints are the significant upfront expenditures that many of the newer techniques require. In many of the developing countries in which these techniques would wield some of their most important benefits, awareness of both the techniques and the benefits remain limited. In some settings there is limited capacity to implement them even when people are aware of them.

Mobilizing and targeting resources to overcome these constraints has been an important reason the World Bank became determined to get climate-smart agriculture more firmly onto the agenda of the international dialogue on climate change. It is our hope that this report moves that agenda forward by making the “triple win” of soil carbon sequestration for increased productivity, improved climate resilience, and enhanced mitigation an integral part of that dialogue.

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This report improves the knowledge base for scaling-up investments in land management technologies that sequester soil carbon for increased productivity under changing climate conditions.

# ABBREVIATIONS

| | |
|---|---|
| AEZ | Agroecological Zone |
| BIO | microbial biomass |
| CBP | Carbon Benefits Project |
| CSA | climate-smart agriculture |
| DPM | decomposable plant material |
| EX-ACT | Ex Ante Appraisal Carbon-Balance Tool |
| FAOSTAT | Food and Agriculture Organization of the United Nations |
| GEF | Global Environment Facility |
| GHG | greenhouse gas |
| GIS | geographical information system |
| GPS | global positioning system |
| ha | hectare |
| HUM | humified organic matter |
| INS | inelastic neutron scattering |
| IOM | inert organic matter |
| IPCC | Intercontinental Panel on Climate Change |
| LIBS | laser-induced breakdown spectroscopy |
| MAC | marginal abatement cost |
| MMV | measurement, monitoring, and verification |
| NPP | net primary productivity |
| RPM | resistant plant material |
| SALM | Sustainable Agricultural Land Management |
| SLM | sustainable land management |
| UNFCCC | UN Framework Convention on Climate Change |

# EXECUTIVE SUMMARY

Ensuring food security in a context of growing population and changing climate is arguably the principal challenge of our time. The current human population of 7 billion will increase to more than 9 billion by 2050.

Moreover, rising incomes and the increasing proportion of the global population living in urban areas are changing the composition of food demand in fundamental ways. Higher income urban populations have more diverse diets that feature a variety of high-value food sources, such as livestock that are more resource intensive to produce and process. This adds to the challenge of maintaining and preserving the resilience of both natural and agricultural ecosystems. Based on these developments, projections indicate that global food production must increase by 70 percent by 2050. In many African countries, where the challenge is most acute, food production must increase by more than 100 percent—it must effectively double.

The onus of this challenge falls on agriculture, which is the sector of the global economy that is most vulnerable to the effects of global warming, such as more variable rainfall and more extreme weather-generated events. At the same time, agriculture and the changes in land-use that are associated with it, are one of the principal contributors to climate change, accounting for one-third of global greenhouse gas (GHG) emissions. Projected increases in demand for food and bioenergy by 2050 have profound implications for the pressure that agriculture wields on forests and other natural ecosystems in the tropics. These ecosystems are vital, both in the role their biomass plays in sequestering carbon and in providing habitat for biodiversity. When they are lost, they become a massive source of GHG emissions.

Increasing agricultural productivity, enhancing its resilience to climate change, and reducing the emissions that come from the agriculture sector are therefore triple imperatives that require alternative sets of practices. Climate-smart agriculture (CSA) seeks to increase productivity in an environmentally and socially sustainable way, strengthen farmers' resilience to climate change, and reduce agriculture's contribution to climate change by reducing GHG emissions and sequestering carbon. A key element of CSA is sustainable land management (SLM), involving the implementation of land-use systems and management practices that enable humans to maximize the economic and social benefits from land while maintaining or enhancing the ecosystem services that land resources provide.

Because soil is the basic resource in agricultural and forest land use, it is the central element of most SLM technologies. Soil carbon has a direct correlation with soil quality. It is a major determinant of the soil's ability to hold and release water and other nutrients that are essential for plants and their root systems to grow. Soil carbon also plays an important role in maintaining the biotic habitats that make land management systems sustainable, resilient, and able to resist degradation. Carbon sequestration, the process by which atmospheric carbon dioxide is taken up by plants through photosynthesis and stored as carbon in biomass and soils, can help reverse soil fertility loss, limit GHG concentrations in the atmosphere, and reduce the impact of climate change on agricultural ecosystems.

The objective of this report is to improve the knowledge base that informs investment decisions in land management technologies that purposefully sequester soil carbon. The findings reported are based on three exercises. The first was a review of soil carbon dynamics and assessment methods and a meta-analysis of soil carbon sequestration rates in Africa, Asia, and Latin America. The second exercise was to apply an ecosystem simulation modeling technique to predict future carbon storage in global cropland soils. The third consisted of a series of estimations of marginal abatement costs and trade-offs to assess the cost-effectiveness of deploying the land management technologies for climate-smart agriculture. The results reported in this document complement a number of related publications, including empirical lessons from recent project examples and policy briefs that were used as inputs at the Durban Climate Change Conference in November 2011.

At least four key messages emerge over the course of this report, and these relate to profitability, managing trade-offs, barriers to adoption, and the need for targeted public support.

### *Profitability*

In addition to storing soil carbon, sustainable land management technologies can be beneficial to farmers because they can increase yields and reduce production costs. Total private profits by the year 2030 are estimated at US$105 billion for Africa, $274 billion for Latin America, and $1.4 trillion for Asia.

### *Maximizing Benefits and Managing Trade-Offs*

Soil carbon sequestration can be maximized by managing trade-offs across space, time, and sectors. Working at the landscape level is useful for addressing food security and rural livelihood issues and in responding to the impacts of climate change and contributing to its mitigation.

### *Barriers to Adoption and Up-Front Costs*

The adoption of sustainable land management practices can face a variety of socioeconomic and institutional barriers. These include the need for significant up-front expenditures on the part of poorer farmers, the nonavailability of some inputs in the local markets, lack of information about the potential of improved techniques, and often limited capacity to implement the techniques. Certain techniques associated with sustainable land management can be incompatible with traditional practices. In some instances, the diffusion of new technologies relies on a level of social capital and experience with collective action that farmers simply do not yet have.

### *The Need for Targeted Public Support*

Without public support for farmers, poor agricultural land management will intensify land degradation, increase farmers' vulnerability to the effects of climate change, and lead to the emission of additional GHGs into the atmosphere. The amount of support that governments will need to provide by the year 2030 to enable farmers to implement SLM practices are projected at US$20 billion in Africa, $41 billion in Latin America, and $131 billion in Asia.

## Mechanisms for Carbon Enhancement in Agro-Ecosystems

Sustainable land management delivers carbon benefits in three important ways. The first is carbon conservation, in which the large volumes of carbon stored in natural forests, grasslands, and wetlands remain stored as carbon stocks. Conserving this terrestrial carbon represents a "least-cost opportunity" in terms of climate change adaptation and mitigation and is essential to increasing the resilience of agricultural ecosystems. The second benefit is carbon sequestration, in which the growth of agricultural and natural biomass actively removes carbon from the atmosphere and stores it in soil and biomass. The third benefit delivered by SLM is to reduce the emissions of GHGs that emanate from agricultural production, including those emissions that result from land-use change in which carbon stocks become carbon sources as agricultural production expands into natural ecosystems.

SLM practices are alternatives to conventional agriculture in all three of these paths—conservation, sequestration, and reductions in GHG emissions. While it capitalizes more purposefully on the positive impacts of conservation and sequestration, its reversal of agriculture's negative impacts also presents profound contrast with conventional practices. These conventional agricultural practices include deforestation, the burning of biomass, draining of wetlands, uncontrolled grazing, and plowing and other forms of soil disturbance that release not only carbon dioxide into the atmosphere, but also nitrous oxide and methane—GHGs with extremely high impacts on global warming. Investment in soil quality improvement practices such as erosion control, water management, and judicious application of fertilizers can reduce these emissions directly and increase rates of soil carbon sequestration.

## The Dynamics of Soil Organic Carbon

Different ecosystems store different amounts of carbon depending on their species compositions, soil types, climate, relief, and other biophysical features. (Globally, volumes of carbon are generally measured in gigatonnes [Gt], which is equal to

**PHOTO E.1:** Terracing and Landscape Management in Bhutan

*Source:* Curt Carnemark/World Bank.

1 billion tons, or metric tons in the United States.) The amount of carbon stored in plant biomass ranges from 3 Gt in croplands to 212 Gt in tropical forests (table E1). Soils hold more carbon than plant biomass (or vegetation) and account for 81 percent of the world's terrestrial carbon stock. Soil carbon stocks also vary by ecosystem, ranging, for instance, from 100 Gt in temperate forests to 471 Gt in boreal forests. Boreal ecosystems are a particular concern. Because much of the soil organic carbon stored there is permafrost and wetlands, any large-scale melting caused by global warming will release massive volumes of carbon into the atmosphere. Conservation and protection are therefore widely recognized as major priorities, with the exception of limited areas selected for forest management.

**TABLE E1:** Carbon Stocks in Vegetation and Top 1 Meter of Soils of World Biomes

| | | CARBON STOCKS (Gt C) AND PROPORTION IN THE ECOSYSTEM (%) | | | | |
|---|---|---|---|---|---|---|
| BIOMES | AREA (MILLION $km^2$) | VEGETATION | PROPORTION (%) | SOILS | PROPORTION (%) | TOTAL |
| Tropical forests | 17.6 | 212 | 49.5 | 216 | 50.5 | 428 |
| Temperate forests | 10.4 | 59 | 37.1 | 100 | 62.9 | 159 |
| Boreal forests | 13.7 | 88 | 15.7 | 471 | 84.3 | 559 |
| Tropical savannas | 22.5 | 66 | 20.0 | 264 | 80.0 | 330 |
| Temperate grasslands | 12.5 | 9 | 3.0 | 295 | 97.0 | 304 |
| Deserts | 45.5 | 8 | 4.0 | 191 | 96.0 | 199 |
| Tundra | 9.5 | 6 | 4.7 | 121 | 95.3 | 127 |
| Wetlands | 3.5 | 15 | 6.3 | 225 | 93.8 | 240 |
| Croplands | 16 | 3 | 2.3 | 128 | 97.7 | 131 |
| Total | 151.2 | 466 | | 2,011 | | 2,477 |
| Proportion (%) | | 19 | | 81 | | 100 |

*Source:* Watson, Robert, *et al.* (2000).

**TABLE E2:** Estimates of Erosion-Induced Carbon Emission Across World Regions

| REGION | GROSS EROSION (Gt/YEAR) | SOIL CARBON DISPLACED BY EROSION (2 TO 3 PERCENT OF SEDIMENT; Gt C/YEAR) | EMISSION (20 PERCENT OF DISPLACED SOIL CARBON; Gt C/YEAR) |
|---|---|---|---|
| Africa | 38.9 | 0.8–1.2 | 0.16–0.24 |
| Asia | 74.0 | 1.5–2.2 | 0.30–0.44 |
| South America | 39.4 | 0.8–1.2 | 0.16–0.24 |
| North America | 28.1 | 0.6–0.8 | 0.12–0.16 |
| Europe | 13.1 | 0.2–0.4 | 0.04–0.08 |
| Oceania | 7.6 | 0.1–0.2 | 0.02–0.04 |
| Total | 201.1 | 4.0–6.0 | 0.8–1.2 |

*Source:* Lal, R. (2003).

The global carbon cycle describes the transfer of carbon in the earth's atmosphere, vegetation, soils, and oceans. The two most important anthropogenic processes responsible for the release of carbon dioxide into the atmosphere are the burning of fossil fuels (coal, oil, and natural gas) and land use. Rapidly growing emissions are outpacing the growth in natural sinks (lands and oceans). The efficiency of oceans and lands as carbon dioxide sinks has declined over time. These sinks currently remove an average of 55 percent of all anthropogenic carbon dioxide emissions; 50 years ago they removed 60 percent.

Soils are critically important in determining global carbon cycle dynamics because they serve as the link between the atmosphere, vegetation, and oceans. Globally, the soil carbon pool (also referred to as the pedologic pool) is estimated at 2,500 Gt up to a 2-m depth. Out of this, the soil organic carbon pool comprises 1,550 Gt, while the soil inorganic carbon and elemental pools make up the remaining 950 Gt (Batjes 1996). The soil carbon pool is more than 3 times the size of the atmospheric pool (760 Gt) and about 4.5 times the size of the biotic pool (560 Gt).

The soil organic carbon pool represents a dynamic balance between gains and losses. The amount changes over time depending on photosynthetic C added and the rate of its decay. Under undisturbed natural conditions, inputs of carbon from litter fall and root biomass are cycled by output through erosion, organic matter decomposition, and leaching. The potential carbon sequestration is controlled primarily by pedological factors that set the physico-chemical maximum limit to storage of carbon in the soil. Such factors include soil texture and clay mineralogy, depth, bulk density, aeration, and proportion of coarse fragments.

Attainable carbon sequestration is determined by factors that limit the input of carbon to the soil system. Net primary productivity (NPP)—the rate of photosynthesis minus autotrophic respiration—is the major factor influencing attainable sequestration and is modified by above-ground versus below-ground allocation. Land management practices that increase carbon input through increasing NPP tend to increase the attainable carbon sequestration to nearer to the potential level. Climate has both direct and indirect effects on attainable sequestration. Decomposition rate increases with temperature but decreases with increasingly anaerobic conditions. Actual carbon sequestration is determined by land management factors that reduce carbon storage such as erosion, tillage, residue removal, and drainage. Theoretically, the potential soil carbon sequestration capacity is equivalent to the cumulative historical carbon loss. However, only 50 to 66 percent of this capacity is attainable through the adoption of sustainable land management practices.

The current rate of carbon loss due to land-use change (deforestation) and related land-change processes (erosion, tillage operations, biomass burning, excessive fertilizers, residue removal, and drainage of peat lands) is between 0.7 and 2.1 Gt carbon per year. Soil erosion is the major land degradation process that emits soil carbon. Because soil organic matter is concentrated on the soil surface, accelerated soil erosion leads to progressive depletion of soil carbon. The annual rate of soil loss ranges from 7.6 Gt for Oceania to 74.0 Gt for Asia (table E2). This corresponds to carbon emissions ranging from 0.02 to 0.04 Gt per year for Oceania to 0.30 to 0.44 Gt per year for Asia. Globally, 201 Gt of soil is lost to erosion, corresponding to 0.8 to 1.2 Gt of emitted carbon per year. Africa, Asia, and South America emit between 0.60 and 0.92 Gt of carbon per year through soil erosion. Agricultural soils must be prevented from being washed into streams and rivers where the relatively stable soil carbon pools are rapidly oxidized to carbon dioxide.

Soil respiration, the flux of microbially and plant-respired carbon dioxide, estimated at 75 to 100 Gt carbon per year, is the next largest terrestrial carbon flux following photosynthesis. Soil respiration is a potentially important mechanism of positive feedback to climate change. A small change in soil respiration can significantly alter the balance of atmospheric carbon dioxide concentration compared to soil carbon stores. Conventional tillage leads to the destruction of soil aggregates, excessive respiration, and soil organic matter decomposition, leading to reduced crop production and decreased resilience of the soil ecosystem. When other factors are at optimum, conservation tillage, use of cover crops (green manure), crop rotations, use of deep-rooted crops, application of manure, and water management can optimize soil respiration in addition to improving soil carbon leading to the triple win of enhanced agricultural productivity, adaptation, and mitigation.

**Approaches to Soil Carbon Assessment**

Soil carbon assessment in different parts of the world requires methods that are appropriate to the circumstances. The variety of methods that have been developed and tested for use in different countries raises concerns about their comparability. Ensuring this comparability warrants serious international priority. In the case of carbon projects, credible and cost-effective techniques of monitoring changes in soil carbon still need to be developed.

Soil carbon assessment methods can be broadly classified into direct and indirect methods, depending on whether carbon content in soil samples is directly measured or inferred through a proxy variable. The most established type of direct soil carbon assessment entails collecting soil samples in the field and analyzing them in the laboratory using combustion techniques. Field sampling is technically challenging, but most of its challenges can be addressed through an appropriate design that accounts for soil spatial variation. The degree and nature of sampling depend on the objectives of the carbon assessment objective, whether, for instance, the assessment is used for national or regional accounting or for a carbon offset project. Each context will require a differing degree of granularity and measurement set to assess uncertainty in the estimates. Direct methods are more precise and accurate but also more time and labor intensive as well as very expensive. Some *in situ* soil carbon analytical methods are being developed with the objective of offering increased accuracy, precision, and cost-effectiveness over conventional *ex situ* methods. The *in situ* soil carbon analytical methods include mid-infrared (IR) spectroscopy, near-IR spectroscopy, laser-induced breakdown spectroscopy (LIBS), and inelastic neutron scattering (INS). While LIBS and INS technologies are still in their infancy, IR spectroscopy has proven valuable in developing soil spectral libraries and for rapid characterization of soil properties for soil quality monitoring and other agricultural applications in developed and developing countries.

Indirect estimation of soil organic carbon changes over large areas using simulation models has become increasingly important. Indirect methods are needed to fill knowledge gaps about the biogeochemical processes involved in soil carbon sequestration. One of the more important indirect methods involves the use of simulation models that project changes in soil organic carbon under varying climate, soil, and management conditions. Although simulation models can have limited accuracy, particularly in the context of developing countries in which land resources data are scarce, they are a cost-effective means of estimating GHG emissions in space and time under a wide range of biophysical and agricultural management conditions. The data can be particularly useful in scaling-up site-specific information to larger scales of magnitude.

Monitoring and verifying soil carbon sequestration at the project or regional scale require five activities. These include selection of landscape units suitable for monitoring soil carbon changes, development of measurement protocols, use of remote sensing to estimate soil organic carbon controlling parameters, spatially explicit biogeochemical modeling, and scaling-up the results to the entire project area. The selection of landscape monitoring units is based on the responsiveness of the area to land management practices as determined by climate, soil properties, management history, and availability of historical data. Protocols for temporally repeated measurements at fixed locations will generally include stratification and selection of sampling sites, sampling depth and volume, measurement of bulk density, laboratory analyses, other ancillary field measurements, and estimation of the marginal cost of carbon sequestration.

Remote sensing can provide information on net primary productivity, leaf area index, tillage practices, crop yields and location, and amounts of crop residues. All of this is critical information used for input into models. Recently, the cellulose absorption index, derived from remote imaging spectroscopy, has been used to infer tillage intensity and residue quantity. These parameters are fed into biogeochemical models to predict soil carbon sequestration. Scaling-up to larger areas requires integration from a variety of sources including field measurements, existing databases, models, geographical information systems, and remote sensing. Multitemporal moderate resolution remote sensing such as the Landsat Thematic Mapper and Moderate

Resolution Imaging Spectroradiometer can provide information such as land-use and land-cover change, crop rotations, and soil moisture, which can markedly improve our ability to scale-up soil carbon assessments.

Monitoring trends in soil carbon over a large geographical area through repeated sampling is, for the most part, restricted to industrialized countries and a handful of developing countries. Examples of national carbon accounting system and tools include Australia's National Carbon Accounting System; Canada's National Forest Carbon Monitoring, Accounting, and Reporting System; Indonesia's National Carbon Accounting System; and New Zealand's Carbon Accounting System.

The Agriculture and Land Use National Greenhouse Gas Inventory Software tool was recently developed by Colorado State University to support countries' efforts to understand current emission trends and the influence of land-use and management alternatives on future emissions. The tool can be used to estimate emissions and removals associated with biomass C stocks, soil C stocks, soil nitrous oxide emissions, rice methane emissions, enteric methane emissions, and manure methane and nitrous oxide emissions, as well as non-$CO_2$ GHG emissions from biomass burning.

**PHOTO E.2:** Crop Residue Management in Irrigated Fields in Indonesia

*Source:* Curt Carnemark/World Bank.

The Food and Agriculture Organization of the United Nations has developed the Ex Ante Appraisal Carbon-Balance Tool (EX-ACT) to assess GHGs in the agricultural sector. EX-ACT can provide ex ante assessments of the impact of agriculture and related forestry, fisheries, livestock, and water development projects on GHG emissions and carbon sequestration, thereby indicating the overall effects on the carbon balance. A detailed analysis of lessons learned in testing EX-ACT in World Bank agriculture projects can be found in a separate report.

The BioCarbon Fund of the World Bank has also developed a methodology to encourage adoption of sustainable land management practices by small-scale farmers in developing countries. The methodology, referred to as Sustainable Agricultural Land Management (SALM), provides a protocol for quantifying carbon emissions and removals and includes guidelines for identifying baseline scenario and assessing additionality in all carbon pools relevant to sustainable land management projects.

### Factors Affecting Soil Carbon Sequestration

Climate significantly influences large-scale patterns of soil carbon sequestration. In this study, irrespective of land management practices, higher sequestration rates were observed in the wettest locations with annual precipitation above 1,500 mm.

There was also a trend to lower sequestration rates in the coolest (mean annual temperature less than 20°C) and warmest (mean annual temperature greater than 30°C) conditions. Sites in warmer and middle temperature regions tend to accumulate soil carbon more rapidly than those in colder regions, while semi-humid areas have higher sequestration rates than their semi-arid counterparts.

Soil type is significant to soil carbon sequestration as well. Soils with higher clay content sequester carbon at higher rates. In Africa and Latin America, carbon sequestration rates and variability are highest on inceptisols—relatively young soils that constitute about 9 percent of soils in the tropics. In Asia, the highest sequestration rates and variability are observed in oxisols, formed principally in humid tropical zones under rain forest, scrub, or savanna vegetation. Oxisols comprise about 24 percent of tropical land mass and are typically found on old landscapes that have been subject to shifting cultivation for some time.

Timing is another factor that warrants careful consideration when introducing improved land management practices that increase carbon sequestration. Most of the potential soil carbon sequestration takes place within the first 20 to 30 years of adopting improved land management practices. The patterns of change in sequestration rates are nonlinear and differ between major types of practices. With most practices, the highest rates of sequestration are achieved in the intermediate term, with lower or even negative rates in the short term.[1]

### Greenhouse Gas Mitigation by Sustainable Land Management Technologies

The climate benefits of sustainable land management technologies are measured by the net rate of carbon sequestration adjusted for emissions associated with the technologies—a measurement referred to as the abatement rate. The emissions associated with the technologies are classified as land emissions and process emissions. Land emissions are the differences between emissions of nitrous oxides and methane by conventional and improved practices. Process emissions are those arising from fuel and energy use. The abatement rate is expressed in tons of carbon dioxide equivalent (t $CO_2e$) per hectare (ha) per year.

Increases in productivity from nitrogen fertilizers need to be considered against the increased emission of GHGs from soils as well as the energy-related emissions associated with the fertilizer's production and transport. In Latin America, the abatement rate of inorganic fertilizer is –0.23 t $CO_2e$ per ha per year compared to 0.13 t $CO_2e$ per ha per year for Asia and 0.29 t $CO_2e$ per ha per year for Africa. The greenhouse mitigation of manure is much higher at about 2.2 to 2.7 t $CO_2e$ per ha per year across the regions.

No-tillage and residue management generated abatement rates ranging from 0.9 to 3.5 t $CO_2e$ per ha per year across the three regions. These rates represent the marginal carbon benefit of mulching or incorporating residues relative to burning, grazing, and removal of the residues for other uses. Commonly applied residues on croplands include biomass from trees, sugarcane, rice, and other grain crops.

Cover crops and crop rotation are key complementary practices for successful implementation of no-tillage. Cover crops improve soil quality by increasing soil organic carbon through their biomass, and they also help in improving soil aggregate stability and protecting the soil from surface runoff. Crop rotation is the deliberate order of specific crops sown on the same field. The succeeding crop may be of a different species (e.g., maize or sorghum followed by legumes) or a variety from the previous crop, and the planned rotation may be for 2 or more years. GHG abatements of cover crops were 1.7 to 2.4 t $CO_2e$ per ha per year, while those of crop rotation were 0.7 to 1.5 t $CO_2e$ per ha per year. There is a tendency toward higher carbon sequestration rates in triple cropping systems, although variation is high. Differences in soils, climate, and cropping systems also affect carbon sequestration under crop rotation.

Supplemental irrigation and water harvesting are needed to minimize production risks in dry land agriculture. They also sequester carbon in the soil. Improved irrigation generated low to moderately high abatement rates (0.2 to 3.4 t $CO_2e$ per ha

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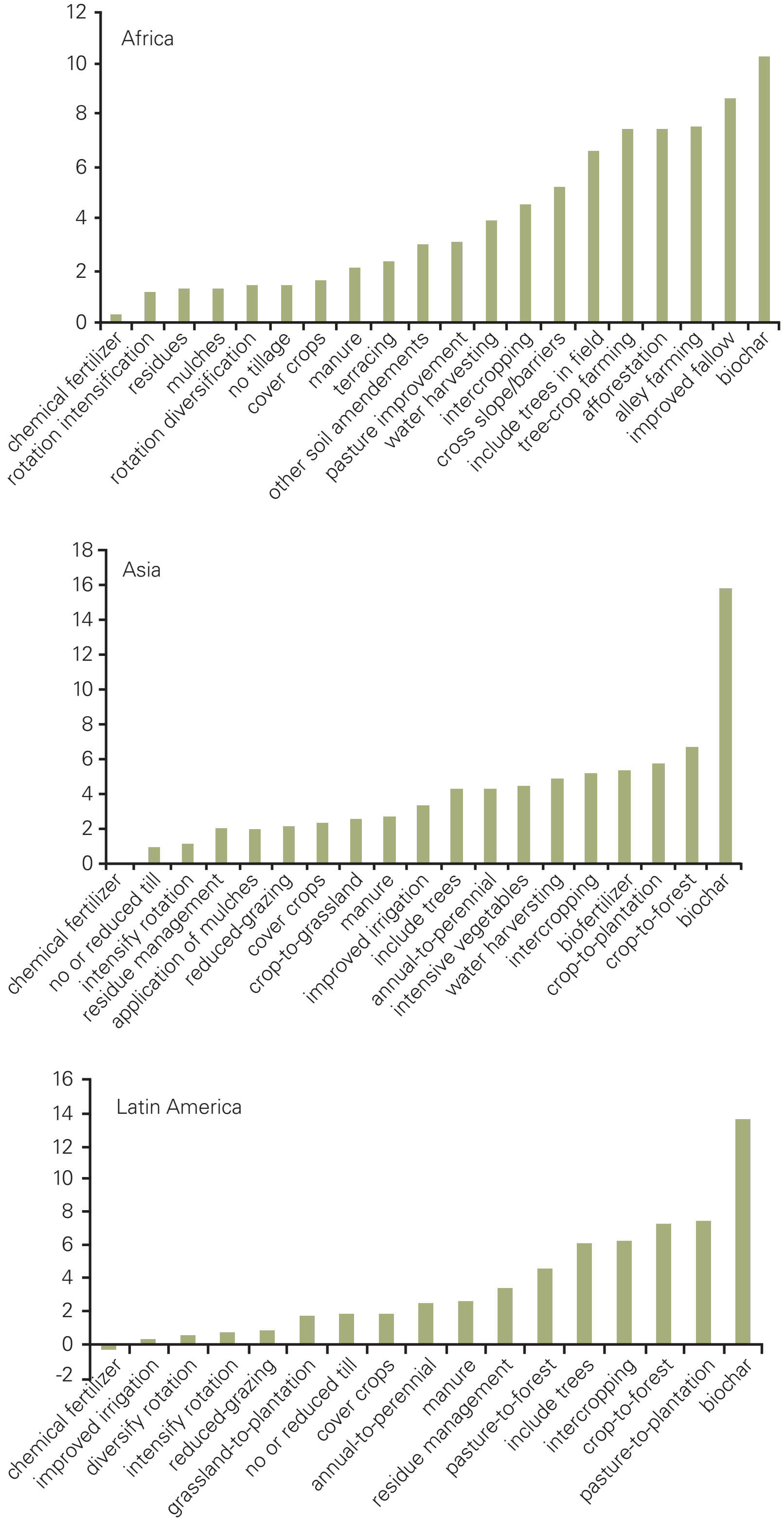
[1] The World Bank has posted a useful geographical information system tool on the Internet that summarizes the results of a series of ecosystem modeling exercises (see http://www-esd.worldbank.org/SoilCarbonSequestration/). The tool comprises several land management scenarios reflecting situations typically encountered in agricultural projects. The Internet GIS database provides per-hectare estimates of soil carbon sequestration under different land management practices for a period of 20 to 25 years. Information on carbon sequestration potential of a location can be derived by point-and-click or by searching using place names. Users can download data from the database and integrate them with other GIS information to estimate soil carbon stock changes for different agricultural projects.

**FIGURE E1:** Abatement Rates of the Land Management Practices (t $CO_2$e Per Hectare Per Year)



*Source:* This study.

per year). Process and land emissions under irrigation can significantly offset gains from carbon sequestration. Apart from energy-related emissions, a critical issue for soil carbon sequestration activities in irrigated areas is reduced emissions of methane from rice fields. Mid-season drainage is a viable practice to reduce such emissions. The GHG abatement of water harvesting, the process of concentrating runoff from a larger area for use in a smaller target area, averaged 3.9 to 4.8 t $CO_2e$ per ha per year. Terracing and construction of slope barriers on sloping lands for soil and water conservation produced abatements of 2.4 to 5.3 t $CO_2e$ per ha per year.

**PHOTO E.3:** Water Management in a Field in India

*Source:* Ray Witlin/World Bank.

Abatement rates of agroforestry systems, integrated land-use systems combining trees and shrubs with crops and livestock, are fairly high. This is due to the relatively large time-averaged biomass of trees compared to crops. The average abatement rates in t $CO_2e$ per ha per year are 7.6 for alley farming (the growing of crops simultaneously in alleys of perennial, preferably leguminous trees or shrubs), 7.5 for tree-crop farming, 8.7 for improved fallow (involving the use of fast-growing trees to accelerate soil rehabilitation), 4.6 to 6.3 for intercropping (the growing of crops near existing trees), and 4.3 to 6.7 for croplands where trees are introduced.

The impacts of land-use changes on tree-based systems are also relatively large. Conversion of cropland to forest or pasture to plantation resulted in an abatement of 6.7 to 7.5 t $CO_2e$ per ha per year, while conversion of cropland to plantation generated an abatement of 5.7 t $CO_2e$ per ha per year. Pasture improvement generated an abatement of 3.21 t $CO_2e$ per ha per year, whereas conversion of cropland to grassland produced GHG mitigation of 2.6 t $CO_2e$ per ha per year. By definition, most of the potential impact of changes in agricultural practices on carbon stocks is below ground. However, land-use changes away from cropland to agroforestry or plantations provide more convincing examples where it is useful to think of both above- and below-ground sequestration rates at the same time and possible trade-offs or interactions between them.

Application of biochar, on average, resulted in the highest overall GHG abatement rate (10.3 to 15.7 t $CO_2e$ per ha per year), but its impact on crop productivity and soil resilience is still uncertain. In general, biochar production should not deplete the soil of the crop residues needed to protect against erosion and increase soil resilience.

Decisions to adopt any of the land management practices should not be based solely on their respective climate mitigation benefits. Rather, they should be based on whole farm systems analysis that comprehensively assesses the productivity,

**PHOTO E.4:** Maize Growing under *Faidherbia Albida* Trees in Tanzania

*Source:* World Agroforestry Centre.

on-farm resource use, and environmental load of the system. Farm-scale management decisions, taken within a wider socio-economic context, particularly the influence of public policy and markets, will most likely generate optimum social benefits.

### Profitability of Soil Carbon Sequestration

In addition to storing soil carbon, sustainable land management technologies can be beneficial to farmers by increasing yields and reducing production costs. Increases in crop yields derive from the ability of the land management technologies to maintain soil organic matter and biological activity at levels suitable for soil fertility. The pattern of increase in yield, however, varies from crop to crop. The profitability of no-tillage systems results mainly from the reduced labor requirement for seedbed preparation and other tillage operations compared to conventional tillage systems. In Zambia, yields have doubled for maize and increased by 60 percent for cotton compared to the conventional tillage system.

Farmers also frequently reported significant crop yield increases for maize, sorghum, millet, cotton, and groundnut in agroforestry systems, but relatively high labor inputs are required to reduce competition effects of trees from negatively impacting crop growth. Inorganic fertilizers also show relatively high profits because they provide nutrients that can be readily absorbed by plants. Judicious fertilizer application counters soil nutrient depletion, reduces deforestation and expansion of cultivation to marginal areas, and increases crop yields. Excessive fertilizer use is less environmentally friendly, however, due to nitrous oxide emissions associated with high application rates of nitrogen fertilizers and fossil fuel–based emissions associated with fertilizer production and transportation.

### Capitalizing on Synergies and Managing Trade-Offs in Soil Carbon Sequestration

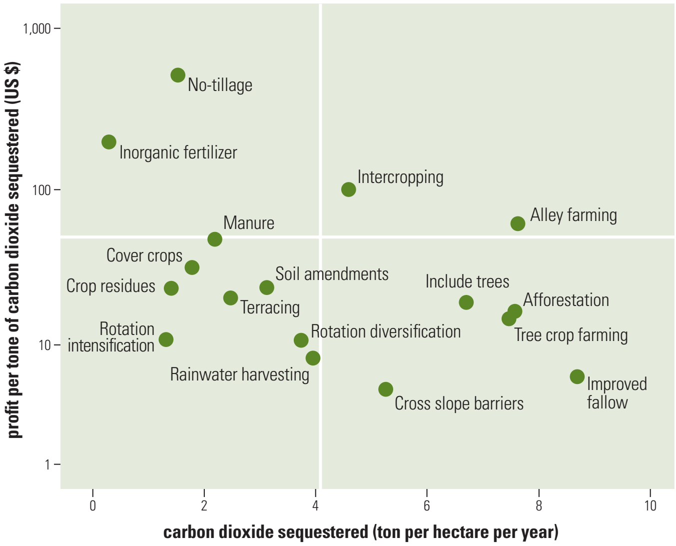
Synergies occur when there is a positive correlation between carbon sequestration and profitability (where profitability refers to the net present value of implementing the land management practices). Trade-offs occur when attempts to increase carbon storage reduce profits. Increasing food security under a changing climate requires the analysis and identification of the land management technologies that maximize synergies and minimize trade-offs. A plot of profit versus carbon sequestration reveals synergies in two agroforestry systems—intercropping and alley farming (top right quadrant of figure E2).

In figure E2, land management technologies in the lower right quadrant have high mitigation potentials but are modestly profitable. Afforestation, improved fallow (including trees in croplands), and establishing barriers across sloping areas tend to take land out of production for a significant period of time. They reduce the amount of land available for cultivation in the short run but can lead to overall increases in productivity and improved resilience in the long run. The time-averaged, above-ground

**PHOTO E.5:** Crop Harvesting in Mali. The Biomass Is Smaller Compared to that of Agroforestry Systems

*Source:* Curt Carnemark/World Bank.

**FIGURE E2:** Trade-Offs Between Profitability and Carbon Sequestration of Sustainable Land Management Technologies



*Source:* This study.

biomass of crop residues and other technologies in the lower left quadrant of figure E2 is relatively small compared to that of agroforestry systems. Also, the biomass of crop residues does not accumulate easily, resulting in lower mitigation benefits.

Judicious fertilizer application increases crop yields and profitability. Yields also increase with manure application and accumulation of soil carbon, but with patterns that depend on crop type. Manure is less profitable than inorganic fertilizer because of the labor costs associated with collecting and processing manure (top left quadrant of figure E2). The relatively high profitability of no-tillage derives primarily from the decrease in production costs after the establishment of the system.

The trade-offs exhibited by the land management technologies have important implications for land-use decision making. Sustainable land management interventions should be planned and implemented in a coordinated manner across space, time, and sectors. Working at the landscape level within an ecosystems approach is useful for addressing food security and rural livelihood issues and in responding to the impacts of climate change and contributing to its mitigation. The landscape approach entails the integrated planning of land, agriculture, forests, fisheries, and water at local, watershed, and regional scales to ensure that synergies are properly captured. The landscape approach provides a framework for the better management of ecosystem services, such as agricultural productivity, carbon storage, freshwater cycling, biodiversity protection, and pollination.

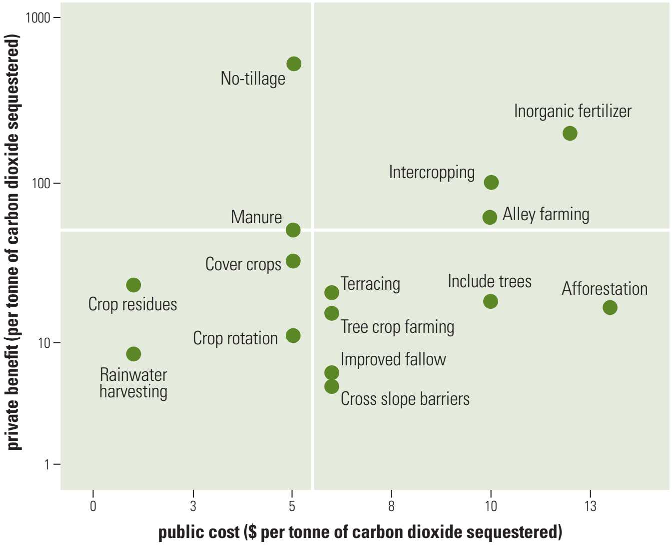
### Public Costs of Soil Carbon Sequestration

Public cost refers to government support toward the implementation of land management practices. They include investments in seeds and seedlings, input subsidies, extension services, and other administrative costs. The pattern of public support is as crucial as the amount of support for full realization of productivity, adaptation, and mitigation benefits in agriculture. Public support that focuses on research, investments in improved land management, and land tenure rather than on input support is generally more effective, benefits more farmers, and is more sustainable in the long run.

Technologies that involve significant change in land use (such as afforestation and improved fallows) and landscape alteration (such as terracing and cross-slope barriers) incur high public costs but generate low private benefits (lower right quadrant of figure E3). The low profits suggest that farmers may be reluctant to privately invest in these technologies. Strong public involvement in these technologies is required given their relatively high mitigation potentials. Crop residues, cover crops, crop rotation, and rainwater harvesting with lower profits and also manure and no tillage that generate relatively higher profits require minimal government support (lower left and upper left quadrants of figure E3, respectively). These technologies generally have low mitigation potentials. The relatively high public cost of inorganic fertilizer (top right quadrant, figure E3) reflects the use of subsidies in spurring farmers' access to the technology.

Fertilizer subsidies are associated with high fiscal costs, difficult targeting, and crowding out of commercial sales. Thus, fertilizer subsidies are appropriate in situations when the economic benefits clearly exceed costs, the subsidies help achieve social rather than economic objectives, and the support helps improve targeting through market-smart subsidies while providing impetus for private sector input development. Examples of market-smart subsidies include demonstration packs, vouchers, matching grants, and loan guarantees.

**FIGURE E3:** Relationship Between Private Benefits and Public Costs



*Source:* This study.

The overall biophysical mitigation, potential savings, and the costs of soil carbon sequestration by 2030 depend on the emission scenarios influenced by a wide range of driving forces from demographic to social and economic developments. The total mitigation potential varies from 2.3 Gt $CO_2$-eq for Latin America to 7.0 Gt $CO_2$-eq for Asia (table E3). Total private profits range from US$105 billion in Africa to $1.4 trillion in Asia, while total public costs range from US$20 billion in Africa to $160 billion in Asia.

### Barriers to the Adoption of Sustainable Land Management Practices

Despite the fact that improved land management technologies generate private and public benefits, their adoption faces many socioeconomic and institutional barriers: Most of the land management technologies require significant up-front expenditure that poor farmers cannot afford; the nonavailability of inputs in the local markets can be a significant obstacle; lack of information on the potentials of alternative techniques of farming and limited capacity is a major constraint in many developing countries; when technologies are inconsistent with community rules and traditional practices, their adoption is often resisted; and willingness and ability to work together is crucial for many technologies such as improved irrigation and communal pastures. The absence of collective action will hinder successful uptake, diffusion, and impact of such land management technologies.

Factors affecting adoption tend to be more specific to the land management technologies. Table E4 suggests that lack of credit and inputs and land tenure problems are by far the most important factors for adoption across the range of technologies. However, improved availability of inputs is a necessary but insufficient condition for adoption of land management practices. Better market prices for crops and other agricultural produce are crucial. Secure land rights is a precondition for climate-smart agriculture as it provides incentive for local communities to manage land more sustainably. Ill-defined land ownership may inhibit sustainable land management changes.

**TABLE E3:** Technical Mitigation Potential, Private Benefits, and Public Costs of the Land Management Technologies by 2030

| SCENARIO | TECHNICAL POTENTIAL (MILLION TONS $CO_2$-eq) | PRIVATE BENEFITS (US$, BILLION ) | PUBLIC COSTS (US$, BILLION ) |
|---|---|---|---|
| **Africa** | | | |
| B1 | 3,448 | 105.4 | 19.6 |
| A1b | 3,505 | 108.6 | 19.7 |
| B2 | 3,678 | 111.4 | 20.8 |
| A2 | 3,926 | 120.9 | 22.3 |
| **Asia** | | | |
| B1 | 5,977 | 1,224.5 | 131.3 |
| A1b | 6,388 | 1,259.3 | 143.6 |
| B2 | 7,007 | 1,368.1 | 159.7 |
| A2 | 6,678 | 1,310.8 | 150.4 |
| **Latin America** | | | |
| B1 | 2,321 | 273.8 | 40.8 |
| A1b | 2,425 | 279.4 | 42.9 |
| B2 | 2,538 | 288.8 | 44.3 |
| A2 | 3,097 | 319.4 | 55.1 |

*Source:* This study.
*Notes:* B1 = a world more integrated and more ecologically friendly; A1b = a world more integrated with a balanced emphasis on all energy sources; B2 = a world more divided but more ecologically friendly; A2 = a world more divided and independently operating self-reliant nations.

**TABLE E4:** Relative Importance of Different Factors for Adopting Improved Land Management Practices

| LAND MANAGEMENT TECHNOLOGY | INPUTS/ CREDITS | MARKET ACCESS | TRAINING/ EDUCATION | LAND TENURE | RESEARCH | INFRASTRUCTURE |
|---|---|---|---|---|---|---|
| Inorganic fertilizer | *** | ** | ** | ** | * | ** |
| Manure | ** | ** | * | ** | * | ** |
| Conservation agriculture | ** | ** | *** | ** | ** | * |
| Rainwater harvesting | ** | ** | ** | *** | ** | ** |
| Cross-slope barriers | ** | * | ** | ** | ** | * |
| Improved fallows | ** | * | * | *** | ** | * |
| Grazing management | *** | *** | ** | *** | ** | * |

*Source:* Synthesized from Liniger *et al.* 2011.

*Liniger, H. P., Mekdaschi Studer, R., Hauert, C., and Gurtner, M. 2011. Sustainable Land Management in Practice—Guidelines and Best Practices for Sub-Saharan Africa. World Overview of Conservation Approaches and Technologies and Food and Agriculture Organization of the United Nations.*
*Key * = Low importance, ** = Moderate importance; *** = High importance.*

Behavioral change through education and extension services is required to enable change-over to improved land management technologies. For instance, conservation agriculture, the farming system involving no-tillage, residue management, and use of cover crops is highly knowledge intensive, requiring training and practical experience of those promoting its adoption. Learning hubs, regional platforms, scientific research, south-south knowledge exchange, and technical support mechanisms may increase innovation and facilitate adoption of improved land management technologies. The knowledge base of land management practices at the local level can be also improved through careful targeting of capacity development programs.

### Policy Implications

Private benefits that drive land-use decisions often fall short of social costs; thus, carbon sequestration may not reach the optimal level from a social point of view unless some mechanisms exist to encourage farmers. Some public policies that can potentially incentivize carbon sequestration include the following options.

1. *Strengthen the capacity of governments to implement climate-smart agriculture.* Countries must be prepared to access new and additional finance. There is a need to build the technical and institutional capacity of government ministries to implement climate-smart agriculture programs. Existing national policies, strategies, and investment plans should be strengthened to form the basis for scaling-up investments for climate-smart agriculture. Readiness for carbon sequestration and climate-smart agriculture can be achieved through improved extension services and training in relevant land management technologies for different locales.
2. *Global cooperative agreement*. Given the tremendous significance that agriculture has for the global climate, progress in incorporating it into the UN Framework Convention on Climate Change (UNFCCC) has been slower than many people hoped for. While the negative impacts of agricultural production in terms of land-use change and GHG emissions were reasonably well covered by the convention, the real and potential contributions the sector can and does make in terms of sequestering carbon in agricultural biomass and soils were for the most part omitted. Redressing this omission promises to foster a more balanced perspective in which food security is not necessarily at odds with climate change adaptation and mitigation (an unworkable conflict in which longer term environmental concerns are virtually guaranteed to universally lose out politically to the more immediate concern of food supply). A more practical and thorough picture makes it possible for agriculture to be rewarded for its positive environmental impacts and to be an integral part of the solution as well as part of the problem. This is vitally important because agriculture needs to be fully incorporated into adaptation and mitigation strategies. As a result, the international community has recognized the importance of integrating agriculture into the ongoing negotiations on the international climate change regime. At the 17th Conference of Parties to the UNFCCC in Durban, South Africa, in November 2011, the parties asked the UNFCCC Subsidiary Body for Scientific and Technological Advice to explore the possibility of a formal work program on agriculture.

3. *Boost financial support for early action*. A blend of public, private, and development finance will be required to scale-up improved land management practices. Integrating sources of climate finance with those that support food security may be one of the most promising ways to deliver to climate-smart agriculture the resources it requires. For technologies that generate significant private returns, grant funding or loans may be more suitable to overcoming adoption barriers. For technologies such as conservation agriculture that require specific machinery inputs and significant up-front costs, payment for an ecosystem services scheme could be used to support farmers and break the adoption barrier. There is also the potential for carbon finance to support farmers during the initial period before the trees in agroforestry systems generate an economic return.
4. *Raise the level of national investment in agriculture*. While this may appear a tall order in countries with severe budget constraints, finite public resources can be more selectively targeted using the criteria given above—prioritizing technologies that generate no short-term returns and those that most effectively address the barriers that prevent prospective adopters from moving forward. In some cases, relatively affordable technologies that generate quick and demonstrable benefits may warrant priority and potentially establish some of the channels through which more sophisticated technologies are dispersed in the future. Nationally owned climate-smart agricultural policies and action frameworks will increase the adoption of sustainable land management practices. However, public investment is only one sphere, and involving the private sector in climate-smart agriculture and sustainable land management is the other.
5. *Create enabling environments for private sector participation*. Introducing policies and incentives that provide an enabling environment for private sector investment can increase overall investment. This private investment can be targeted to some degree as well, particularly when government priorities translate clearly into business opportunities and certain areas of investment are looked upon favorably by public officials and institutions. Public investment can also be used to leverage private investment in areas such as research and development, establishing tree plantations, and developing improved seeds and seedlings. Particular attention should go to encouraging private financial service providers to tailor instruments that enable farmers who adopt SLM practices to overcome the barriers described above. Bundling agricultural credit and insurance together and providing different forms of risk management such as index-based weather insurance or weather derivatives are areas of private investment that can be encouraged through public policy and public-private partnerships.

# Chapter 1: INTRODUCTION

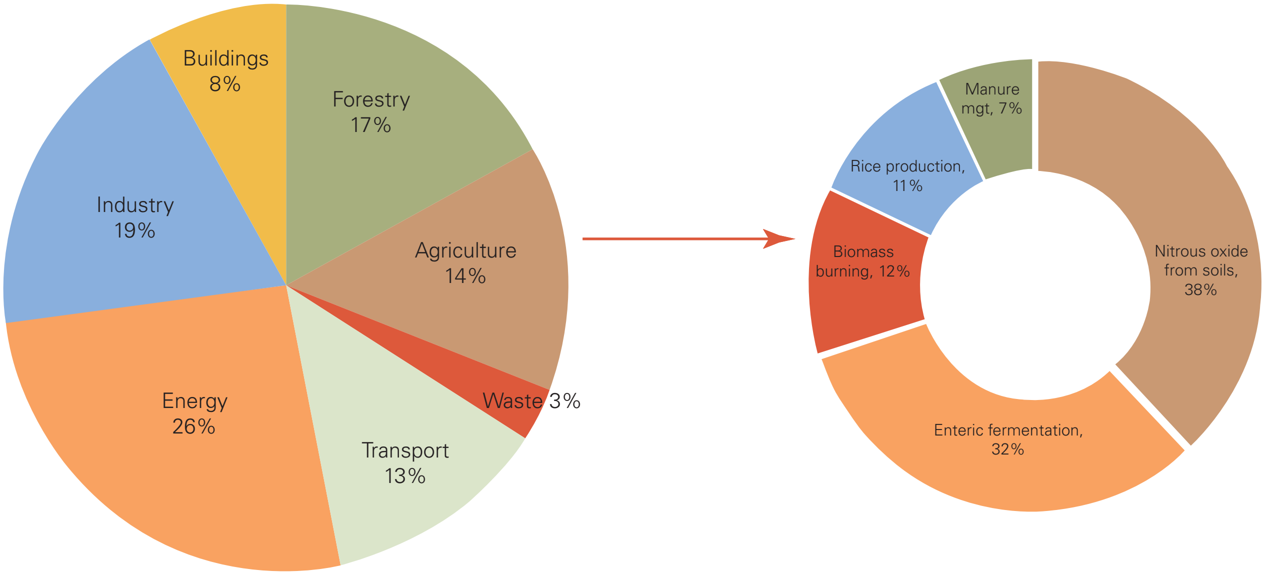
## 1.1 FOOD SECURITY UNDER A CHANGING CLIMATE

Ensuring food security under changing climate conditions is one of the major challenges of our era. There are about 925 million food-insecure people in the world—about 16 percent of the population in developing countries. Global population will increase from 7 billion currently to over 9 billion people by 2050, creating a demand for a more diverse diet that requires additional resources to produce. Competition for land, water, and energy will intensify in an attempt to meet the need for food, fuel, and fiber and will contribute to economic development and poverty reduction. Over this period, globalization may further expose the food system to the vagaries of economic and political forces. Various projections suggest that global food requirements must increase by 70 to 100 percent by 2050 (Burney, Davis, and Lobell 2010), in addition to maintaining and, where possible, enhancing the resilience of natural ecosystems.

Agriculture is highly vulnerable to climate change and needs to adapt to changing climate conditions. Under optimistic lower end projections of temperature rise, climate change may reduce crop yields by 10 to 20 percent (Jones and Thornton 2009), while increased incidence of droughts and floods may lead to a sharp increase in prices of some of the main food crops by the 2050s. Climate change will also impact agriculture through effects on pests and disease. The interactions between ecosystems and climate change are complex, and the full implications in terms of productivity and food security are uncertain (Gornall *et al.* 2010)

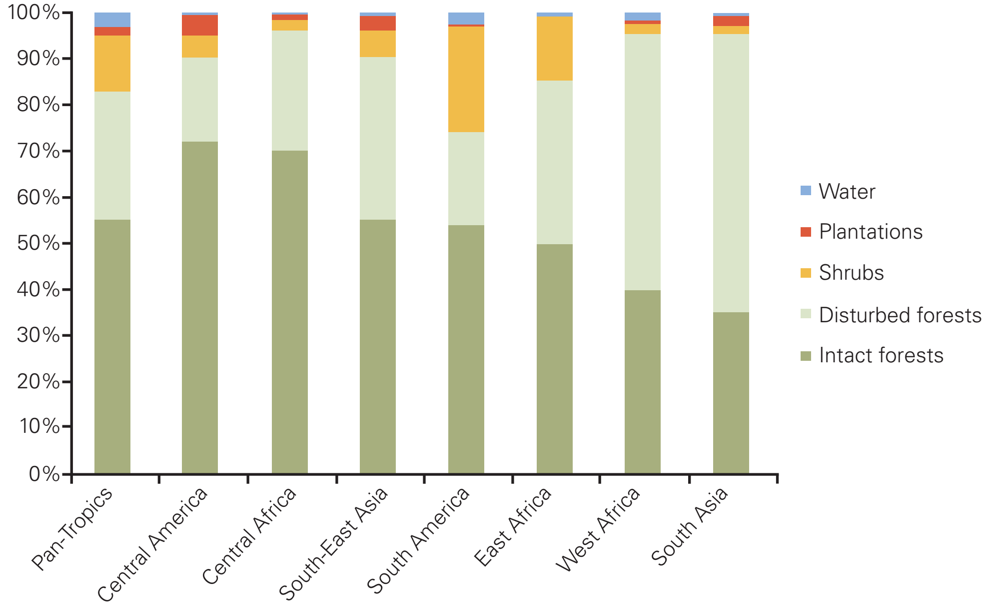
The agriculture sector has a pivotal role to play in mitigating greenhouse gas (GHG) emissions. Agriculture and land-use change currently account for about one-third of total emissions (figure 1.1). Agriculture is the primary driver of deforestation in many developing countries. The net increase in agricultural land during the 1980s and 1990s was more than 100 million ha across the tropics. About 55 percent of the new

**FIGURE 1.1:** Contribution of Different Sectors to Greenhouse Gas Emissions



*Source:* IPCC 2007; Smith *et al.* 2008.

**FIGURE 1.2:** Proportion of Agricultural Land Derived From Different Land Covers in the Tropics, 1980–2000



*Source:* Redrawn from Gibbs *et al.* (2010).

agricultural land in the tropics came at the expense of intact forests, while another 28 percent came from the conversion of degraded forests (Gibbs *et al.* 2010; figure 1.2). Projected increases in demand for food and bioenergy by 2050 may further increase pressure on forests in the tropics with profound implications for an increase in GHG emissions. Even if emissions in all other sectors were eliminated by 2050, growth in agricultural emissions under a business-as-usual world with a near doubling in food production would perpetuate climate change.

## 1.2 CARBON BENEFITS THROUGH CLIMATE-SMART AGRICULTURE

The triple imperatives of increasing productivity, reducing emissions, and enhancing resilience to climate change call for alternative approaches to practicing agriculture. Climate-smart agriculture (CSA) seeks to increase productivity in an environmentally and socially sustainable way, strengthen farmers' resilience to climate change, and reduce agriculture's contribution to climate change by reducing GHG emissions and increasing soil carbon storage. One of the key elements of CSA is sustainable land management (SLM) involving the implementation of land-use systems and management practices that enable humans to maximize the economic and social benefits from land while maintaining or enhancing the ecosystem services from land resources.

Soil is central to most SLM technologies because it is the basic resource for land use. It supports all the terrestrial ecosystems that cycle much of the atmospheric and terrestrial carbon. It also provides the biogeochemical linkage between other major carbon reservoirs, namely the biosphere, atmosphere, and hydrosphere. Soil carbon is held within the soil, primarily in association with its organic constituent. Soil carbon has a strong correlation with soil quality, defined as the ability of soils to function in natural and managed ecosystems. Soil carbon influences five major functions of the soil (Larson and Pierce 1991), namely the ability to

- accept, hold, and release nutrients;
- accept, hold, and release water both for plants and for surface and groundwater recharge;
- promote and sustain root growth;
- maintain suitable biotic habitat; and
- respond to management and resist degradation.

Increasing soil organic carbon can reverse soil fertility deterioration, the fundamental cause of declining crop productivity in developing countries. Table 1.1 indicates the potential increase in crop yields from increasing the soil organic carbon pool in the root zone by 1 ton C/ha/yr through SLM technologies. The overall increase in grain productivity in Africa, Asia, and Latin America due to such increase in soil organic carbon is estimated at 24 to 40 million tons per year (table 1.2).

**TABLE 1.1:** Improvement in Crop Yields per Ton of Carbon in the Root Zone

| CROP | POTENTIAL YIELD INCREASE (kg/ha) |
|---|---|
| Maize | 200–400 |
| Wheat | 20–70 |
| Soybean | 20–30 |
| Cowpea | 5–10 |
| Rice | 10–50 |
| Millet | 50–60 |

*Source:* Lal (2011).

Soil carbon also enhances resilience to climate variability and change by improving soil structure and stability, reducing soil erosion, improving aeration and water-holding capacity, reducing the impacts of drought, improving soil biodiversity, and increasing nutrient use efficiency.

Sustainable land management provides carbon benefits through three key processes, namely carbon conservation, reduced emissions, and carbon sequestration. Many natural land systems such as native forests, grasslands, and wetlands have relatively high carbon stocks. Conserving this terrestrial carbon pool accumulated over millennia should be a major priority, as it offers the greatest least-cost opportunity for climate mitigation and ecosystem resilience. Zero tolerance for soil erosion is indispensable for soil carbon conservation. Removal of the vegetation cover aggravates losses by soil erosion and increases the rate of decomposition due to changes in soil moisture and temperature regimes. Because soil organic matter is concentrated on the soil surface, accelerated soil erosion leads to progressive depletion of soil carbon. Agricultural soils should be prevented from being washed to streams and rivers where the relatively stable soil C pools are rapidly oxidized to carbon dioxide (Lal 2003). Furthermore, the removal of crop residues and cattle manure for fuel leads creates a negative carbon budget and must be prevented.

Sustainable land management practices are an alternative to several conventional agricultural practices that lead to emissions of GHG from the soil to the atmosphere. These conventional practices include biomass burning (that releases carbon dioxide, methane, and nitrous oxide), plowing and soil disturbance (carbon dioxide), deforestation (carbon dioxide, methane, and nitrous oxide), draining of wetlands (carbon dioxide and nitrous oxide), and uncontrolled grazing (carbon dioxide and nitrous oxide). Emission of these gases from agricultural ecosystems is increased through subsistence agricultural practices that do not invest in soil quality improvement practices such as erosion control, water management, and application of fertilizers and other amendments (World Bank 2010).

Soil carbon sequestration is the process by which atmospheric carbon dioxide is taken up by plants through photosynthesis and stored as carbon in biomass and soils. It entails replenishing lost carbon and adding new carbon (organic inputs) beyond original levels. Historically, agricultural soils have lost more than 50 Gt (1 Gt = 1 billion tons) of carbon. Some of this carbon, however, can be recaptured through sustainable land management practices. For instance, new technologies such as deeper-rooted crops and pasture grasses can enhance original soil carbon up to a given equilibrium. The use of crop residues as mulch, intercropping food crops with trees, and integrated nutrient and water management also sequester carbon in the soil. By adopting improved land management practices to increase soil carbon, farmers can increase crop yields, reduce rural poverty, limit GHG concentrations in the atmosphere, and reduce the impact of climate change on agricultural ecosystems.

**TABLE 1.2:** Estimated Increase in Grain Crop Production from Land Management Technologies That Sequester Soil Carbon (Million Tons/Year)

| CROP | AFRICA | ASIA | LATIN AMERICA | TOTAL |
|---|---|---|---|---|
| Maize | 0.8–1.3 | 4.1–8.2 | 4.5–6.9 | 9.4–16.4 |
| Wheat | 0.2–0.4 | 2.9–4.9 | 0.5–0.6 | 3.6–5.9 |
| Rice | 0.1–0.2 | 4.1–6.9 | 0.2–0.3 | 4.7–7.4 |
| Sorghum | 1.7–2.6 | 1.3–1.8 | 0.4–0.6 | 3.4–5.0 |
| Millet | 0.6–1.0 | 0.4–0.7 | 0.01–0.01 | 1.0–1.8 |
| Beans | 0.1–0.2 | 0.4–0.7 | 0.3–0.5 | 0.8–1.4 |
| Soybean | 0.02–0.03 | 0.3–0.5 | 0.7–1.2 | 1.0–1.7 |
| Total | 3.5–5.7 | 13.5–23.7 | 6.6–10.1 | 23.6–39.5 |

*Source:* Lal (2003).

## 1.3 OBJECTIVES AND SCOPE OF THE REPORT

The purpose of this report is to improve the knowledge base for facilitating investments in land management technologies that sequester soil organic carbon. While there are many studies on soil carbon sequestration, there is no single unifying volume that synthesizes knowledge on the impact of different land management practices on soil carbon sequestration rates across the world.[2] A meta-analysis was carried out to provide soil carbon sequestration rates in Africa, Asia, and Latin America. This is one important element in decision-making for sustainable agricultural intensification, agro-ecosystems resilience, and comprehensive assessments of greenhouse mitigation potentials of SLM practices. Furthermore, the ecosystem simulation modeling technique was used to predict future carbon storage in global cropland soils. Last, marginal abatement cost curves and trade-off graphs were used to assess the cost-effectiveness of the technologies in carbon sequestration.

The remainder of the report is organized as follows. Chapter 2 provides a brief review of soil organic carbon dynamics and the methods for soil carbon assessment. The chapter concludes with brief information on carbon assessment in The World Bank's sustainable land management projects portfolio. Chapter 3 reports the increase in soil carbon for selected sustainable land management practices in Africa, Asia, and Latin America. Chapter 4 reports the estimates from ecosystem simulation, while Chapter 5 concludes with the benefits and costs of adopting carbon sequestering practices and a discussion of policy options to support climate-smart agriculture in developing countries. The report will provide a broad perspective to natural resource managers and other professionals involved in scaling up CSA.

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[2] Major exceptions are Guo and Gifford (2002) and Ogle *et al.* (2005), but the sequestration rates in these papers are highly variable and not specific to local conditions.

# Chapter 2: SOIL ORGANIC CARBON DYNAMICS AND ASSESSMENT METHODS

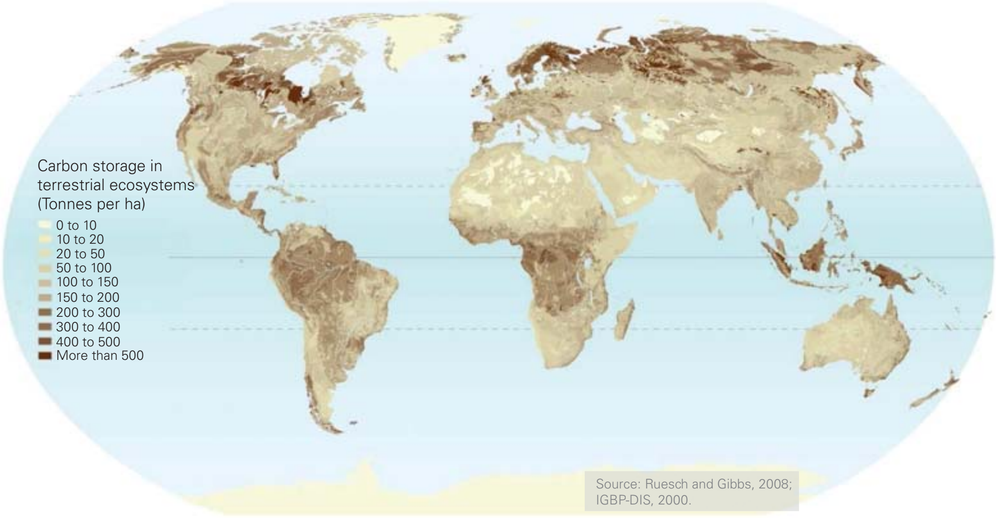
## 2.1 SOIL ORGANIC CARBON DYNAMICS

Different ecosystem types store different amounts of carbon depending on their species compositions, soil types, climate, relief, and other biophysical features (figure 2.1). Of the estimated over 150 million km$^2$ of terrestrial ecosystems area, forests account for more than 40 million km$^2$ (about 28 percent). Savannahs and grasslands both cover about 23 percent, while croplands occupy about 11 percent (table 2.1). Among the biomes, vegetation carbon stocks range from 3 Gt for croplands to 212 Gt for tropical forests, while soil carbon stocks range from 100 Gt for temperate forests to 471 Gt for boreal forests. The tundra biome, covering an area of less than 10 million km$^2$, has the highest density of carbon storage. Soils generally hold more carbon than vegetation across biomes and account for 81 percent of terrestrial carbon stock at the global level.

The global carbon cycle describes the transfer of carbon in the earth's atmosphere, vegetation, soils, and oceans. The two most important anthropogenic processes responsible for the release of carbon dioxide into the atmosphere are burning of fossil fuels (coal, oil, and natural gas) and land use (table 2.2). Emissions from land-use change are about 1.5 Gt C per year, largely determined by tropical deforestation that exacerbates soil erosion and organic matter decomposition. The underlying driving factors of tropical deforestation are highly interconnected and include poverty, policy and institutional failures, population growth, and the attendant demand for natural resources, urban expansion, and international trade.

Rapidly growing emissions are outpacing the growth in natural sinks. The efficiency of oceans and lands as carbon dioxide sinks has declined over the years. Currently, natural sinks remove an average of 55 percent of all anthropogenic carbon dioxide emissions, which is slightly lower than 60 percent they removed some 50 years ago (Global Carbon Project 2009).

**FIGURE 2.1:** Carbon Stocks in Biomass and Soils



*Source:* UNEP/GRID, http://www.grida.no/publications/rr/natural-fix/page/3724.aspx.

**TABLE 2.1:** Carbon Stocks in Vegetation and Top 1 Meter of Soils of World Biomes

| BIOMES | AREA (MILLION km²) | CARBON STOCKS (Gt C) AND PROPORTION IN THE ECOSYSTEM (%) | | | | |
|---|---|---|---|---|---|---|
| | | VEGETATION | PROPORTION (%) | SOILS | PROPORTION (%) | TOTAL |
| Tropical forests | 17.6 | 212 | 49.5 | 216 | 50.5 | 428 |
| Temperate forests | 10.4 | 59 | 37.1 | 100 | 62.9 | 159 |
| Boreal forests | 13.7 | 88 | 15.7 | 471 | 84.3 | 559 |
| Tropical savannas | 22.5 | 66 | 20.0 | 264 | 80.0 | 330 |
| Temperate grasslands | 12.5 | 9 | 3.0 | 295 | 97.0 | 304 |
| Deserts | 45.5 | 8 | 4.0 | 191 | 96.0 | 199 |
| Tundra | 9.5 | 6 | 4.7 | 121 | 95.3 | 127 |
| Wetlands | 3.5 | 15 | 6.3 | 225 | 93.8 | 240 |
| Croplands | 16 | 3 | 2.3 | 128 | 97.7 | 131 |
| Total | 151.2 | 466 | | 2,011 | | 2,477 |
| Proportion (%) | | 19 | | 81 | | 100 |

*Source:* Based on Watson *et al.* (2000) and Ravindranath and Ostwald (2008).

**TABLE 2.2:** Global Carbon Budget (Gt C)

| SOURCE | 1980s | 1990s | 2000–2008 |
|---|---|---|---|
| Atmospheric increase | 3.3 ± 0.1 | 3.2 ± 0.1 | 4.1 ± 0.1 |
| Fossil fuel emissions | 5.4 ± 0.3 | 6.4 ± 0.4 | 7.2 ± 0.3 |
| Net ocean-to-atmosphere flux | –1.8 ± 0.8 | –2.2 ± 0.4 | –2.3 ± 0.5 |
| Net land-to-atmosphere flux | –0.3 ± 0.9 | –1.0 ± 0.6 | –1.3 ± 0.7 |
| *Partitioned as:* | | | |
| Land-use change flux | 1.4 ± 1.0 | 1.6 ± 0.7 | 1.4 ± 0.7 |
| Residual land sink | –1.7 ± 1.7 | –2.6 ± 0.9 | –2.7 ± 1.0 |

*Sources:* IPCC (2007) and the Global Carbon Project (2009).

Soils are critically important in determining global carbon cycle dynamics because they serve as the link between the atmosphere, vegetation, and oceans. Globally, the soil carbon pool (also referred to as the pedologic pool) is estimated at 2,500 Gt up to 2 meters deep. Out of this, the soil organic carbon pool comprises 1,550 Gt, while the soil inorganic carbon and elemental pools make up the remaining 950 Gt (Batjes 1996). The soil carbon pool is more than three times the size of the atmospheric pool (760 Gt) and about 4.5 times the size of the biotic pool (560 Gt).

The elemental and inorganic forms of soil carbon primarily result from mineral weathering and are less responsive to land management than soil organic carbon (table 2.3). Soil organic carbon is a complex mixture of organic compounds composed of decomposing plant tissue, microbial organisms, and carbon bound to soil minerals. These compounds originate from the photosynthetic activities of plants. Through photosynthesis, plants reduce carbon from its oxidized form to organic forms (net primary productivity; NPP) useful for growth and energy storage. Over time, the C fixed in the atmosphere becomes soil carbon through the process of above- and below-ground decomposition of materials, release of sap exudates from plant roots into the soil, and root die-off. Breeding crop plants with deeper and bushy root ecosystems could simultaneously sequester more carbon, improve soil structure, improve water and nutrient retention, and increase crop yields (Kell 2011).

Different fractions or soil organic carbon pools have different functions within the soil system. Crop residues are readily broken down and serve as substrates to soil microorganisms. Particulate organic carbon is broken down relatively quickly but more slowly than other crop residues and is important for soil structure, energy for biological processes, and provision of nutrients for plants. A more stable fraction,

**TABLE 2.3:** Forms of Carbon in the Soil

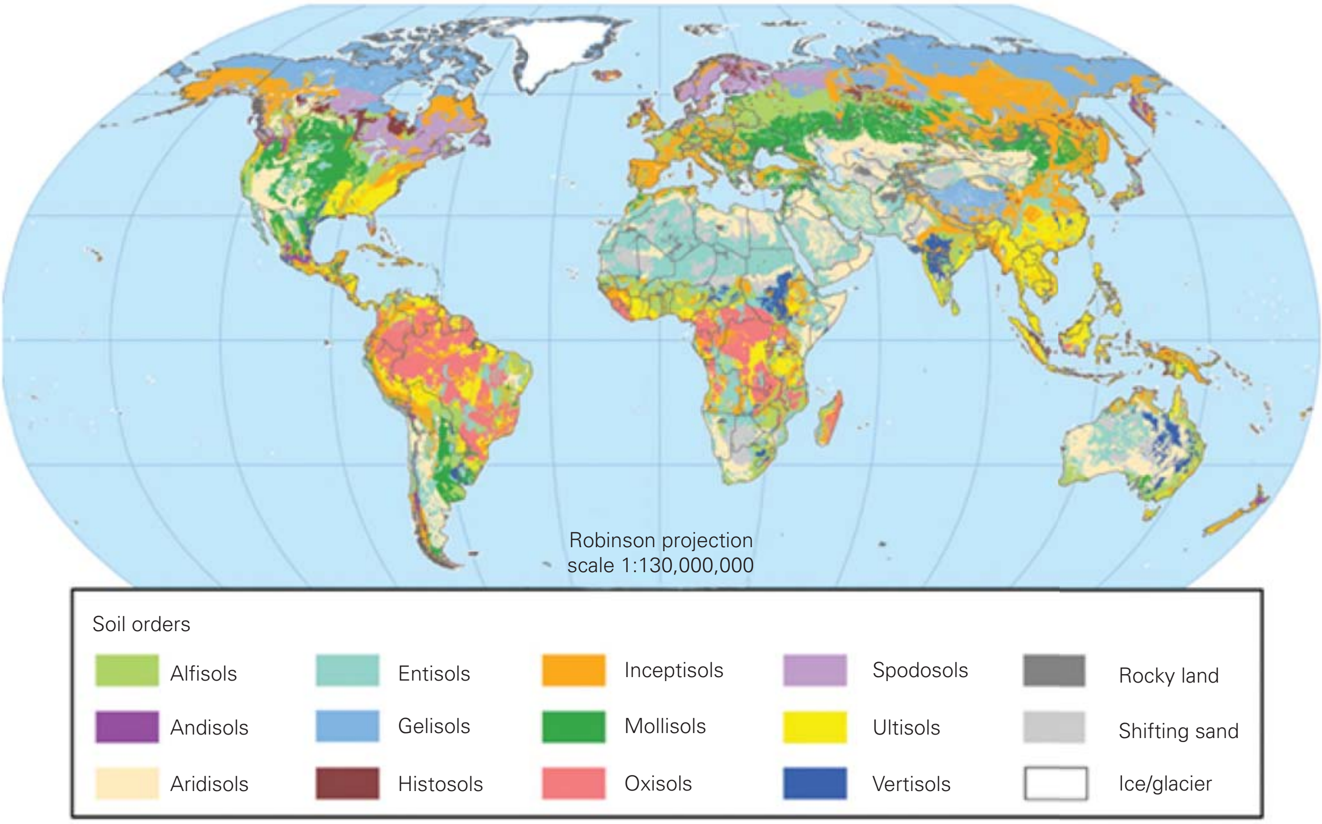
| FORMS | SOURCES |
|---|---|
| Elemental | Geologic materials (e.g., graphite and coal)<br>Incomplete combustion of organic materials (e.g., charcoal, graphite, and soot)<br>Dispersion of these carbon forms during mining |
| Inorganic | Geologic or soil parent materials, usually as carbonates—that is, calcite, CaCO$_3$ dolomite, CaMg(CO3)$_2$ and, to some extent, siderite (Fe CO$_3$)<br>Agricultural inputs such as liming can also introduce calcite and dolomite into the soil. |
| Organic | Plant and animal materials at various stages of decomposition ranging from crop residues with size of 2 mm or more<br>Plant debris, also referred to as particulate organic carbon, with size between 0.05 and 2 mm humus, highly decomposed materials less than 0.05 mm that are dominated by molecules attached to soil minerals |

*Source:* Synthesized from Schumacher (2002).

humus, can be classified into two depending on the level of decomposability: The first is active humus that is still subject to further decomposition, and the other is passive humus (or recalcitrant carbon), the highly stable, insoluble form that is not subject to further decomposition. Active humus is an excellent source of plant nutrients (nitrates and phosphates), while passive humus is important for soil physical structure, water retention, and tilth. Some very stable humus complexes can remain in the soil for centuries or millennia.

At the global level, the soil organic carbon pool is concentrated in five major soil orders: histosols, inceptisols, entisols, alfisols, and oxisols. In the tropics, the largest amount of soil organic carbon is found in oxisols, histosols, ultisols, and inceptisols (figure 2.2, table 2.4, and box 2.1).

**FIGURE 2.2:** Global Soil Regions



*Source:* United States Department of Agriculture.

**TABLE 2.4:** Soil Carbon Pool up to 1-M Deep for Soil Orders of the World's Ice-Free Land Surface

| | GLOBAL LAND AREA | | | | TROPICAL LAND AREA | | | |
|---|---|---|---|---|---|---|---|---|
| SOIL ORDER | EXTENT (1000 km$^2$) | PROPORTION (%) | SOIL ORGANIC CARBON POOL (Gt) | PROPORTION (%) | EXTENT (1000 km$^2$) | PROPORTION (%) | SOIL ORGANIC CARBON POOL (Gt) | PROPORTION (%) |
| Alfisols | 18,283 | 13.5 | 127 | 8.1 | 6,411 | 12.9 | 30 | 5.9 |
| Andisols | 2,552 | 1.9 | 78 | 4.9 | 1,683 | 3.4 | 47 | 9.3 |
| Aridisols | 31,743 | 23.5 | 110 | 7 | 9,117 | 18.4 | 29 | 5.7 |
| Entisols | 14,921 | 11 | 148 | 9.4 | 3,256 | 6.6 | 19 | 3.8 |
| Histosols | 1,745 | 1.3 | 357 | 22.7 | 286 | 0.6 | 100 | 19.8 |
| Inceptisols | 21,580 | 16 | 352 | 22.3 | 4,565 | 9.2 | 60 | 11.9 |
| Mollisols | 5,480 | 4.1 | 72 | 4.6 | 234 | 0.5 | 2 | 0.4 |
| Oxisols | 11,772 | 8.7 | 119 | 7.6 | 11,512 | 23.2 | 119 | 23.5 |
| Spodosols | 4,878 | 3.6 | 71 | 4.5 | 40 | 0.1 | 2 | 0.4 |
| Ultisols | 11,330 | 8.4 | 105 | 6.7 | 9,018 | 18.2 | 85 | 16.8 |
| Vertisols | 3,287 | 2.4 | 19 | 1.2 | 2,189 | 4.4 | 11 | 2.2 |
| Others | 7,644 | 5.7 | 18 | 1.1 | 1,358 | 2.7 | 2 | 0.4 |
| Total | 135,215 | 100 | 1,576 | 100 | 49,669 | 100 | 506 | 100 |

*Source:* Eswaran *et al.* (1993).

The soil organic carbon pool represents a dynamic balance between gains and losses. The amount changes over time depending on photosynthetic C added and the rate of its decay. Under undisturbed natural conditions, inputs of carbon from litter fall and root biomass are cycled by output through erosion, organic matter decomposition, and leaching.

The potential carbon sequestration is controlled primarily by pedological factors that set the physico-chemical maximum limit to storage of carbon in the soil. Such factors include soil texture and clay mineralogy, depth, bulk density, aeration, and proportion of coarse fragments (figure 2.3). The attainable carbon sequestration is set by factors that limit the input of carbon to the soil system. NPP—the rate of photosynthesis minus autotrophic respiration—is the major factor influencing attainable sequestration and is modified by above-ground versus below-ground allocation. Land management practices that increase carbon input through increasing NPP tend to increase the attainable level to nearer the potential level. Climate has both direct and indirect effects on attainable sequestration. The decomposition rate increases with temperature but decreases with increasingly anaerobic conditions. The actual carbon sequestration is determined by land management factors that reduce carbon storage such as erosion, tillage, residue removal, and drainage. Theoretically, the potential soil carbon sequestration capacity is equivalent to the cumulative historical carbon loss. However, only 50 to 66 percent of this capacity is attainable through the adoption of sustainable land management practices (Lal 2004; box 2.2).

The current rate of carbon loss due to land-use change (deforestation) and related land change processes (erosion, tillage operations, biomass burning, excessive fertilizers, residue removal, and drainage of peat lands) is between 0.7 and 2.1 Gt carbon per year (table 2.2). This is more than 50 percent of the carbon absorbed by land. The conversion of natural vegetation to agricultural ecosystems leads to a depletion of the soil organic carbon pool by as much as 60 percent in the temperate regions and by 75 percent or more in the tropics (box 2.1). The degree of loss is higher in soils that are susceptible to accelerated erosion and other soil degradation processes. Soil erosion is the major land degradation process that emits soil carbon. The annual soil losses in Africa, South America, and Asia are estimated at 39 to 74 Gt, corresponding to carbon emissions of 0.16 to 0.44 Gt per year (table 2.5). Globally, soil erosion accounts for up to 1.2 Gt of C emitted to the atmosphere each year. This is more than 57 percent

**BOX 2.1:** Brief Description of Soil Orders

*Alfisols*: Formed primarily under forest or mixed vegetative cover, alfisols result from weathering processes that leach clay minerals from the surface to the subhorizon.

*Andisols*: Common in cool areas with moderate to high precipitations, andisols result from weathering processes that generate minerals with little orderly crystalline structure (volcanic glass) and usually have high nutrient- and water-holding capacity.

*Aridisols*: Formed under arid climates, the lack of moisture markedly restricts the intensity of weathering and development of aridisols. The paucity of vegetation also leads to low organic matter content.

*Entisols*: Occurring in areas of recently deposited parent materials or areas where erosion or deposition rates exceed the rate of soil development, entisols are characterized with little or no horizon development. They occur in many environments such as on steep slopes, flood plains, or sand dunes.

*Gelisols*: Found mostly in very cold areas under the influence of glaciation, gelisols are characterized by permafrost within 2 m of the soil surface. High amounts of soil organic matter accumulate in the upper layer, making most gelisols black or dark brown in color. Gelisols are not highly fertile because nutrients are very easily leached above the permafrost.

*Histosols*: Formed in decomposed organic materials that accumulate faster than they decay, histosols have a high content of organic matter and no permafrost. Most histosols are saturated all the year round. They are commonly called peats, bogs, mucks, or moors.

*Inceptisols*: Exhibiting modest soil weathering and horizon development, inceptisols are formed on recent geomorphic surfaces in semi-arid to humid environments. Included in this category are partially developed soils of the Sahel region of West Africa, some soils of the riverine floodplains of the Ganges and Brahmaputra Rivers in Bangladesh and India, and the floodplains of Southeast Asia.

*Mollisols*: Formed under moderate to pronounced seasonal moisture deficits, mollisols are grassland soils with dark-colored surface horizons, relatively high organic matter, and high base saturation.

*Oxisols*: Dominated by low activity minerals, oxisols are highly weathered soils of tropical and subtropical regions. They are found on stable landscapes, have low natural fertility, and low capacity to retain fertilizer and soil amendments.

*Spodosols*: Commonly occurring in areas of coarse-textured deposits of humid regions, spodosols have developed from weathering processes that strip organic matter and iron and aluminum oxides from the surface to the subsoil. Spodosols tend to be acidic and are inherently infertile.

*Ultisols*: Formed from fairly intense weathering and leaching that results in clay accumulation at the subsoil, ultisols are typically acidic with most nutrients concentrated in the topsoil. They have moderately low capacity to retain fertilizer and soil amendments.

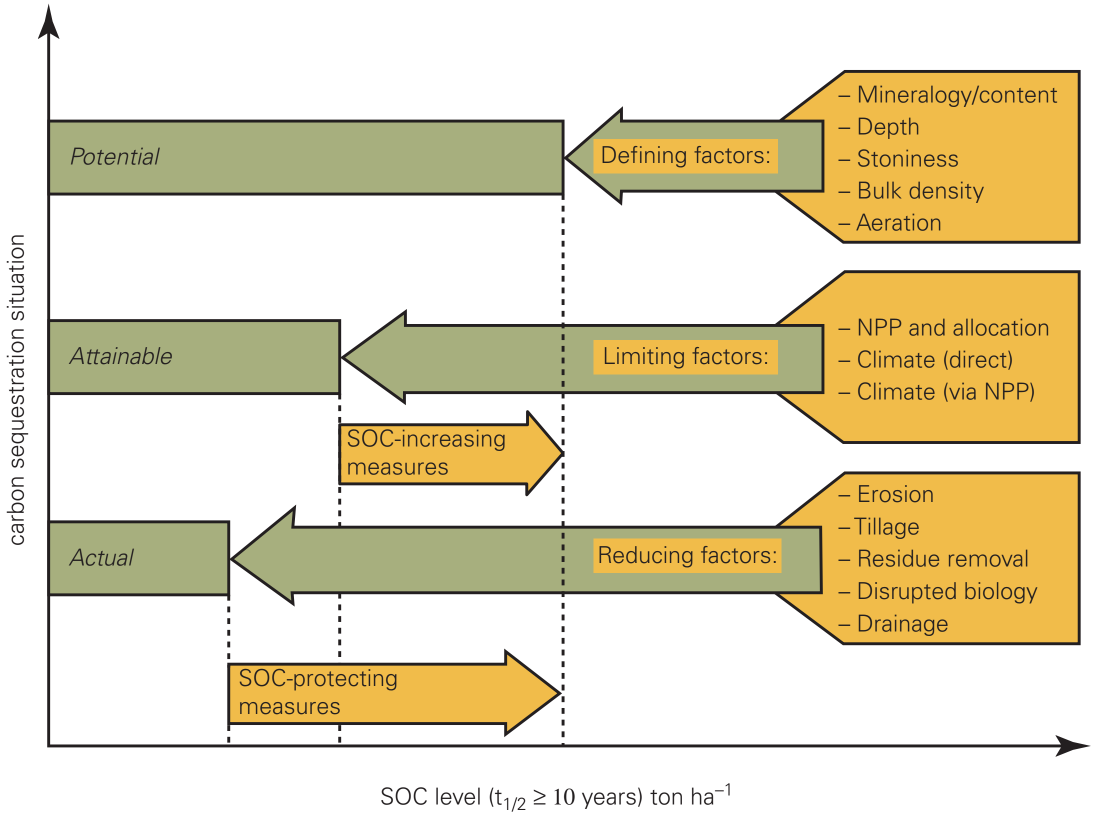
*Vertisols*: Dominated by high content of swelling and shrinking clay minerals, vertisols typically form from highly basic rocks in climates that are seasonally humid or subject to erratic floods, droughts, or impeded drainage. Vertisols tend to be high in natural fertility, but they are difficult to till.

*Source:* Modified from United States Department of Agriculture.

of the emission through land-use change and underscores the need for carbon conservation through zero tolerance for soil erosion.

Each year, the terrestrial carbon pool assimilates 120 Gt C from the atmosphere in the form of gross primary productivity (or photosynthesis). Soil respiration, the flux of microbially and plant-respired carbon dioxide ($CO_2$) from the soil surface to the atmosphere, estimated at 75 to 100 Gt C per year is the next largest terrestrial carbon flux (Raich and Potter 1995). It is about 60 times the annual contribution of land-use change and about 11 times that of fossil fuel to atmospheric emissions. Thus, a small change in soil respiration can significantly alter the balance of atmospheric carbon dioxide concentration compared to soil carbon stores. Soil respiration is regulated by several factors including temperature,

**FIGURE 2.3:** Factors Affecting Soil Carbon Sequestration



*Source:* Redrawn from Ingram and Fernandes (2001).

**TABLE 2.5:** Estimate of Erosion-Induced Carbon Emission

| CONTINENT | GROSS EROSION (X $10^9$ Mg/YEAR) | SOIL CARBON DISPLACED BY EROSION (2 TO 3 PERCENT OF SEDIMENT; Gt C/YEAR) | EMISSION (20 PERCENT OF DISPLACED SOIL CARBON; Gt C/YEAR) |
|---|---|---|---|
| Africa | 38.9 | 0.8–1.2 | 0.16–0.24 |
| Asia | 74.0 | 1.5–2.2 | 0.30–0.44 |
| South America | 39.4 | 0.8–1.2 | 0.16–0.24 |
| North America | 28.1 | 0.6–0.8 | 0.12–0.16 |
| Europe | 13.1 | 0.2–0.4 | 0.04–0.08 |
| Oceania | 7.6 | 0.1–0.2 | 0.02–0.04 |
| Total | 201.1 | 4.0–6.0 | 0.8–1.2 |

*Source:* Adapted from Lal (2003).

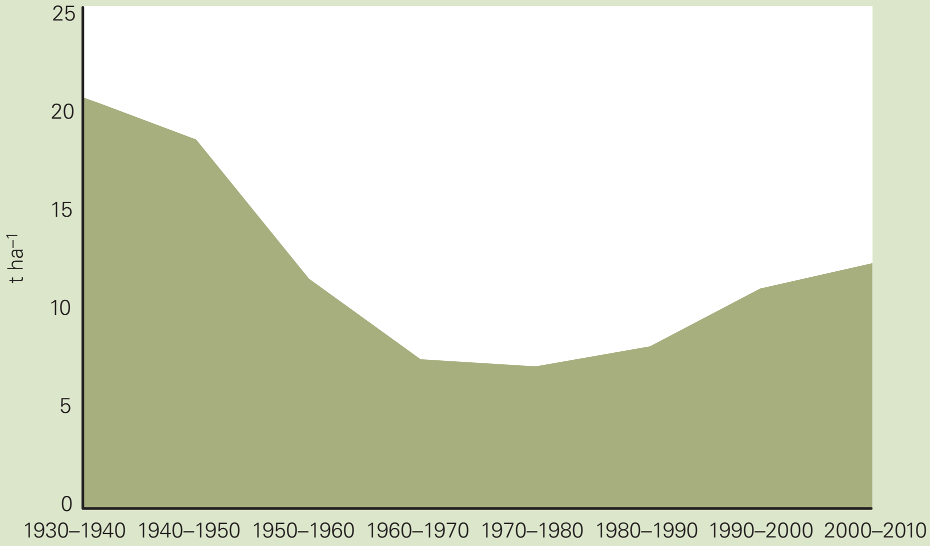
moisture, vegetation type, nitrogen content, and level of aeration of the soil.

Climate change is positively correlated with increasing rate of soil respiration. Higher temperatures trigger microbes to speed up their consumption of plant residues and other organic matter. Variations in temperature are significantly and positively correlated with changes in global soil respiration (Bond-Lamberty and Thompson 2010). In 2008, the global soil respiration reached roughly 98 Gt, about 10

**BOX 2.2:** Sustainable Land Management Practices Reverse Soil Carbon Loss in Java

Research in the tropics has demonstrated the decline of soil organic carbon by as much as 60 percent after conversion of forest to cropland. However, sustainable land management practices can accumulate soil organic carbon, reverse chronic soil degradation, improve soil quality, and enhance ecosystem services supply from the soil. Some soil scientists have recently used legacy soil survey data to capture the long-term trend of soil organic carbon in Java in Indonesia (Minasny *et al.* 2010). With an estimated population density of 1,026 persons km$^{-2}$, Java is undoubtedly the most densely populated and the most intensively cultivated island in Indonesia. An analysis over the period from 1930 to 2010 revealed that human activities are more important than environmental factors in explaining soil organic carbon trend. The median soil organic carbon stock in the topsoil dropped from 20.4 t ha$^{-1}$ between 1930 and 1940 to 7.3 t ha$^{-1}$ between 1960 and 1970 (see figure below). This huge drop was mostly due to the high conversion of forests and natural vegetation into plantations and subsequently to food crops. During the Dutch colonial period, most land development was for plantations such as tea, rubber, and coffee. Between 1930 and 1950, decline in soil carbon stock was primarily due to conversion of forests to cropland. From the Japanese occupation in 1942, throughout its independence years, and until the early 1960s, Indonesia faced a serious problem of food scarcity. The Green Revolution of the 1960s saw Java producing close to two-thirds of the country's rice. As a result, between 1960 and 1970, soil organic carbon markedly declined by 62 percent of its natural condition.

Since the late 1960s, soil organic C has increased slightly as a result of the government extension program to disseminate new agricultural production knowledge among farmers, including the use of high-yielding varieties and chemical inputs. The increased biomass and the return of crop residues, green compost, and animal manure application were mostly responsible for the increase in soil organic carbon stock. By the 1990s, soil organic carbon stock had risen to about 11 t ha$^{-1}$ as there was also a large interest in organic farming in Java. Further intensification has resulted in improved environmental awareness, increased likelihood of adoption of sustainable land management practices, increased soil carbon sequestration, and increased resilience of the agricultural system.



*Source:* Minasny, B., Sulaeman, Y., and McBrateney A.B. 2010. Is soil carbon disappearing? The dynamics of soil organic carbon in Java. Global Change Biology 17:1917–1924.

times more carbon than humans release into the atmosphere each year. Soil respiration increased 0.1 Gt C per year between 1989 and 2008. A rise in temperature by 2°C is estimated to release an additional 10 Gt C per year to the atmosphere through soil respiration (Friedlingstein *et al.* 2003).

Tillage operations can significantly affect soil respiration. Conventional tillage leads to the destruction of soil aggregates, excessive respiration, and soil organic matter decomposition, leading to reduced crop production and decreased resilience of the soil ecosystem. Excessive application of large amounts of nitrogenous fertilizer can markedly increase root biomass and stimulate soil respiration rates. When other factors are at optimum, conservation tillage, use of cover crops (green manure), crop rotations, use of deep-rooted crops, application of manure, and water management can optimize soil respiration in addition to improving soil carbon.

## 2.2 CARBON ASSESSMENT FOR LAND MANAGEMENT PROJECTS

Carbon assessment entails the estimation of stocks and fluxes of carbon from different land-use systems in a given area over a period of time. The assessment covers four biomass pools—above ground, below ground, dead wood, and litter—and the soil organic carbon pool. The assessment can be undertaken either at national or project level.

Signatory parties of the UN Framework Convention on Climate Change (UNFCCC) are required to prepare national GHG inventories on a periodic basis and report them to the body. Annex I or industrialized countries are required to estimate and report emissions and removals annually, while non-Annex I or developing countries only need to report every 3 to 5 years. The key steps involved are as follows:

1. Estimating the area under a given land-use category in a given year and the area under each category subjected to land-use change
2. Estimating the stocks of carbon in each pool at the beginning and end of the period to calculate net emissions or removal (stock difference approach)
3. Estimating the gain in carbon stock for each pool due to accumulation or losses and calculating the difference between gains and losses as net emissions or removal (a gain-loss approach).

Typically, different countries adapt the Intergovernmental Panel on Climate Change (IPCC) guideline for national GHG by using sampling methods, measurement techniques, and models tailored to their particular circumstances.

Carbon assessment for land management projects can be either purposely for climate mitigation or for nonclimate mitigation. Mitigation projects involve estimation of verifiable changes in carbon stocks over a given period in the defined project area and require methods for estimating carbon stocks and changes for the baseline scenario (without the project) and the project. Carbon assessment for land management projects not principally designed for climate change mitigation is carried out for a number of reasons:

- The need to assess the carbon footprint of the operational work of funding agencies (see section 2.4).
- Changes in soil carbon over the lifetime of a project are an indicator of the success of SLM intervention.
- Changes in soil carbon stocks can help track changes in regulating, supporting, and provisioning ecosystem services.
- Interest in benefiting from carbon finance, though this is hardly a prime objective.

The key differences for carbon assessment for the two types of projects are summarized in table 2.6.

## 2.3 TECHNIQUES OF SOIL CARBON ASSESSMENT

Methods to assess above-ground biomass are more advanced than for soil carbon. The three major methods for above-ground carbon assessment include the following (Gibbs *et al.* 2007):

1. Biome averages involving the estimation of average forest carbon stocks for broad forest categories based on a variety of input data sources,
2. Forest inventory that relates tree diameters or volume to forest carbon stocks using allometric relationships, and
3. Use of optical, radar, or laser remote-sensing data integrated with allometry and ground measurements.

Soil carbon assessment in different parts of the world requires methods that are appropriate to the circumstances. Many different methods have been tested in a number of countries, but effort is required to ensure that the methods are comparable. Furthermore, for carbon projects, credible

**TABLE 2.6:** Comparison of Carbon Assessment for Carbon Mitigation and Non-Carbon-Mitigation Projects

| PROJECT PHASE | CARBON MITIGATION PROJECTS | NONCARBON-MITIGATION PROJECTS (SUSTAINABLE LAND MANAGEMENT INCLUDING FOREST, GRASSLAND, CROPLAND MANAGEMENT) |
|---|---|---|
| Conceptualization | Primary focus: carbon mitigation and carbon credits—global environmental benefit<br>Secondary focus: soil and biodiversity conservation | Primary focus: forest and biodiversity conservation, watershed protection, and livelihoods enhancement<br>Cobenefits: carbon mitigation is implicit though often not mentioned in proposal |
| Proposal development | Clear historical records of the past vegetation and soil carbon status are required<br>Project boundary[a] impacted by project activities needs clear definition<br>Estimation of baseline carbon stocks is crucial as well as rigorous plan for monitoring carbon stock changes | Historical vegetation status not so critical to project eligibility<br>Project boundary needed for estimating environmental and socioeconomic benefits restricted to project area<br>Baseline economic benefits, soil fertility, and biodiversity need to be clearly identified. Also, well-defined plan is required for monitoring of local environmental and socioeconomic impacts |
| Project review and appraisal | Baseline and project scenario carbon monitoring methods are critical | Monitoring plan for local environmental and socioeconomic benefits is important |
| Implementation | Activities aimed at maximizing carbon benefits, followed by other cobenefits | Activities are aimed at maximizing biomass production, crop yields, biodiversity conservation, and livelihood improvement |
| Monitoring and evaluation | Approved methodologies[b] are crucial. Additionality must be demonstrated<br>All the relevant carbon pools must be considered<br>Large transaction cost likely for carbon inventory and monitoring | Project-specific methodology is used<br>Additionality of local environmental and socioeconomic benefits are critical<br>Soil carbon critical for land development projects due to effects on agricultural sustainability<br>Moderate transaction cost for monitoring |

*Source:* Modified from Ravindranath and Ostwald (2008).

[a] Project boundary refers to the physical boundary of the land area delineated either with a geographical information system or a global positioning system and the greenhouse gas boundary that includes all fluxes of all gases affected by project activity.

[b] Carbon assessment methodologies are the blueprints to design, verify, and operate carbon projects. They document the protocol for quantifying carbon emissions and removals and include guidelines for identifying baseline scenario and assessing additionality in all carbon pools relevant to the project.

and cost-effective techniques of monitoring changes in soil carbon are required.

Soil carbon assessment methods can be broadly classified into direct and indirect methods depending on whether carbon content in soil samples is directly measured or inferred through a proxy variable (table 2.7). Most assessments typically involve a combination of these techniques. Each of the methods depicted in table 2.7 has unique constraints related to costs, inadequacies, geographic scope, and sampling design requirements and associated levels of bias or uncertainty. The most established type of direct soil carbon assessment entails collecting soil samples in the field and analyzing them in the laboratory by combustion techniques. Field sampling is technically challenging, but it can be addressed with appropriate design that accounts for soil spatial variation. The degree and nature of sampling depend on the carbon assessment objective, whether for national or regional accounting or for carbon offset project. Each context will require a differing degree of granularity and measurement set to assess uncertainty in the estimates. The direct method, though more precise and accurate, is quite laborious and very expensive. In Finland, Makipaa *et al*. (2008) observed that organic layer carbon measurements cost €520 per plot if 10 samples are analyzed. The precision obtained with such sampling corresponds to detection of soil carbon change greater than 860 g C $m^{-2}$. At the national level, two measurements for a minimum of 3,000 plots are needed to detect an expected change of 11 g C $m^{-2}$ $yr^{-1}$ in the organic layer of upland forest soils at 10-year sampling intervals. One round of measurement was estimated to cost about €4 million, corresponding to 8 percent of the value of the annual sequestration of about 3 million $tCO_2$ of Finland's upland forest soils. Strategies to reduce the cost of soil carbon monitoring include lengthening the sampling interval, increasing the efficiency of sampling through stratification, pooled sampling, use of *in situ* analytical methods, and the use of biogeochemical models.

Several *in situ* soil carbon analytical methods are being developed with the objective of offering increased accuracy, precision, and cost-effectiveness over conventional *ex situ* methods. A comparison of these techniques is provided in table 2.8. Most of the *in situ* techniques are still in their infancy. The exception is infrared spectroscopy currently being

**TABLE 2.7:** Direct and Indirect Methods of Soil Carbon Assessment

| DIRECT METHODS | INDIRECT METHODS |
|---|---|
| 1. Field sampling and laboratory measurements using dry combustion or wet combustion | Accounting techniques<br>• Stratified accounting with database<br>• Remote sensing to infer factors determining above-ground carbon inputs |
| 2. Eddy covariance; flux tower measurements | Biogeochemical/ecosystem simulation modeling to understand below-ground biological processes, for example,<br>• *RothC*<br>• Century<br>• DNDC<br>• PROCOMAP<br>• $CO_2$FIX |
| 3. Emerging technologies for *in situ* determination<br>• Laser-Induced Breakdown Spectroscopy<br>• Inelastic Neutron Scattering (still being assessed for improved reliability for measurement)<br>• Near-infrared and mid-infrared spectroscopy | |

*Source:* Modified from Post *et al.* (2001).

**TABLE 2.8:** Characteristics of Emerging *In Situ* Methods of Soil Carbon Analytical Techniques

| DIRECT METHOD | PROCESS | TYPE OF RADIATION MEASURED | PENETRATION DEPTH (CM) | SAMPLED VOLUME ($CM^3$) | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|---|---|---|
| Mid-infrared spectroscopy | Molecular/diffuse reflectance | Infrared | 1 | 10 | *In situ*–based measurement of carbon. Better than near infrared in distinguishing soil organic from inorganic carbon. | Costs are prohibitive on per project basis |
| Near-infrared spectroscopy | Molecular/diffuse reflectance | Near infrared | 0.2 | 1 | Rapid, low cost, *in situ* method | Less accurate than mid-infrared in predicting soil organic carbon |
| Laser-induced breakdown spectroscopy | Atomic/ plasma-induced emission | Visible | 0.1 | 0.1 | Very fast—provides total soil carbon measurements in seconds; capable of spectrally resolving several elements apart from carbon | Interference with iron compounds around 248 nm wavelength; currently, the technology cannot directly distinguish soil inorganic from organic carbon |
| Inelastic neutron scattering | Nuclear/neutron-induced nuclear reactions | Gamma rays | 30 | 100,000 | Large footprint of about 2 $m^2$ and sampling depth | The technology is still at its infancy and needs to be calibrated for wide variety of soil types, and scanner must be adapted to capture large areas |

*Source:* Adapted from Chatterjee and Lal (2009).

used to develop a spectral library for soils of the world.[3] The spectral library provides a valuable resource for rapid characterization of soil properties for soil quality monitoring and other agricultural applications.

Indirect estimation of soil organic carbon changes over large areas using simulation models is increasingly important to fill knowledge gaps about the biogeochemical processes of soil carbon sequestration. Simulation models describe changes in soil organic carbon under varying climate, soil, and management conditions. Though the models could have limited accuracy, they are particularly useful in the context of developing countries where land resources data are scarce. Models provide a cost-effective means of estimating GHG emissions in space and time under a wide range of biophysical and agricultural management conditions, and they are particularly useful for up-scaling site-specific information to the regional level. Table 2.9 compares the features of some of the biogeochemical models commonly used for soil carbon assessment.

Monitoring and verifying soil carbon sequestration at the project or regional scale require five components (Post *et al.* 1999). These include the selection of landscape units suitable for monitoring soil carbon changes, development of measurement protocols, application of remote sensing to estimate soil organic carbon controlling parameters, spatially explicit biogeochemical modeling, and scaling-up the results to the entire project area (table 2.9).

Monitoring the trends in soil carbon over a large geographical area through repeated sampling is mainly restricted to developed and few developing countries. Examples of national carbon accounting system and tools are presented in table 2.11.

Progress is being made in developing and testing cost-effective soil carbon monitoring methods. The Global Environment Facility (GEF) in collaboration with other partners is currently implementing the Carbon Benefits Project (CBP) to develop standardized, cost-effective methods of quantifying the carbon benefits of sustainable land management projects.[4]

**TABLE 2.9:** Comparative Features of Some Carbon Estimation Models

| MODEL | FEATURES | KEY INPUTS | KEY OUTPUTS |
|---|---|---|---|
| CENTURY | Simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur for different ecosystems | Monthly mean maximum and minimum air temperature and total precipitation; plant N, P, and S content; soil texture; atmospheric and soil nitrogen inputs; and initial soil carbon, nitrogen, phosphorus, and sulfur levels | Total carbon, soil water dynamics, commercial crop yield, total dry matter, and carbon in plant residue |
| $CO_2$FIX | Simulates carbon dynamics of single/multiple species, forests, and agroforestry systems | Simulation length, maximum biomass in stand, carbon content, wood density, initial carbon, yield tables, precipitation, temperature, and length of growing period | Carbon stocks and fluxes, total biomass and soil carbon, above- and below-ground biomass, deadwood, and litter and soil organic carbon production |
| *RothC* | Estimation of turnover of organic carbon in topsoil | Clay, monthly rainfall, monthly open pan evaporation, average monthly mean air temperature, and an estimate of the organic input | Total organic carbon content and carbon content in microbial biomass |
| PROCOMAP | Equilibrium model for estimating carbon stocks | Activity data, planting rate, vegetation carbon stocks, rotation period, and mean annual increment in biomass and soil | Biomass and soil carbon stock, incremental carbon stocks, and cost-effectiveness indicators |
| DNDC | DeNitrification-DeComposition is used for predicting crop growth, soil temperature and moisture regimes, carbon sequestration, nitrogen leaching, and emissions of nitrous oxide ($N_2O$), nitric oxide (NO), dinitrogen ($N_2$), ammonia ($NH_3$), methane ($CH_4$), and carbon dioxide ($CO_2$) | Plant growth data, soil clay, bulk density, pH, air temperature, rainfall, atmospheric nitrogen decomposition rate, crop rotation timing and type, inorganic fertilizer timing, amount and type, irrigation timing and amount, residue incorporation timing and amount, and tillage timing and type | Total carbon, total nitrogen, soil water dynamics, biomass carbon, carbon dioxide, crop yield, carbon input into soil, fluxes of gases including $N_2O$, nitric oxide NO, $NH_3$, and methane $CH_4$ |

*Source:* This study.

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[3] World Agroforestry Centre, ISRIC-World Soil Information: A globally distributed soil spectral library: visible near-infrared diffuse reflectance spectra, http://www.africasoils.net/sites/default/files/ICRAF-ISRICSoilVNIRSpectralLibrary.pdf.

[4] http://www.unep.org/climatechange/carbon-benefits/

**TABLE 2.10:** Components of Soil Carbon Monitoring at the Regional Scale

| COMPONENTS | DESCRIPTION |
|---|---|
| Selection of landscape units | The selection will depend on responsiveness of the area to land management practices as determined by climate, soil properties, management history, and availability of historical data. Participation of local agronomists, farmer organizations, and other stakeholders can be of help in selecting pilot areas and the extent to which the results can be extrapolated over the region. |
| Development of protocol | Changes in soil carbon can generally be estimated as changes in stocks (from direct measurement) or fluxes (using eddy covariance methods) (see table 2.7). Protocols for temporally repeated measurements at fixed locations will generally include stratification and selection of sampling sites, sampling depth and volume, measurement of bulk density, laboratory analyses, other ancillary field measurements, and estimation of the marginal cost of carbon sequestration. |
| Application of remote sensing | Remote sensing can provide information on net primary productivity, leaf area index, tillage practices, crop yields, and location and amount of crop residue for input into models. Recently, cellulose absorption index derived from remote imaging spectroscopy has been used to infer tillage intensity and residue quantity (Serbin *et al.* 2009) |
| Biogeochemical modeling | Models are used to determine soil carbon changes over large areas because satellites cannot sense below-ground biological processes. Models are useful for understanding soil properties–land management interactions and for predicting soil carbon sequestration. They can simulate full ecosystem–level carbon balance, multiple land uses, or several land management practices |
| Up-scaling | Scaling-up to large areas requires integration from a variety of sources including field measurements, existing database, models, geographical information system, and remote sensing. Multitemporal moderate resolution remote sensing such as Landsat Thematic Mapper and Moderate Resolution Imaging Spectroradiometer can provide information such as land-use and land cover change, crop rotations, and soil moisture that can markedly improve up-scaling of soil carbon assessment. |

*Source:* Synthesized from Post *et al.* 1999.

**TABLE 2.11:** Carbon Accounting Systems and Tools

| NAME | DESCRIPTION AND INTERNET LOCATION |
|---|---|
| Australia's National Carbon Accounting System (NCAS) | NCAS estimates emissions through a system that combines satellite images to monitor land use and land-use change across Australia that are updated annually; monthly maps of climate information, such as rainfall, temperature, and humidity; maps of soil type and soil carbon; databases containing information on plant species, land management, and changes in land management over time; and ecosystem modeling—the Full Carbon Accounting Model.<br>http://www.climatechange.gov.au/government/initiatives/national-carbon-accounting.aspx |
| National Forest Carbon Monitoring, Accounting and Reporting System, Canada (NFCMARS) | NFCMARS is designed to estimate past changes in forest carbon stocks and to predict, based on scenarios of future disturbance rates and management actions, changes in carbon stocks in the next two to three decades.<br>http://carbon.cfs.nrcan.gc.ca/index_e.html |
| Agriculture and Land Use National Greenhouse Gas Inventory Software (Colorado State University, United States) | The program supports countries' efforts to understand current emission trends and the influence of land-use and management alternatives on future emissions. It can be used to estimate emissions and removals associated with biomass C stocks, soil C stocks, soil nitrous oxide emissions, rice methane emissions, enteric methane emissions, manure methane, and nitrous oxide emissions, as well as non-$CO_2$ GHG emissions from biomass burning. The software accommodates Tier 1 and 2 methods as defined by the Intercontinental Panel on Climate Change. It allows compilers to integrate global information system spatial data along with national statistics on agriculture and forestry and is designed to produce a consistent and complete representation of land use for inventory assessment. http://www.nrel.colostate.edu/projects/ghgtool/software.php |
| National Carbon Accounting System of Indonesia | Provides monitoring capabilities for greenhouse gas (GHG) emissions/sinks to establish a credible reference emission level. The three major activities linked are the remote sensing program, the modeling and measurement program for GHG accounting and reporting, and the data program.<br>http://www.dpi.inpe.br/geoforest/pdf/group2/04%20-%20National%20carbon%20accounting%20system%20of%20Indonesia.pdf |
| New Zealand's Carbon Accounting System | The National Carbon Accounting System for New Zealand's indigenous forest, shrub land, and soils was developed for the Ministry of the Environment by Landcare Research and Scion. It monitors forest definition, land-use change, forest inventory and modeling, and reporting methods. http://www.joanneum.at/carboinvent/workshop/1000_Peter_Stephens_ver_final.pdf |
| Forest Vegetation Simulator, United States | The Forest Vegetation Simulator (FVS) is a family of forest growth simulation models. The basic FVS model structure has been calibrated to unique geographic areas to produce individual FVS variants. Since its initial development in 1973, it has become a system of highly integrated analytical tools. http://www.fs.fed.us/fmsc/fvs/description/index.shtml |

*Source:* This study.

The new suite of tools estimate and model carbon and other GHG flows under present and alternative management and measures. They also monitor changes in carbon under specified land use and management. The CBP comprises a national GHG inventory tool; the Agriculture and Land Use Tool (table 2.11), Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool (http://www.cometvr.colostate.edu/), and the GEF Soil Organic Carbon System that approximates national- and subnational-scale soil carbon stock variations in developing countries using *RothC* and Century models (table 2.9).

## 2.4 CARBON ASSESSMENT IN THE WORLD BANK'S SUSTAINABLE LAND MANAGEMENT PORTFOLIO

### Carbon Assessment Using the Ex Ante Appraisal Carbon-Balance Tool

The World Bank is increasingly looking to assess the carbon footprint of its operational work across sectors. Emphasis is placed on cost-effective approaches that do not add excessively to the burden of project management. The Ex-Ante Appraisal Carbon-Balance Tool (EX-ACT; http://www.fao.org/tc/exact/en/) has been developed with this objective in mind.

EX-ACT can provide ex ante assessments of the impact of agriculture and related forestry, fisheries, livestock, and water development projects on GHG emissions and carbon sequestration, thereby indicating the overall effects on the carbon balance. EX-ACT was developed following the IPCC guideline for national GHG inventory (IPCC 2006), supplemented by other existing methodologies and reviews of default coefficients. It is easy to use in the context of program formulation; it is cost-effective and requires a minimum amount of data. It also has resources (linked tables and maps) that can assist in gathering the information necessary to run the model. While EX-ACT primarily works at the project level, it can easily be up-scaled at the program/sector level.

Carbon assessment in EX-ACT is implemented in the following three steps:

- General description of the project (geographic area, climate and soil characteristics, and duration of the project)
- Identification of changes in land use and technologies foreseen by project components using specific "modules" (deforestation, forest degradation, afforestation/reforestation, annual/perennial crops, rice cultivation, grasslands, livestock, inputs, organic soils, and energy)
- Computation of carbon balance with or without the project using IPCC default values and, when available, ad hoc coefficients.

A detailed analysis of lessons learned in testing EX-ACT in World Bank agriculture projects can be found in World Bank (2012).

### Sustainable Agricultural Land Management Methodology

The BioCarbon Fund of the World Bank has recently developed a carbon accounting methodology to encourage adoption of sustainable land management practices by small-scale farmers in developing countries (http://www.v-c-s.org/sites/v-c-s.org/files/VM0017%20SALM%20Methodolgy%20v1.0.pdf). The methodology, referred to as Sustainable Agricultural Land Management (SALM), provides protocol for quantifying carbon emissions and removals and includes guidelines for identifying baseline scenario and assessing additionality in all carbon pools relevant to sustainable land management projects. SALM is applicable to projects that introduce sustainable land management practices into croplands subject to conditions such that soil organic carbon would remain constant or decrease with time in the absence of the project. The methodology currently being applied in the first African soil carbon project allows small-holder farmers in Kenya to access the carbon market and receive additional carbon revenue streams through the adoption of productivity-enhancing practices and technologies.

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# Chapter 3: META-ANALYSES OF SOIL CARBON SEQUESTRATION

## 3.1 INTRODUCTION

A range of practices has been suggested as important to soil carbon sequestration and thus of potential relevance to increasing crop yield, increasing the resilience of agroecosystems, and mitigating GHG emissions (table 3.1). Mitigation of GHG in agriculture can involve several practices such as avoiding the conversion of native forests and grasslands to croplands; enhancing removal of carbon from the atmosphere through a range of soil and water management practices including crop diversification; restoration of barren, abandoned, or seriously degraded agricultural lands; and livestock and manure management. The impacts of changes in agricultural practices on soil carbon stocks such as changes to crop rotation or reduced grazing are usually more subtle than those brought about by more dramatic changes in land use such as conversion of cropland to forest or grassland to tree crops.

This chapter documents the evidence from the published literature on the impacts of agricultural land management practices and agricultural land-use changes on soil carbon sequestration in Africa, Asia, and Latin America. The main emphasis is on obtaining better estimates of soil carbon sequestration

**TABLE 3.1:** Practices That Sequester Carbon in Forest, Grassland, and Cropland

| FOREST | GRASSLAND | CROPLAND |
|---|---|---|
| Protection of existing forests—Avoided deforestation preserves existing soil C stocks and prevents emissions associated with biomass burning and soil exposure by land clearing | Improved grassland management—Optimize stocking rates to reduce land degradation, depletion of soil organic carbon, and methane emissions through enteric fermentation | No or reduced tillage—Reduces the accelerated decomposition of organic matter associated with intensive (conventional or traditional) tillage |
| Reforestation—Increasing tree density in degraded forests increases carbon accumulation | Introduction of improved pasture species and legumes to increase above- and below-ground biomass production and soil organic carbon accumulation | Mulching/residue management—Improves soil moisture, prevents soil erosion, and increases soil organic matter when incorporated into the soil; crop residues also prevent loss of carbon from the soil system |
| Afforestation—Establishment of new forests on nonforest land (cropland, grassland, or degraded lands) increases carbon stock through the increase in above-ground biomass as well as greater organic materials input for soil decomposition | Application of inorganic fertilizers and manure to stimulate biomass production—Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide ($N_2O$) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers | Application of inorganic fertilizers and manure to stimulate biomass production—Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide ($N_2O$) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers |
| | Water management to increase productivity, but this has to be put in the perspective of emissions associated with the process of irrigation | Use of cover crops/green manure increases the biomass returned to the soil and thus increases soil carbon stock |
| | Introduction of earthworms to improve aeration and aid organic matter decomposition in the soil profile | Use of improved crop varieties—Improved crop varieties help to sequester carbon in the soil through increased above- and below-ground biomass production |
| | Establishment of pasture on degraded land reintroduces large amounts of organic matter into the soil | Agroforestry/tree-crop farming—Introduction of fruit trees, orchards, and woodlots into croplands helps to store more carbon, optimize water use, diversify production, and increase income |
| | | Introduction of improved crop varieties |
| | | Application of biochar and other soil amendments |

*Source:* This study.

rates. This is one important element in making comprehensive assessments of the impact of soil quality on agricultural sustainability and greenhouse mitigation potentials.

## 3.2 METHODS

### Searches and Data Sources

Searches were carried out using online database and search tools, including ProQuest, Scopus, Sciencedirect, SpringerLink, Wiley Science Library, and Google Scholar with an emphasis on key terms such as soil organic matter, organic matter, soil organic carbon, soil carbon, carbon sequestration, soil sequestration, and soil properties, in combination with geographical descriptors (e.g., countries and continents) and terms for particular agricultural practices.

### Inclusion-Exclusion Criteria

For soil fertility and surface management effects that are commonly studied in agricultural science, only studies of at least 3 years duration were included. A major effort was made to collect data from as many long-term studies as possible. Almost all studies adopted formal experimental designs, setting up control and treatments. The variations applied in the treatments accounted for the different levels of carbon added to the soil. In a few cases where paired designs were employed, logical contrasts were made with appropriate controls using final values of stocks under each treatment.

Experimental study designs are rare for land-use change effects. Most adopted nonexperimental designs such as chronosequence where adjacent plots of different ages were compared, paired studies where adjacent plots of different land uses and similar ages were compared, or repeated samples where same plot was measured over time. Only studies of at least 4 years duration were included, and where repeated measures were made, sequestration rates for the longest time interval were taken. A major reason for excluding papers with data on different land uses was difficulty in assuming particular sites could be taken as a reasonable control.

### Effect Sizes

The effect of a land management practice was estimated by comparing the final level of soil carbon stock in one treatment with that practice and an appropriate control. Thus, all soil carbon sequestration rates are estimates of effect size—the difference with respect to a control—and thus represent the marginal benefit of adopting that practice. Effect sizes were estimated for all logical contrasts with sufficient information provided in a paper.

### Analysis

Most studies reported concentrations of carbon in soil samples ($C_c$ in g kg$^{-1}$). These were converted to volumes and then areas to calculate stocks ($C_s$ in kg$^{-1}$ ha$^{-1}$) and sequestration rates (kg ha$^{-1}$ yr$^{-1}$) using bulk density (*BD*, in g cm$^{-3}$) and sample soil depth (*D*, in cm):

$$C_s = BD \times C_c \times D \times 10{,}000$$

In a few studies, value was given in terms of percent soil organic matter. In these cases, concentrations of $C_c$ (g kg$^{-1}$) were calculated as

$$C_c = 0.58 \times OM\% \times 10$$

In some cases, only a single value, either initial or average across treatments, was provided for bulk density. In these cases, that value was assumed to apply to all treatments. If no bulk density information was provided in a paper (or other reports about the same study cited by that paper), then bulk density was estimated using known pedotransfer functions (that is, simple regression equations) developed for that region or extracted from the International Soil Reference Information Center–derived soil properties database (www.isric.org).

Effect sizes and importance of contextual variables (e.g., temperature, precipitation, duration, and soil type) were summarized by means and 95 percent confidence intervals for the mean. Associations of the context variables with carbon sequestration were assessed by grouping observations into a few classes so that nonlinear patterns could be clearly identified. Geographical distribution of datasets is shown in figure 3.1, while the characteristics of the estimates with respect to duration of study, soil sampling depth, and experimental design are shown in Appendix 3.1.

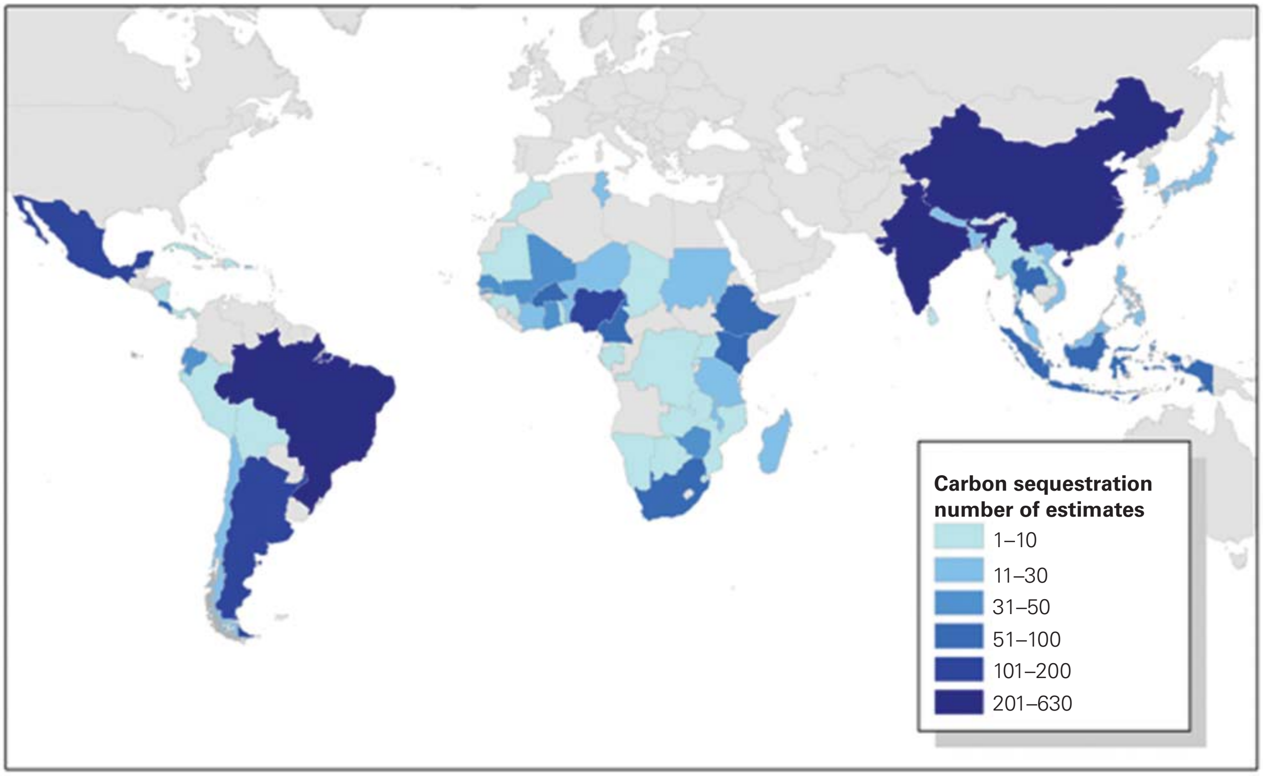
## 3.3 RESULTS

### Contextual Factors and Soil Carbon Sequestration

*Climate*

Climate significantly influences large-scale patterns of soil carbon sequestration. In this study, higher sequestration rates were observed in the wettest locations (figure 3.2). There was also a trend to lower sequestration rates in the coolest and warmest conditions (figure 3.3). Sites in warmer and middle temperature regions tended to accumulate soil carbon more rapidly than those in colder regions, whereas semi-humid areas had higher average rates than their semi-arid counterparts. Potter *et al.* (2007) explored interactions with residue management practices in maize fields at six

**FIGURE 3.1:** Geographical Distribution of Carbon Sequestration Estimates



*Source:* This study.

sites across a wide range of annual temperature regimes in Mexico and discovered that as temperature increased, more crop residues needed to be retained to increase levels of soil organic carbon. An increase in soil temperature exacerbated the rate of mineralization, leading to a decrease in the soil organic carbon pool (SOC). However, decomposition by-products at higher temperatures may be more recalcitrant than those at lower temperatures.

### *Soils*

Soil type, especially those with a higher clay content, leads to higher carbon sequestration rates. However, obtaining comparable data is difficult as not all studies provide sufficient information on soil properties, and those that do use different soil classification schemes at different levels of detail. As a first-level analysis, the reported soil types were reclassified into major soil orders of the U.S. Department of Agriculture classification system (figure 3.4). Carbon sequestration rates were highest and also highly variable on inceptisols in Africa and Latin America. Inceptisols are relatively young soils characterized by having only the weakest appearance of horizons, or layers, produced by soil-forming factors. Inceptisol soil profiles give some indication of humus, clay minerals, or metal oxides accumulating in their layers. In Asia, the highest sequestration rates and variability were observed on oxisols, formed principally in humid tropical zones under rain forest, scrub, or savanna vegetation on flat to gently sloping uplands. Oxisols are typically found on old landscapes that have been subject to shifting cultivation for several years.

### *Duration*

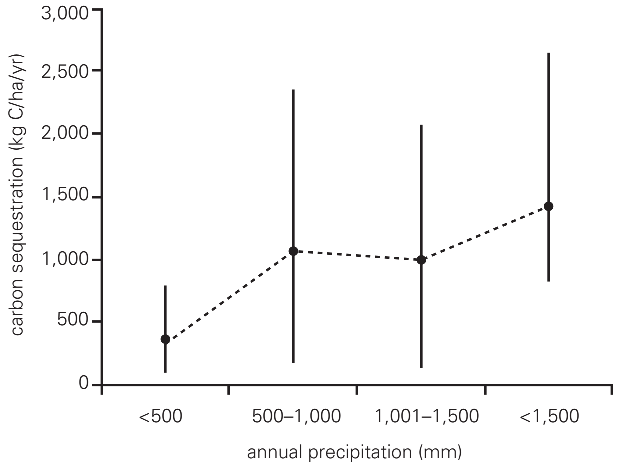
Longer term studies on average have resulted in lower sequestration rates, as would be expected from saturation (figure 3.5). Most of the potential soil carbon sequestration takes place within the first 20 to 30 years. The pattern of change in sequestration rates is nonlinear and differs between major groups of practices, with the highest rates at intermediate times and low or even negative rates in the short term.

## Nutrient Management

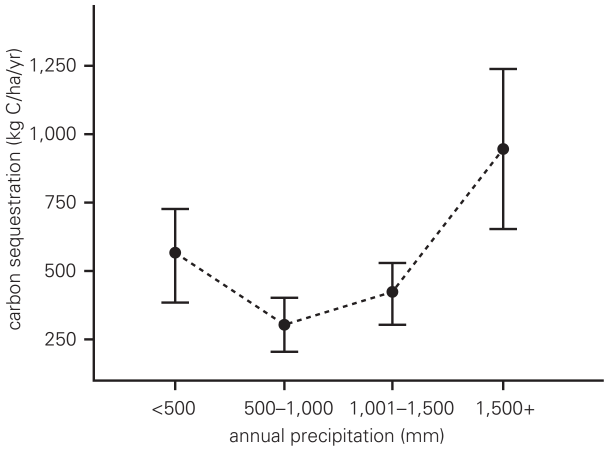
Fertilizer use sequesters carbon by stimulating biomass production. Judicious fertilizer application also counters nutrient depletion, reduces deforestation and expansion of cultivation

**FIGURE 3.2:** Soil Carbon Sequestration and Precipitation

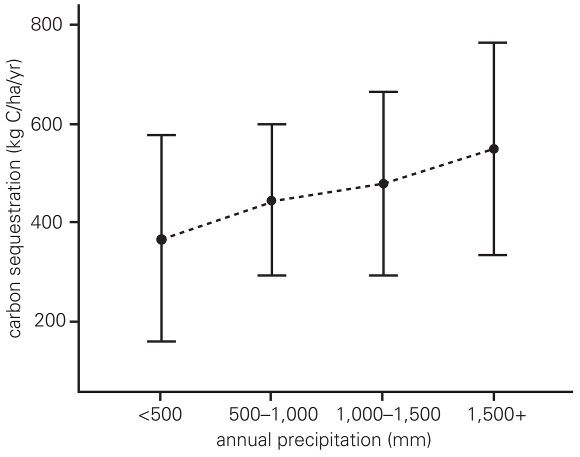
**Africa**



**Asia**



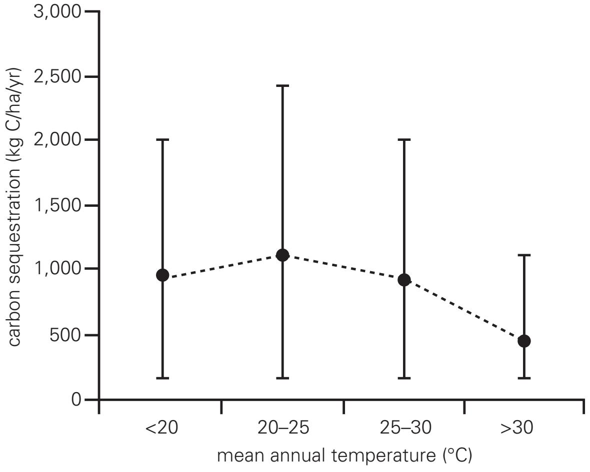
**Latin America**



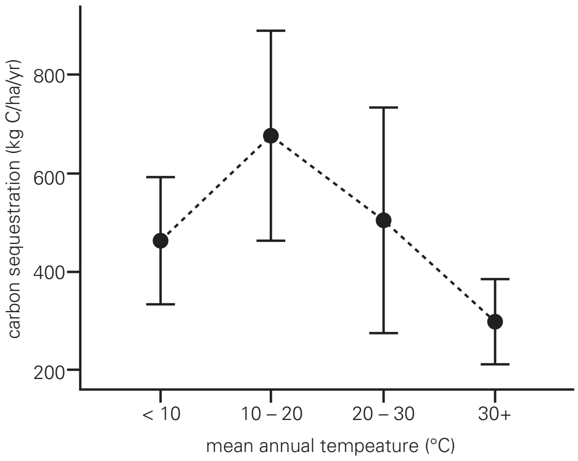
*Source:* This study.

**FIGURE 3.3:** Soil Carbon Sequestration and Temperature

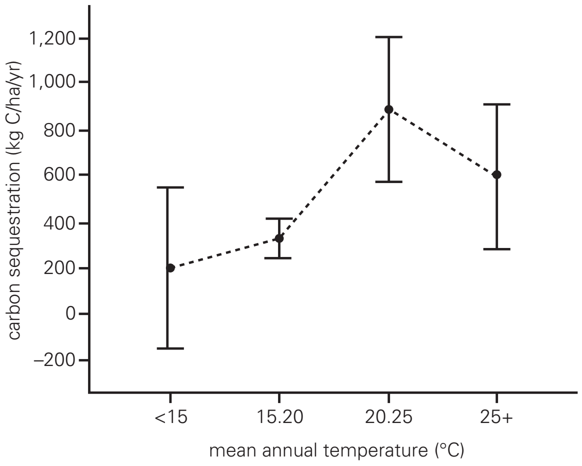
**Africa**



**Asia**

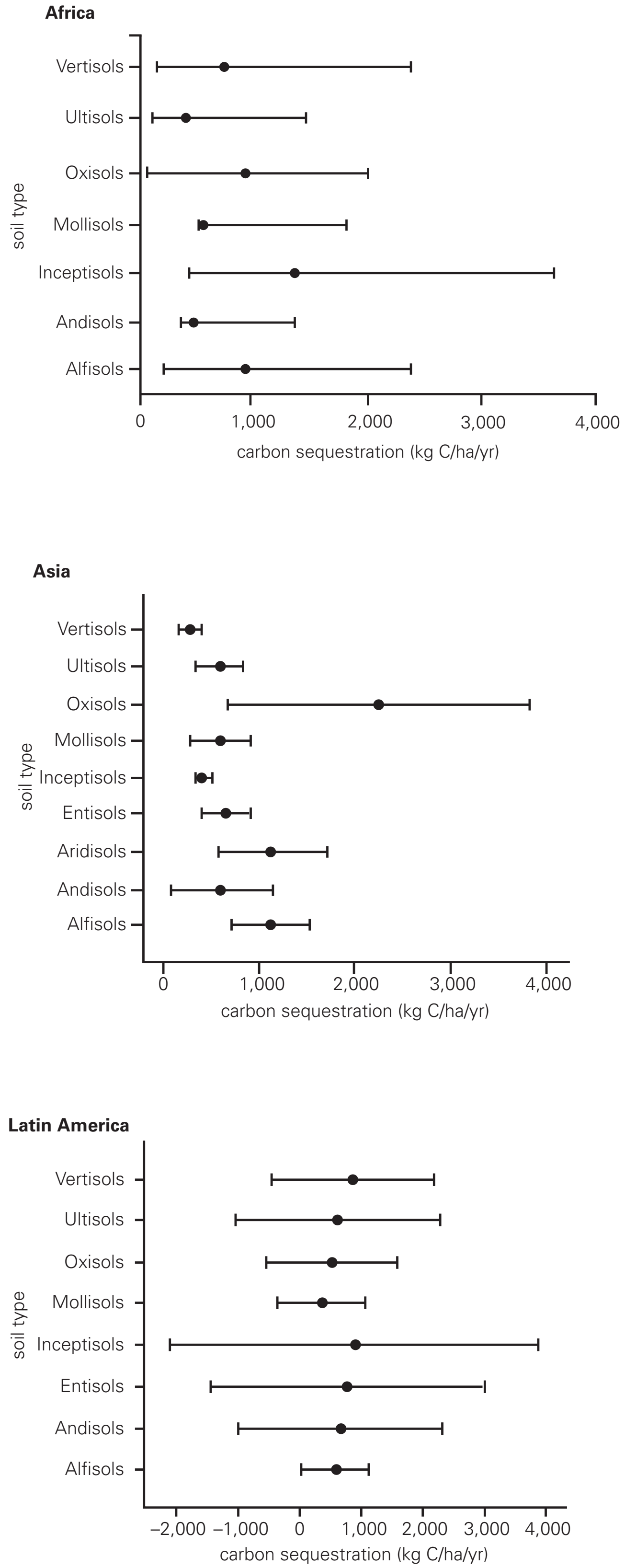


**Latin America**



*Source:* This study.

**FIGURE 3.4:** Soil Carbon Sequestration and Soil Order



*Source:* This study.

to marginal areas, and increases crop yields. Strategies to promote nutrient use efficiency include the following:

- Adjusting application rates based on assessment of crop needs
- Minimizing losses by synchronizing the application of nutrients with plant uptake
- Correcting placement to make the nutrients more accessible to crop roots (microfertilization and microdosing)
- Using controlled-release forms of fertilizer that delay its availability for plant uptake and use after application
- Using nitrification inhibitors that hold-up microbial processes leading to nitrous oxide formation

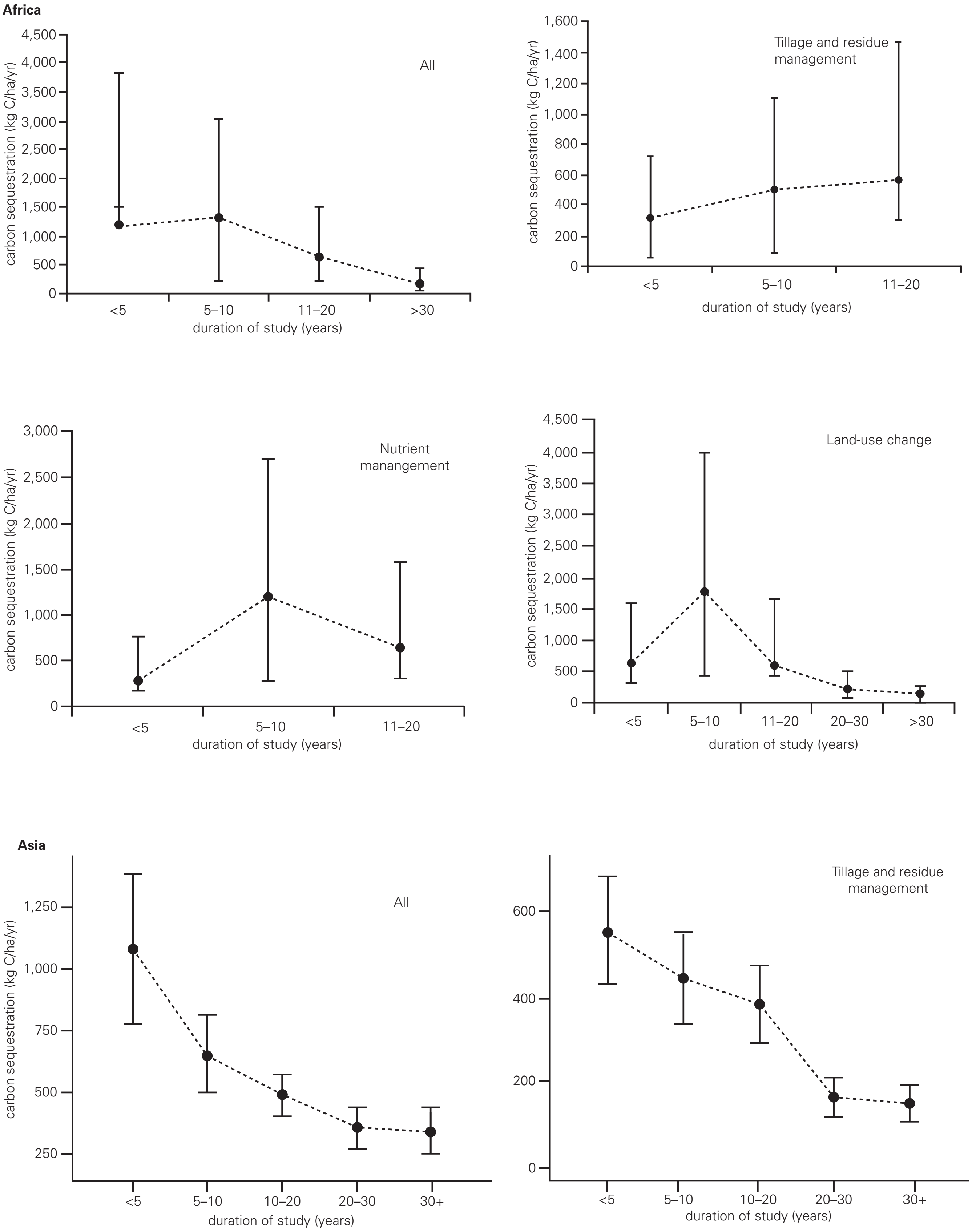
The average effect size of applying fertilizer was an additional 124 kg C ha$^{-1}$ yr$^{-1}$ sequestered for Latin America, 222 kg C ha$^{-1}$ yr$^{-1}$ for Asia, and 264 kg C ha$^{-1}$ yr$^{-1}$ for Africa (table 3.2). The majority of studies have designs focused on the influence of different levels of nitrogen and, in some cases, the combination of fertilizer with locally available manure sources. Aggregating across locations and cropping systems there was no significant association between level of N applied across annual cropping cycles and carbon sequestration rates (figure 3.6).

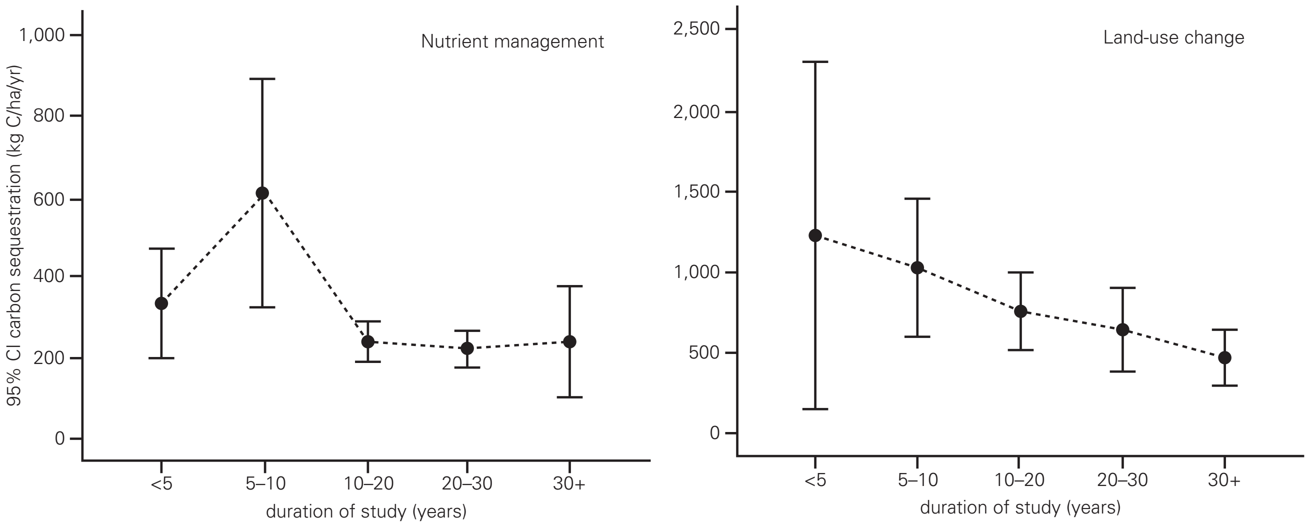
Across the full dataset, studied average sequestration rates with NPK - Nitrogen, Phosphorus and Potassium compound fertilizers N = Nitrogen, P = Phosphorus, K = Potassium were significantly higher than other combinations (Figure 3.7). Within individual experiments, some studies show that integrated management of N, P, and K fertilizers is important to maintaining or increasing soil carbon and nitrogen and thus soil fertility.

Alvarez's (2005a) analysis of a global dataset indicated that for every additional tonne of nitrogen fertilizer applied, two more tonnes of soil organic carbon were stored in fertilized than unfertilized plots. Soil organic carbon levels clearly increased under nitrogen fertilization only when crop residues were returned to the soil. Another meta-analysis at the global level concluded that addition of nitrogen fertilizer resulted, on average, in a 3.5 percent increase in soil carbon in agricultural ecosystems (Lu *et al.* 2011).

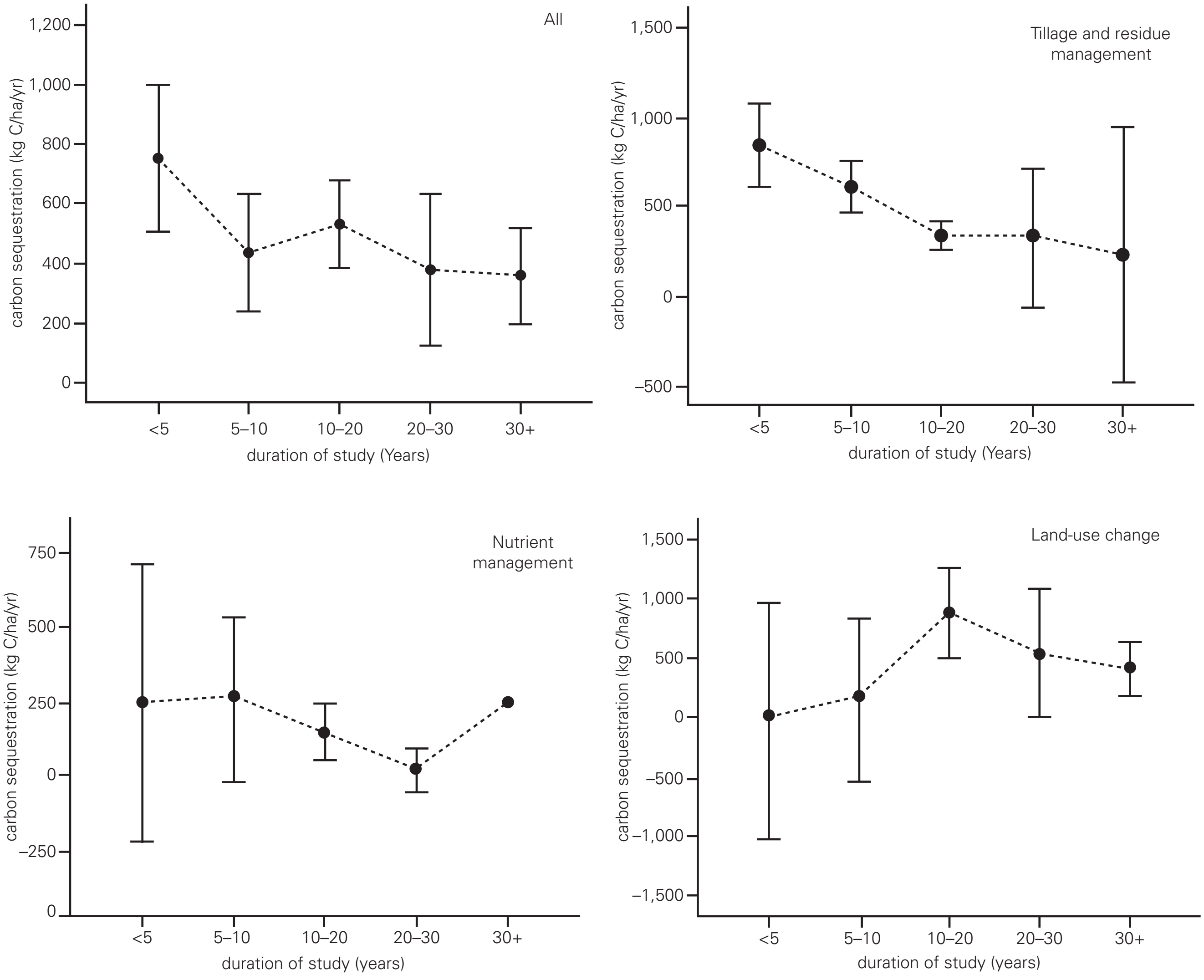
Biofertilizers are an essential component of organic farming. They contain living microorganisms that colonize the rhizosphere and promote plant growth by increasing the supply of nutrients through nitrogen fixation or enhancing the availability of primary nutrients to the host plant by solubilizing phosphorus and other nutrients. The microorganisms in

**FIGURE 3.5:** Soil Carbon Sequestration and Time



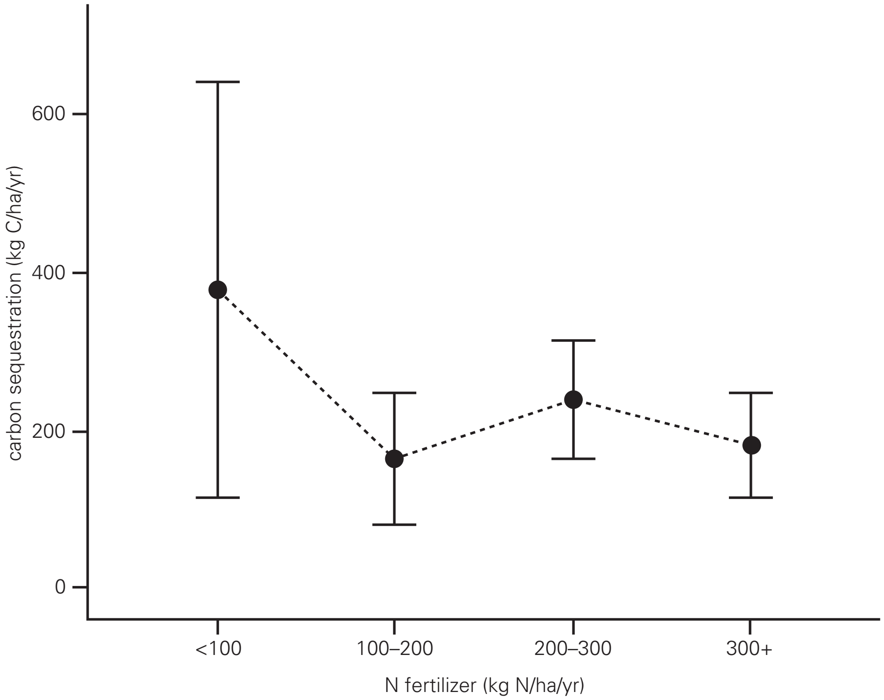


**Latin America**



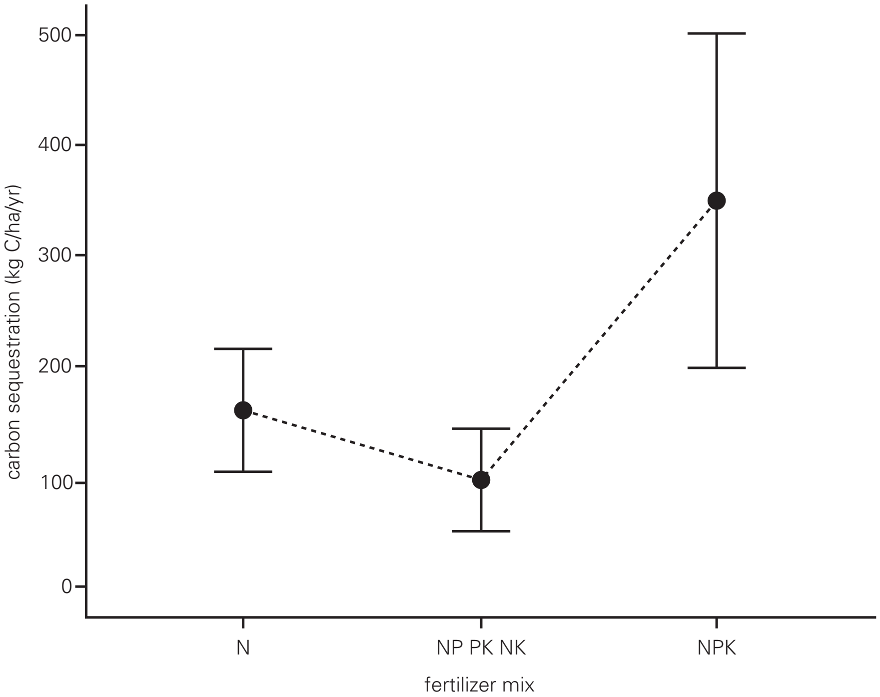
*Source:* This study.

**FIGURE 3.6:** Soil Carbon Sequestration and Application Levels of Nitrogen Fertilizer (Means and 95 Percent Confidence Intervals, *n* = 285)



*Source:* This study.
*Note:* N = Nitrogen.

**FIGURE 3.7:** Soil Carbon Sequestration and Fertilizer Combinations (Means and 95 Percent Confidence Intervals, *n* = 285)



*Source:* This study.
*Note:* N = Nitrogen only; NP = Nitrogen and Phosphorus only; PK = Phosphorus and Potassium only; NK = Nitrogen and Potassium only; NPK = combination of Nitrogen, Phosphorus and Potassium.

**TABLE 3.2:** Nutrient Management and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Chemical fertilizer | 264 | 169 | 359 | 30 |
| Manure | 325 | 224 | 427 | 30 |
| **Asia** | | | | |
| Chemical fertilizer | 222 | 157 | 288 | 297 |
| Manure | 465 | 374 | 556 | 146 |
| Biofertilizer | 1,459 | –42 | 2,960 | 3 |
| **Latin America** | | | | |
| Chemical fertilizer | 124 | –15 | 262 | 74 |
| Manure | 455 | 23 | 887 | 25 |

*Source:* This study.

biofertilizers restore the soil's natural nutrient cycle and help in building soil organic matter. Biofertilizers are more environmentally friendly and cost-effective relative to chemical fertilizers. Three studies reviewed indicate that biofertilizers sequestered about 1.4 t C $ha^{-1}$ $yr^{-1}$.

Manure application to agricultural soils can reduce nitrous oxide emissions by displacing N fertilizer use. Methane emissions can also be minimized by displacing anaerobic storage options with aerobic decomposition. These benefits have already been recognized in efforts to divert organic waste from landfills. Pattey, Trzcinski, and Desjardins (2005) found that compared to untreated manure storage, composting reduced total GHG emissions ($CH_4$ and $N_2O$) by 31 to 78 percent, depending on carbon-to-nitrogen ratio, moisture content, and aeration status.

The impact of composting on emissions post-land application is of further interest. Fronning, Thelen, and Min (2008) examined GHG fluxes following land application of solid beef manure and composted dairy manure over a 3-year period. Net $CH_4$ flux was minimal (less than 0.01 t $CO_2$e $ha^{-1}$ $yr^{-1}$), while untreated manure application generated higher $N_2O$ emissions than did compost (0.9 versus 0.7 t $CO_2$e $ha^{-1}$ $yr^{-1}$). However, these land emission impacts were small when compared to soil C sequestration rates, which were 1.8 times greater for compost than for manure, suggesting that the organic matter stabilization during composting reduces post-application respiration losses.

Manure sequestered more carbon than fertilizer, yielding 61 kg C $ha^{-1}$ $yr^{-1}$ more in Africa, 243 C $ha^{-1}$ $yr^{-1}$ more in Asia, and 331 kg C $ha^{-1}$ $yr^{-1}$ more in Latin America (table 3.2). Yields also increased with manure application and accumulation of soil carbon but with patterns that depend on crop. In China, yields of maize and maize-wheat systems increased over the longer term, while in rice-based systems, the gains happened in the first few years and were not followed by further yield improvements (Zhang *et al.* 2009).

One major constraint is the availability of manure and labor costs associated with collecting and processing it. Studies in Nepal (Acharya *et al.* 2007) and Thailand (Matsumoto, Paisancharoen, and Hakamata 2008) have pointed to trends of declining livestock numbers and speculated on impacts of this on manure application practices. The impact of manure on soil carbon sequestration is best realized in farming systems that integrate crops and livestock. Crop-livestock integration can occur in space, time, management, or ownership domains. The agronomic and economic justification for the integration is based on the exchange of four main types of resources: crop residues, manure, animal power, and financial income (Sumberg 2003). The spatial domain integration is based on the idea that crops and livestock activities can be colocated with the level of integration increasing as the scale becomes smaller. Close spatial integration is required for crop-livestock interactions involving crop residues, manure, and animal power (table 3.3). At large distances (scale), economic movement of crop residues, manure, and livestock is markedly curtailed, hindering interaction.

Integration in the temporal domain connotes that crop and livestock production can take place simultaneously (in parallel) or can be temporally segregated (in sequence). Temporal integration can only occur after some form of spatial integration has taken place, and the latter is important given the

**TABLE 3.3:** Relative Importance of the Four Domains of Integration on Crop-Livestock Interaction

| | SPACE | TIME | OWNERSHIP | MANAGEMENT |
|---|---|---|---|---|
| Crop residue | *** | ** | * | ** |
| Manure | *** | * | * | ** |
| Animal power | *** | *** | * | * |
| Financial income | * | ** | *** | * |

*Source:* Adapted from Sumberg (2003).
*Note:* * = little importance; ** = some importance, *** = much importance.

seasonality of feed and water for livestock. Integration in the ownership domain underscores the fact that a given crop-livestock combination can be owned by the same or a different entity, thereby promoting control and secure access to resources. However, the formal and informal links between crop and livestock producers for accessing manure, crop residue, or power implies that though desired, integration in the ownership domain is not required for beneficial crop-livestock interaction.

Last, integration in the management domain implies that management of crop and livestock production may or may not be in the hands of the same entity and that management may not necessarily coincide with ownership of both crops and livestock. While ownership may increase the efficiency of the beneficial effects of interaction, integration in the management domain is not a prerequisite for successful beneficial crop-livestock interaction (Sumberg 2003).

### Crop Residue Management and Tillage

Crop residues are an important renewable resource for agro-ecosystems. Crop residue management influences soil resilience, agronomic productivity, and GHG emissions by

- aiding nutrient cycling;
- intercepting raindrops, thereby allowing water to gently percolate into the soil;
- lowering soil evaporation;
- increasing aggregation of soil particles; and
- reducing run-off and erosion.

The quality and quantity of residues markedly influence the amount of carbon sequestered (figure 3.8). The quantity of residue produced is a function of the cropland area and agronomic practices, including tillage method. Cereals are two to three times better than legumes at sequestering carbon. Cereals also have higher concentrations of lignin that are resistant to decomposition. High-quality residues of perennial legumes are generally the most effective in supplying nitrogen in the short to medium term, while low-quality residues tend to immobilize nitrogen. As large carbon losses occur under very wet conditions, the best results are obtained when residues are applied shortly before the beginning of the rainy season.

One of the main barriers to the use of crop residues and mulch for soil fertility management is the numerous competing uses for feed, fodder, thatch, and biofuel. Crop-livestock integration can minimize the trade-off in the use of residues for feed (see the section of this report on nutrient management on page 21). Controlled grazing and the establishment of plots of permanent forages for direct grazing can also reduce conflicts between soil organic matter accumulation and grazing needs. Zero grazing involving the confinement of livestock in a stall and developing a cut-and-carry fodder system can make for more residue retention on the field, but it requires more labor. The establishment of bioenergy plants to meet the demand for biofuel may also help. In general, desirable results will be achieved if integrated food-feed-energy systems are tailored to specific local conditions. Examples include intercropping maize and pigeon pea, and using cookstoves for rural dwellers in Malawi and using agroforestry systems for food, income generation, and bioethanol production in Mozambique. The effects of crop residues and mulches on carbon sequestration are highest in Latin America and lowest in Africa (table 3.4). In Latin America, most studies looked specifically at the effects on soil carbon sequestration of mulching or incorporating residues relative to burning. Others were on the effects of sugar cane residues on sequestration, while others looked at the effects of grazing crop residues on soil carbon sequestration. Apart from biomass from trees, use of straw from rice and other crop residues was found to be prevalent in Asia.

Tillage, the agricultural preparation of the soil for planting, has three primary purposes: to facilitate seed germination

**PHOTO 3.1:** Crop Residue Management in Irrigated Fields in Indonesia

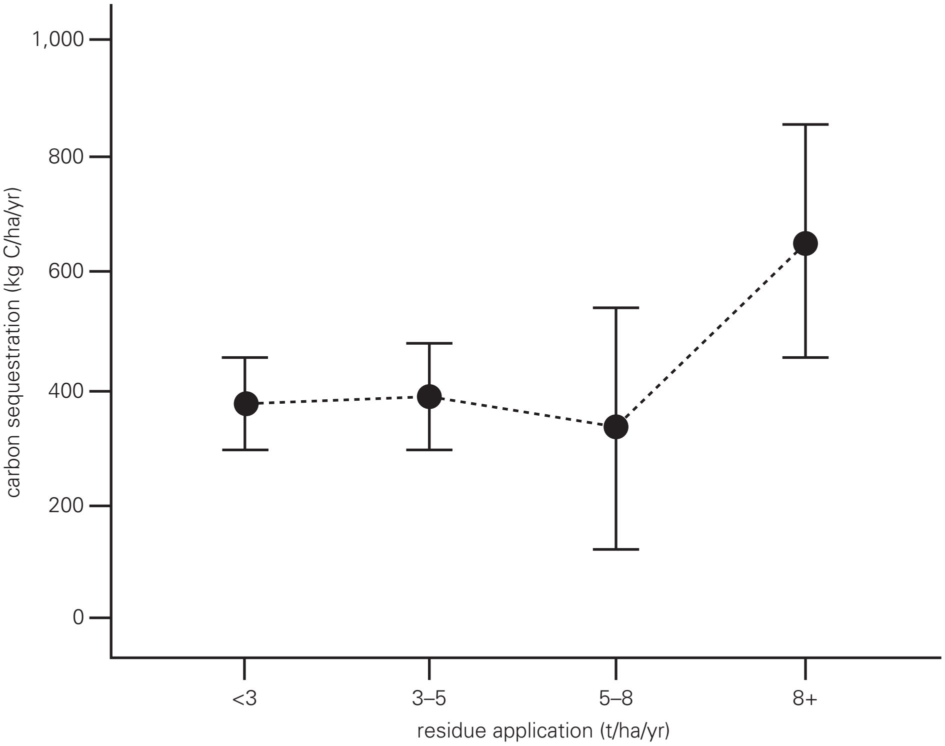
*Source:* Curt Carnemark/World Bank.

**TABLE 3.4:** Tillage, Crop Residue Management, and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Crop residues | 374 | 292 | 457 | 46 |
| Mulches | 377 | 159 | 595 | 6 |
| Cover crops | 406 | 298 | 515 | 24 |
| No-tillage | 370 | 322 | 418 | 108 |
| **Asia** | | | | |
| Crop residues | 450 | 379 | 521 | 189 |
| Mulches | 565 | 371 | 759 | 53 |
| Cover crops | 414 | 233 | 594 | 38 |
| No-tillage | 224 | 97 | 351 | 48 |
| **Latin America** | | | | |
| Crop residues | 948 | 638 | 1,258 | 56 |
| Mulches | 748 | 262 | 1,108 | 16 |
| Cover crops | 314 | 108 | 520 | 33 |
| No-tillage | 535 | 431 | 639 | 249 |

*Source:* This study.

**FIGURE 3.8:** Mean Soil Carbon Sequestration and Levels of Residue Returned



*Source:* This study.
*Notes:* *n* = 165; the 95 percent confidence intervals are shown as whiskers.

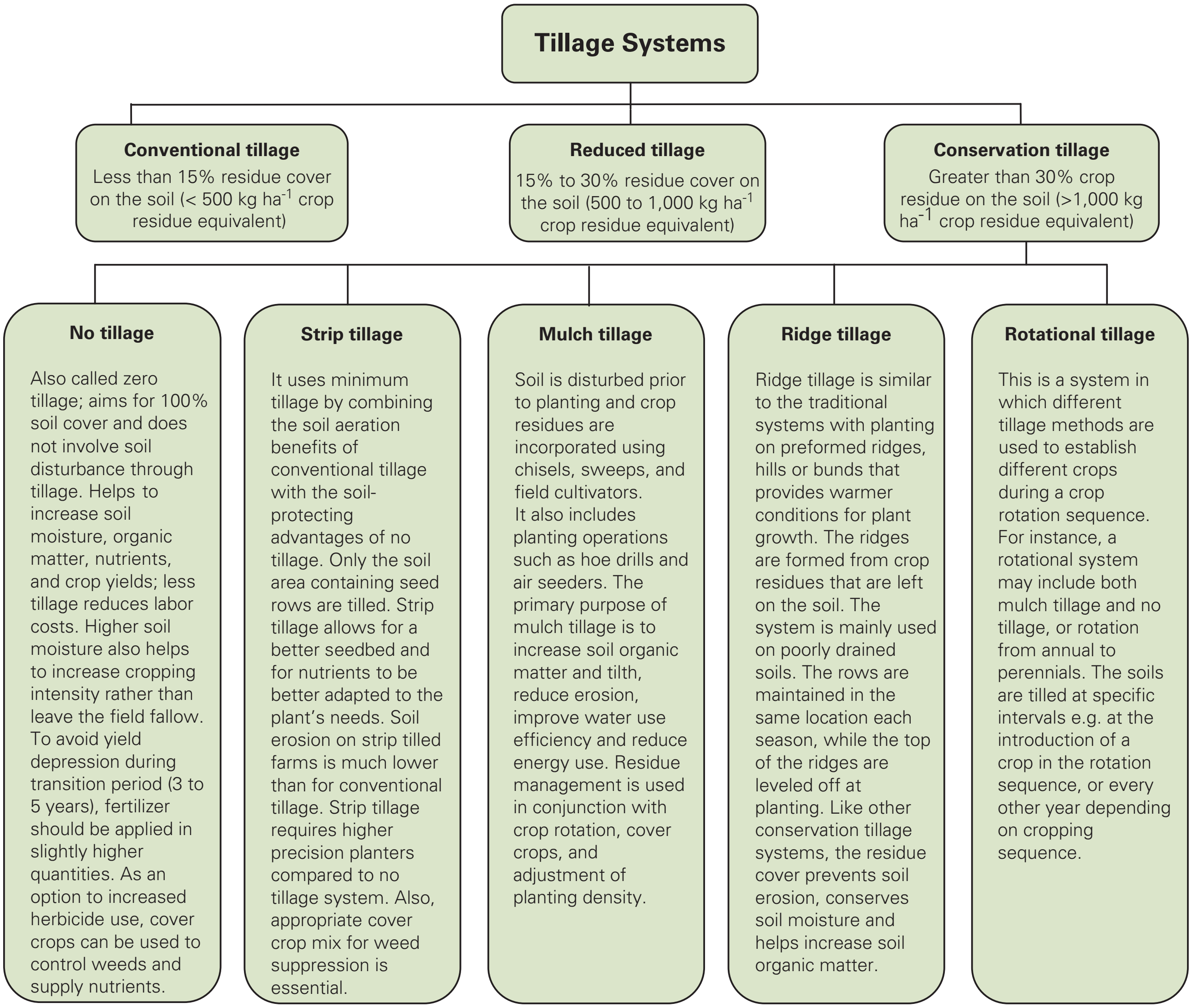
by creating a smooth, uniform soil surface for planting; to incorporate fertilizer, manures and crop residues into the soil; and to control weeds. Depending on the amount of residue left on the soil surface, tillage systems can be broadly classified into conventional, reduced, and conservation tillage (figure 3.9). The conventional method, more appropriately referred to as intensive tillage, entails motorized multiple farm operations with mold board, disk, plow, and harrow for seedbed preparation. Conventional tillage should not be confused with traditional tillage techniques involving manual or animal-drawn operations. Conventional tillage leaves the least residue on the soil surface. While plowing loosens and aerates the topsoil and facilitates seedling establishment, it can lead to many unfavorable effects including soil compaction, destruction of soil aggregates, decrease in infiltration rate, increase in soil erosion and loss of nutrients, increase in evaporation loss, and reduction in soil organic matter. Conservation tillage systems leave the most crop residues on the surface, and they are the precursor to conservation agriculture, the holistic agricultural production system that integrates management of soil, water, and biological resources (Liniger *et al.* 2011). Conservation agriculture is based on

- minimum soil disturbance through mechanical tillage,
- permanent soil cover through residue management, and
- crop rotation and diversification using legumes and green manure or cover crops (figure 3.2).

In this study, carbon sequestration under conservation tillage ranged from 224 kg $ha^{-1}$ $yr^{-1}$ for Asia to 535 kg $ha^{-1}$ $yr^{-1}$ for Latin America (table 3.4).

Most of the conservation tillage systems are large-scale farms in the United States, Canada, Brazil, Argentina, and Australia. Africa lags behind with only about 500,000 ha under conservation agriculture. Recent experience in Zambia—conservation agriculture with trees—suggests that the system holds promise for replenishing soil fertility and improving productivity and rural livelihoods. Conservation agriculture in Zambia entails (1) dry season land preparation using minimum tillage methods and utilizing fixed planting stations (small shallow basins), (2) retention of crop residue from previous harvests in the field or use of other mulches from the tree component (*Faidherbia albida*) or other cover crops, and (3) rotation of grains with legumes in the field.

**FIGURE 3.9:** Classification of Tillage Systems Based on Crop Residue Management



**Tillage Systems**

**Conventional tillage**
Less than 15% residue cover on the soil (< 500 kg $\text{ha}^{-1}$ crop residue equivalent)

**Reduced tillage**
15% to 30% residue cover on the soil (500 to 1,000 kg $\text{ha}^{-1}$ crop residue equivalent)

**Conservation tillage**
Greater than 30% crop residue on the soil (>1,000 kg $\text{ha}^{-1}$ crop residue equivalent)

**No tillage**
Also called zero tillage; aims for 100% soil cover and does not involve soil disturbance through tillage. Helps to increase soil moisture, organic matter, nutrients, and crop yields; less tillage reduces labor costs. Higher soil moisture also helps to increase cropping intensity rather than leave the field fallow. To avoid yield depression during transition period (3 to 5 years), fertilizer should be applied in slightly higher quantities. As an option to increased herbicide use, cover crops can be used to control weeds and supply nutrients.

**Strip tillage**
It uses minimum tillage by combining the soil aeration benefits of conventional tillage with the soil-protecting advantages of no tillage. Only the soil area containing seed rows are tilled. Strip tillage allows for a better seedbed and for nutrients to be better adapted to the plant's needs. Soil erosion on strip tilled farms is much lower than for conventional tillage. Strip tillage requires higher precision planters compared to no tillage system. Also, appropriate cover crop mix for weed suppression is essential.

**Mulch tillage**
Soil is disturbed prior to planting and crop residues are incorporated using chisels, sweeps, and field cultivators. It also includes planting operations such as hoe drills and air seeders. The primary purpose of mulch tillage is to increase soil organic matter and tilth, reduce erosion, improve water use efficiency and reduce energy use. Residue management is used in conjunction with crop rotation, cover crops, and adjustment of planting density.

**Ridge tillage**
Ridge tillage is similar to the traditional systems with planting on preformed ridges, hills or bunds that provides warmer conditions for plant growth. The ridges are formed from crop residues that are left on the soil. The system is mainly used on poorly drained soils. The rows are maintained in the same location each season, while the top of the ridges are leveled off at planting. Like other conservation tillage systems, the residue cover prevents soil erosion, conserves soil moisture and helps increase soil organic matter.

**Rotational tillage**
This is a system in which different tillage methods are used to establish different crops during a crop rotation sequence. For instance, a rotational system may include both mulch tillage and no tillage, or rotation from annual to perennials. The soils are tilled at specific intervals e.g. at the introduction of a crop in the rotation sequence, or every other year depending on cropping sequence.

*Source:* This study.

Over 180,000 farmers used this system at the end of 2010, and this figure was projected to rise to 250,000 farmers by 2011, representing some 30 percent of the population of small-scale farmers in Zambia. The tree component provides mulch and nutrients. By eliminating the need for laborious land preparation, farmers adopting the system have been better able to plant close to the onset of the rains. Using conservation agriculture, yields have doubled for maize and increased by 60 percent for cotton compared to conventional tillage system.

### *Cover Crops*

In this study, the practice of growing cover crops *in situ* was distinguished from mulches and crop residues of main harvested crops. Cover crops help to improve soil macronutrients and micronutrients and are termed *green manure* because of their ability to enhance soil fertility. Green manure crops are commonly leguminous crops with high nitrogen content. Examples include cowpea, groundnut and mucuna. Cover crops can also improve soil quality by increasing soil organic carbon through their biomass, and they also help in improving soil aggregate stability, protecting the soil from surface runoff and suppressing weeds.

### Crop Rotation

Crop rotation is a key complementary practice for successful implementation of no-tillage. Crop rotation is the deliberate order of specific crops sown on the same field. The succeeding crop may be of a different species (e.g., grain crops followed by legumes) or variety from the previous crop, and the planned rotation may be for 2 or more years. Rotating to a different crop such as cowpea or soybean usually results in higher grain yields when compared to continuous cropping of maize. Other benefits of crop rotation include improved soil fertility, increased soil water management, reduced soil erosion, and reduced pest and diseases. The recommended crop rotation strategies include

- producing large amounts of biomass and residue for soil protection and incorporation in the soil,
- maintaining a continuous sequence of living vegetation,
- including perennial crops in the rotation, and
- diversifying the rotation to include nitrogen-fixing legumes.

Two variants of crop rotation observed in the review are rotation intensification and diversification (table 3.5). Intensifying rotation means replacing a fallow with another crop, while diversifying rotation implies altering cropping sequences within or across years while keeping the same number of crops in the rotation.

There is a tendency toward higher sequestration rates in triple cropping systems, but variation is high (figure 3.10). The apparent lower level for double compared to single or triple cropping may reflect differences in soils, climate, and cropping systems rather than effects of cropping intensity. Rotation diversification is different in Africa compared to Latin America. In Africa, the traditional element of crop rotation is the replenishment of nitrogen through the use of legumes in sequence with other crops. In the Sahel, a typical cropping sequence is millet/sorghum, followed by maize, groundnuts, cowpea, sesame, cassava, yams, and tree legumes, while in Ethiopia, the sequence is usually maize/barley, followed by sorghum, millet, and tef.

### Water Management

Improved water productivity in agriculture is achieved by reducing water loss, harvesting water, managing excess water, and maximizing water storage. Rainwater harvesting is particularly important for rain-fed agriculture in arid and semiarid regions. The practice aims at minimizing the effects of seasonal variations in water availability due to droughts and dry periods and enhancing the reliability of agricultural production. Conveyance and distribution efficiency are also important measures in irrigation. Terracing on steep slopes and cross-slope barriers helps in reducing surface runoff. Improved irrigation sequestered carbon the most, while terracing sequestered the least (table 3.6).

### Agroforestry

Agroforestry is an integrated land-use system combining trees and shrubs with crops and livestock. Agroforestry maintains soil organic matter and biological activity at levels suitable for soil fertility. It also contributes to agro-ecosystem resilience by controlling runoff and soil erosion, thereby

**TABLE 3.5:** Crop Rotation and Soil Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

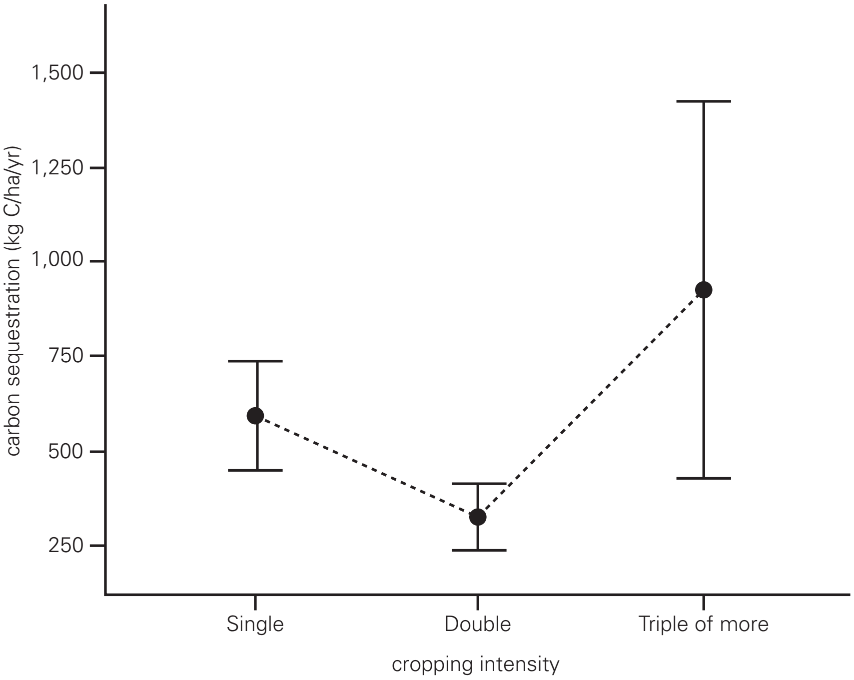
| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Diversify rotation | 378 | 306 | 451 | 49 |
| Intensify rotation | 342 | 277 | 407 | 55 |
| **Asia** | | | | |
| Intensify rotation | 345 | 87 | 604 | 43 |
| **Latin America** | | | | |
| Intensify rotation | 331 | 165 | 496 | 25 |
| Diversify rotation | 136 | –62 | 334 | 43 |

*Source:* This study.

**PHOTO 3.2:** Water Management in a Field in India

*Source:* Ray Witlin/World Bank.

**FIGURE 3.10:** Mean Soil Carbon Sequestration and Cropping Intensity



*Source:* This study.
*Note:* The 95 percent confidence intervals are shown as whiskers ($n = 536$).

**TABLE 3.6:** Water Management and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Rainwater harvesting | 839 | 556 | 1,122 | 33 |
| Cross-slope barriers | 1,193 | 581 | 1,805 | 22 |
| Terracing | 421 | 276 | 566 | 15 |
| **Asia** | | | | |
| Rainwater harvesting | 1,086 | 405 | 1,767 | 4 |
| Improved irrigation | 1,428 | 477 | 2,379 | 10 |
| **Latin America** | | | | |
| Improved irrigation | 571 | –59 | 1,201 | 34 |

*Source:* This study.

reducing losses of water and nutrients. The shade provided by the trees helps in moderating microclimate and reducing crops and livestock stress and helps to improve crop yields. One of the most promising fertilizer tree species is *Faidherbia albida,* an Acacia species native to Africa and the Middle East. *Faidherbia* is widespread throughout Africa, thrives on a range of soils, and occurs in different ecosystems ranging from dry lands to wet tropical climates. It fixes nitrogen and has the special feature of reversed leaf phenology, a characteristic that makes it dormant and sheds its leaves during the early rainy season and leafs out at the onset of the dry season. This makes *Faidherbia* compatible with food crop production because it does not compete for light, nutrients, and water. Farmers have frequently reported significant crop yield increases for maize, sorghum, millet, cotton, and groundnut when grown in proximity to *Faidherbia*.

**PHOTO 3.3:** Maize Growing under *Faidherbia Albida* Trees in Tanzania

*Source:* World Agroforestry Centre.

Improved fallow involves the use of fast-growing trees to accelerate the process of soil rehabilitation and thereby shorten the length of fallow sequester carbon the most (about 2.5 t $ha^{-1}$ $yr^{-1}$). Nitrogen-fixing plants are normally used because they are generally sturdy, easy to establish, deep rooted, drought tolerant, and fix atmospheric nitrogen. The improved fallow trees and shrubs are left in the field for several months or years. During the fallow period, the plants accumulate nitrogen from the atmosphere and deep layers of the soil, while leaf litter protects the soil from erosion, enriches the soil with nutrients, and helps to conserve moisture. When the trees are removed after fallow, their roots remaining in the soil gradually decompose, releasing additional nutrients to the subsequent crops. Examples of species used for improved fallow include pigeon pea, sesban, sun hemp, *Gliricidia sepium*, and *Tephrosia vogelii*.

The average soil carbon sequestration rate of tree-crop farming is approximately 1.4 t C $ha^{-1}$ $yr^{-1}$.The estimates covered cocoa in Ghana and Cameroon, coffee in Burkina Faso, indigenous fruit trees in South Africa, oil palm in Cote d'Ivoire, exotic tree species in Ethiopia, rubber plantation in Nigeria and Ghana, and cashew and teak plantation in Nigeria. Cocoa planted at low plant density and under shade stores more carbon per unit area of soil than an equivalent area of cocoa planted at high density without shade. In addition to C sequestration in biomass and soil, tropical plantations are needed for timber and, more importantly, as fuel for cooking. Thus, the area under tropical plantations has increased drastically since the 1960s from 7 Million hectares (Mha) in 1965 to 21 Mha in 1980, 43 Mha in 1990, and 187 Mha in 2000.

Intercropping examines the effects of crops on soils where there are trees, as opposed to the effects of including trees where there are crops. The responses over time vary in different studies and may be affected by biomass harvesting. Competition with crops is an important trade-off. Although including the nitrogen-fixing tree *Dalbergia sisso* leads to more accumulation of organic carbon in the soil, the incorporation of more trees reduces spacing between crops, and shading of crops by trees may reduce crop yields. The highest effects recorded in Latin America for intercropping were 1.1 t $ha^{-1}$ $yr^{-1}$, while the highest effects for trees recorded in Africa was 1.2 t $ha^{-1}$ $yr^{-1}$ (table 3.7).

### Land-Use Changes

The review captured diverse categories of land-use changes in Asia and Latin America compared to Africa (table 3.8). Replacing annual crops with perennials increased soil carbon sequestration on average by 1 t C $ha^{-1}$ $yr^{-1}$ in Asia and by 0.5 t C $ha^{-1}$ $yr^{-1}$ in Latin America. In virtually all cases, the switch was to perennial grasses used as fodder for livestock. On

**TABLE 3.7:** Agroforestry and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Include trees in field | 1,204 | 798 | 1,610 | 125 |
| Intercropping | 629 | 162 | 1,421 | 14 |
| Alley farming | 1,458 | 869 | 2,047 | 46 |
| Tree-crop farming | 1,359 | 755 | 1,964 | 44 |
| Improved fallow | 2,413 | 1,886 | 2,941 | 71 |
| **Asia** | | | | |
| Include trees in field | 562 | 220 | 904 | 58 |
| Intercropping | 803 | 65 | 1,541 | 17 |
| **Latin America** | | | | |
| Include trees in field | 1,065 | 270 | 1,860 | 43 |
| Diversify trees | 1,365 | 516 | 2,213 | 6 |
| Intercropping | 1,089 | 116 | 2,063 | 7 |

*Source:* This study.

**TABLE 3.8:** Land-Use Changes and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Crop-to-forest | 1,163 | 619 | 1,706 | 37 |
| Pasture improvement | 799 | 469 | 1,129 | 32 |
| **Asia** | | | | |
| Crop-to-forest | 932 | 554 | 1,309 | 60 |
| Crop-to-plantation | 878 | 662 | 1,094 | 158 |
| Crop-to–grassland | 302 | –36 | 640 | 35 |
| Exclusion or reduction in grazing | 502 | 126 | 877 | 39 |
| Restoration of wetlands | 471 | | | 1 |
| Annual-to-perennial | 1,004 | 615 | 1,392 | 36 |
| Intensive vegetables and specialty crops | 2,580 | 1,226 | 3,933 | 56 |
| **Latin America** | | | | |
| Crop-to-forest | 528 | –80 | 1,135 | 59 |
| Pasture-to-forest | 362 | –32 | 756 | 62 |
| Crop-to-plantation | 893 | 299 | 1,488 | 14 |
| Pasture-to-plantation | 1,169 | 315 | 2,024 | 53 |
| Grassland–to-plantation | –406 | –842 | 32 | 32 |
| Exclusion or reduction in grazing | 172 | –393 | 737 | 30 |
| Crop-to-pasture | 1,116 | –32 | 2,265 | 7 |
| Annual-to-perennial | 526 | 239 | 812 | 13 |
| Pasture improvement | 1,687 | 825 | 2,549 | 13 |

*Source:* This study.

average, conversion of cultivated lands to secondary forests sequestered more than 1 t C $ha^{-1}$ $yr^{-1}$ in Africa. The Global Partnership on Forest Landscape Restoration estimates that over 400 Mha of degraded forest landscapes offer opportunities for restoring or enhancing the functionality mosaic landscapes of forest, agriculture, and other land uses in the continent. In any afforestation project, emphasis should be placed on maximizing the use of available land by planting high-yielding tree species. The species may be similar or mixed in a manner that will generate the highest yield and biodiversity. The growing of plantations on former agricultural land sequestered on average an additional 0.9 t C $ha^{-1}$ $yr^{-1}$ in Asia and Latin America—a value comparable to that for secondary forests. However, more C is sequestered when the former land use is pasture (about 1.2 t C $ha^{-1}$ $yr^{-1}$ in Latin America). The establishment of pasture on cultivated land sequesters 1.1 t C $ha^{-1}$ $yr^{-1}$.

In Latin America, the conversion of native grasslands including savannahs, which are frequently grazed, to plantations, on average, resulted in a net loss of soil carbon of 0.4 t C $ha^{-1}$ $yr^{-1}$ (table 3.8). This is in sharp contrast to findings for conversion of pastures to forest or plantation. Converting grasslands to plantations in the Pampas region results in acidification of soils (Jobbagy and Jackson 2003), an impact also observed in some studies of savannas in Brazil (Lilienfein *et al.* 2000). Other studies have suggested that grassland soils may not accumulate carbon once forested and that some humid soils may even lose carbon (Paruelo *et al.* 2010).

The highest soil carbon sequestration rate for land-use change observed in this review was for intensive vegetable production in Asia (2.6 t C $ha^{-1}$ $yr^{-1}$). One greenhouse system in Taiwan had 26 crops in 4 years with high inputs of fertilizers and manures (Chang, Chung, and

Wang 2008). But other systems included farms with organic production using no pesticides or chemical fertilizers (Ge *et al.* 2010c). Although intensified cultivation in greenhouses produced the highest average rates of soil carbon sequestration, the differences from estimates from field or agroforestry settings were not statistically significant. One repeated-sampling design study in India, for example, documented the consequences of intensive cultivation of high-value medicinals and aromatics in an agroforestry setting (Sujatha *et al.* 2011), while another looked at growing vanilla orchids under different organic manure and mulch combinations in an agroforestry setting (Sujatha and Bhat 2010). Fertigation, the inclusion of liquid fertilizers as part of a drip irrigation system, has been experimented with for high-value crops in arecanut agroforestry systems (Bhat and Sujatha 2009). Increases in soil organic carbon under these high-input systems are likewise rapid (Bhat and Sujatha 2009).

Grazing management, the control of animal grazing to sustain productivity and ensure continuous supply of forages to animals, sequesters about 0.5 and 0.2 t C $ha^{-1}$ $yr^{-1}$ in Asia and Latin America, respectively. Grazing management helps to

- maintain a healthy and productive pasture;
- increase water use efficiency by increasing infiltration and reducing runoff;
- reduce soil and nutrient losses in runoff, thereby maintaining soil physical and chemical quality; and
- maintain higher amounts of soil organic matter and rapid cycling of nutrients.

Grazing management and pasture improvement should be integrated for optimal benefits. An efficient grazing system uses the appropriate mix of grass or legume species for pasture, manages stocking rates, encourages more uniform use of paddocks, and adjusts the timing of grazing. Pasture improvement sequestered 0.8 and 1.7 t C $ha^{-1}$ $yr^{-1}$ in Africa and Latin America, respectively.

Livestock grazing is relevant to many different land-use and agricultural practices. This study looks at livestock management practices from several perspectives, recognizing that there is not always a clear boundary between categories of effects. These different practices are summarized in table 3.9 to aid comparison.

### Biochar and Other Soil Amendments

Of the soil amendments studied, biochar sequestered carbon the most (table 3.10). Biochar is produced by pyrolysis, the thermal decomposition of biomass under limited oxygen supply and at temperatures below 700°C. Biochar is a key ingredient in the formation of anthropogenic Amazonian dark earth (soils). Its application has gained recognition in the last few years for both climate change mitigation and soil improvement. The climate mitigation benefit of biochar lies in the fact that it decomposes more slowly and stabilizes biomass carbon. Application of biochar also leads to avoided emissions of nitrous oxide and methane. As a soil amendment, biochar

- adds nutrients and improves uptake of applied fertilizers,
- increases water holding capacity of the soil,
- increases microbial biomass and activity, and
- increases mycorrhizal abundance linked to enhanced agronomic efficiency and yield.

**TABLE 3.9:** Summary of Observed Rates of Soil Carbon Sequestration (kg C $ha^{-1}$ $yr^{-1}$) as a Result of Land-Use Changes and Other Practices Relevant to Livestock Management

| PRACTICE EFFECT | GRASS PLANTED | TREES PLANTED | GRAZING | AFRICA | ASIA | LATIN AMERICA |
|---|---|---|---|---|---|---|
| Pasture improvement (perennial, productive grasses) | Y | N | Y | 799 |  | 1687 |
| Pasture to plantation | Y | Y | (N) |  |  | 1169 |
| Include trees (silvopasture) | (N) | Y | Y |  |  | 1167 |
| Pasture to forest | Y | N | (N) |  |  | 362 |
| Excluding grazing | (N) | N | N |  | 502 | 172 |
| Grassland to plantation | N | Y | (N) |  |  | –406 |
| Crop to grassland | Y | N | Y |  | 302 |  |

*Source:* This study.
*Note:* Letters in parentheses indicate typical but not absolute conditions.

**TABLE 3.10:** Soil Amendments and Soil Carbon Sequestration Rates (kg C $ha^{-1}$ $yr^{-1}$)

| PRACTICE | MEAN | LOWER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | UPPER 95 PERCENT CONFIDENCE INTERVAL OF MEAN | NUMBER OF ESTIMATES |
|---|---|---|---|---|
| **Africa** | | | | |
| Biochar | 2,303 | 1,219 | 3,387 | 11 |
| Soil amendment[a] | 569 | 299 | 839 | 15 |
| **Asia** | | | | |
| Biochar | 3,818 | 747 | 6,889 | 6 |
| Sulfur | 425 | 106 | 743 | 5 |
| Lime | 39 | | | 1 |
| Zinc | 53 | | | 1 |
| **Latin America** | | | | |
| Biochar | 3,237 | 1,079 | 5,395 | 8 |
| Lime | 114 | –287 | 516 | 9 |

*Source:* This study.

[a] Ash, sawdust, cocoa husk, rice bran.

Biochar can remain resident in the soil approximately 10 to 1,000 times longer than the residence time of most soil organic matter. However, research results on biochar's effect on some soil properties are not consistent. No significant increase in nutrient-holding capacity was observed after the addition of biochar to a coastal plain soil (Novak *et al.* 2009). Other studies have also indicated an adverse effect of biochar application on earthworm survival, possibly due to increases in soil pH. In general, the use of biochar should ensure that crop residues and mulch needed for soil protection are not removed from the field.

### Net Climate Change Mitigation Benefits of the Land Management Practices

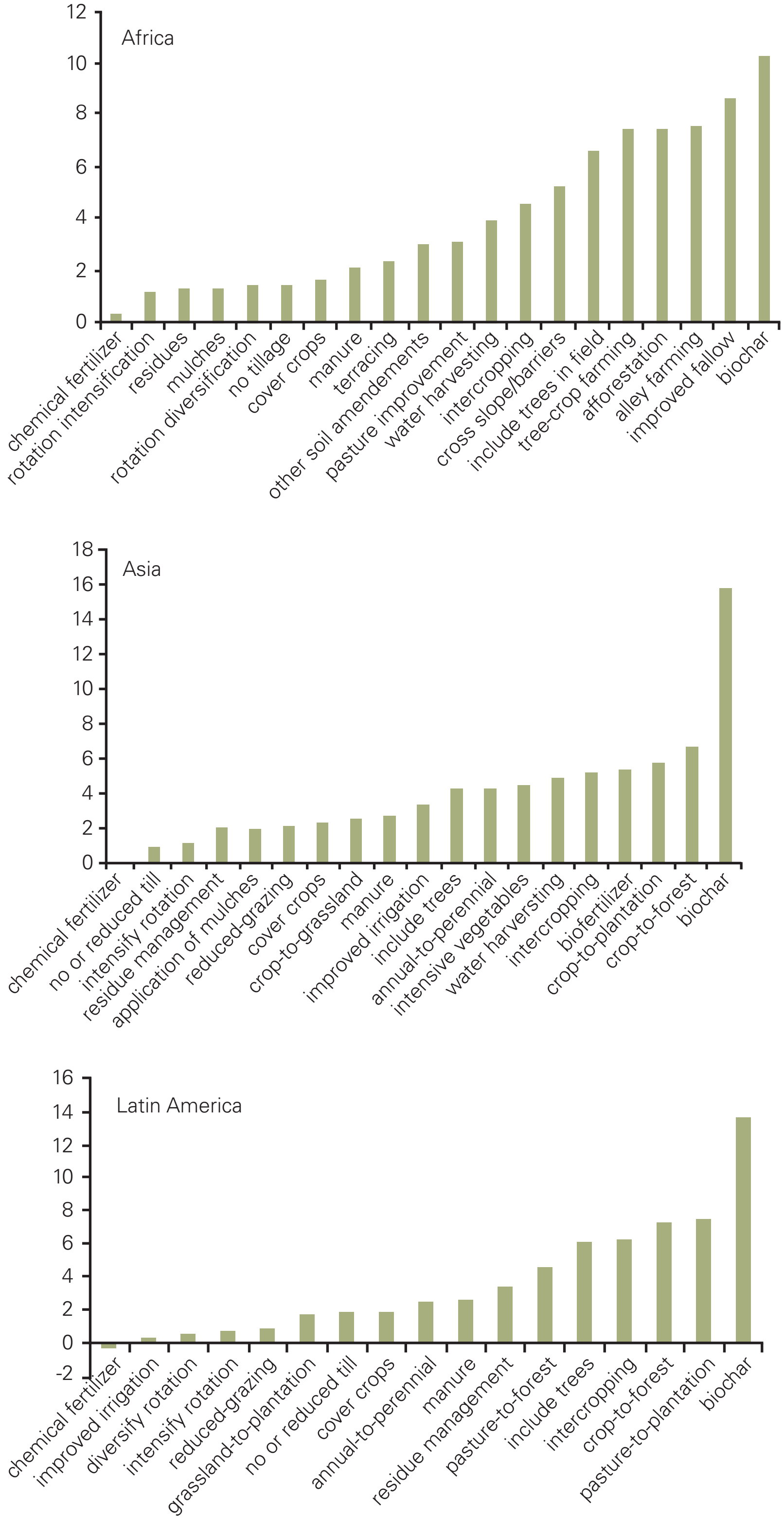
Estimates of the net climate change mitigation benefits of the agricultural land management practices are summarized in figure 3.11. The estimates were derived by converting carbon sequestration rates from this study to carbon dioxide equivalent by multiplying by 3.67 and also by accounting for land and process emissions. Land emissions are the differences between emissions of nitrous oxides and methane expressed in $CO_2$ equivalents by conventional and improved practices, while process emissions are those arising from fuel and energy use (Eagle *et al.*, 2010).

#### *Net Mitigation Benefits for Nutrient Management*

Increases in productivity from nitrogen fertilizers and irrigation need to be considered against increased emission of GHGs from soils as well as energy-related emissions. It should be noted that as much as 70 to 75 percent of fossil fuel use in the agricultural sector in the tropics is for the production and use of chemical fertilizers (Vlek, Rodriquez-Kuhl, and Sommer 2004). Fertilizers may make no net contribution to mitigation of climate change if the $CO_2$ emitted to produce and transport them exceeds the soil storage benefit (Schlesinger, 2010). Shang *et al.* (2010) calculated full GHG budgets over a 3-year period in a long-term experiment on fertilization in a double rice-cropping system in China. They found fertilizer plots sequestered 470 kg C $ha^{-1}$ $yr^{-1}$ more carbon in soil than controls but that long-term fertilization increased $CH_4$ emissions during flooded rice and increased $N_2O$ emissions from drained soils at other times. They estimated a net impact of 4.1 t $CO_2e$ $ha^{-1}$ $yr^{-1}$ above unfertilized controls although in terms of emissions per unit yield fertilization was still beneficial. Shang *et al.* noted that mixtures of inorganic fertilizer and chemical fertilizers increased net annual greenhouse warming potential even further, to as much as 13.5 t $CO_2e$ $ha^{-1}$ $yr^{-1}$ above unfertilized controls.

A modeling study for Indian rice and wheat suggested that increased irrigation and fertilizer application would increase the carbon efficiency ratio even as net emissions rise (Bhatia *et al.* 2010). At the same time, intensification of agricultural production (using more fertilizers) on better lands may make less suitable land available for conversion to grasslands and forests with high soil carbon sequestration potential (Vlek, Rodriquez-Kuhl, and Sommer 2004). Reducing wasteful

**FIGURE 3.11:** Carbon Dioxide Abatement Rates of the Land Management Practices



*Source:* This study.

fertilizer use by ensuring that applied rates do not exceed crop requirements is an important mitigation strategy.

### *Net Mitigation Benefits for Residue Management and Tillage*

The net GHG mitigation potential of residue management has been assessed in a few instances. Key constraints include controlling methane emission from rice paddies. The net potential of straw return (rather than burning) in China was assessed using a GHG budget model by Lu and *et al.* (2010). They found that across 10 provinces, straw return increased net GHG emissions; in the other provinces, the total net mitigation potential at soil saturation was equivalent to just 1.7 percent of the fossil fuel emission budget in China for 2003.

The life cycle analysis by Koga, Sawamoto, and Tsuruta (2006) of conventional and reduced tillage in intensive cropping systems in Hokkaido, Japan, suggested that soil-derived $CO_2$ emissions accounted for 64 to 76 percent of total GHG emissions, emphasizing the importance of soil management practices. Adoption of reduced till in these systems was expected to reduce total GHG emissions by 4 to 18 percent for various crops as a result of slower decomposition rates and fuel saving for plowing. The experimental study by Harada, Kobayashi, and Shindo (2007), for example, found 43 percent lower $CH_4$ emissions in no-till rice.

The GHG mitigation benefits of residue management also require consideration of processes apart from soil carbon sequestration. Returning straw to fields rather than burning it helps avoid emissions associated with producing synthetic fertilizer as well as $CH_4$ and $N_2O$ emissions from burning (Lu *et al.* 2010). Improved management of compost processes and mulches can reduce non-$CO_2$ emissions (Zeman, Depken, and Rich 2002).

### *Net Mitigation Benefits of Intensification and Water Management*

Very intensive systems such as vegetable production under greenhouses can sequester a lot of carbon in the soil, but they obviously depend a lot on high levels of inputs as well. Wang *et al.* (2011) made one of the few full carbon budgets for a greenhouse system. Their analyses suggest that greenhouses are a net sink of 1,210 and 1,230 kg C $ha^{-1}$ $yr^{-1}$ in temperate and subtropical areas, respectively. The conversion from conventional agriculture enhances carbon sink potential as much as 8 times in temperate and 1.3 times in tropical areas. The mitigation potential of improved irrigation is almost offset by land and process emissions, but cross-slopes/barriers achieve moderate mitigation impact.

**PHOTO 3.4:** Crop Harvesting in Mali. The Biomass Is Smaller Compared to that of Agroforestry Systems

*Source:* Curt Carnemark/World Bank.

A critical issue for soil carbon sequestration activities across humid parts of Asia is how to reduce emissions of $CH_4$ from rice fields. There is a very large scientific literature on factors influencing emissions and management options (e.g., Babu *et al.*, 2006; Li *et al.* 2006, Minamikawa and Sakai 2005, Pathak 2010, Wassmann *et al.* 2000, and Zheng *et al.* 2007). For example, midseason drainage is a viable practice in some locations in India to reduce $CH_4$ emissions (Babu *et al.* 2006). Increasing fertilizer use increased both yields and $CH_4$ emissions. Other more complex water management strategies have been proposed and demonstrated to reduce $CH_4$ emissions (Minamikawa and Sakai 2007).

### Net Mitigation Benefits for Agroforestry and Land-Use Changes

The impacts of land-use changes to trees are positive and large. The effects of some practices such as excluding grazers from rangelands or grasslands are, however, fairly small. Most of the potential impacts of changes in agricultural practices on carbon stocks are by definition below ground. The time-averaged above-ground biomass of crops is small and does not accumulate easily. Land-use changes away from cropping, such as to agroforestry or plantations, provide more compelling examples where it is useful to think of both above- and below-ground sequestration rates at the same time and possible trade-offs or interactions between them. One estimate for humid tropics globally suggested that tree-based agroforestry systems could sequester 70 Mg C $ha^{-1}$ in vegetation and up to 25 Mg C $ha^{-1}$ in the topsoil (Mutuo *et al.* 2005).

### Net Mitigation Benefits for Biochar Application

Applications of biochar or charcoal, on average, resulted in higher overall GHG mitigation potential than other practice changes reviewed in this study, but precise estimates were not possible given the paucity of data. These findings are consistent with reviews that suggest potential value of biochar for improving soil conditions and increasing sequestration of GHGs (Lehmann *et al.*, 2006; Sohi *et al.*, 2010).

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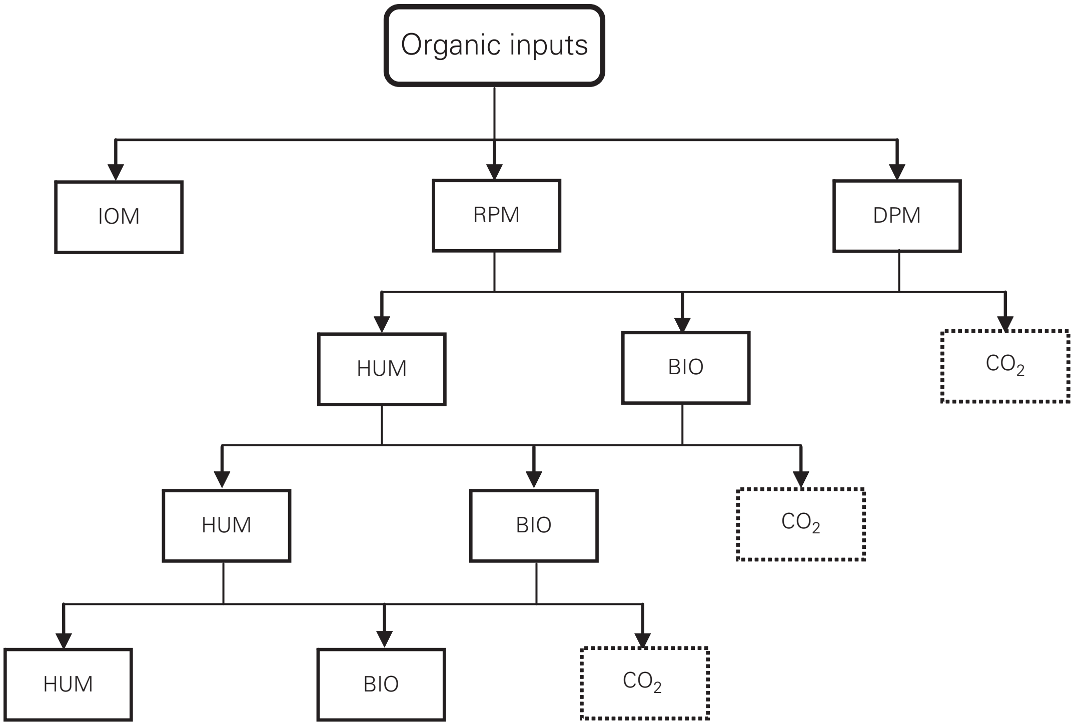
# Chapter 4: ECOSYSTEM SIMULATION MODELING OF SOIL CARBON SEQUESTRATION

## 4.1 MODEL DESCRIPTION

The *RothC* model (Coleman and Jenkinson 2008) was used to project the amount of soil carbon sequestered by different land management practices up to 2035. The *RothC* model describes the fate of organic inputs entering the soil environment, the undergoing decomposition within the soil biomass to form a number of carbon pools, and the release of $CO_2$. The pools have different susceptibilities to decomposition, ranging from highly labile to inert materials. The pools include easily decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), and inert organic matter (IOM), which is highly resistant to microbial decomposition (figure 4.1). Both DPM and RPM decompose to form $CO_2$, BIO, and HUM. The proportion that is converted to $CO_2$ and to BIO plus HUM is primarily determined by the clay content of the soil. Subsequent further decomposition of the BIO and HUM produces more $CO_2$, BIO, and HUM.

One of the main advantages of the *RothC* model is its requirement of a few, easily obtainable inputs to estimate soil carbon. The required inputs are monthly rainfall, monthly open pan evaporation, average monthly mean air temperature (in degrees Celsius), clay content of the soil, and an estimate of the decomposability of the incoming organic

**FIGURE 4.1:** Representation of the *RothC* Model



*Source:* This study.
*Note:* DPM = decomposable plant material, RPM = resistant plant material, BIO = microbial biomass, HUM = humified organic matter, IOM = inert organic matter.

material referred to as the DPM/RPM ratio (Coleman and Jenkinson 2008). The model has been validated across the agro-ecological zones of the world and has been used for many subnational and national GHG inventories.

The amount of carbon (Y) that decomposes from an active pool in a given month can be represented by an exponential decay function of the form

$$Y = Y_0(1 - e^{-abckt}), \quad [1]$$

where $Y_0$ is the initial amount of carbon in the particular pool, $a$ is the rate-modifying factor for temperature, $b$ is the rate-modifying factor for soil moisture, $c$ is the rate-modifying factor for soil cover, $k$ is the yearly decomposition rate constant for that particular compartment, and $t = 1/12$ is to scale $k$ into monthly values.

Equations for calculating each of these factors can be found in Coleman and Jenkinson (2008). While the above factors contribute exponentially to the soil carbon remaining at the end of each month, others related to the input of carbon such as crop yields, root biomass, and the proportion of carbon in plant residues are linearly related to the amount of carbon decomposing. The *RothC* model also adjusts for clay content by altering the partitioning between evolved $CO_2$ and soil C decomposition rates (BIO plus HUM) pools formed during decomposition using the following exponential equation:

$$x = 1.67(1.85 + 1.60e^{-0.0786\% clay}), \quad [2]$$

where $x$ is the ratio $CO_2$/(BIO + HUM) and BIO and HUM are the corresponding biomass and humic pools formed initially as incoming plant materials.

The global soil carbon mitigation potential due to the adoption of sustainable land management practices was modeled to a depth of 30 cm using the following relationship:

$$C_s = A \times f, \quad [3]$$

where $C_s$ is the change in soil organic carbon as a result of adoption, $A$ is the activity data or land area (in ha) where a given sustainable land management practice was adopted, and $f$ the emission factor is the sequestered carbon in t C $ha^{-1}$ $yr^{-1}$. The activity data (global cropland area) were derived from available spatial datasets (table 4.1). The harvested areas of eight major crops (barley, maize, millet, pulses, rice, sorghum, soybean, and wheat) occupying more than 70 percent of the global agricultural area were estimated within a geographical information system and used for modeling.

**TABLE 4.1:** Spatial Datasets Used in the Study

| DATA | PURPOSE | REFERENCES |
|---|---|---|
| Clay content, initial soil carbon content | *RothC* model parameterization | Harmonized World Soil Database v 1.1: FAO/IIASA/ISRIC/ISSCAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria. http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html |
| Temperature and precipitation | *RothC* model parameterization | FAOCLIM 2; World-wide Agro Climatic Data Base; Food and Agriculture Organization of the United Nations; Environment and Natural Resources Service—Agrometerology Group |
| Crop calendar | *RothC* model parameterization, modeling | FAO Crop Calendar—a crop production information tool for decisionmaking (FAO 2010): http://www.fao.org/agriculture/seed/cropcalendar/welcome.do |
| Direct manure/composted manure input data | Carbon input for modeling | Global Fertilizer and Manure Application Rates; Land Use and the Global Environment, Department of Geography, McGill University; Food and Agriculture Organization of the United Nations livestock data for Africa, 2009: http://faostat.fao.org/site/569/default.aspx#ancor |
| Harvested area (ha) of selected crops and crop yield (t/ha/year) data | Carbon input for modeling | Harvested area and yields of selected crops; Harvested area and Yields of 175 crops (M3-Crops Data); Navin Ramankutty; Land Use and the Global Environment, Department of Geography, McGill University |
| Carbon input data for agroforestry and cover crops | From several published literature | See references |
| Land-use systems | Additional data used to estimate land area for which a given technology is applicable | FAO Land Use Systems<br>http://www.fao.org/geonetwork/srv/en/main.home<br>http://www.fao.org/geonetwork/srv/en/metadata.show |
| Sustainability and the Global Environment Global Agro-Ecological Zones | Stratification of Africa | Center for Sustainability and the Global Environment, University of Wisconsin |

*Source:* This study.

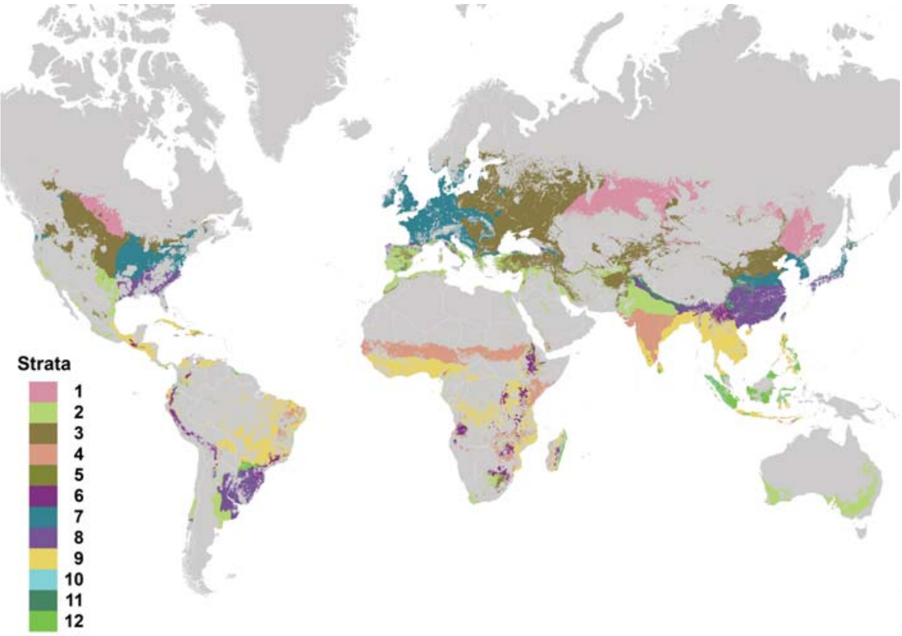
Using cluster analysis, the global cropland extent was stratified into *mapping units* based on temperature, precipitation, and clay content. This resulted in 12 distinct clusters (strata) within eight regions (Africa, Asia, Central America, Europe, North America, Oceania, Russia, and South America) (Figure 4.2). Crop yields and manure were converted into organic residues as model inputs using IPCC standard equations (IPCC, 2006). A standard DPM/RPM ratio of 1.44 was set for modeling sustainable land management scenarios except for agroforestry, where a ratio of 0.25 was assumed. The specific organic inputs for the land management practice being modeled were set on a monthly basis using crop calendars specific for each stratum. For each stratum and region, the most dominant cropping systems were identified from the literature. A summary of the farming systems is given in Appendix 4.1.

The choice of the suitable mitigation scenarios for each world region was guided by the following baseline considerations:

- The most dominant cropping systems in a specific region. For instance, mixed smallholder farming systems are the dominant system in Africa, cropping systems in South Asia are dominated by rice, and maize-soybeans systems are dominant in several parts of South America.
- The typical land management practices associated with the cropping systems. For example, most of the farming systems in North America already leave the residues on the field, while in Africa, a common practice is to burn or remove the residues from the field.
- Documented impact of agricultural land management practices on carbon sequestration (see Chapter 3).

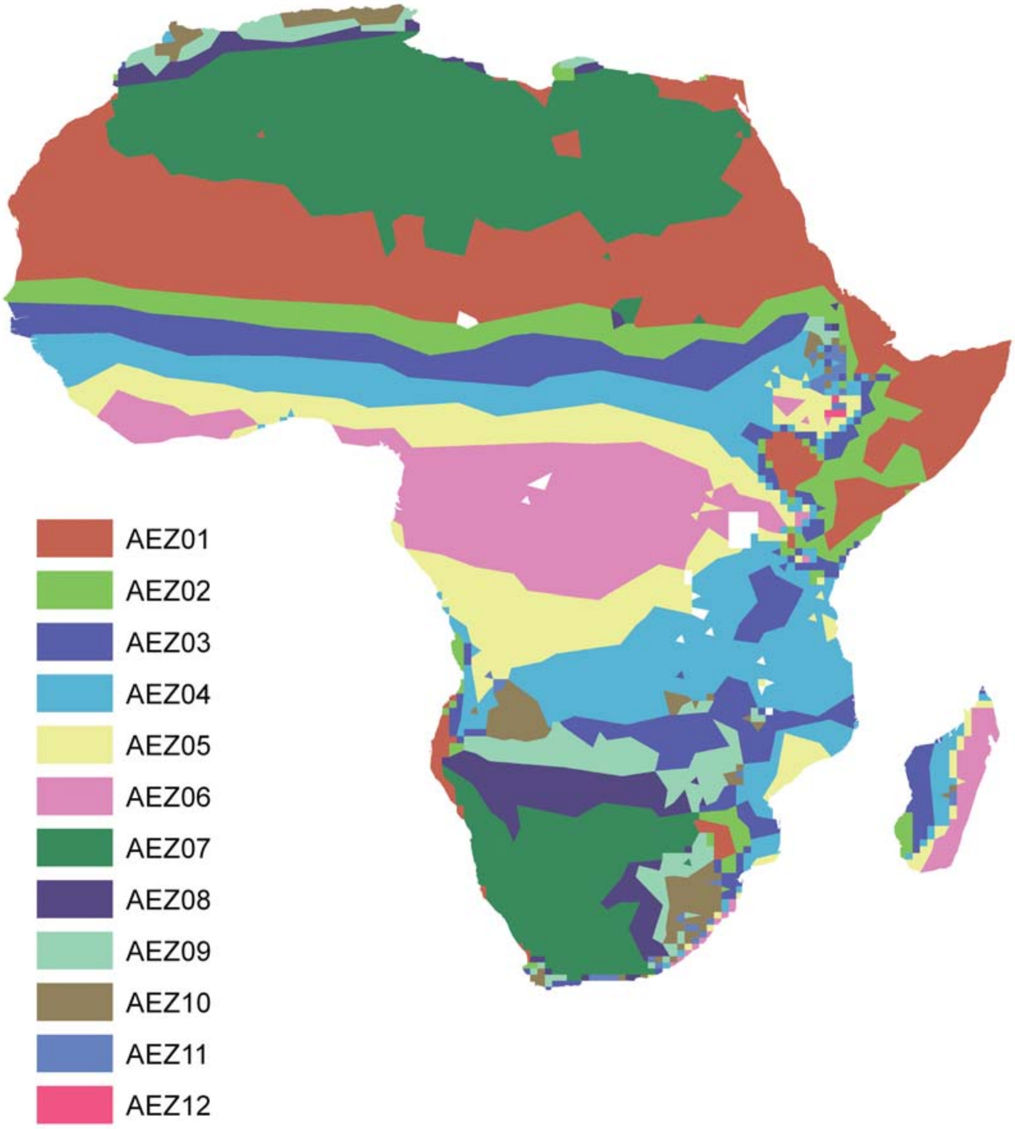
As a result, residue management, manure management, tillage management, agroforestry, and integrated fertility management were modeled. A detailed description of the baseline and mitigation scenarios is provided in Appendix 4.1. The study also took advantage of the recently released crop calendar for Africa (http://www.fao.org/agriculture/seed/cropcalendar/welcome.do) to model carbon sequestration under various levels of organic inputs for Africa. Africa was classified into four agroecological zones using procedures similar to the global cropland extent (Figure 4.3). The land management practices include integrated residue and manure management; agroforestry systems including perennial crops; land rehabilitation; coppice and improved fallow; and cropping systems involving mucuna, cowpea, and groundnut as cover crops. To account for trade-offs between mulch residues and livestock and fuel biomass, different fractions of retained residues (i.e., 25 percent, 50 percent, and 75 percent) were modeled. A detailed description of the scenarios for Africa is provided in Appendix 4.2.

**FIGURE 4.2:** The 12 Strata Used for Ecosystem Simulation Modeling



*Source:* This study.

**FIGURE 4.3:** Africa Agroecological Zone



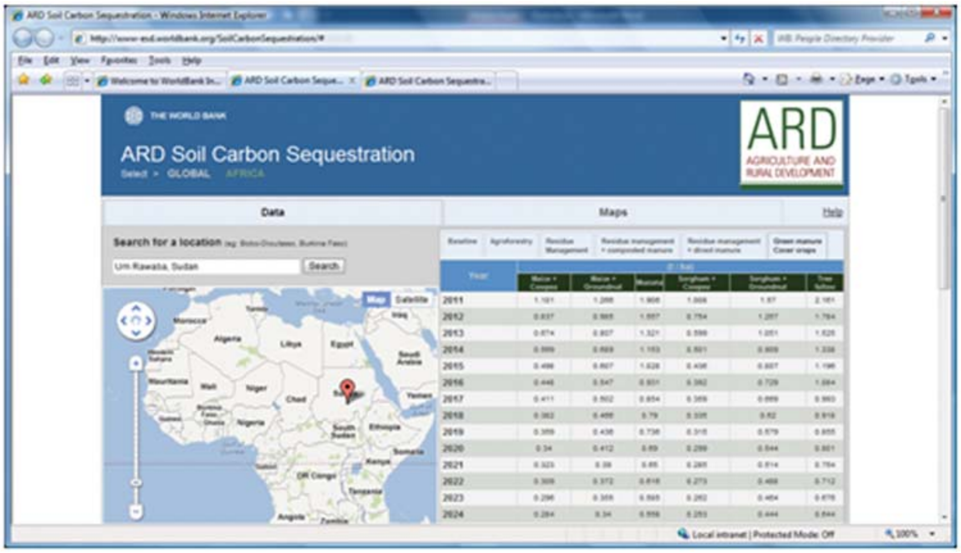
Uncertainties in model parameters were estimated following the adoption of the Sustainable Agricultural Land Management (SALM) methodology (http://www.v-c-s.org/sites/v-c-s.org/files/SALM%20Methodolgy%20V5%202011_02%20-14_accepted%20SCS.pdf). The procedures are provided in Appendix 4.3.

## 4.2 RESULTS

### Soil Carbon Sequestration Internet Tool

Modeling results are summarized in an Internet geographical information system (GIS) tool at http://www.esd.worldbank.org/SoilCarbonSequestration/. The tool includes over 4,000 land management scenarios carefully chosen to reflect situations typically encountered in agricultural projects. The Internet GIS database provides per-ha estimates of soil carbon sequestration under different land management practices for a period of 20 to 25 years (figure 4.4). Information on carbon sequestration potential of a location can be derived by point-and-click or by searching using place name. Users can download data from the Internet database and integrate with other GIS information to estimate soil carbon stock changes for different agricultural projects.

**FIGURE 4.4:** A Screen Shot of the Soil Carbon Internet Database



*Source:* http://www.esd.worldbank.org/SoilCarbonSequestration/.

### Soil Carbon Loss Under Low Input Baseline Scenario

The predicted cumulative C loss by 2030 varies for different cropping systems and regions of the world. The loss is highest for Russia under wheat, rice, pulses, and barley (35 to 40 t C ha$^{-1}$) where the drive to exploit minerals and other natural resources has spread agriculture to unproductive soils and low fertilizer use has led to a sharp decrease in soil fertility. Middle America is predicted to experience the next highest loss due to depletion of crop residues in virtually all its cropping systems (25 to 37 t C ha$^{-1}$). The highest cumulative C loss under the low input scenario occurs under rice and pulses for Africa (20 t C ha$^{-1}$), under pulses for South America (26 t C ha$^{-1}$), and under millet for Europe (23 t C ha$^{-1}$). The cumulative C loss is around 15 to 20 t C ha$^{-1}$ for all cropping systems in Asia.

### Soil Carbon Sequestration Under Different Land Management Practices

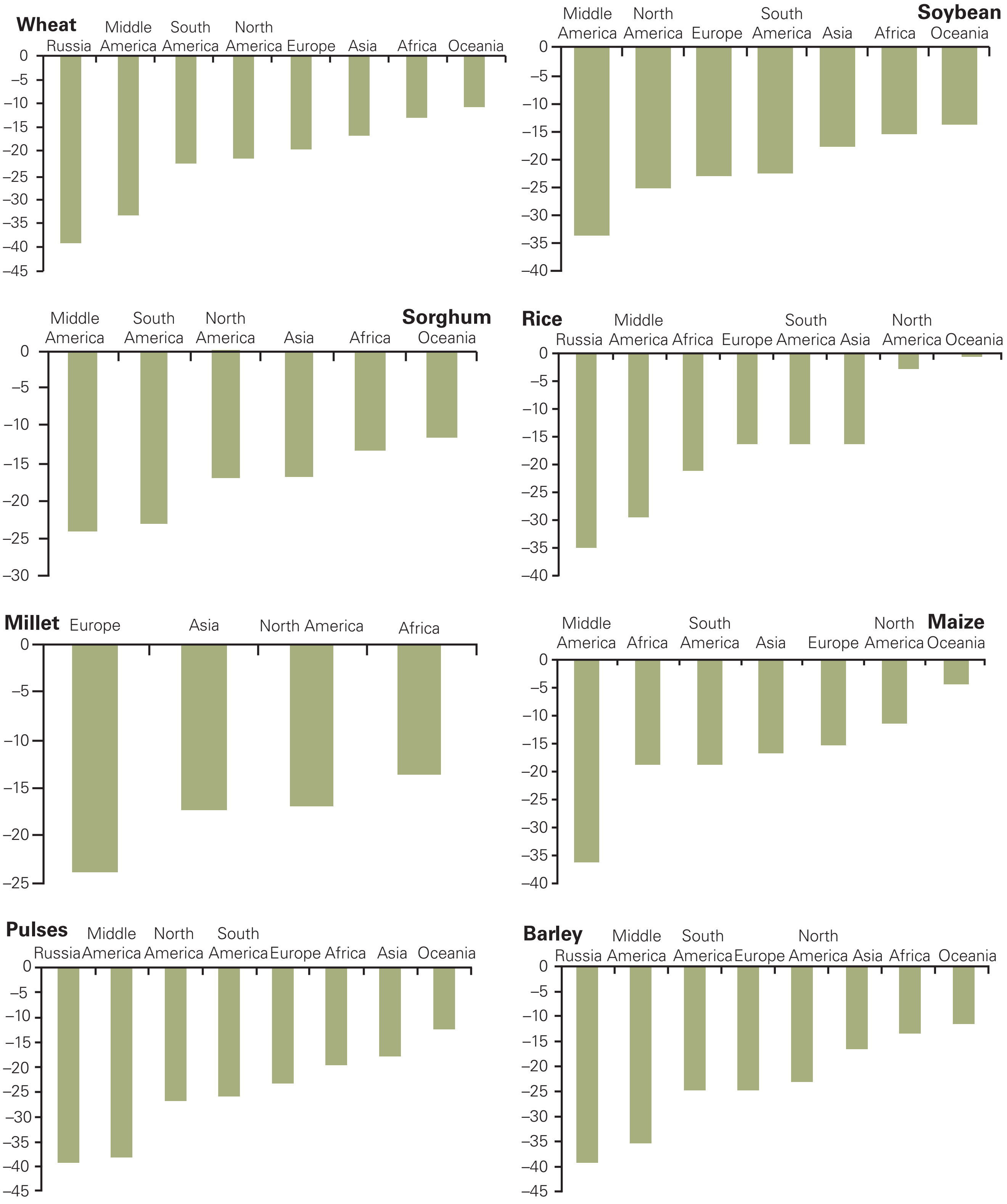
Carbon sequestration through residue management depends much on the land area devoted to a given crop (table 4.2). Based on the assumption of 50 percent residue retention, cumulative carbon sequestration by 2030 varies from 0.5 Million tons (Mt) C for soybean to 37 Mt C for maize (figure 4.5). In Asia, the sequestered carbon varies from 10 Mt for millet to 517 Mt for rice. The lowest amount of sequestered carbon from cover crops was recorded for Middle America (15 Mt), while the highest was recorded for Asia (1 Gigaton). The highest sequestration potentials for direct and composted manure (550 and 587 Mt, respectively) were observed for North America, while Russia has the least (less than 0.2 Mt). Agroforestry by far has the highest sequestration potentials for all world regions. The time-averaged above-ground biomass of trees is relatively large compared to crops.

Carbon sequestration potential of the land management practices is in the order of agroforestry > cover crops > manure > crop residues > no-tillage. The highest emphasis should be placed on agroforestry systems because of the diverse benefits they provide including compatibility of some tree species with crops and livestock production, increased income through production of indigenous fruit trees, and suitability of certain tree species for bioenergy. Agroforestry is also vital for the restoration of marginal and degraded lands.

### Carbon Sequestration Maps

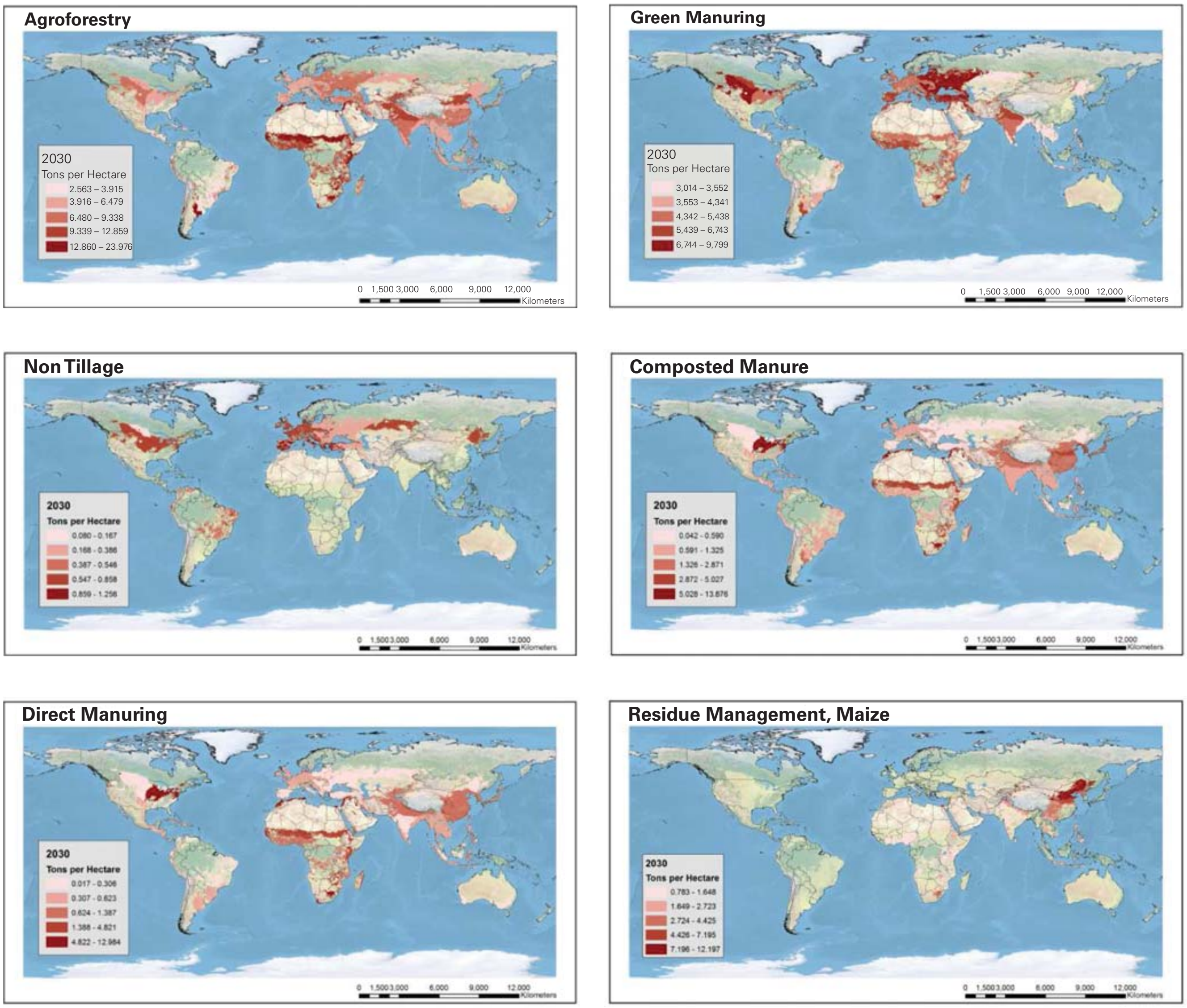
Figure 4.6 reveals differences in the predicted spatial pattern of carbon sequestration for the land management practices. High sequestration rates are generally observed in the Guinea savannah areas in Africa for most of the practices. The highest cumulative sequestration for green manure (6 to 10 t C ha$^{-1}$) are predicted for Europe and North America, while the highest for maize residue (7 to 12 t C ha$^{-1}$) are predicted for Asia. The spatial patterns of composted and direct manure are similar because both models are based on frequency of livestock. Composted manure sequesters slightly higher than direct manure (0.04 to 14 t C ha$^{-1}$ versus 0.02 to 13 t C ha$^{-1}$). No-tillage sequesters least (0.08 to 1.3 t C ha$^{-1}$); its estimates markedly suffer from lack of good resolution spatial data of no-tillage adopting areas.

**FIGURE 4.5:** Cumulative Soil Carbon Loss by 2030 Assuming 15 Percent Residue Retention (t $ha^{-1}$) Under Different Cropping Systems



*Source:* This study.

**FIGURE 4.6:** Predicted Cumulative C Sequestration for Different Land Management Practices by 2030



**Agroforestry**

**Green Manuring**

**Non Tillage**

**Composted Manure**

**Direct Manuring**

**Residue Management, Maize**

*Source:* This study.

**TABLE 4.2:** Modeled Cumulative Soil Carbon Sequestration Potential by 2030 (Mt C) Under Different Land Management Practices

| | AFRICA | ASIA | EUROPE | MIDDLE AMERICA | NORTH AMERICA | OCEANIA | RUSSIA | SOUTH AMERICA |
|---|---|---|---|---|---|---|---|---|
| **Residue management** | | | | | | | | |
| Barley | 7.898 | 16.359 | | | | | | |
| Maize | 37.281 | 209.574 | | | | | | |
| Millet | 10.657 | 9.993 | | | | | | |
| Pulses | 13.664 | 32.995 | | | | | | |
| Rice | 17.771 | 516.843 | | 1.637 | | | | 3.279 |
| Sorghum | 21.494 | 11.562 | | | | | | |
| Soybean | 0.524 | 35.120 | | | | | | |
| Wheat | 34.504 | 360.966 | | | | | | |
| No-tillage | | 20.763 | 33.209 | | 33.128 | 0.700 | 0.557 | 7.131 |
| Cover crops | 513.237 | 1009.402 | 772.082 | 14.727 | 632.415 | | | 136.495 |
| Direct manure | 400.101 | 203.703 | 23.556 | 2.252 | 549.558 | 1.740 | 0.080 | 20.098 |
| Composted manure | 427.890 | 478.064 | 57.106 | 5.460 | 586.731 | 4.218 | 0.193 | 48.721 |
| Agroforestry | 1309.511 | 2416.434 | 803.907 | 18.608 | 727.361 | 81.229 | 19.868 | 210.233 |

*Source:* This study.

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Coleman, K., and Jenkinson, D. S.2008 *ROTHC-26.3, A Model for the Turnover of Carbon in Soil: Model Description and Windows Users Guide*. Rothamsted Research, Harpenden, UK. Available online at http://www.rothamsted.ac.uk/aen/carbon/mod26_3_win.pdf.

Intergovernmental Panel on Climate Change. 2006. "Volume 4. Agriculture, Forestry, and Other Land Uses," in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, ed. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Institute for Global Environmental Strategies, Japan.

# Chapter 5: ECONOMICS OF SOIL CARBON SEQUESTRATION

## 5.1 MARGINAL ABATEMENT COSTS

Sustainable land management technologies can generally be deployed at varying costs, creating the need to evaluate their cost-effectiveness. Such analysis helps in identifying potential mitigation pathways for a given context. The cost-effectiveness of the land management practices in mitigating climate change has been evaluated using the marginal abatement cost (MAC) curve. The MAC curve analysis was a quantitative assessment of all possible costs and benefits that would accrue if the various management practices were implemented. A MAC curve depicts the relationship between the cost-effectiveness of different land management practices vis-à-vis the amount of GHG abated. The MAC is plotted on the *y*-axis and GHG abated on the *x*-axis, with the land management practices ranked against the MAC from the lowest to the highest. Moving along the curve from left to right worsens the cost-effectiveness of the mitigation measures. The width of the column is the amount of GHG mitigated by the land management practice, while the area of each column equals the cost or benefit of adopting the practice. The MAC curve can also be used for cost-benefit analysis by comparing the unit mitigation cost with the shadow price of carbon or the cost of purchasing emissions allowance. Negative MACs indicate that a land management practice is self-financing (that is, it both reduces emissions and saves money), while positive MACs imply that the land management practice reduces emissions at a cost and thus requires judgment against the cost of inaction.

In this study, private and public marginal abatement costs were computed. For the private MACs, all possible costs and benefits that would accrue to the farmers were valued at market prices the farmers are likely to face in switching to the practices. The public costs, on the other hand, refer to government support toward the implementation of land management practices. Without public support to farmers, poor agricultural land management will intensify land degradation, increase farmers' vulnerability, and contribute additional GHGs in the atmosphere. Computed public costs included investments in seeds and seedlings, input subsidies, extension services, and other administrative costs. The cost-benefit flows were discounted to present value to calculate NPV using a discount rate of 9 percent. The adoption period was assumed to be 25 years; the time carbon sequestration reaches saturation for most of the land management technologies.

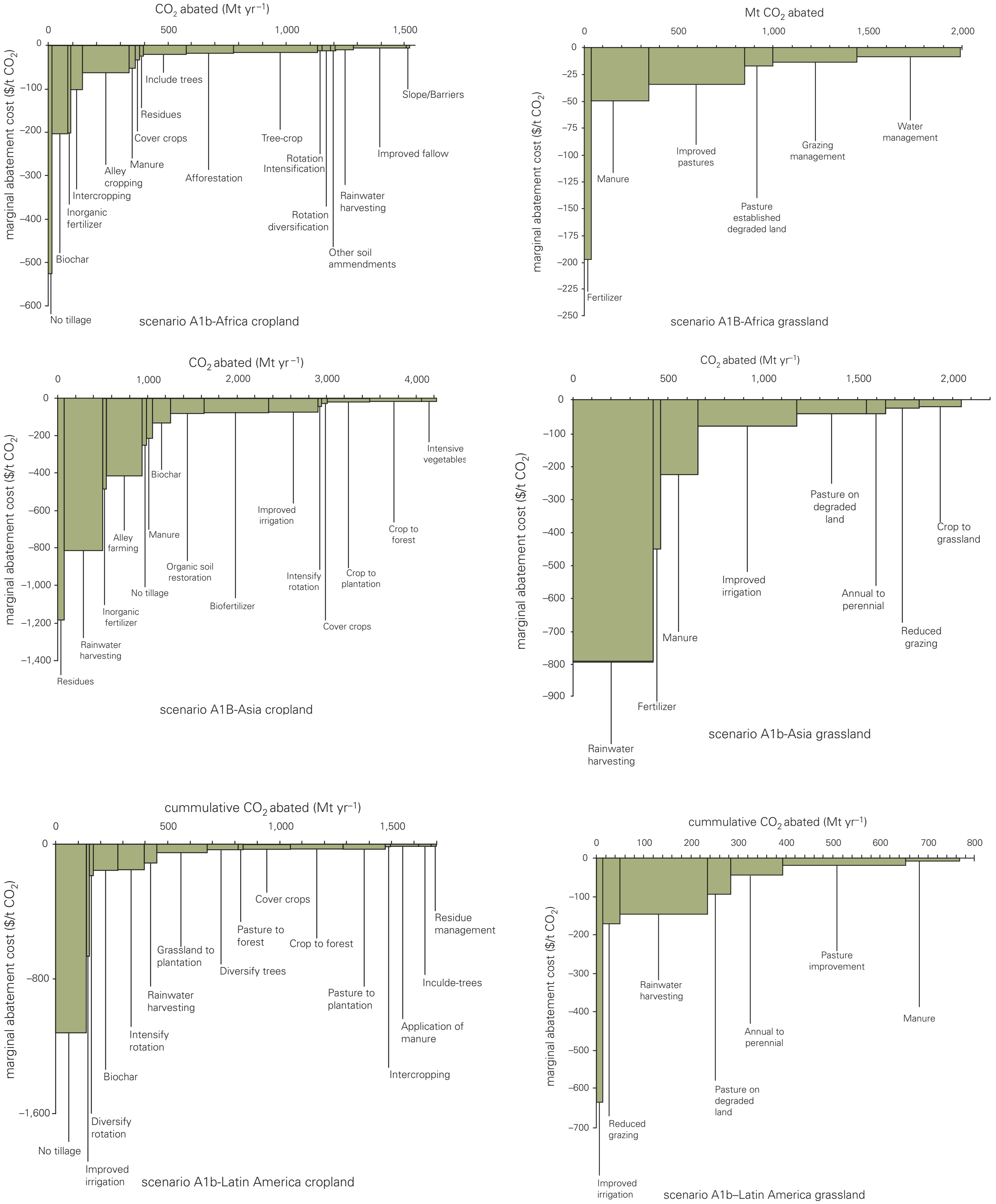
The abatement rates of the land management practices (figure 3.11) were used to scale-up for each continent by multiplying by the suitable areas for each practice within a continent in 2030. The assumptions for estimating the suitable areas for the four IPCC special reports on emission scenarios are described in Appendix 5.1. Efforts were made to avoid double counting as some of the practices are mutually exclusive.

Figure 5.1 shows the MACs for Africa, Asia, and Latin America. The shapes of the curve are similar across scenarios, so only the curves for the A1b scenario are presented.

All the land management practices are profitable to the farmer, but to varying degrees (table 5.1). The marginal benefit of no-tillage is greater than US$100 per tonne of carbon dioxide mitigated for the three regions. Alley farming and intercropping also yield relatively high profits in Africa. With the exception of Asia, the marginal benefit of residues for the regions is modest (less than US$50). Table 5.1 also reveals the inherent trade-off between the profitability of the land management practices and their mitigation potentials. Afforestation and pasture establishment on degraded land with relatively high mitigation potentials are modestly profitable. This suggests that farmers may be reluctant to privately implement land rehabilitation. On the other hand, manure and fertilizer with modest mitigation potential yielded relatively high profits.

The public costs of all the land management practices are lower than US$20 per ton of GHG mitigated in Africa. Afforestation and grassland rehabilitation cost governments more than $20 per ton of GHG mitigated in Asia and Latin

**FIGURE 5.1:** The Private Marginal Abatement Cost Curves



*Source:* This study.

**TABLE 5.1:** Private Savings of Different Technologies Per Ton of Carbon Dioxide Sequestered

| | LESS THAN US$50 | US$51 TO $100 | MORE THAN US$100 |
|---|---|---|---|
| Africa | Cover crops, residues, other soil amendments, terracing, afforestation, tree crop farming, rotation, rainwater harvesting, cross-slope barriers, pasture improvement, grazing management, pasture on degraded lands | Manure | No tillage, biochar, inorganic fertilizer, intercropping, alley farming |
| Asia | Intensify rotation, cover crops, crop-to-plantation, afforestation, annual-to-perennial grass, pasture on degraded land, grazing management, crop-to–grassland | Include trees, organic soil restoration, biofertilizer, improved irrigation | Residues, rainwater harvesting, inorganic fertilizer, no-tillage, manure, biochar |
| Latin America | Diversify trees, pasture-to-forest, cover crops, afforestation, pasture- to-plantation, intercropping, manure, include trees, residues, annual-to-perennial grass, pasture improvement | Pasture on degraded land | No-tillage, improved irrigation, diversify rotation, biochar, intensify rotation, rainwater harvesting, grassland–to-plantation, grazing management |

*Source:* This study.

America (table 5.2). Intensive vegetable production, biofertilizer application, and organic soil restoration also display relatively high costs in Asia, while in Latin America, the land management practices with the largest costs are mainly those associated with trees.

Figure 5.2 indicates that all the land management practices generate benefits to the farmers, but at varying costs to the public. Private benefits that motivate decisions often fall short of social costs, with the implication that in the absence of countervailing policies, GHGs from poor land management will continue to accumulate in the atmosphere. The total cost for afforestation was highest for Africa (US$2.8 billion), Asia (US$16.7 billion), and Latin America (US$5.5 billion), while the lowest total public cost was for terracing in Africa (US$18.7 million), inorganic fertilizer in Asia (US$154.7 million), and rotation diversification in Latin America (US$30.1 million).

The total mitigation potential varies from 2.3 Gt $CO_2$-eq for Latin America to 7.0 Gt $CO_2$-eq for Asia (table 5.3). Total private profits range from US$105 billion in Africa to $1.4 trillion in Asia, while total public costs range from $20 billion in Africa to $160 billion in Asia.

## 5.2 TRADE-OFFS IN SOIL CARBON SEQUESTRATION

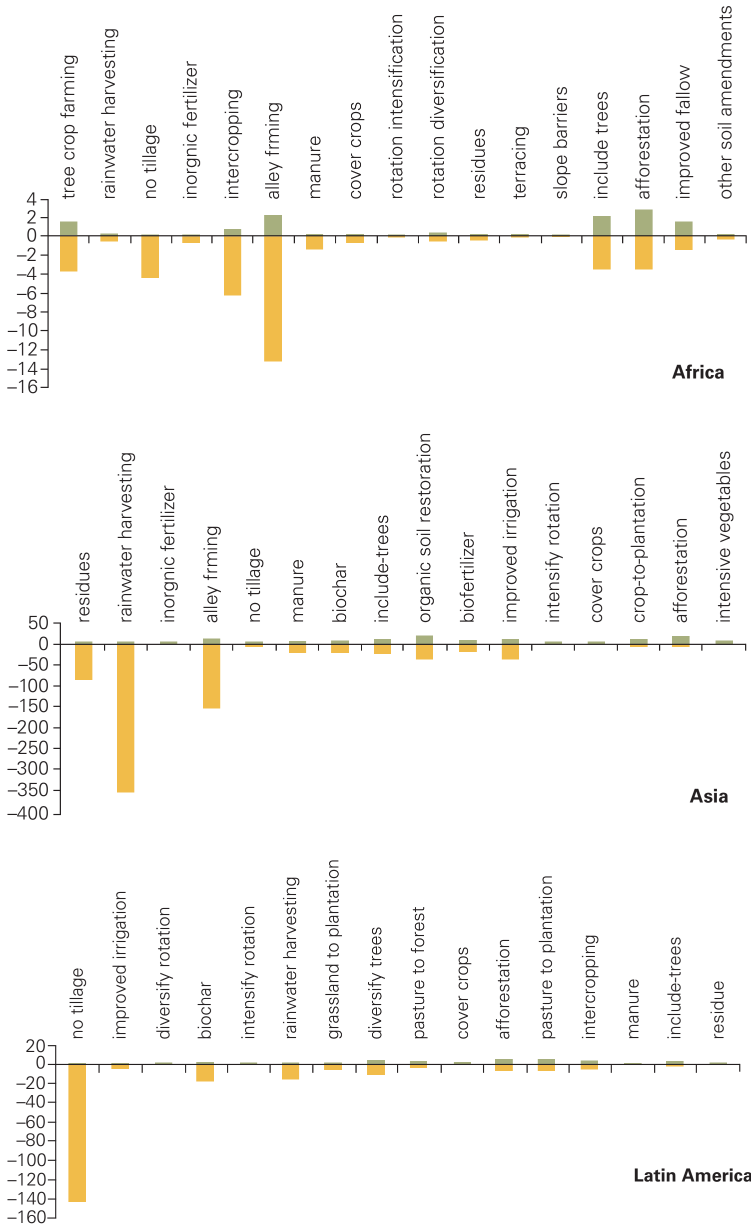
Trade-off is inherent in the attempt to achieve the triple wins of food security, increased resilience, and reduced GHG emissions. For instance, attempts to increase soil carbon storage through afforestation may reduce productivity (profitability), as afforestation tends to take land out of production for a significant period of time. Conversely, intercropping, the growing of crops near existing trees, provides synergy between profitability and increased soil carbon sequestration.

**TABLE 5.2:** Public Costs of Different Technologies Per Ton of Carbon Dioxide Sequestered

| | LESS THAN US$10 | US$10 TO $20 | MORE THAN US$20 |
|---|---|---|---|
| Africa | Tree crop farming, rainwater harvesting, no-tillage, manure, cover crops, rotation intensification, rotation diversification, residues, terracing, slope barriers, improved fallows, other soil amendments, improved pastures | Biochar, inorganic fertilizer, intercropping, alley farming, include trees, afforestation, pasture establishment on degraded land | |
| Asia | Residues, rainwater harvesting | No-tillage, manure, improved irrigation, intensify rotation, cover crops, crops-to-plantation, grazing management, cropland–to–grassland | Inorganic fertilizer, alley farming, biochar, include trees, organic soil restoration, biofertilizer, afforestation, intensive vegetables, annual-to-perennial grass, pasture establishment on degraded land |
| Latin America | No-tillage, diversify rotation, intensify rotation, rainwater harvesting, cover crops, manure, residues, grazing management | Improved irrigation, biochar | Grassland–to-plantation, diversify trees, pasture to forest, afforestation, pasture to plantation, intercropping, include trees |

*Source:* This study.

**FIGURE 5.2:** Total Private Benefits (Orange) and Public Costs (Green) of Land Management Practices (US$, Billion) for the B1 Scenario



*Source:* This study.

*Notes:* The public costs for Africa were adapted from a World Bank study on Nigeria's Agricultural, Forest, and Other Land Use sectors where public support for agriculture is 3 percent. The public costs for Asia and Latin America were assumed to increase proportionately to the state support for agriculture for China (8 percent) and Brazil (6 percent), respectively.

Synergies and trade-offs analyses can therefore help in quantifying the extent of "triple wins" of different land management technologies. Synergies and trade-offs in CSA affect decision making at various levels ranging from the household to the policy levels.

In this study, trade-off was analyzed by using two-dimensional graphs to depict relationships between carbon and profitability and between private benefits and public costs. The analysis was limited to the Africa dataset, as the graphs for other regions exhibit similar patterns leading to the same conclusions.

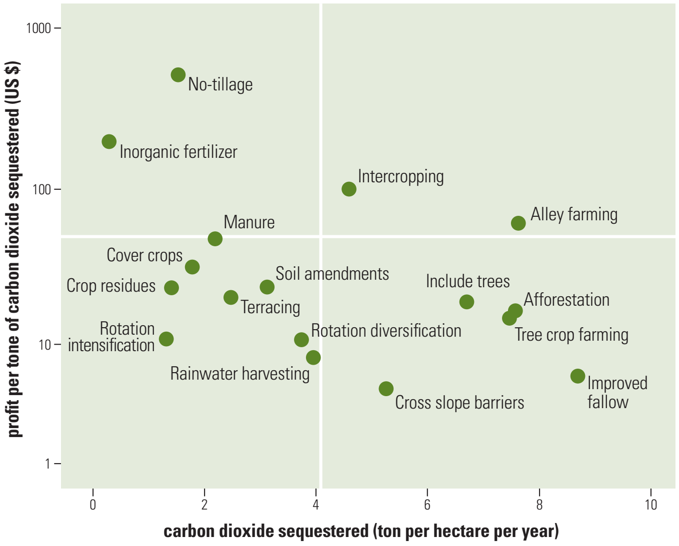
Figure 5.3 reveals synergies between profitability and mitigation in two agroforestry systems: intercropping and alley farming (top right quadrant of figure 5.3). Intercropping is

**TABLE 5.3:** Technical Mitigation Potential, Private Benefits, and Public Costs of the Land Management Technologies by 2030

| SCENARIO | TECHNICAL POTENTIAL (MILLION TONS $CO_2$-eq) | PRIVATE BENEFITS (US$, BILLION ) | PUBLIC COSTS (US$, BILLION ) |
|---|---|---|---|
| **Africa** | | | |
| B1 | 3,448 | 105.4 | 19.6 |
| A1b | 3,505 | 108.6 | 19.7 |
| B2 | 3,678 | 111.4 | 20.8 |
| A2 | 3,926 | 120.9 | 22.3 |
| **Asia** | | | |
| B1 | 5,977 | 1,224.5 | 131.3 |
| A1b | 6,388 | 1,259.3 | 143.6 |
| B2 | 7,007 | 1,368.1 | 159.7 |
| A2 | 6,678 | 1,310.8 | 150.4 |
| **Latin America** | | | |
| B1 | 2,321 | 273.8 | 40.8 |
| A1b | 2,425 | 279.4 | 42.9 |
| B2 | 2,538 | 288.8 | 44.3 |
| A2 | 3,097 | 319.4 | 55.1 |

*Source:* This study.
*Notes:* B1 = a world more integrated and more ecologically friendly; A1b = a world more integrated with a balanced emphasis on all energy sources; B2 = a world more divided but more ecologically friendly; A2 = a world more divided and independently operating self-reliant nations.

**FIGURE 5.3:** Trade-Offs Between Profitability and Carbon Sequestration of Sustainable Land Management Technologies in Africa



*Source:* This study.

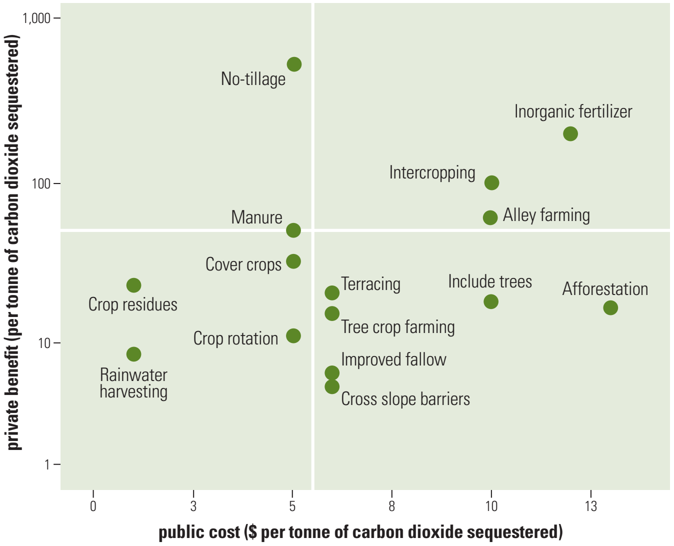
growing crops near existing trees, whereas alley farming is growing crops simultaneously in alleys of perennials, preferably leguminous trees or shrubs. Both are important strategies for increased productivity and resilience of the farming system. Land management technologies in the lower right quadrant of figure 5.3 have high carbon sequestration rates but are modestly profitable. Afforestation, improved fallow involving the use of fast-growing trees to accelerate soil rehabilitation, including trees in croplands, and establishing barriers across sloping areas, tends to take land out of production for a significant period of time. It reduces the amount of land available for cultivation in the short run, but can lead to overall increases in productivity and stability in the long run. The time-averaged, above-ground biomass of crop residues and other technologies in the lower left quadrant of figure 5.3 is relatively small compared to that of agroforestry systems. Also, the biomass of crop residues does not accumulate easily, resulting in lower mitigation benefits.

Judicious fertilizer application counters soil nutrient depletion, reduces deforestation and expansion of cultivation to marginal areas, and increases crop yields. Reversing developing countries' (especially Africa's) soil productivity declines cannot be adequately addressed without increased fertilizer use. Farmers apply 9 kg/ha of fertilizer in Africa compared to 86 kg/ha in Latin America, 104 kg/ha in South Asia, and 142 kg/ha in Southeast Asia (Kelly 2006). Yields also increase with manure application and accumulation of soil carbon, but with patterns that depend on crop type. Manure plays a crucial role in improving fertilizer use efficiency and soil moisture conservation Manure is less profitable than inorganic fertilizer because of the labor costs associated with collecting and processing manure (top left quadrant of figure 5.3). Manure also has quite low nutrient content relative to inorganic fertilizers, so a large amount needs to be applied on relatively small fields. This explains why manure works well for small-scale intensive and high-value vegetable gardening. Manure systems are also associated with high methane emissions. The relatively high profitability of no-tillage derives primarily from the decrease in production costs after establishment of the system.

The relationship between public costs and private benefits of the land management technologies is shown in figure 5.4. Public cost refers to government support toward the implementation of land management practices. They include investments in seeds and seedlings, input subsidies, extension services, and other administrative costs. The pattern of public support is as crucial as the amount of support for full realization of productivity, mitigation, and adaptation benefits in agriculture. Public support that focuses on research, investments in improved land management, and land tenure rather than on input support are generally more effective, benefit more farmers, and are more sustainable in the long run.

Technologies that involve significant change in land-use (afforestation and improved fallows) and landscape alteration (terracing and cross-slope barriers) incur high public costs but generate low private benefits (lower right quadrant of figure 5.4). The low profits suggest that farmers may be reluctant to privately invest in these technologies. Strong public

**FIGURE 5.4:** Relationship between Private Benefits and Public Costs in Africa



*Source:* This study.

involvement in these technologies is justifiable given their relatively high mitigation potentials. Crop residues, cover crops, crop rotation, and rainwater harvesting with lower profits and also manure and no tillage that generate relatively higher profits require minimal government support (lower left and upper left quadrants of figure 5.4, respectively). These technologies generally have low mitigation potentials. The relatively high public cost of inorganic fertilizer (top right quadrant, figure 5.4) reflects the use of subsidies in spurring farmers' access to the technology. Fertilizer subsidy is, however, associated with high fiscal costs, difficult targeting, and crowding out of commercial sales. Thus, fertilizer subsidies are appropriate in situations when the economic benefits exceed costs, the subsidies help achieve social rather than economic objectives, and the support helps improve targeting through market-smart subsidies while providing impetus for private sector input development. Examples of market-smart subsidies include demonstration packs, vouchers, matching grants, and loan guarantees (Agwe, Morris, and Fernandes 2007).

## 5.3 IMPLICATIONS OF THE TRADE-OFFS IN LAND-USE DECISIONS

The trade-offs exhibited by the land management technologies have important implications for land-use decision making. Sustainable land management interventions should be planned and implemented in a coordinated manner across space, time, and sectors. Working at the landscape level with an ecosystems approach is useful for addressing food security and rural livelihood issues and in responding to the impacts of climate change and contributing to its mitigation. The landscape level is the scale at which many ecosystem processes operate and at which interactions among agriculture, environment, and development objectives are mediated. It entails the integrated planning of land, agriculture, forests, fisheries, and water at local, watershed, and regional scales to ensure synergies are properly captured. The landscape approach provides a framework for the better management of ecosystem services, such as agricultural productivity, carbon storage, fresh water cycling, biodiversity protection, and pollination. It allows trade-offs to be explicitly quantified and addressed through negotiated solutions among various stakeholders.

Two examples taken from World Bank (2011c) illustrate the efficacy of the landscape approach. The first example is the silvopastoral farming systems of Costa Rica and Nicaragua. After several years of intensive grazing in Costa Rica and Nicaragua, pastures were degraded, erosion was accelerating, and livestock productivity was falling. To address these challenges, a pilot project introduced silvopastoral techniques

**PHOTO 5.1:** Terracing and Landscape Management in Bhutan

*Source:* Curt Carnemark/World Bank.

to 265 farms on 12,000 ha between 2001 and 2007. A payment scheme for environmental services—carbon sequestration and biodiversity conservation—was introduced as an additional income stream for livestock production. Silvopastoral techniques were used to transform degraded lands with monocultures of one grass species into more complex agroforestry systems of different tree species, live fences, riparian forests, and trees dispersed in pastures. The techniques have been shown to enhance biodiversity, sequester carbon, and reduce methane emissions. Results showed a typical win-win situation: An annual sequestration of 1.5 Mt of $CO_2$-equivalent was accompanied with increases of 22 percent in milk production, 38 percent in stocking rate, and 60 percent in farm income. The methane emission per product kilogram decreased, while biodiversity (measured by the number of bird species and water quality) increased.

The last example is one of the world's largest erosion control programs in China. Revegetation has successfully restored the devastated Loess Plateau to sustainable agricultural production, improving the livelihoods of 2.5 million people and securing food supplies in an area where food was sometimes scarce in the past. The project encouraged natural regeneration of grasslands, trees, and shrubs on previously cultivated sloping lands. Replanting and a grazing restriction allowed the perennial vegetation cover to increase from 17 to 34 percent between 1999 and 2004, sustaining soil fertility and enhancing carbon sequestration. Together with terracing, these measures not only increased average yields, but also significantly lowered their variability. Agricultural production has changed from generating a narrow range of food and low-value grain commodities to high-value products. As a result, the evolution of farm and family incomes has shown a steady increase. It is estimated that as many as 20 million people have benefited from the replication of the Loess Plateau approach throughout China.

## 5.4 SUSTAINABLE LAND MANAGEMENT ADOPTION BARRIERS

Despite the fact that improved land management technologies generate private benefits, their adoption faces many socioeconomic and institutional barriers. The commonly cited risk-related barriers to adoption of carbon sequestering technologies in agriculture are permanence, leakage, and additionality (box 5.1). Beyond these, there are a number of other implementation constraints.

First, most of the land management technologies require significant up-front expenditure that poor farmers cannot afford. Second, the nonavailability of inputs in the local markets can be a significant barrier in situations where farmers might want to invest in a technique. Third, lack of information on the potentials of alternative techniques of farming and limited capacity is a major constraint in many developing countries. Fourth, when technologies are inconsistent with community rules and traditional practices, their adoption will most likely encounter the resistance of the people. Last, willingness and the ability to work together are crucial for many technologies such as improved irrigation and communal pastures. The absence of collective action will hinder successful uptake, diffusion, and impact of these land management technologies.

Factors affecting adoption tend to be more specific to the land management technologies. Table 5.4 suggests that lack of credit and inputs and land tenure problems are by far the most important factors for adoption across the range of technologies. However, improved availability of inputs is a necessary but insufficient condition for adoption of land management practices. Better market prices for crops and other agricultural produce are crucial. Secure land rights is a precondition for climate-smart agriculture as it provides incentive for local communities to manage land more sustainably. Ill-defined land ownership may inhibit sustainable land management changes.

Behavioral change through education is required to enable changeover to improved land management technologies. For instance, conservation agriculture, the farming system involving no-tillage, residue management, and use of cover crops, is highly knowledge intensive, requiring training and practical experience of those promoting its adoption. Learning hubs, regional platforms, scientific research, south-south knowledge exchange, and technical support mechanisms may increase innovation and facilitate adoption of improved land management technologies. The knowledge base of land management practices at the local level can also be improved through careful targeting of capacity development programs.

Table 5.5 summarizes possible demand- and supply-side interventions for facilitating the adoption of sustainable land management inputs. It is unlikely that any of these interventions alone will be effective in increasing input use. Careful selection of combinations of demand- and supply-side measures will allow the demand and supply to grow, leading to the emergence of viable private sector–led input markets.

## 5.5 POLICY OPTIONS FOR SOIL CARBON SEQUESTRATION

Private benefits that drive land-use decisions often fall short of social costs; thus, carbon sequestration may not reach an

### **BOX 5.1:** Risk-Related Barriers to Adoption of Soil Carbon Sequestration Activities

- *Permanence:* Permanence refers to the secure retention of newly sequestered carbon. Carbon sequestration only removes carbon from the atmosphere until the maximum capacity of the ecosystem is reached, which may be about 25 years for most land management practices. Storage of carbon in soils is relatively volatile and subject to re-emission into the atmosphere in a subsequent change in land management. The risk of nonpermanence is lower when the adoption of soil carbon sequestration practices also leads to more profitable farming systems. Note that not all agricultural mitigation options are transient. Substitution of fossil fuels by bioenergy is a permanent mitigation option, and reduction in nitrous oxide and methane emissions are nonsaturating.
- *Leakage:* Leakage occurs when a project displaces greenhouse gas emissions outside its boundary. For instance, control of grazing in an area might force herders to move their animals to another location. Economic adjustment to meet market demand is the underlying driver of leakage. Macroeconomic policies induce changes in market conditions and prices, which in turn influence farmers' land-use and management practices. While most occurrence of leakage has a negative effect on project benefits, positive leakage spillover effects that lead to reduction in emissions outside the project boundary can occur. This could be as a result of technology transfer or changes in market conditions that stimulate mitigation activities.
- *Additionality*: The concept implies that in order to attract compensation, emissions reduction must be in addition to what would have occurred under the business-as-usual scenario. Additionality is usually calculated as postproject carbon stocks less the forward-looking baseline, less deduction for leakage and risk of reversal, and less emission generated by the project (Fynn *et al*. 2010).

Permanence, leakage, and additionality can be addressed through temporary crediting, ex ante discounting, and comprehensive accounting (Murray *et al*. 2007).

| | TEMPORARY CREDITING | EX ANTE DISCOUNTING | COMPREHENSIVE ACCOUNTING |
|---|---|---|---|
| Description | Balances debits and credits for finite periods with provision for reversal | Accounts for the possibility of future loss by reducing the amount of credit at the onset based on the expectation of reversal | Balances debits and credits as they occur in the course of the project. These can be based on stock change or average stock change during the period |
| Environmental rigor | Rigorous as temporary credits must be replaced when they expire | Credits may not equal debits for a given project; as such, *ex ante* discounting may lead to underdebiting or overdebiting of ex post reversal. | This achieves consistency as long as the system is monitored perpetually |
| Feasibility of implementation | Enables up-front payment; book balancing at the end of the project is also possible | Relatively easy to impose discounts on credits if amounts of reversal can be reasonably projected | Boosts attractiveness of investment by allowing credits to be earned as soon as they are generated by the project; however, perpetual accounting may hinder balancing the books at the end of a finite-life project |
| Transaction costs | Measurement, monitoring, and verification (MMV) and contract renewal costs need to be borne by the project | MMV are not necessary; rather, credits are reduced by formula, not observed changes in carbon | MMV are carried out into perpetuity |

*Source:* Table synthesized from Murray *et al*. 2007.

optimal level from a social point of view unless some mechanisms exist to encourage farmers. Some public policies that can potentially incentivize carbon sequestration include the following:

1. *Strengthen the capacity of governments to implement climate-smart agriculture.* Countries must be prepared to access new and additional finance. There is a need to build the technical and institutional

**TABLE 5.4:** Relative Importance of Different Factors for Adopting Improved Land Management Practices

| LAND MANAGEMENT TECHNOLOGY | INPUTS/ CREDITS | MARKET ACCESS | TRAINING/ EDUCATION | LAND TENURE | RESEARCH | INFRASTRUCTURE |
|---|---|---|---|---|---|---|
| Inorganic fertilizer | *** | ** | ** | ** | * | ** |
| Manure | ** | ** | * | ** | * | ** |
| Conservation agriculture | ** | ** | *** | ** | ** | * |
| Rainwater harvesting | ** | ** | ** | *** | ** | ** |
| Cross-slope barriers | ** | * | ** | ** | ** | * |
| Improved fallows | ** | * | * | *** | ** | * |
| Grazing management | *** | *** | ** | *** | ** | * |

_Source:_ Synthesized from Liniger _et al._ 2011.
_Key * = Low importance, ** = Moderate importance; *** = High importance._

**TABLE 5.5:** Interventions for Facilitating Increased Input Use

| DEMAND-SIDE INTERVENTIONS | SUPPLY-SIDE INTERVENTIONS |
|---|---|
| **Strengthen soil-crop research and extension**<br>Support to public agencies<br>Public-private partnership<br>On-farm trials and demonstrations | **Reduce input sourcing costs**<br>Lowering trade barriers to increase national and regional market size |
| **Improve farmers' ability to purchase inputs**<br>Improve access to credits<br>Phased and incremental use (e.g., small bags for fertilizers)<br>Implement laws that enables farmers to use risk-free collaterals for loans | **Reduce distribution costs**<br>Improve road and rail infrastructure to lower transport costs |
| **Provide farmers with risk management tools**<br>Improved weather forecasting, weather-indexed crop insurance | **Strengthen business finance and risk management**<br>Use credit guarantee and innovative insurance schemes |
| **Improved quality and dissemination of market information**<br>Public and private sector information systems easily accessible to farmers | **Improve supply chain coordination mechanisms**<br>Product grades and standards<br>Market information systems to reduce information costs |
| **Protecting farmers against low and volatile output prices**<br>Investment in measures to reduce production variability such as drought-tolerant crops, deep-rooted crops, irrigation, and storage systems | |
| **Empowering farmers by supporting producer organizations**<br>Investment in rural education<br>Training farmers in organizational management | |
| **Improving the resource base so that input use is more profitable**<br>Investment in soil and water management and irrigation infrastructure | |

_Source:_ Modified from Agwe, Morris, and Fernandes (2007).

capacity of government ministries to implement climate-smart agriculture programs. Existing national policies, strategies, and investment plans should be strengthened to form the basis for scaling-up investments for climate-smart agriculture. Readiness for carbon sequestration and climate-smart agriculture can be achieved through improved extension services and training in relevant land management technologies for different locales.

2. *Global cooperative agreement*. Given the tremendous significance that agriculture has for the global climate, progress in incorporating it into the UNFCCC has been slower than many people hoped for. Although the negative impacts of agricultural production in terms of land-use change and GHG emissions were reasonably well covered by the convention, the real and potential contributions the sector can and does make in terms of sequestering carbon in agricultural biomass and soils were for the most part omitted. Redressing this omission promises to foster a more balanced perspective in which food security is not necessarily at odds with climate change adaptation

and mitigation (an unworkable conflict in which longer term environmental concerns are virtually guaranteed to universally lose out politically to the more immediate concern of food supply). A more practical and thorough picture makes it possible for agriculture to be rewarded for its positive environmental impacts, and to be an integral part of "the solution" as well as part of "the problem." This is vitally important because agriculture needs to be fully incorporated into adaptation and mitigation strategies. As a result, the international community has recognized the importance of integrating agriculture into the ongoing negotiations on the international climate change regime. At the 17th Conference of Parties to the UNFCCC in Durban, South Africa, in November, 2011, the parties asked the UNFCCC Subsidiary Body for Scientific and Technological Advice to explore the possibility of a formal work program on agriculture.

3. *Boost financial support for early action*. A blend of public, private, and development finance will be required to scale-up improved land management practices. Integrating sources of climate finance with those that support food security may be one of the most promising ways to deliver climate-smart agriculture with the resources it requires. For technologies that generate significant private returns, grant funding or loans may be more suitable to overcoming adoption barriers. For technologies such as conservation agriculture that require specific machinery inputs, and significant up-front costs, payment for ecosystem services scheme could be used to support farmers and break the adoption barrier. There is also the potential for carbon finance to support farmers during the initial period before the trees in agroforestry systems generate an economic return.
4. *Raise the level of national investment in agriculture.* While this may appear a tall order in countries with severe budget constraints, finite public resources can be more selectively targeted using the criteria given above—prioritizing technologies that generate no short-term returns and those that most effectively address the barriers that prevent prospective adopters from moving forward. In some cases, relatively affordable technologies that generate quick and demonstrable benefits may warrant priority and potentially establish some of the channels through which more sophisticated technologies are dispersed in the future. Nationally owned climate-smart agricultural policies and action frameworks will increase the adoption of sustainable land management practices. However, public investment is only one sphere, involving the private sector in climate-smart agriculture and sustainable land management is the other.
5. *Create enabling environments for private sector participation*. Introducing policies and incentives that provide an enabling environment for private sector investment can increase overall investment. This private investment can be targeted to some degree as well, particularly when government priorities translate clearly into business opportunities and certain areas of investment are looked upon favorably by public officials and institutions. Public investment can also be used to leverage private investment in areas such as research and development, establishing tree plantations, and in developing improved seeds and seedlings. Particular attention should go to encouraging private financial service providers to tailor instruments that enable farmers who adopt SLM practices to overcome the barriers described above. Bundling agricultural credit and insurance together and providing different forms of risk management, such as index-based weather insurance or weather derivatives, are areas of private investment that can be encouraged through public policy and public-private partnerships.

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# Appendix A: FARMING PRACTICE EFFECT, NUMBER OF ESTIMATES, AND FEATURE IN LAND MANAGEMENT PRACTICES

## Africa

| LAND MANAGEMENT PRACTICES | NUMBER OF ESTIMATES | SUBTOTALS | MEAN DURATION | MEAN DEPTH | EXPERIMENTAL DESIGN (%) |
|---|---|---|---|---|---|
| **Nutrient management** | | **60** | **8.3** | **15** | **100** |
| Chemical fertilizer | 30 | | | | |
| Animal manure | 30 | | | | |
| **Tillage and residue management** | | **184** | **4** | **15** | **100** |
| No tillage | 108 | | | | |
| Residues | 46 | | | | |
| Mulches | 6 | | | | |
| Cover crops | 24 | | | | |
| **Agroforestry** | | **185** | **6** | **22** | **100** |
| Trees/forest | 125 | | | | |
| Intercropping | 14 | | | | |
| Alley farming | 46 | | | | |
| Tree-crop farming | 44 | 44 | 2.2 | 18.4 | |
| **Land-use changes** | | **103** | **3** | **20** | **100** |
| Afforestation | 16 | | | | |
| Grazing pasture | 32 | | | | |
| Cropping intensity | 55 | | | | |
| **Soil management** | | **187** | **4.5** | **10** | **100** |
| Crop rotation | 49 | | | | |
| Improved fallow | 71 | | | | |
| Natural fallow | 68 | | | | |
| **Water management** | | **56** | **2.5** | **12** | **100** |
| Water/rain harvesting | 33 | | | | |
| Slope/barriers | 22 | | | | |
| Terracing | 15 | | | | |
| **Others** | | | | | **100** |
| Biochar | 11 | 11 | 1.8 | 7.4 | |
| Soil amendment | 15 | 15 | 1.8 | 10 | |

### Asia

| PRACTICES | NUMBER OF ESTIMATES | SUBTOTALS | MEAN DURATION (yr) | MEAN DEPTH (cm) | EXPERIMENTAL DESIGN (%) |
|---|---|---|---|---|---|
| **Nutrient management** | | **443** | **17.0** | **26** | **97** |
| Application of fertilizer | 297 | | | | |
| Application of manure | 146 | | | | |
| **Tillage and residue management** | | 328 | 9.3 | 20 | 99 |
| Reduced or no till | 48 | | | | |
| Return of crop residues to field | 189 | | | | |
| Application of mulches | 53 | | | | |
| Cover crops | 38 | | | | |
| **Agroforestry** | | **75** | **8.3** | **27** | **64** |
| Inclusion of trees | 58 | | | | |
| Intercropping | 17 | | | | |
| **Intensification** | | **150** | **14.4** | **49** | **34** |
| Intensive vegetables | 57 | | | | |
| Annual-to-perennial | 36 | | | | |
| Intensify rotation | 43 | | | | |
| Improved irrigation | 10 | | | | |
| Rain harvest | 4 | | | | |
| **Land-use change** | | **292** | **18.5** | **29** | **5** |
| Crop-to-forest | 60 | | | | |
| Crop-to-plantation | 158 | | | | |
| Crop-to-grassland | 35 | | | | |
| Reduced grazing | 39 | | | | |
| **Other amendments and practices** | | **25** | **8.6** | **18** | **100** |
| Biochar | 6 | | | | |
| Bio-inoculant | 3 | | | | |
| Gypsum | 8 | | | | |
| Sulfur | 5 | | | | |
| Lime | 2 | | | | |
| Zinc | 1 | | | | |
| **TOTAL** | | | **14.5** | **29** | **68** |

**Latin America**

| PRACTICES | NUMBER OF ESTIMATES | SUBTOTALS | MEAN DURATION (yr) | MEAN DEPTH (cm) | EXPERIMENTAL DESIGN (%) |
|---|---|---|---|---|---|
| **Nutrient management** | | **99** | **9.7** | **17.2** | **92** |
| Application of fertilizer | 74 | | | | |
| Application of manure | 25 | | | | |
| **Tillage and residue management** | | **364** | **8.9** | **21.8** | **90** |
| Reduce or no till | 249 | | | | |
| Return of crop residues to field | 56 | | | | |
| Application of mulches | 16 | | | | |
| Cover crops | 33 | | | | |
| Graze residues | 10 | | | | |
| **Agroforestry** | | **56** | **8.1** | **24.3** | **61** |
| Inclusion of trees | 43 | | | | |
| Diversify trees | 6 | | | | |
| Intercropping | 7 | | | | |
| **Intensification** | | **138** | **15.5** | **33.0** | **64** |
| Intensify rotation | 25 | | | | |
| Diversify rotation | 43 | | | | |
| Improved irrigation | 34 | | | | |
| Improved pasture | 15 | | | | |
| Improved fallow | 8 | | | | |
| Annual-to-perennial | 13 | | | | |
| **Land-use change** | | **257** | **19.0** | **38.5** | **5** |
| Pasture-to-forest | 62 | | | | |
| Crop-to-forest | 59 | | | | |
| Pasture-to-plantation | 53 | | | | |
| Grassland-to-plantation | 32 | | | | |
| Crop-to-plantation | 14 | | | | |
| Crop-to-pasture | 7 | | | | |
| Reduced or excluded grazing | 30 | | | | |
| **Other amendments** | | **17** | **5.2** | **29.1** | **82** |
| Biochar | 8 | | | | |
| Lime | 9 | | | | |
| **TOTAL** | | **931** | **12.6** | **28.5** | **61** |

*Source:* This study.

# Appendix B: GENERAL SCENARIO ASSUMPTIONS AND APPLICATION FOR WORLD REGIONS

## B.1 BASELINE SCENARIO

Using the initial soil carbon stocks (in t C/ha) from the Harmonized World Soil Database, the models were run in reverse mode to estimate

- initial carbon mass of decomposable plant material (DPM),
- initial carbon mass of resistant plant material (RPM),
- initial carbon mass of fast decomposing biomass (BIO-F),
- initial carbon mass of slow decomposing biomass (BIO-S),
- initial carbon mass of humified organic matter (HUM), and
- initial carbon mass of soil.

All models were run to equilibrium state increasing the organic inputs in 0.1 t C steps until the initial carbon stock represented the equilibrium of the specific soil in each stratum. The required addition of organic inputs to the soil varied greatly depending on climate parameters and the clay content of the soil. However, the inputs were in line with observations made by Young (1997), who estimated plant biomass requirements to maintain soil organic matter range between 3.5, 7, and 14 t d.m. per ha per year for semi-arid, subhumid, and humid ecosystems, respectively.

For each stratum, one low organic input baseline scenario was modeled for each crop and crop area, respectively, assuming a conventional management of 15 percent of residues left on the ground after harvesting.

## B.2 GLOBAL MITIGATION SCENARIOS

### Residue and Integrated Nutrient Management

This scenario implies additional residue inputs due to crop management improvement. The calculation of residues inputs from the crops was based on the global crop yield data. The average fresh yield was converted to amount of residues produced on the basis of IPCC equations (IPCC 2006).

Crop yields were grouped into three bins representing the 25th percentile, the 50th percentile, and the 75th percentile of the yields of a specific crop in one stratum to assess the opportunity of adapting the residue management to local situations.

Further, it served as a proxy to consider increase of yields over time due to improved management practices including the increase in application of inorganic fertilizer (integrated nutrient management). For instance, a farmer in a specific stratum whose current maize yield is within the 25th percentile may be able to increase the yields to within the 75th percentile due to increased inorganic fertilizer application.

Two scenarios were considered with regard to increased productivity as a result of integrated nutrient management practices: A shift from low productivity to medium productivity (25 percentile to 50 percentile of crop yields in a specific stratum) and a shift from medium to high productivity (50 percentile to 75 percentile of crop yields in a specific stratum). The crop yields for each stratum are presented in Appendix C.

### Manure Management

Generally, manure management can be classified into direct manure application and application of composted manure. Similar to the procedure for residue calculation, the raw manure and composted manure model inputs in tC/ha were estimated by applying IPCC factors to the average amount of farm animals per ha (IPCC 2006). The global data estimated manure application in kg per ha of nitrogen. Therefore, the C input per ha for each kg N was calculated based on Food and Agriculture Organization of the United Nations (FAOSTAT) numbers of cattle, sheep, goats, pigs, and poultry for each region.

The amount of manure/composted manure represents the amount of potential manure production and not the amount of manure actually spread on the field in the baseline. For each stratum, the average manure/composted manure production was calculated for its use in the *RothC* model. Improved manure and composted manure application are considered mitigation opportunities for all climatic regions.

### Green Manure/Cover Crops

Green manure is a type of cover crop grown to add organic matter and nutrients to the soil. On average, such crops yield around 4 t dry matter $ha^{-1}$ $yr^{-1}$. The above-ground biomass was converted into t C $ha^{-1}$ $yr^{-1}$ using the IPCC equations for N-fixing forage, non-N-fixing forage, and grass, and then computing the average value for *RothC* modeling. Based on this average conversion, the input value for the model was 1.44 t C $ha^{-1}$, of which 0.43 C $ha^{-1}$ was allocated as above-ground input and 1.01 C $ha^{-1}$ as below-ground input.

### Agroforestry and Improved Fallow

Agroforestry, including improved fallow, was considered a mitigation potential for all climate regions.

Based on the literature research, the input value for the *RothC* model concerning improved fallow is found to be similar to that of other agroforestry systems. Take for instance, the following:

- In Zambia, improved fallows in maize systems with several nitrogen-fixing tree species (both coppiced and noncoppiced) resulted in above-ground carbon inputs of 2.8 tC/ha on average (Kaonga and Coleman 2008).
- In Asia, the introduction of the mungbean (*Vigna radiata*) as a grain legume in the short fallow of the wheat-rice system produced a total biomass of 4.5 t d.m./ha (Yaqub *et al.* 2010).
- In Mexico, the use of several varieties of mucuna (*Mucuna pruriens*) in rotation with maize produced on average 6.8 t d.m./ha (Eilittä *et al.* 2003).

Compared to green manure/cover crops, a robust average input value was used based on input values from various studies for tropical and temperate climate regions, covering a wide range of different agroforestry practices such as alley cropping, trees on cropland, and so forth (Oelbermann, Voroney, and Gordon 2005a, 2005b; Gama-Rodrigues and Antonio 2011). Based on this, the input value for tropical and temperate agroforestry systems averaged 2.3 tC/ha and 1.06 tC/ha, respectively. These values represent the organic input from trees to the soil, either as litter or through pruning and mulching.

## B.3 APPLICATION TO WORLD REGIONS

### Africa

In Africa, crop yields have remained stagnant for decades due to continuous depletion of soil organic matter over time from unsustainable practices. To reverse this situation, sustainable practices such as cover cropping, water harvesting, agroforestry, and water and nutrient management to improve soil carbon sequestration, increase yields, and enhance resilience to climate change need to be adopted.

Agroforestry options that produce high-value crops and additional sources of farm revenues offer additional mitigation benefits. In general, the best package of practices for soil carbon sequestration for the region consists of a combination of manure application, fertilizer application, and residue management.

There is a significant trade-off between residues on the field versus residues used for livestock feeding. Therefore, 50 percent residue retention was assumed, and the remaining 50 percent was assumed to be removed as animal feed. All mapping units (see page 45) in Africa were considered for the modeling. A residue management scenario of 50 percent of available residues per ha was modeled for each of the main crops in Africa. In addition, manure management (direct and composting), green manuring, and agroforestry were modeled for each cluster.

### Asia

In many areas, the most dominant farming system is intensive wetland rice cultivation with or without irrigation. Rice is grown in the wet season under dry land farming. In the dry season, a second crop of rice (where irrigated) or another less water–demanding crop (legumes and coarse grains) is grown. Apart from rice, mixed smallholder farming systems are dominant (soybean, maize, wheat, and roots and tubers) with currently low input (organic and inorganic), apart from Southeast Asian countries.

Like Africa, there exists a significant trade-off between residues on the field versus residues used for livestock feeding. All mapping units in Asia were considered for the modeling. A residue management scenario of 50 percent of available residues per ha was modeled for each of the main crops in Asia. In addition, manure management (direct and composting), green manuring, and agroforestry were modeled for each of the strata.

**TABLE B.1:** Agricultural Systems and Mitigation Scenario in South America

| MAPPING UNIT/ STRATUM | WHEAT<br>SOYBEAN<br>MAIZE | SOYBEAN<br>MAIZE | BEANS<br>MAIZE | RICE | AGROFORESTRY |
|---|---|---|---|---|---|
| **2** | | | | | |
| **4** | | | | | |
| **6** | | | | | |
| **8** | | | | | |
| **9** | | | | | |
| **12** | | | | | |
| **Mitigation options** | Cover crop | Cover crop no-tillage | Cover crop | Cover crop<br>residue management | |

*Source:* This study.

### South America

Several agricultural systems exist in South America. The agricultural systems found in the mapping units/stratum are displayed in Table B.1.

Common land management practices in South America include rotational wheat/soybean and fallow systems, maize and soybean systems with residue management, and tillage. The use of a cover crop during the fallow period was identified as a promising mitigation opportunity. No-tillage was identified as another mitigation option. Residue management in rice systems was modeled. No-tillage in soybean/maize systems was modeled and applied to the area where soybeans and maize are grown. Cover crop was modeled and applied to the total area of crops for which green manuring is practiced.

### Central America

The most dominant agricultural systems in Central America are sorghum, beans/maize, rice, and agroforestry (table B.2). Compared to South America, cover crops and residue management of rice-based systems were identified as mitigation options.

### North America

The dominant crops in mapping unit 1 are barley, wheat, soybean, maize, and pulses. Those in zone 3 are barley, wheat, soybean, maize, pulses, and sorghum. In zone 7, wheat, soybean, and maize predominate. Crops are mostly cultivated during the summer with bare fallow during the winter. In recent years, no-tillage has been adopted by many producers, but there are still opportunities to increase its use. No-tillage was considered a mitigation option in 50 percent of the cropped area. Green manure using winter cover crops during the fallow period was also modeled.

### Oceania

The main crops are wheat, barley, and pulses cultivated as winter crops and usually in rotations. No-tillage is used in

**TABLE B.2:** Agricultural Systems and Mitigation Scenario in Central America

| MAPPING UNIT/ STRATUM | SORGHUM | BEANS<br>MAIZE | RICE | AGROFORESTRY |
|---|---|---|---|---|
| **2** | 🟩 | | | |
| **4** | | 🟩 | | |
| **6** | | 🟩 | | |
| **9** | | 🟩 | 🟩 | |
| **10** | | 🟩 | 🟩 | 🟩 |
| **12** | | 🟩 | 🟩 | 🟩 |
| **Mitigation options** | | Cover crop | Cover crop<br>Residue management | |

*Source:* This study.

approximately 50 percent of the cropped area. Residue is commonly left on the field or incorporated (around 75 percent of the cropped area). Residues are sometimes burnt just before sowing.

### Russia

The main crops are wheat and barley cultivated as summer crops with bare fallow during the rest of the year. Tillage is frequently used. No-tillage was modeled with the average value for organic inputs for the two main crops used. Winter cover crops during the fallow period for green manure were also modeled.

### Europe

The main crops are wheat and barley in winter and maize in summer. Cover crops and no-tillage techniques are rarely used (around 1 percent). The scenarios modeled include use of no-tillage. For each climate zone, the average value of inputs for the main crops was used. For mapping units 2, 7, and 8, no-tillage was assumed to be suitable on 35 percent of the cropped area. Cover crops during the fallow period for green manure were also modeled. For each zone, the average value for summer and winter cover crops was used.

## B.4 DETAILED MODELING FOR AFRICA

### Residue and Integrated Nutrient Management

This scenario implies additional residue inputs due to crop management improvement. The calculation of residues inputs from the crops was based on the crop yield data identified above. The average fresh yield (for instance maize) was converted to amount of residues using IPCC Guidelines.

Crop yields were grouped into three bins representing the 25th percentile, the 50th percentile, and the 75th percentile of the yields of a specific crop in one stratum to assess the opportunity of adapting the residue management to local situations. To account for possible trade-offs between retention of residues in the field and residues needed as livestock feed, different fractions of residues applied in the field were modeled (25 percent, 50 percent, and 75 percent). Each crop was modeled separately, but if there was more than one cropping season, each season was modeled separately (e.g., maize 1s and maize 2s).

### Manure Management

Generally, manure management can be classified into direct manure application and application of composted manure. Similar to the procedure for residue calculation, the raw manure and composted manure model inputs in t C/ha were estimated by applying IPCC factors to the average amount of farm animals per ha (IPCC 2006). The C input per ha was calculated based on FAOSTAT numbers of cattle, sheep, goats, pigs, and poultry for each country of each region. For each mapping unit, the average manure/composted manure production was calculated for its use in the *RothC* model (table B.3).

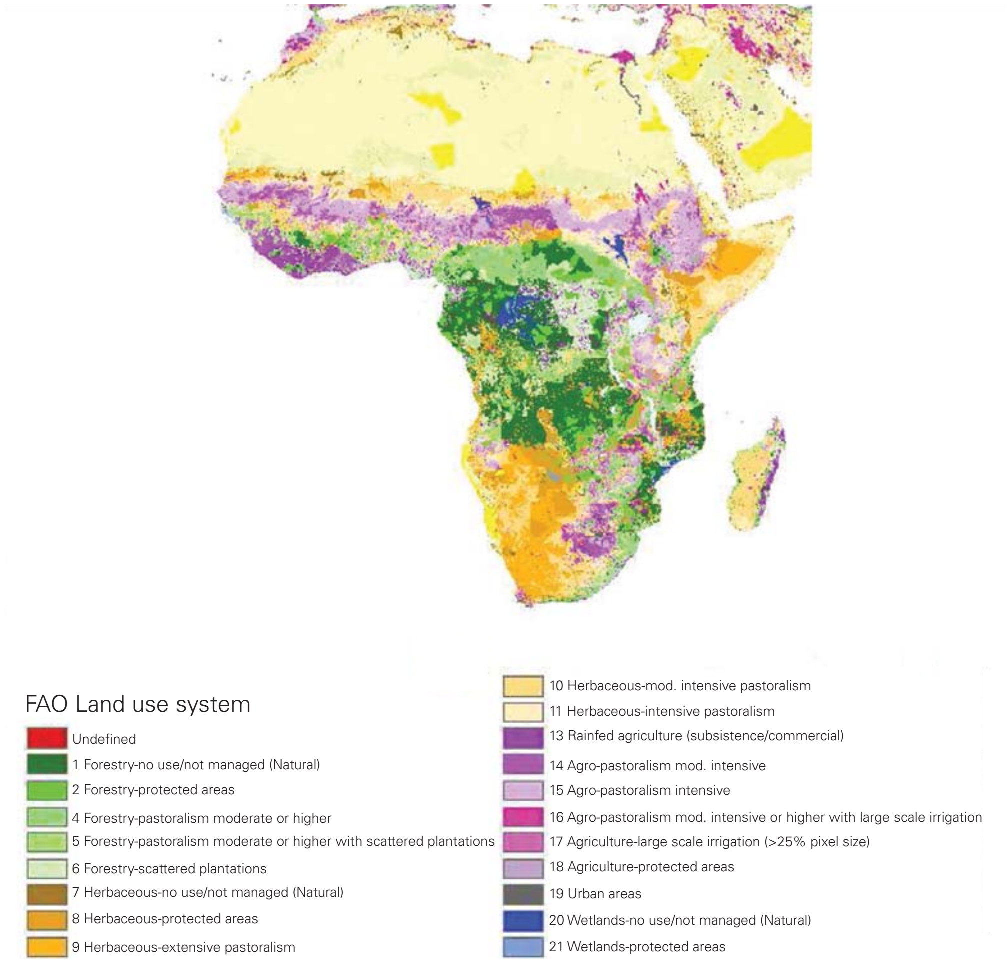
Direct manure and composted manure application were modeled in combination with different fractions of crop residues (25 percent, 50 percent, and 75 percent) left in the field.

**TABLE B.3:** Manure C Inputs for the Agroecological Zones (AEZs) in Africa Based on FAOSTAT

| MAPPING UNIT/AEZ | DIRECT MANURE t C/hA/APPL. | COMPOSTED MANURE t C/hA/APPL. |
|---|---|---|
| 1 | 0.031 | 0.075 |
| 2 | 0.035 | 0.085 |
| 3 | 0.032 | 0.078 |
| 4 | 0.029 | 0.070 |
| 5 | 0.030 | 0.073 |
| 6 | 0.017 | 0.042 |
| 7 | 0.046 | 0.110 |
| 8 | 0.019 | 0.046 |
| 9 | 0.023 | 0.057 |
| 10 | 0.025 | 0.061 |
| 11 | 0.056 | 0.136 |
| 12 | 0.096 | 0.232 |

*Source:* This study.

**FIGURE B.1:** FAO Land-Use Map



*Source:* FAO and World Bank.

### Green Manure/Cover Crops (GMCCS)

Based on a study by Barahona (2004), the largest share of GMCCs worldwide is from Africa (51 percent) with maize cropping systems being the most dominant (66 percent). Other main crops include cassava and sorghum. The most frequently used GMCCs are *Mucuna* sp., Cowpeas, pigeon peas, and groundnuts. The following GMCCs scenarios are considered for the modeling:

- ***Mucuna* sp.:** An input value of 3.27 t C/ha/year was used for the modeling in all strata based on Kaizzi *et al*. (2006) and Anthofer (2005). The activity data for this scenario are potentially the area of all crops.
- **Cowpea + maize and cowpea + sorghum:** This scenario assumes that cowpeas are predominantly intercropped with maize and sorghum. The input values are the strata-specific combinations of crop residues of cowpeas in addition to the residues of maize and sorghum, respectively. Only mean values of residues were used for the modeling. The activity data were the crop areas of maize and sorghum.
- **Groundnuts + maize and groundnuts + sorghum:** This scenario assumes that groundnuts are intercropped with maize and sorghum. The input values are the strata-specific combinations of crop residues of groundnuts in addition to the residues of maize and sorghum, respectively. Only the mean values of residues were used for the modeling. The activity data are the crop areas of maize and sorghum. The input values are shown in table B.4.

### Agroforestry, Improved Fallow, and Land Rehabilitation

Five different agroforestry mitigation scenarios were considered in this study.

#### *The General Agroforestry Mitigation Scenario*

This scenario can be seen as representative for all agroforestry systems on cropland. The input values were calculated

**TABLE B.4:** C Inputs for Different Green Manure/Cover Crop Systems

| MAPPING UNIT (AFRICA) | MUCUNA (tC/ha/YEAR) | COWPEA + MAIZE (tC/ha/YEAR) | COWPEA + SORGHUM (tC/ha/YEAR) | GROUNDNUTS + MAIZE (tC/ha/YEAR) | GROUNDNUTS + SORGHUM (tC/ha/YEAR) |
|---|---|---|---|---|---|
| AEZ 01, Clay 25 | 3.27 | 1.45 | 1.24 | 1.83 | 2.51 |
| AEZ 01, Clay 50 | 3.27 | 2.12 | 1.58 | 2.37 | 3.15 |
| AEZ 01, Clay 75 | 3.27 | 1.73 | 1.40 | 2.13 | 2.87 |
| AEZ 02, Clay 25 | 3.27 | 1.51 | 1.34 | 1.85 | 2.59 |
| AEZ 02, Clay 50 | 3.27 | 1.61 | 1.40 | 1.94 | 2.71 |
| AEZ 02, Clay 75 | 3.27 | 1.61 | 1.35 | 1.99 | 2.73 |
| AEZ 03, Clay 25 | 3.27 | 1.66 | 1.43 | 1.93 | 2.71 |
| AEZ 03, Clay 50 | 3.27 | 1.76 | 1.46 | 2.02 | 2.81 |
| AEZ 03, Clay 75 | 3.27 | 1.62 | 1.40 | 1.89 | 2.65 |
| AEZ 04, Clay 25 | 3.27 | 1.63 | 1.44 | 1.88 | 2.69 |
| AEZ 04, Clay 50 | 3.27 | 1.79 | 1.50 | 2.03 | 2.84 |
| AEZ 04, Clay 75 | 3.27 | 1.73 | 1.44 | 1.98 | 2.80 |
| AEZ 05, Clay 25 | 3.27 | 1.70 | 1.52 | 1.89 | 2.67 |
| AEZ 05, Clay 50 | 3.27 | 1.86 | 1.57 | 2.06 | 2.87 |
| AEZ 05, Clay 75 | 3.27 | 1.77 | 1.57 | 1.91 | 2.73 |
| AEZ 06, Clay 25 | 3.27 | 1.78 | 1.55 | 1.95 | 2.72 |
| AEZ 06, Clay 50 | 3.27 | 1.78 | 1.58 | 1.87 | 2.61 |
| AEZ 06, Clay 75 | 3.27 | 1.81 | 1.62 | 1.92 | 2.71 |
| AEZ 07, Clay 25, N | 3.27 | 3.76 | 2.93 | 3.27 | 4.52 |
| AEZ 07, Clay 25, S | 3.27 | 1.78 | 1.42 | 2.10 | 2.85 |
| AEZ 07, Clay 50, N | 3.27 | 4.58 | 3.17 | 4.25 | 5.74 |
| AEZ 07, Clay 50, S | 3.27 | 2.53 | 1.88 | 3.12 | 4.33 |
| AEZ 07, Clay 75, N | 3.27 | 3.81 | 3.20 | 3.51 | 5.03 |
| AEZ 07, Clay 75, S | 3.27 | 2.55 | 1.84 | 3.26 | 4.42 |
| AEZ 08, Clay 25, N | 3.27 | 0.00 | 0.00 | 2.14 | 2.99 |
| AEZ 08, Clay 25, S | 3.27 | 1.55 | 1.40 | 1.72 | 2.44 |
| AEZ 08, Clay 50, N | 3.27 | 0.00 | 0.00 | 1.91 | 2.79 |
| AEZ 08, Clay 50, S | 3.27 | 2.19 | 1.83 | 2.59 | 3.74 |
| AEZ 08, Clay 75, N | 3.27 | 0.00 | 0.00 | 1.78 | 2.64 |
| AEZ 08, Clay 75, S | 3.27 | 1.88 | 1.56 | 2.08 | 2.96 |
| AEZ 09, Clay 25, N | 3.27 | 0.00 | 0.00 | 2.11 | 3.06 |
| AEZ 09, Clay 25, S | 3.27 | 1.72 | 1.50 | 1.87 | 2.71 |
| AEZ 09, Clay 50, N | 3.27 | 0.00 | 0.00 | 2.15 | 3.09 |
| AEZ 09, Clay 50, S | 3.27 | 2.19 | 1.57 | 2.49 | 3.41 |
| AEZ 09, Clay 75, N | 3.27 | 0.00 | 0.00 | 1.94 | 2.91 |
| AEZ 09, Clay 75, S | 3.27 | 2.08 | 1.62 | 2.34 | 3.28 |
| AEZ 10, Clay 25, N | 3.27 | 0.00 | 0.00 | 2.62 | 3.47 |
| AEZ 10, Clay 25, S | 3.27 | 2.15 | 1.91 | 2.45 | 3.71 |
| AEZ 10, Clay 50, N | 3.27 | 0.00 | 0.00 | 2.23 | 3.02 |
| AEZ 10, Clay 50, S | 3.27 | 2.49 | 1.76 | 2.94 | 4.10 |
| AEZ 10, Clay 75, N | 3.27 | 0.00 | 0.00 | 2.36 | 3.18 |
| AEZ 10, Clay 75, S | 3.27 | 2.12 | 1.71 | 2.50 | 3.62 |
| AEZ 11, Clay 25, N | 3.27 | 0.00 | 0.00 | 2.68 | 3.62 |
| AEZ 11, Clay 25, S | 3.27 | 2.66 | 1.87 | 3.08 | 4.28 |
| AEZ 11, Clay 50, N | 3.27 | 0.00 | 0.00 | 2.70 | 3.66 |
| AEZ 11, Clay 50, S | 3.27 | 2.65 | 1.62 | 3.04 | 3.97 |
| AEZ 11, Clay 75, N | 3.27 | 0.00 | 0.00 | 2.81 | 3.82 |
| AEZ 11, Clay 75, S | 3.27 | 2.19 | 1.90 | 2.36 | 3.58 |
| AEZ 12, Clay 25 | 3.27 | 0.00 | 0.00 | 2.35 | 3.25 |
| AEZ 12, Clay 50 | 3.27 | 0.00 | 0.00 | 2.29 | 3.23 |
| AEZ 12, Clay 75 | 3.27 | 0.00 | 0.00 | 2.58 | 3.38 |

*Source:* This study.
*Note:* AEZ = Agroecological Zone.

**TABLE B.5:** C Inputs for Different Agroforestry Systems

| MAPPING UNIT (AFRICA) | AGROFORESTRY GENERAL (tC/ha/YEAR) | COFFEE AND COCOA SHADE TREE SYSTEMS (tC/ha/YEAR) | LEGUME IMPROVED FALLOW + MAIZE (tC/ha/YEAR) | COPPICED IMPROVED FALLOW + MAIZE (tC/ha/YEAR) | LAND REHABILITATION (tC/ha/YEAR) |
|---|---|---|---|---|---|
| AEZ 01, Clay 25 | 1.58 | 8.19 | 2.85 | 4.35 | 3.843 |
| AEZ 01, Clay 50 | 1.58 | 8.19 | 3.27 | 4.77 | 3.843 |
| AEZ 01, Clay 75 | 1.58 | 8.19 | 3.03 | 4.53 | 3.843 |
| AEZ 02, Clay 25 | 5.17 | 8.19 | 2.86 | 4.36 | 3.843 |
| AEZ 02, Clay 50 | 5.17 | 8.19 | 2.94 | 4.44 | 3.843 |
| AEZ 02, Clay 75 | 5.17 | 8.19 | 2.95 | 4.45 | 3.843 |
| AEZ 03, Clay 25 | 5.17 | 8.19 | 2.96 | 4.46 | 3.843 |
| AEZ 03, Clay 50 | 5.17 | 8.19 | 3.05 | 4.55 | 3.843 |
| AEZ 03, Clay 75 | 5.17 | 8.19 | 2.93 | 4.43 | 3.843 |
| AEZ 04, Clay 25 | 5.17 | 8.19 | 2.95 | 4.45 | 3.843 |
| AEZ 04, Clay 50 | 5.17 | 8.19 | 3.05 | 4.55 | 3.843 |
| AEZ 04, Clay 75 | 5.17 | 8.19 | 3.06 | 4.56 | 3.843 |
| AEZ 05, Clay 25 | 5.17 | 8.19 | 2.91 | 4.41 | 3.843 |
| AEZ 05, Clay 50 | 5.17 | 8.19 | 3.04 | 4.54 | 3.843 |
| AEZ 05, Clay 75 | 5.17 | 8.19 | 2.97 | 4.47 | 3.843 |
| AEZ 06, Clay 25 | 5.17 | 8.19 | 2.94 | 4.44 | 3.843 |
| AEZ 06, Clay 50 | 5.17 | 8.19 | 2.89 | 4.39 | 3.843 |
| AEZ 06, Clay 75 | 5.17 | 8.19 | 2.92 | 4.42 | 3.843 |
| AEZ 07, Clay 25, N | 1.58 | 8.19 | 4.03 | 5.53 | 3.843 |
| AEZ 07, Clay 25, S | 1.58 | 8.19 | 3.05 | 4.55 | 3.843 |
| AEZ 07, Clay 50, N | 1.58 | 8.19 | 4.85 | 6.35 | 3.843 |
| AEZ 07, Clay 50, S | 1.58 | 8.19 | 3.80 | 5.30 | 3.843 |
| AEZ 07, Clay 75, N | 1.58 | 8.19 | 4.08 | 5.58 | 3.843 |
| AEZ 07, Clay 75, S | 1.58 | 8.19 | 3.83 | 5.33 | 3.843 |
| AEZ 08, Clay 25, N | 1.58 | 8.19 | 3.09 | 4.59 | 3.843 |
| AEZ 08, Clay 25, S | 5.17 | 8.19 | 2.82 | 4.32 | 3.843 |
| AEZ 08, Clay 50, N | 1.58 | 8.19 | 2.95 | 4.45 | 3.843 |
| AEZ 08, Clay 50, S | 5.17 | 8.19 | 3.46 | 4.96 | 3.843 |
| AEZ 08, Clay 75, N | 1.58 | 8.19 | 2.81 | 4.31 | 3.843 |
| AEZ 08, Clay 75, S | 5.17 | 8.19 | 3.15 | 4.65 | 3.843 |
| AEZ 09, Clay 25, N | 1.58 | 8.19 | 3.06 | 4.56 | 3.843 |
| AEZ 09, Clay 25, S | 5.17 | 8.19 | 3.01 | 4.51 | 3.843 |
| AEZ 09, Clay 50, N | 1.58 | 8.19 | 3.14 | 4.64 | 3.843 |
| AEZ 09, Clay 50, S | 5.17 | 8.19 | 3.48 | 4.98 | 3.843 |
| AEZ 09, Clay 75, N | 5.17 | 8.19 | 2.92 | 4.42 | 3.843 |
| AEZ 09, Clay 75, S | 5.17 | 8.19 | 3.35 | 4.85 | 3.843 |
| AEZ 10, Clay 25, N | 5.17 | 8.19 | 3.44 | 4.94 | 3.843 |
| AEZ 10, Clay 25, S | 5.17 | 8.19 | 3.46 | 4.96 | 3.843 |
| AEZ 10, Clay 50, N | 5.17 | 8.19 | 3.08 | 4.58 | 3.843 |
| AEZ 10, Clay 50, S | 5.17 | 8.19 | 3.83 | 5.33 | 3.843 |
| AEZ 10, Clay 75, N | 5.17 | 8.19 | 3.22 | 4.72 | 3.843 |
| AEZ 10, Clay 75, S | 5.17 | 8.19 | 3.47 | 4.97 | 3.843 |
| AEZ 11, Clay 25, N | 5.17 | 8.19 | 3.72 | 5.22 | 3.843 |
| AEZ 11, Clay 25, S | 5.17 | 8.19 | 3.94 | 5.44 | 3.843 |
| AEZ 11, Clay 50, N | 5.17 | 8.19 | 3.75 | 5.25 | 3.843 |
| AEZ 11, Clay 50, S | 5.17 | 8.19 | 3.91 | 5.41 | 3.843 |
| AEZ 11, Clay 75, N | 5.17 | 8.19 | 3.86 | 5.36 | 3.843 |
| AEZ 11, Clay 75, S | 5.17 | 8.19 | 3.46 | 4.96 | 3.843 |
| AEZ 12, Clay 25 | 5.17 | 8.19 | 3.40 | 4.90 | 3.843 |
| AEZ 12, Clay 50 | 5.17 | 8.19 | 3.33 | 4.83 | 3.843 |
| AEZ 12, Clay 75 | 5.17 | 8.19 | 3.62 | 5.12 | 3.843 |

*Source:* This study.
*Note:* AEZ = Agroecological Zone.

as mean values of more than 30 different systems taking into account different climate regions (humid, subhumid, and semi-arid) (see Schroeder 1995; Oelbermann, Voroney, and Kass 2005a, 2005b; and Lemma *et al.*, 2006). It is modeled for all areas classified as FAO Land Use System 13-18 (i.e., rain-fed agriculture, agro-pastoralism, and irrigated agriculture) (see Figure B.1).

### *Perennial Crop—Tree Systems*

This scenario considered two cash crops: coffee and cocoa. It assumes combinations of improved perennial crop management (pruning and mulching) and the introduction of shade trees (see Szott, Palm, and Sanchez 1991; Szott, Fernandez, and Sanchez 1991; van Noordwijk *et al.* 2002; and Dossa *et al.*, 2008).

### *Improved Fallows + Maize*

Improved fallows, in which leguminous trees and coppiced trees and shrubs are grown in association with crops, can sequester substantial amounts of C in plants and the soil. Following a study by Kaonga and Coleman (2008), two improved fallow scenarios were modeled in association with maize.

- Legume improved fallow + maize: This system assumes a 2-year fallow period and a 1-year trees and maize period. The tree species considered are *Tephrosia vogelli, Cajanus cajan*, and *Sesbania sesban.*
- Coppiced improved fallow + maize: This system assumes a 3-year fallow period and a 7-year trees and maize period. The tree species considered are *Gliricidia sepium, Callliandra callothyrsus,* and *Senna siamea*.

The input values from the trees are mean values of the different tree species. In addition, the mapping unit-specific maize residues were included as organic inputs in this system (mean residues of maize). The input values represent the mean annual input values over the whole system (fallow and cropping period). These two mitigation scenarios were modeled for all maize areas.

### *Land Rehabilitation*

Land degradation may be defined as the long-term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided. Due to the non-availability of reliable spatial data of degraded lands in Africa, the mitigation potential was applied to the FAO Land Use Systems 7-11 (herbaceous land-use systems in Figure B.1). The input value is based on organic inputs from tree-dominated fallow systems (Szott *et al.* 1994). The C inputs for the five agroforestry systems are shown in table B.5.

## REFERENCE

Young, A. 1997. Agroforestry for soil management. CAB International, Wallingford, UK

# Appendix C: GLOBAL CROP YIELDS (T HA$^{-1}$ YR$^{-1}$) GROUPED INTO 25TH, 50TH, AND 75TH PERCENTILE BINS CORRESPONDING TO LOW, MEDIUM, AND HIGH

## BARLEY

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| (Leer) | 1.45 | 2.72 | 3.99 |
| 10South America | 1.97 | 2.42 | 2.86 |
| 11Asia | 0.99 | 1.58 | 2.17 |
| 11Oceania | 2.55 | 2.61 | 2.66 |
| 12South America | 0.61 | 1.29 | 1.98 |
| 1Asia | 1.26 | 1.52 | 1.78 |
| 1North America | 2.50 | 2.70 | 2.90 |
| 1Russia | 1.73 | 1.73 | 1.73 |
| 2Africa | 0.56 | 1.22 | 1.87 |
| 2Asia | 1.35 | 1.98 | 2.61 |
| 2Europe | 1.92 | 2.42 | 2.92 |
| 2North America | 3.42 | 4.60 | 5.77 |
| 2Oceania | 1.79 | 2.02 | 2.24 |
| 2South America | 2.47 | 2.52 | 2.56 |
| 3Africa | 0.63 | 0.99 | 1.36 |
| 3Asia | 1.33 | 1.92 | 2.52 |
| 3Europe | 1.63 | 2.06 | 2.49 |
| 3North America | 2.21 | 2.78 | 3.35 |
| 3Oceania | 2.41 | 2.55 | 2.69 |
| 3Russia | 1.63 | 1.75 | 1.88 |
| 3South America | 1.06 | 1.15 | 1.23 |
| 4Africa | 0.81 | 1.11 | 1.41 |
| 4Asia | 0.93 | 1.10 | 1.27 |
| 4North America | 3.16 | 4.13 | 5.11 |
| 4South America | 0.69 | 0.70 | 0.70 |
| 5Asia | 0.92 | 1.37 | 1.83 |
| 5Europe | 2.38 | 2.70 | 3.02 |
| 6Africa | 0.97 | 1.21 | 1.45 |
| 6Asia | 1.18 | 1.89 | 2.59 |
| 6North America | 1.15 | 2.08 | 3.02 |
| 6South America | 0.97 | 1.36 | 1.75 |
| 7Africa | 0.71 | 1.03 | 1.35 |
| 7Asia | 2.19 | 2.79 | 3.38 |
| 7Europe | 3.98 | 4.97 | 5.96 |
| 7North America | 3.18 | 3.60 | 4.02 |
| 7Oceania | 3.26 | 4.29 | 5.31 |
| 7Russia | 1.58 | 1.69 | 1.81 |
| 8Asia | 2.14 | 2.70 | 3.26 |
| 8Europe | 2.83 | 3.60 | 4.37 |
| 8North America | 3.50 | 3.80 | 4.10 |
| 8Oceania | 3.47 | 4.45 | 5.44 |
| 8South America | 1.81 | 2.04 | 2.26 |
| 9Africa | 1.33 | 1.51 | 1.68 |
| 9Asia | 1.10 | 1.16 | 1.22 |
| 9Middle America | 0.86 | 1.35 | 1.83 |
| 9South America | 0.56 | 0.69 | 0.83 |

**BEANS**

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10Africa | 0.49 | 0.65 | 0.81 |
| 10Asia | 0.81 | 0.98 | 1.15 |
| 10Middle America | 0.39 | 0.44 | 0.50 |
| 10South America | 0.94 | 1.24 | 1.53 |
| 11Africa | 0.67 | 0.86 | 1.04 |
| 11Asia | 0.75 | 0.98 | 1.21 |
| 11South America | 1.05 | 1.11 | 1.17 |
| 12Africa | 0.49 | 0.68 | 0.87 |
| 12Asia | 0.77 | 0.82 | 0.87 |
| 12Middle America | 0.67 | 0.78 | 0.89 |
| 12South America | 0.67 | 0.84 | 1.02 |
| 1Asia | 1.41 | 1.47 | 1.53 |
| 1North America | 1.60 | 1.76 | 1.92 |
| 1Russia | 1.46 | 1.46 | 1.46 |
| 2Africa | 0.45 | 0.93 | 1.40 |
| 2Asia | 0.52 | 0.64 | 0.76 |
| 2Europe | 0.54 | 0.87 | 1.20 |
| 2North America | 0.76 | 1.28 | 1.79 |
| 2Oceania | 1.03 | 1.13 | 1.22 |
| 2South America | 0.83 | 1.16 | 1.48 |
| 3Africa | 0.58 | 0.83 | 1.08 |
| 3Asia | 1.15 | 1.36 | 1.57 |
| 3Europe | 0.88 | 1.24 | 1.60 |
| 3North America | 1.44 | 1.78 | 2.12 |
| 3Oceania | 1.04 | 1.09 | 1.13 |
| 3Russia | 1.45 | 1.46 | 1.47 |
| 3South America | 0.93 | 1.03 | 1.12 |

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 4Africa | 0.23 | 0.37 | 0.51 |
| 4Asia | 0.48 | 0.57 | 0.66 |
| 4Middle America | 0.70 | 0.78 | 0.86 |
| 4North America | 0.86 | 1.20 | 1.54 |
| 4South America | 0.17 | 0.32 | 0.47 |
| 5Asia | 1.19 | 1.37 | 1.54 |
| 6Africa | 0.50 | 0.67 | 0.84 |
| 6Asia | 0.71 | 0.92 | 1.13 |
| 6Middle America | 0.55 | 0.69 | 0.82 |
| 6North America | 0.43 | 0.65 | 0.86 |
| 6South America | 0.70 | 0.94 | 1.18 |
| 7Africa | 0.42 | 0.54 | 0.67 |
| 7Asia | 0.99 | 1.22 | 1.45 |
| 7Europe | 3.15 | 3.86 | 4.56 |
| 7North America | 1.56 | 1.71 | 1.86 |
| 7Oceania | 0.92 | 1.35 | 1.79 |
| 7Russia | 0.81 | 0.86 | 0.92 |
| 8Asia | 0.73 | 0.99 | 1.25 |
| 8Europe | 2.19 | 3.39 | 4.60 |
| 8Oceania | 1.36 | 2.02 | 2.67 |
| 8South America | 0.73 | 0.96 | 1.19 |
| 9Africa | 0.39 | 0.54 | 0.68 |
| 9Asia | 0.61 | 0.71 | 0.80 |
| 9Middle America | 0.62 | 0.74 | 0.87 |
| 9North America | 0.47 | 0.55 | 0.64 |
| 9South America | 0.36 | 0.72 | 1.08 |

## MAIZE

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10Africa | 0.72 | 0.89 | 1.06 |
| 10Asia | 1.85 | 2.35 | 2.86 |
| 10Middle America | 0.84 | 1.00 | 1.16 |
| 10South America | 1.88 | 2.98 | 4.08 |
| 11Africa | 1.94 | 3.69 | 5.43 |
| 11Asia | 1.88 | 2.59 | 3.29 |
| 11South America | 3.28 | 4.20 | 5.12 |
| 12Africa | 0.66 | 0.75 | 0.85 |
| 12Asia | 1.52 | 2.11 | 2.70 |
| 12Middle America | 1.26 | 1.84 | 2.42 |
| 12South America | 2.02 | 2.68 | 3.35 |
| 1Asia | 4.85 | 5.81 | 6.78 |
| 1North America | 6.30 | 7.17 | 8.05 |
| 2Africa | 1.04 | 2.53 | 4.02 |
| 2Asia | 0.95 | 1.83 | 2.70 |
| 2Europe | 6.12 | 7.96 | 9.80 |
| 2North America | 3.56 | 6.34 | 9.12 |
| 2Oceania | 3.73 | 5.79 | 7.86 |
| 2South America | 4.29 | 5.59 | 6.89 |
| 3Africa | 1.42 | 2.54 | 3.66 |
| 3Asia | 3.82 | 4.80 | 5.77 |
| 3Europe | 2.61 | 3.82 | 5.02 |
| 3North America | 6.44 | 7.96 | 9.49 |
| 3South America | 2.32 | 3.88 | 5.44 |
| 4Africa | 0.83 | 1.15 | 1.47 |
| 4Asia | 1.15 | 1.65 | 2.14 |
| 4Middle America | 0.78 | 1.16 | 1.54 |
| 4North America | 1.01 | 1.88 | 2.75 |
| 4South America | 0.68 | 1.38 | 2.08 |
| 5Asia | 3.89 | 4.44 | 4.99 |
| 6Africa | 0.84 | 1.60 | 2.35 |
| 6Asia | 2.08 | 2.87 | 3.66 |
| 6Middle America | 1.36 | 1.70 | 2.03 |
| 6North America | 1.23 | 2.27 | 3.31 |
| 6South America | 1.64 | 2.50 | 3.35 |
| 7Africa | 1.55 | 2.54 | 3.54 |
| 7Asia | 3.26 | 4.11 | 4.97 |
| 7Europe | 5.44 | 7.10 | 8.76 |
| 7North America | 6.42 | 7.53 | 8.65 |
| 7Russia | 2.73 | 3.23 | 3.73 |
| 8Africa | 3.86 | 5.16 | 6.45 |
| 8Asia | 2.19 | 2.96 | 3.73 |
| 8Europe | 4.46 | 6.25 | 8.04 |
| 8North America | 5.40 | 6.38 | 7.37 |
| 8Oceania | 6.54 | 8.28 | 10.02 |
| 8South America | 3.33 | 4.58 | 5.83 |
| 9Africa | 0.92 | 1.22 | 1.52 |
| 9Asia | 1.78 | 2.49 | 3.21 |
| 9Middle America | 1.22 | 1.64 | 2.05 |
| 9North America | 0.93 | 1.45 | 1.96 |
| 9South America | 1.56 | 2.48 | 3.41 |

## MILLET

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 11Asia | 1.06 | 1.18 | 1.30 |
| 1Asia | 0.88 | 1.21 | 1.54 |
| 2Africa | 0.34 | 0.54 | 0.75 |
| 2Asia | 0.39 | 0.67 | 0.95 |
| 2North America | 1.05 | 1.12 | 1.20 |
| 3Africa | 0.57 | 0.59 | 0.62 |
| 3Asia | 1.67 | 1.81 | 1.96 |
| 3Europe | 0.79 | 0.88 | 0.97 |
| 3North America | 1.23 | 1.43 | 1.62 |
| 4Africa | 0.34 | 0.56 | 0.79 |
| 4Asia | 0.53 | 0.82 | 1.11 |
| 5Asia | 1.41 | 1.50 | 1.58 |
| 6Africa | 0.62 | 0.94 | 1.26 |
| 6Asia | 0.55 | 0.72 | 0.89 |
| 7Asia | 1.43 | 1.71 | 1.99 |
| 8Asia | 0.62 | 0.90 | 1.18 |
| 9Africa | 0.80 | 1.03 | 1.26 |
| 9Asia | 0.66 | 0.92 | 1.18 |

### RICE

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10Africa | 1.75 | 2.17 | 2.59 |
| 10Asia | 3.29 | 3.83 | 4.37 |
| 10Middle America | 2.40 | 3.22 | 4.05 |
| 10South America | 2.97 | 4.70 | 6.44 |
| 11Asia | 2.83 | 4.25 | 5.68 |
| 12Africa | 1.33 | 1.62 | 1.92 |
| 12Asia | 2.58 | 3.14 | 3.70 |
| 12Middle America | 2.31 | 3.42 | 4.53 |
| 12South America | 2.79 | 3.74 | 4.68 |
| 1Asia | 5.73 | 6.77 | 7.82 |
| 2Africa | 4.15 | 6.39 | 8.63 |
| 2Asia | 2.30 | 3.05 | 3.81 |
| 2Europe | 6.23 | 6.69 | 7.15 |
| 2North America | 7.54 | 8.29 | 9.04 |
| 2Oceania | 8.78 | 8.93 | 9.07 |
| 2South America | 4.33 | 5.24 | 6.15 |
| 3Asia | 3.44 | 4.91 | 6.38 |
| 3Europe | 3.43 | 4.50 | 5.57 |
| 3North America | 9.22 | 9.27 | 9.33 |
| 3Russia | 3.14 | 3.14 | 3.14 |
| 3South America | 5.46 | 6.18 | 6.90 |
| 4Africa | 0.84 | 1.56 | 2.28 |
| 4Asia | 1.62 | 2.54 | 3.46 |
| 4Middle America | 2.66 | 3.42 | 4.18 |
| 4North America | 4.79 | 5.71 | 6.64 |
| 4South America | 2.60 | 3.71 | 4.82 |
| 5Asia | 4.45 | 4.90 | 5.36 |
| 6Africa | 1.36 | 2.04 | 2.72 |
| 6Asia | 3.75 | 4.99 | 6.23 |
| 6Middle America | 3.66 | 4.37 | 5.09 |
| 6North America | 5.39 | 5.89 | 6.38 |
| 6South America | 3.57 | 4.94 | 6.30 |
| 7Asia | 5.17 | 6.19 | 7.21 |
| 7Europe | 5.97 | 6.34 | 6.70 |
| 7North America | 6.35 | 6.57 | 6.79 |
| 7Russia | 3.32 | 4.05 | 4.78 |
| 8Asia | 4.26 | 5.45 | 6.63 |
| 8Europe | 6.01 | 6.08 | 6.14 |
| 8North America | 5.74 | 6.26 | 6.77 |
| 8South America | 4.28 | 4.97 | 5.67 |
| 9Africa | 1.19 | 1.64 | 2.09 |
| 9Asia | 2.38 | 3.09 | 3.79 |
| 9Middle America | 2.65 | 3.39 | 4.13 |
| 9South America | 1.43 | 2.54 | 3.66 |

### SORGHUM

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10South America | 3.13 | 3.20 | 3.27 |
| 11Africa | 0.73 | 1.43 | 2.12 |
| 11Asia | 0.78 | 1.90 | 3.01 |
| 11Oceania | 2.91 | 3.18 | 3.44 |
| 12South America | 2.37 | 2.85 | 3.34 |
| 1Asia | 3.93 | 4.12 | 4.31 |
| 2Africa | 0.59 | 1.69 | 2.80 |
| 2Asia | 0.45 | 0.62 | 0.80 |
| 2Middle America | 0.70 | 0.70 | 0.70 |
| 2North America | 2.45 | 3.10 | 3.75 |
| 2Oceania | 2.18 | 2.69 | 3.21 |
| 2South America | 4.26 | 4.55 | 4.84 |
| 3Africa | 1.02 | 1.67 | 2.33 |
| 3Asia | 3.08 | 3.53 | 3.98 |
| 3North America | 3.16 | 3.59 | 4.01 |
| 3Oceania | 2.23 | 2.91 | 3.59 |
| 4Africa | 0.51 | 0.74 | 0.96 |
| 4Asia | 0.58 | 0.80 | 1.02 |
| 4Middle America | 0.70 | 0.70 | 0.70 |
| 4North America | 1.61 | 2.64 | 3.67 |
| 4South America | 0.64 | 1.10 | 1.56 |
| 5Asia | 3.81 | 3.81 | 3.81 |
| 6Africa | 0.89 | 1.24 | 1.60 |
| 6Asia | 0.48 | 0.82 | 1.16 |
| 6Middle America | 0.55 | 1.13 | 1.71 |
| 6North America | 4.49 | 5.52 | 6.54 |
| 6South America | 1.60 | 2.16 | 2.72 |
| 7Asia | 3.22 | 3.70 | 4.19 |
| 7North America | 4.48 | 4.95 | 5.42 |
| 7Oceania | 3.26 | 3.52 | 3.78 |
| 8Asia | 0.38 | 0.77 | 1.17 |
| 8North America | 4.20 | 4.68 | 5.17 |
| 8Oceania | 2.24 | 2.78 | 3.31 |
| 8South America | 4.13 | 4.54 | 4.96 |
| 9Africa | 0.81 | 1.02 | 1.23 |
| 9Asia | 0.71 | 0.95 | 1.18 |
| 9Middle America | 0.94 | 1.54 | 2.15 |
| 9North America | 1.45 | 2.07 | 2.69 |
| 9South America | 1.75 | 2.13 | 2.51 |

## SOYBEANS

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10Asia | 1.07 | 1.17 | 1.27 |
| 10South America | 2.63 | 2.79 | 2.95 |
| 11Asia | 0.96 | 1.28 | 1.59 |
| 11South America | 2.40 | 2.44 | 2.48 |
| 12Asia | 1.08 | 1.16 | 1.25 |
| 12South America | 2.35 | 2.55 | 2.76 |
| 1Asia | 1.55 | 1.95 | 2.35 |
| 1North America | 1.80 | 2.04 | 2.27 |
| 2Africa | 1.06 | 1.81 | 2.55 |
| 2Asia | 0.59 | 0.77 | 0.95 |
| 2Europe | 2.23 | 2.56 | 2.88 |
| 2North America | 1.84 | 2.11 | 2.39 |
| 2Oceania | 1.02 | 1.02 | 1.02 |
| 2South America | 2.35 | 2.45 | 2.55 |
| 3Asia | 1.09 | 1.50 | 1.90 |
| 3Europe | 1.46 | 1.98 | 2.50 |
| 3North America | 2.21 | 2.52 | 2.83 |
| 3South America | 2.33 | 2.34 | 2.35 |
| 4Africa | 0.70 | 0.97 | 1.25 |
| 4Asia | 0.74 | 1.00 | 1.26 |

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 4North America | 0.93 | 1.06 | 1.19 |
| 4South America | 1.63 | 1.77 | 1.91 |
| 5Asia | 1.14 | 1.45 | 1.76 |
| 6Africa | 0.47 | 0.51 | 0.55 |
| 6Asia | 0.98 | 1.49 | 2.01 |
| 6South America | 2.19 | 2.46 | 2.72 |
| 7Asia | 1.40 | 1.82 | 2.24 |
| 7Europe | 2.37 | 2.86 | 3.34 |
| 7North America | 2.13 | 2.47 | 2.82 |
| 7Russia | 1.06 | 1.21 | 1.36 |
| 8Asia | 1.13 | 1.60 | 2.07 |
| 8Europe | 2.61 | 3.06 | 3.50 |
| 8North America | 1.53 | 1.77 | 2.02 |
| 8Oceania | 1.75 | 1.86 | 1.96 |
| 8South America | 2.18 | 2.41 | 2.63 |
| 9Africa | 0.61 | 0.75 | 0.89 |
| 9Asia | 1.10 | 1.34 | 1.58 |
| 9Middle America | 1.69 | 1.83 | 1.97 |
| 9North America | 1.31 | 1.31 | 1.31 |
| 9South America | 2.04 | 2.29 | 2.55 |

**WHEAT**

| STRATUM | LOW | MEDIUM | HIGH |
|---|---|---|---|
| 10Asia | 1.56 | 1.74 | 1.92 |
| 10South America | 1.95 | 2.22 | 2.49 |
| 11Africa | 1.38 | 2.28 | 3.18 |
| 11Asia | 1.41 | 1.87 | 2.33 |
| 11Oceania | 2.10 | 2.27 | 2.44 |
| 11South America | 2.19 | 2.30 | 2.42 |
| 12South America | 1.48 | 1.71 | 1.95 |
| 1Asia | 0.92 | 1.48 | 2.04 |
| 1North America | 1.98 | 2.20 | 2.42 |
| 1Russia | 1.06 | 1.26 | 1.46 |
| 2Africa | 0.97 | 2.08 | 3.19 |
| 2Asia | 1.72 | 2.36 | 3.00 |
| 2Europe | 1.85 | 2.41 | 2.96 |
| 2North America | 1.76 | 2.92 | 4.08 |
| 2Oceania | 1.55 | 1.85 | 2.15 |
| 2South America | 2.10 | 2.63 | 3.16 |
| 3Africa | 0.96 | 1.72 | 2.48 |
| 3Asia | 1.58 | 2.67 | 3.76 |
| 3Europe | 1.70 | 2.30 | 2.91 |
| 3North America | 1.82 | 2.60 | 3.38 |
| 3Oceania | 1.69 | 2.03 | 2.36 |
| 3Russia | 1.02 | 1.30 | 1.58 |
| 3South America | 1.24 | 2.11 | 2.99 |
| 4Africa | 0.81 | 1.74 | 2.66 |
| 4Asia | 1.13 | 1.58 | 2.03 |
| 4North America | 4.46 | 5.05 | 5.63 |
| 4South America | 0.68 | 0.84 | 1.01 |
| 5Asia | 1.00 | 1.77 | 2.53 |
| 5Europe | 2.66 | 3.01 | 3.36 |
| 5Russia | 0.87 | 1.09 | 1.31 |
| 6Africa | 1.05 | 1.33 | 1.61 |
| 6Asia | 1.68 | 2.23 | 2.77 |
| 6North America | 2.05 | 3.30 | 4.55 |
| 6South America | 1.05 | 1.48 | 1.91 |
| 7Africa | 0.83 | 1.23 | 1.64 |
| 7Asia | 2.71 | 3.66 | 4.61 |
| 7Europe | 4.33 | 5.70 | 7.08 |
| 7North America | 3.30 | 3.80 | 4.31 |
| 7Oceania | 2.64 | 4.01 | 5.39 |
| 7Russia | 2.61 | 3.07 | 3.52 |
| 7South America | 4.08 | 4.31 | 4.54 |
| 8Africa | 6.11 | 6.31 | 6.51 |
| 8Asia | 1.84 | 2.55 | 3.25 |
| 8Europe | 2.70 | 3.51 | 4.32 |
| 8North America | 2.96 | 3.29 | 3.62 |
| 8Oceania | 2.67 | 4.27 | 5.87 |
| 8South America | 1.83 | 2.20 | 2.57 |
| 9Africa | 1.21 | 1.48 | 1.75 |
| 9Asia | 1.56 | 1.92 | 2.29 |
| 9Middle America | 1.67 | 1.68 | 1.69 |
| 9North America | 1.70 | 1.85 | 1.99 |
| 9South America | 1.19 | 1.52 | 1.86 |

*Source:* This study.

# Appendix D: UNCERTAINTY ANALYSIS

Uncertainty in the *RothC* soil carbon modeling was estimated following the adoption of Sustainable Agricultural Land Management methodology. A precision of 15 percent at the 95-percent confidence level was chosen as the criterion for reliability.

The analysis calculates the soil model response using the model input parameters with the upper and lower confidence levels. The range of model responses demonstrates the sensitivity of the soil modeling. The input parameters for which the uncertainty was estimated were minimum and maximum monthly temperatures, monthly precipitation, and clay content in percent of the soil. Uncertainty analysis took place in two steps:

1. For each mapping unit, the mean values and the standard deviation for the three parameters were calculated. Thereafter, the standard error in the mean was estimated using

$$SE_p = \frac{\partial_p}{\sqrt{n_p}},$$

where

$SE_p$ is the standard error in the mean of parameter $p$ in year $t$,

$\partial p$ is the standard deviation of the parameter $p$ in year $t$, and

$n_p$ is the number of samples used to calculate the mean and standard deviation of parameter $p$.

In this case, $n_p$ represents the total number of data points of a parameter used in this analysis for each mapping.

2. The minimum $P_{\min}$ and maximum $P_{\max}$ values of the confidence interval for the mean of the parameters $\overline{X_p}$ were estimated as

$$P_{\min} = \overline{X_p} - 1.96 \times SE_p$$

$$P_{\max} = \overline{X_p} + 1.96 \times SE_p$$

where

$P_{\min}$ is the minimum value of the parameter at the 95 percent confidence interval,

$P_{\max}$ is the maximum value of the parameter at the 95 percent confidence interval,

$SE_p$ is the standard error in the mean of parameter $p$ in year $t$, and

1.96 is the value of the cumulative normal distribution at the 95-percent confidence interval.

Twenty repetitions were selected randomly among the different scenarios and years for which SOC change values were modeled (table D.1). For each of these 20 data points, two separate models were done with the minimum and maximum values as model inputs. Carbon sequestration rates using the minimum and maximum values of the input parameters are given by $PRS_{\min,\,t}$ and $PRS_{\max,\,t}$, respectively.

The uncertainty (UNC) in the output model was finally calculated as

$$UNC_t = \frac{|PRS_{\max,\,t} - PRS_{\min,\,t}|}{2 \times \mathrm{PRS}_t}.$$

**TABLE D.1:** Uncertainty Analyses Using Random Samples from the Mitigation Scenarios

| SCENARIO | | | | | | |
|---|---|---|---|---|---|---|
| **MAPPING UNIT** | **YIELD BIN** | **CROP** | **RESIDUE FRACTION** | **MITIGATION SCENARIO** | **YEAR** | **UNC t** |
| AEZ01-50 | 50% | Maize 1s | 50% | Residue | 2012 | 2.3% |
| AEZ02-50 | 25% | Millet | 50% | Residue | 2014 | 2.1% |
| AEZ03-50 | 50% | Sorghum 1s | 50% | Residue | 2019 | 1.4% |
| AEZ04-50 | 50% | Maize 1s | 75% | Residue + compost | 2019 | 2.0% |
| AEZ04-50 | 75% | Rice 2s | 25% | Residue + compost | 2029 | 1.5% |
| AEZ06-50 | 50% | Maize 2s | 50% | Residue | 2025 | 1.5% |
| AEZ06-50 | 50% | Sorghum 1s | 75% | Residue | 2025 | 0.9% |
| AEZ06-50 | 50% | Sorghum 2s | 15% | Baseline | 2021 | 1.8% |
| AEZ06-50 | 75% | Sorghum 2s | 75% | Residue + compost | 2030 | 0.9% |
| AEZ08-50 N | 75% | Maize | 15% | Baseline | 2026 | 6.7% |
| AEZ09-50 N | 75% | Maize | 25% | Residue | 2016 | 9.3% |
| AEZ09-50 S | 75% | Maize | 25% | Residue | 2032 | 2.2% |
| AEZ10-50 S | 25% | Maize | 75% | Residue | 2020 | 3.9% |
| AEZ10-50 S | 50% | Maize | 75% | Residue | 2027 | 6.9% |
| AEZ10-50 S | 75% | Maize | 25% | Residue + manure | 2027 | 3.9% |
| AEZ11-50 N | 25% | Barley | 75% | Residue | 2034 | 10.7% |
| AEZ11-50 N | 50% | Wheat | 15% | Baseline | 2035 | 7.5% |
| AEZ11-50 N | 50% | Wheat | 25% | Residue | 2017 | 10.8% |
| AEZ12-50 | 75% | Maize | 75% | Residue + compost | 2029 | 25.9% |
| AEZ07-50 S | | Mucuna | | Cover crop | 2024 | 0.6% |
| | | | | | **Average:** | **5.1%** |

*Source:* This study.
*Note:* UNC = Uncertainty , AEZ = Agroecological Zone.

The uncertainty ranges from below 1 percent to 26 percent with an average value of 5.1 percent.

# Appendix E: ASSUMPTIONS FOR DERIVING THE APPLICABLE MITIGATION AREA FOR THE LAND MANAGEMENT PRACTICES

## E.1 AFRICA

### Cropland

The difference between current (table E.1) and projected cropland area (table E.2) under each of the four IPCC scenarios was allocated to land-use and agroforestry-related land management practices in equal proportion. Tree-crop farming was projected to increase by the same proportion the entire cropland area for the continent increased for A1B and A2 (the more economic focus scenarios), but by just 15 percent under the two other scenarios that are more environmentally focused.

No-tillage was assumed to cover 2 percent of cropland area in the B1 and A1B scenarios, but only 1 percent in the remaining two scenarios. About 3.6 million ha were estimated as having erosion hazard in Africa. Terracing and sloping barriers were applied to 75 percent of this land area in equal proportion. Sustainable biochar application was assumed for 15 percent of current tree crop area for B1 and B2 scenarios, and 15 percent of projected tree crop area for the remaining two scenarios.

Rainwater harvesting was assumed applicable to 19.5 million ha under each scenario; about 7 percent increase in potential irrigable area for 1990. The remaining cropland area under each scenario was distributed evenly among inorganic fertilizer, manure, cover crops, rotation diversification, rotation intensification, and crop residue application.

### Grassland

The respective abatement rates for fertilizer, manure, improved pastures, pasture establishment on degraded land, and rainwater harvesting were each applied to one-sixth of projected grassland area for each of the four IPCC scenarios for the continent by 2030 (table E.2).

### Asia

#### *Cropland*

The difference between current (table E.1) and the projected cropland area (table E.2) under each of the four IPCC scenarios was allocated to land-use and agroforestry-related land management practices in equal proportion. Organic soil restoration was applied to the estimated degraded peat land area of 13 million ha for each scenario. The abatement rate for organic soil restoration was taken from Smith *et al.* (2008). The estimated irrigable area in Asia is 270 million ha. Two-thirds of this was applied to improved irrigation and rainwater harvesting in equal proportions. Land devoted to intensive vegetables was assumed to increase by 15 percent under the B1 and B2 scenarios, while it was assumed to increase by the same proportion for total cropland area under the remaining two scenarios.

Current land area under biofertilizer is 29 million ha. This was assumed to increase by 5 percent under scenarios A2 and B2 and by 6 percent under the remaining two scenarios. Biochar was applied to only 15 percent of the applicable area for each agroforestry-related practice for each scenario. No-tillage is currently practiced on 3 percent of land in Asia, and it was assumed to increase to 7 percent of current land area by 2030 for all scenarios. The remaining cropland area under each scenario was distributed evenly among inorganic fertilizer, manure, cover crops, rotation intensification, and crop residue application.

**TABLE E.1:** Estimated Cropland Area in the 2000s

| | MILLION ha |
|---|---|
| Africa | 165.8 |
| Asia | 497.4 |
| Latin America | 110.3 |

*Source:* Based on Monfreda *et al.* (2008).

**TABLE E.2:** Estimated Cropland and Grassland Area by 2030 (Million ha)

| | B1 | | A1B | | B2 | | A2 | |
|---|---|---|---|---|---|---|---|---|
| | CROPLAND | GRASSLAND | CROPLAND | GRASSLAND | CROPLAND | GRASSLAND | CROPLAND | GRASSLAND |
| Africa | 279.7 | 813.7 | 271.2 | 826.4 | 321.3 | 863.5 | 325.4 | 891.9 |
| Asia | 799.3 | 656.9 | 847.3 | 678.7 | 943.4 | 701.7 | 871.6 | 714.4 |
| Latin America | 351.0 | 282.1 | 361.8 | 295.6 | 358.2 | 384.0 | 414.3 | 426.0 |

*Source:* Based on Smith *et al.* (2008).

### *Grassland*

The respective abatement rates for fertilizer, manure, pasture establishment on degraded land, grazing management, rainwater harvesting, improved irrigation, cropland–to-pasture, and annual-to-perennial grass were each applied to one-eighth of projected grassland area for each of the four IPCC scenarios on the continent by 2030 (table E.2).

## Latin America

### *Cropland*

The difference between current (table E.1) and projected cropland area (table E.2) under each of the four IPCC scenarios was allocated to land-use and agroforestry-related land management practices in equal proportion. No-tillage is currently practiced on 50 Mha. This was assumed to increase to 66 Mha under each scenario by 2030. Sustainable biochar production was assumed applicable to 30 percent of the agroforestry area in each scenario. The potential irrigable area is 77.8 Mha. Two-thirds of this was applied to improved irrigation and rainwater harvesting in equal proportions. The remaining cropland area under each scenario was distributed evenly among manure, residue, cover crops, rotation intensification, and diversification.

### *Grassland*

The respective abatement rates for manure, pasture establishment on degraded land, grazing management, rainwater harvesting, improved irrigation, cropland–to-pasture, and annual-to-perennial grass were each applied to one-seventh of projected grassland area for each of the four IPCC scenarios continents by 2030 (table E.2).

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