

Framework for Carbon Sequestration and Accounting of SLM Practices for Climate Change Mitigation in Ethiopia



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Submission: July 15, 2017; Published: August 10, 2017

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Abstract

Carbon sequestration projects present mutual benefits for environmental conservation and economic development opportunities in poor countries requiring effective strategies to combat the growing threat of widespread natural resource degradation. A variety of strategies are needed to reduce CO₂ emissions and remove carbon from the atmosphere in order to mitigate the potential effects of climate change. One possible mechanism for climate change mitigation is carbon sequestration. Accordingly, efforts to mitigate climate change through carbon sequestration projects could bring in money both to raise local incomes and regenerate natural resources. Carbon sequestration projects in Africa have the potential to provide increased investments for poverty alleviation.

Potential benefits include sustainable development, biodiversity conservation, and ecological restoration. The Kyoto protocol was a lost opportunity for Africa and it has only benefitted 3% from carbon trading. Massive sustainable local community based natural resource management efforts have been undertaken and there had been lots of success stories in the last 25 years in Ethiopia. Sustainable Land Management (SLM) practices constitute key adaptation and mitigation measures by resulting in reduced soil erosion, improved water retention, and improved land productivity. The overall objective of SLM Program is to improve the livelihood of land users and communities through implementation of SLM activities in the framework of community-based participatory watershed development plans.

Environmental rehabilitation efforts in Ethiopia have brought about reclamation of waste lands, re-vegetation of degraded hillsides, restoration of damaged pasturelands, and adoption of improved soil and water conservation and management technologies in cultivated lands. In consequence, these efforts have apparently led to enhanced carbon sequestration and both above- and below-ground carbon stocks. SLM practices and climate change adaptation and mitigation strategies are mutually supportive and represent win-win options. Carbon stocks could be quantified through different approaches from plot to country level and an integrated approach to quantify and identify carbon pools at a country level on land use basis and different SLM practices would add values in economics and environmental sustainability to encourage Ethiopia to further contribute to the mitigation of global warming while generating income to the community. Quantification at landscape and spatiotemporal pattern facilitates carbon trading at country, East Africa Region, and continental level. This calls for establishing frameworks, integrated approaches and synergy among actors in modeling and predicting carbon sequestration potentials and promote best SLM practices to enhance marketing channels and institutional settings for effective carbon trading.

Keywords: Carbon trading; Mitigation; Carbon pools; Synergy; Global warming; Carbon stock; Frameworks

Abbreviations: SLM : Sustainable Land Management; CDM: Clean Development Mechanism; SOM: Soil Organic Matter; GPP: Gross primary productivity

Introduction

Background

Carbon sequestration projects in Africa have the potential to provide increased investments for poverty alleviation. Potential benefits include sustainable development, biodiversity conservation, and ecological restoration. The Kyoto Protocol's Clean Development Mechanism (CDM) recognizes carbon

sequestration through forestry as a way to mitigate global warming and also allows industrialized countries to offset their carbon emissions by investing in forestry projects in developing countries UNFCCC (2003). In addition, many private organizations are voluntarily promoting carbon sequestration projects to reduce their carbon emissions. Carbon sequestration projects present mutual benefits for environmental conservation

and economic development opportunities in poor countries UNEP (2004) Rosa et al. (2003).

Countries also require effective strategies to combat the growing threat of widespread natural resource degradation. Accordingly, efforts to mitigate climate change through carbon sequestration projects could bring in money both to raise local incomes and regenerate natural resources Kituyi (2002). Parts of Africa and Central Asia are recognized as being particularly vulnerable to adverse climate change brought about by global warming. In particular, these areas likely will face higher inter-annual variability of rainfall, more extreme climate events such as floods and droughts, and the dry land areas already severely affected by land degradation-irreversible desertification Anil De (1989). Numerous studies have been conducted on climate change impact on various facets of human life including agriculture, weather pattern, and wildlife (IPCC 2001). The potential consequences of the steady increase in atmospheric CO₂ emissions are partially mitigated by photosynthesis in plants that removes CO₂ from the atmosphere and sequesters it in soil (Lucian Wielopolski (2002).

Carbon sequestration through different land uses has gained attention in recent years as it might become a source of additional income to farmers. In this paper, we review the prospects for farmers making money by adopting practices that sequester carbon for the comparative potential of carbon sequestration as a GHG mitigation alternative. Reducing net carbon emissions to the atmosphere is increasingly being considered as a way of addressing the climate change problem. Carbon sequestration is an appealing alternative as it allows continued energy consumption, while potentially benefiting farmers and the environment. As a result, the sequestration alternative has attracted interest of researchers, energy industry, policy makers, and farmers alike. Numerous methodologies for carbon sequestration projects (CSP) have been developed targeted at reducing carbon fluxes primarily through management interventions involving land use, land use changes and forestry (LULUCF) Smith (2004) Lehmann et al. (2006) Bondeau et al. (2006), Batjes [1]; Smith et al. (1993), Brown et al. (1993).

Two critical considerations to be borne in mind are impacts of planned project activities on ecology and human welfare. Therefore, it is essential that carbon management is adequately formulated within national and international climate policies. Carbon sequestration activities such as carbon sinks could be incorporated into emission trading systems to create "carbon credit" for each additional equivalent unit of CO₂ in the soil. These credits could then be sold to sources of greenhouse gas in order to permit their emissions. Credit trading would give farmers a bonus for adopting methods that promote soil carbon retention. It should be noted that forestation and reforestation are considered carbon sinks under the Kyoto Protocol. In addition to creating a soil sink by sequestering carbon in soil, the conversion of marginal farmland to forest would also be a forest

sink that would make it possible to obtain additional carbon credits.

Statement of the Problem

Climate change can significantly reverse the progress towards poverty reduction and food security in Africa and other developing nations. Those least able to cope will be hit the hardest. Global warming as a result of excessive GHG emissions is challenging global economic, social and environmental development and sustainability. Carbon sequestration is one of the mitigation and adaptation strategies. This is achieved through capturing of GHGs from the atmosphere and sinking it through terrestrial sequestration via photosynthesis. Yet, carbon sequestration is affected by land degradation, climate variability, biophysical factors, land use, and land use dynamics. The carbon sequestered in different land uses and its spatiotemporal changes should be monitored and updated so that contribution of sequestration can be envisaged in relation to emissions in order to take positive actions to narrow down the gap between emissions and sink for carbon balance and management FAO [2].

To date, existing carbon sequestration methods depend on field measurements, modeling and include some components of remote sensing and lab analysis. Measurements become complex with increased ecological diversity in multistory vegetation dynamics. Most studies are plot based and upscale to land use and regional level for aggregation with limited parameters. Spatiotemporal climate and land use dynamics are not mostly incorporated to assess their impact on carbon dynamics and related effects on biological productivity and livelihoods dependent on agriculture. Integration of all measurement techniques and scrutinizing their relationship would help to fill gaps to date and develop dependable and cost-effective methods that can facilitate carbon accounting and trading procedures. Hence, this study deals to address these research gaps. Availability of up-to-date geospatial data will help facilitate inventoried, monitor changes, assess impacts of climate, land use and environmental changes on carbon, agriculture and livelihoods to support planners, decision makers, academia and other development actors to make decisions and invest to enhance productivity, utilization and sustainability of land resources. Such information has huge potential in environmental and NRM GIS applications.

Objectives

The objective of C-Sequestration is to reverse land degradation due to deforestation and inadequate land use/management in the tropics and sub-tropics through the promotion of improved land use systems and land management practices which provide win-win effects in terms of economic gains and environmental benefits, greater agro biodiversity, improved conservation and environmental management and increased carbon sequestration with efficient carbon trading systems to empower local communities for their global efforts

of Kyoto protocol, Copenhagen and Paris conventions, and other global and frameworks.

Objectives include:

- a. Estimate carbon stock in different land uses
- b. Quantify Model and predict carbon sequestration
- c. Identify best practices to boost carbon sequestration
- d. The Economics (cost) of Carbon trading
- e. Measures to mitigate global warming
- f. Species, environment, ecology, carbon sequestration relationship.

Objective 1: Quantifying carbon sequestration potential (pool) under present land use context of total above-and below-ground total C stock (TCS: Total Carbon Stock).

Specific objective 1: Above-Ground Biomass (AGB).

Field measurement: for forestry based on 3 methods of biomass estimators: basal area ratio, diameter and height and conversion in to biomass equations

- I. **Method 1:** Basal area ratio
- II. **Method 2:** DBH method
- III. **Method 3:** Canopy/ height
- IV. **Method 4:** Quadrant based estimation for under storey pools such as litters, shrubs, grasses and herbs
- V. **Method 5 :** Estimating total biomass in 10m* 10m plot and converting in to land use or locality level
- VI. **Remote sensing Data:** based biomass estimation for all land uses
- VII. **Quadrant Method:** for estimating wet and dry biomass weight from agricultural fields, grass lands and grazing lands
- VIII. **IPCC frame Work:** for estimating land use level carbon estimation.

Specific objective 2: Soil organic carbon (SOC) estimation.

Quantifying soil organic carbon in a plot and upsacling in to land use and regional level through the following methods:

- a. Lab. analysis of samples
- b. Rapid perchloric acid method
- c. Spectroscopy method
- d. Ratio to above-ground method
- e. Soil carbon dynamics modeling such as CENTURY and ROTH-C Models
- f. Interpolation at land use scale
- g. Using the detailed sub-national scale data available

in FAO, the IPCC indicator of the carbon stock of mineral and organic soil separately is calculated based on thermal climate and length of growing period map and soil type.

Specific objective 3: Total carbon stock estimation

- a. Aggregating above-and below-ground per plot and up scaling in to land use or regional level.
- b. IPCC method for land use-based total carbon estimation.

Objective 2

I. Effects of climate variability and land use change on carbon dynamics, agriculture and livelihoods are estimated through time-series analysis through downscaling global climate land use changes to local level. Spatiotemporal landuse changes and effect on carbon biomass translated in agricultural productivity associated with livelihoods

II. Climate variability and soil properties for their effect on soil organic carbon dynamics estimated by modeling.

III. Three functional relationships tested here:

IV. Carbon = f (Climate, Soil, land use, land management)

V. Yield = f (Soil, climate, land use, land management, tech

VI. Yield = f (carbon stock)

Objective 3

Reliable and cost effective integrated assessment tools for carbon sequestration developed: Innovative and cost-effective method for regional level C-sequestration assessment method through integration of RS, GIS, Statistical, direct field measurement and laboratory analysis methods

a. Relating biomass estimators with RS data for their estimation efficiency

b. Comparison among SOC estimation conventional and spectroscopy methods for better accuracy

c. Better estimation of total biomass per plot through integrating ratio method, Eddy covariance measurement/ analysis and modeling.

Objective 4

Carbon balance estimated through comparison of emission and sink from terrestrial ecosystems and land uses based on IPCC guideline and gaps known and mitigating measures proposed for action.

Objective 5

The economics of carbon sequestration and accounting.

Research Questions

What is the C sequestration potential of land uses and SLM practices at present land use scenario?

Which conventional and RS and GIS techniques generate better carbon stock estimation for above ground biomass in different land uses?

- a. Which SOC estimator is better in accuracy and cost effectiveness?
- b. What type of relationship, linear and/ or polynomial relationship exists between below and above ground biomass; between different estimators for total biomass, between field, lab and RS measurement techniques?
- c. What is the long-term effect of climate variability and land use changes when downscaled from global to local perspectives on carbon dynamics, agriculture and livelihoods?
- d. What is the relationship between up scaling carbon stock measurements from plot to wide area level and IPCC guideline?
- e. What is the carbon balance of the study area based on the IPCC emission and sink measurement guideline?
- f. Which SLM practices and land uses have better C-sequestration potential?
- g. Which carbon pool sinks more carbon?
- h. Which method or integration of methods is reliable and cost-effective?

Mitigating climate change through carbon sequestration

Overview of carbon sequestration

Carbon Sequestration is the process by which CO₂ is removed from the atmosphere and stored as biomass. It can be considered at several levels. At the level of an individual plant, the amount of carbon sequestered is simply as: CO₂ Sequestered = Photosynthesis - Respiration. What this essentially means is the amount of carbon sequestered is equally to the NPP of the plant. However, when considering Carbon sequestration at the ecosystem level (which is ultimately more useful than considering an individual plant), several more factors need to be accounted for. The expansion in GHG emissions has largely been the product of economic development over the last two centuries mainly involving deforestation, land use change, petroleum usage and coal-based electricity generation. Recent atmospheric GHG concentration levels are substantially higher than those in the observable fairly distant past.

A variety of strategies are needed to reduce CO₂ emissions and remove carbon from the atmosphere in order to mitigate the potential effects of climate change. One possible mechanism for climate change mitigation is carbon sequestration, the facilitated redistribution of carbon from the air to soils, terrestrial biomass, geologic formations, and the oceans. For semi-arid and sub-humid regions of the world, carbon sequestration in soils represents the most promising option for climate change mitigation. Carbon

sequestration and reductions in greenhouse gas emissions can occur through a variety of agriculture practices. It renders possible options for farmers and ranchers to have a positive impact on the changing climate and presents opportunities for becoming involved in the emerging carbon market. Innovative farming practices such as conservation tillage, organic production, improved cropping systems, land restoration, land use change and irrigation and water management, are ways that farmers can address climate change.

Good management practices have multiple benefits that may also enhance profitability, improve farm energy efficiency and boost air and soil quality. The primary greenhouse gases associated with agriculture are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Agricultural soils can play in addressing the Global Warming crisis. Farmers can play a central role in sequestering carbon in their soils by fostering deep-rooted perennial plant species that have significant biomass in their root systems. Soil biomass is a natural carbon sink and should be used to create carbon credits which can be traded alongside those currently traded for forests. Actions taken to sequester C in biomass and soils will generally increase the organic matter content of soils, which in turn will have a positive impact on environmental, agricultural and biodiversity aspects of ecosystems. The consequences of an increase in soil carbon storage can include increases in soil fertility, land productivity for food production and security, and prevention of land degradation. Therefore, they might constitute win - win situations. (ULUCF) IPCC 2000 [3,4].

Potential Benefits of Carbon Sequestration

Carbon sequestration projects benefit global society by absorbing excess CO₂ from the atmosphere. They also provide several additional advantages for the host country. Main benefits of improved carbon management at various spatial scales are illustrated.

Sustainable Development

The Kyoto Protocol stipulates that all CDM projects, including carbon sequestration activities, should achieve sustainable development benefits for the host country (UNEP (2004) Izac (1997)).

Biodiversity Conservation

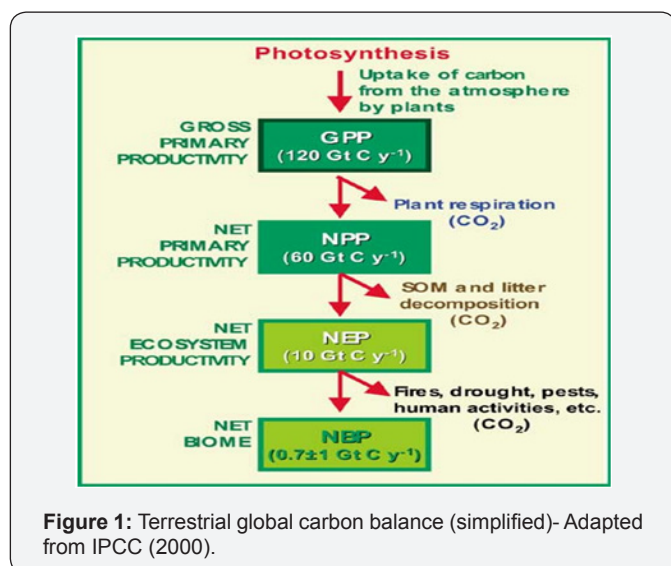
Many natural resource management projects are not viable, either because their benefits are uncompensated environmental services or because national governments and other local agencies do not have adequate funds to undertake conservation activities. Carbon sequestration projects can address both these concerns by paying for some of the services (such as carbon sequestration) and by providing financial assistance to national governments to invest in natural resource projects (Gutman (2003)). This is particularly relevant for Africa where precious natural resources, including biodiversity, are being rapidly lost due to a lack of conservation investments.

Ecological Restoration

Carbon sequestration through afforestation and reforestation can often generate other locally-valued ecosystem services such as improved water quality and reduced soil erosion and sedimentation Scherr et al. (2004).

Soil Quality Enhancement

Carbon and organic matter improve soil fertility, health and productivity. The main entry of C into the biosphere is through the process of photosynthesis or gross primary productivity (GPP) that is the uptake of C from the atmosphere by plants. Part of this C is lost in several processes: through plant respiration (autotrophic respiration); as a result of litter and soil organic matter (SOM) decomposition (heterotrophic respiration) and as a consequence of further losses caused by fires, drought, human activities, etc (Figure 1).



Employing farming practices that involve minimal disturbance of the soil and encourage carbon sequestration, farmers may be able to slow or even reverse the loss of carbon from their fields. In the United States, forest and croplands currently sequester the equivalent of 12 percent of U.S. carbon dioxide emissions from the energy, transportation and industrial sectors EPA [5]. Several farming practices and technologies can reduce greenhouse gas emissions and prevent climate change by enhancing carbon storage in soils; preserving existing soil carbon; and reducing carbon dioxide, methane and nitrous oxide emissions. These include Conservation tillage and cover crops, improved cropping and organic systems, Irrigation and water management, Grazing land management. Crop rotation, Soil erosion management, Nitrogen use efficiency, Land restoration and land use changes, Methane capture, bio fuels and other renewable energy options.

Bio fuel Substitution is the use of agricultural land for the production of biomass that can be converted to bio fuel. This fuel can be used onsite to offset the energy used for agricultural

production or the bio fuel can be transported offsite for large-scale energy production. Every acre used for bio fuel production can produce a net sequestration rate of 1.5 MMT of carbon EPA (2006). The long-term carbon retention capacity of soil depends on sound land management. Soil sinks cannot be created unless practices are adopted that increase the carbon content of the soil. Those practices, which can vary depending on the type of soil and climate, include: decrease in the amount of land left fallow; the use of direct drilling, which does not disturb the soil as much and reduces the amount of CO₂ released into the atmosphere; the use of legumes and/or grasses in crop rotation; the conversion of marginal farmland to perennial grasses or trees; the use of rotation grazing and high-intensity short-term grazing; the planting of shrubs and trees as windbreaks; and the restoration of wetlands. Many management methods aimed at storing carbon in soil sinks also contribute to environmental sustainability.

Increasing the organic matter content of soil helps improve the soil's agronomic capabilities. It also produces better soil and better crops, improves water conservation, reduces erosion, and improves wildlife habitat and species protection, leading to greater biodiversity. Forests and ecosystems in general may have a limited capacity to accumulate C. First, this is because the capacity to sequester C is limited by other factors, such as nutrient availability Oren, Ellsworth and Johnsen (2001) and other biophysical factors. Second, photosynthesis may have a CO₂ saturation point, above which it will no longer respond to an increase in atmospheric CO₂ concentration. A third reason is that climate change may lead to ecosystem degradation, in turn, limiting the capacity to sequester C. Forests in the absence of disturbances are expected to take up C for 20-50 years after establishment and, therefore, they should be considered as a time-buyer until other technologies are developed to reduce emissions.

Research in enhancing the natural terrestrial cycle should identify ways to enhance carbon sequestration of the terrestrial biosphere through CO₂ removal from the atmosphere by vegetation and storage in biomass and soils. This includes the development of effective approaches to enhance potential sequestration in part through advances in the fundamental understanding of biological and ecological processes and the formation of soil organic matter in unmanaged and managed terrestrial ecosystems, including wetlands. It also includes efforts to understand ecological consequences of carbon sequestration. The research strategy focuses on those properties and processes of ecosystems for which alteration can offer significant potential for enhancing the net sequestration of carbon.

Relevant technical areas of research include:

- a. Increasing the net fixation of atmospheric carbon dioxide by terrestrial vegetation with emphasis on physiology and rates of photosynthesis of vascular plants,

- b. Retaining carbon and enhancing the transformation of carbon to soil organic matter;
- c. Reducing the emission of CO₂ from soils caused by heterotrophic oxidation of soil organic carbon; and
- d. Increasing the capacity of deserts and degraded lands to sequester carbon.

Different scenarios for carbon sequestration

The potential capacity for different TEs to sequester carbon is highly dependent on land-use practices and forestry activities. The CS potential of ecosystems depends on the type of land, while in the case of forests management determines substantially the CS rates. The most common methods to increase the sequestration rate in terrestrial ecosystems are reforestation and afforestation (IPCC, 2000). Conversion of cropland to grassland can also provide relatively large annual increase in carbon stock while shift to conservation agriculture is very important for increasing soil organic matter FAO [6].

Agricultural soils can play in addressing the Global Warming crisis. Farmers can play a central role in sequestering carbon in their soils by fostering deep-rooted perennial plant species that have significant biomass in their root systems. Soil biomass is a natural carbon sink and should be used to create carbon credits which can be traded alongside those currently traded for forests.

Soils can save the world: Global facts

- a. The terrestrial biosphere currently sequesters 2 billion metric tons of carbon annually. (US Department of Agriculture)
- b. Soils contain 82% of terrestrial carbon.
- c. "Enhancing the natural processes that remove CO₂ from the atmosphere is thought to be the most cost-effective means of reducing atmospheric levels of CO₂." (US Department of Energy)
- d. "Soil organic carbon is the largest reservoir in interaction with the atmosphere." (Vegetation 650 gigatons, atmosphere 750 gigatons, soil 1500 gelatins (FAO).
- e. The carbon sink capacity of the world's agricultural and degraded soils is 50% to 66% of the historic carbon loss of 42 to 78 gigatons of carbon.
- f. An acre of pasture can sequester more carbon than an acre of forest.
- g. Increased soil fertility, boosting productivity and competitiveness
- h. Better usage of water, reducing erosion, silting, and salination
- i. Reduced danger of rising salt levels, lowering the water table
- j. Reduced loss of topsoil to wind and runoff with 100% ground cover

- k. Increased farm incomes, increasing viability in volatile industries
- l. Increased farm values, giving farm families financial flexibility
- m. Foster growth in farm communities, providing employment opportunities and protecting social infrastructure.

Practicing conservation tillage, improving agricultural productivity, reducing soil erosion, and improving water management improve soil quality and increase the carbon stored in soil. It is estimated that these practices have the potential to restore between 40 to 112 Pg of carbon globally. Successful soil sequestration projects and activities in Africa must have a strong sustainable development component, such that the project improves the livelihood of farmers by improving agricultural productivity, reducing the risk of crop failure, providing access to better agricultural inputs, such as organic fertilizers. Changes in soil carbon can be monitored and measured, however, because carbon sequestration is a new field some technical challenges remain. A good first step to addressing these challenges will be the development of a measurement and monitoring manual. While the majority of land use projects to date have been in the forest sector, soil carbon projects in semi-arid and sub-humid Africa provide the following unique opportunities.

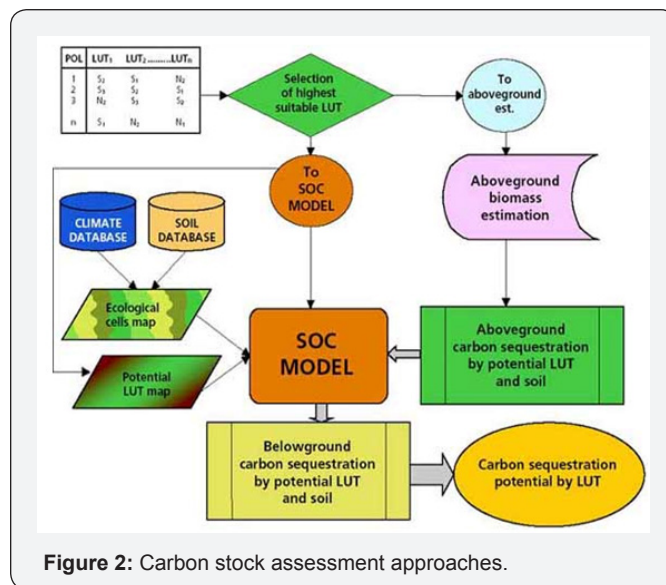


Figure 2: Carbon stock assessment approaches.

The land has relatively low opportunity cost relative to humid tropical forests, where in many cases climate mitigation may not be able to compete with logging or agricultural land demands. Large areas of degraded and desertified lands are in need of technical assistance and capital for restoring farmlands, grasslands, and savannas. While exact estimates of desertification are difficult to obtain, estimates range from 3.47 to 3.97 billion hectares of desertified land Lal et al. [7]. Therefore, while the tons of carbon per hectare are relatively small relative to forests, the overall potential for cost-effective climate mitigation is quite large. Accumulation of sequestered carbon in forests tends to be

slow in the early stages of growth, but accelerates as trees grow towards maturity and then decreases once maturity is reached (Figure 2).

Approximately 50% of the Dry Weight of the Biomass in A Forest is Carbon

All forests are carbon reservoirs and a carbon sink is a carbon reservoir that is increasing in size. Of course, forests can also be carbon sources if they emit more carbon than they sequester, or they may be neutral in terms of carbon when sequestration is balanced by emissions.

- i. When undertaking carbon accounting for forests, the following carbon pools are recognized: tree stem
 - ii. Tree canopy, comprising branches and leaves/needles
 - iii. Tree roots, both coarse and fine
 - iv. Soil carbon, comprising carbon stored as organic matter
 - v. Other vegetation, primarily understory, comprising shrubs, grasses and so on
- litter, comprising large and small logs, branches and leaves/needles on the forest floor.

A carbon accounting system needs to assess the changes in the amount of carbon stored in each of these pools over the life of the forest. The amount of carbon stored in each of these pools is most commonly estimated by developing relationships between easily measured things like stem diameter or stem volume and harder to measure things like canopy and root biomass. It is also necessary to establish the pattern of changes in pools like soil carbon and understory over the time frames of forest growth. Agriculture emits and stores atmospheric gases that absorb radiation. All organic substances contain carbon (C). The C cycle, through which carbon dioxide from the atmosphere is converted to organic forms by plant photosynthesis and then returned to the atmosphere through respiration, is the basis for life on earth.

Forestry Practices That Increase Carbon Sequestration On Forestland Include

- a. Afforestation of agricultural land
- b. Reforestation of harvested or burned timberland storage
- c. Modification of forestry management practices to emphasize carbon storage
- d. Adoption of low impact harvesting methods to decrease carbon release
- e. Lengthening forest rotation cycles
- f. Preservation of forestland from conversion
- g. Adoption of agro forestry practices

h. Establishment of short-rotation woody biomass plantations

- i. Urban forestry practices

Terrestrial carbon sequestration is carbon stored in the biomass created by perennial vegetations such as root systems and tree trunks. Transformation of free floating atmospheric carbon to a fixed-state carbon can be achieved through the following methods:

- I. Tree plantings
- II. Soil Organic Matter (decayed plant remains which hold carbon within)
- III. Perennial grass planting
- IV. Underground traps, including large bodies of water

Soil organic matter (SOM) contains three times as much C as is found in vegetation, on a worldwide scale. Therefore, soil organic matter plays a critical role in the global C balance and the greenhouse effect. In fact, when SOM is measured, it's actually soil organic carbon (SOC) that is measured, and then a conversion factor is used to calculate SOM.

SLM for Carbon sequestration and Climate change Mitigation: Ethiopian Experience

SLM, in addition to its role in adaptation, provides a significant potential as a mitigation measure. Globally, agriculture and land use changes are major contributors of GHGs IPCC [8]. This means, in other words, appropriate agricultural practices and land use and land cover management offers a great mitigation potential. Sustainable forest management, reducing emissions from deforestation and forest degradation (REDD) is one of the recognized mitigation options. Soil carbon sequestration also has a huge mitigation potential with a wide-range of synergies such as improved productivity and soil health Bewuket (2009). Agriculture and SLM are important domains through which developing countries can contribute to global mitigation efforts as they fall within National Appropriate Mitigation Actions (NAMAs). Environmental rehabilitation efforts in Ethiopia have brought about reclamation of waste lands, re-vegetation of degraded hillsides, restoration of damaged pasturelands, and adoption of improved soil and water conservation and management technologies in cultivated lands. In consequence, these efforts have apparently led to enhanced carbon sequestration and both above-and below-ground carbon stocks. SLM practices and climate change adaptation and mitigation strategies are mutually supportive and represent win-win options.

The GHG mitigation potential of Sustainable Land Management (SLM) in agricultural lands is very large. SLM strategies and practices can prevent land degradation, restore degraded lands, and reduce the need for further conversion of natural forests and grasslands. Farmers can, reduce GHG

emissions, increase carbon sequestration, and maintain above- and below-ground carbon stocks at relatively low cost, while also improving food production and livelihoods.

SLM increases carbon storage in soil

Improved agricultural practices can reduce carbon emissions from soil erosion and disturbance, and capture carbon from the atmosphere to store long-term in soils. Practices like cover cropping, applying crop residues, mulch, manuring, reduced tillage, and rotational cropping with legumes increase organic matter in soil, while also increasing crop yields.

Unsustainable cropping practices and overgrazing of pastures have led to large-scale degradation of productive land and watersheds, releasing huge amounts of carbon from soils and vegetation. Bringing degraded lands back into productive use through SLM can sequester carbon while restoring critical watersheds. SLM sequesters carbon while restoring degraded lands and watersheds. Revegetation can sequester 3.5 tons of CO₂ eq per hectare in a year in dry environments and up to 4.5 tons in cool-moist ones. Supporting local, national and regional African farmer organizations in overcoming barriers to adopt SLM technologies and accessing the carbon market is pivotal to enhance carbon trading. Initiatives need to develop cost-efficient methodologies for farmers to access carbon markets and their income benefits, and that lower barriers to adoption of sustainable land management practices which enhance land productivity and sustainability TerrAfrica [9].

Over view of Carbon Sequestration Projects (CSP)

Carbon sequestration projects in Africa have the potential to provide increased investments for poverty alleviation. Potential benefits include sustainable development, biodiversity conservation, and ecological restoration. Carbon sequestration is the process of removing excess carbon dioxide (CO₂) from the atmosphere (3.67 tons CO₂=1 ton sequestered carbon). The Kyoto Protocol's Clean Development Mechanism (CDM) recognizes carbon sequestration through forestry as a way to mitigate global warming and also allows industrialized countries to offset their carbon emissions by investing in forestry projects in developing countries UNFCCC (2003). In addition, many private organizations are voluntarily promoting carbon sequestration projects to reduce their carbon emissions. Carbon sequestration projects present mutual benefits for environmental conservation and economic development opportunities in poor countries UNEP (2004) Rosa et al. (2003).

Countries also require effective strategies to combat the growing threat of widespread natural resource degradation. Accordingly, efforts to mitigate climate change through carbon sequestration projects could bring in money both to raise local incomes and regenerate natural resources Kituyi (2002). However, there are strong concerns that the growth in international carbon projects may bypass Africa, which contributed just 3% of the total global trade in carbon offsets

in 2003-2004 and a negligible share in 2004-2005. The Period of the Kyoto protocol is lost opportunity to Africa and we hope the Copenhagen conference would bring positive impacts. This compares poorly with Asia and Latin America, which contributed 43 percent and 35 percent, respectively, during 2003-2004 Lecoq and Capoor (2005). Attracting more carbon investments to Africa is critical. The analysis of existing carbon sequestration projects in Africa may provide insight toward achieving this objective.

An option for adaptation to climate change and necessary condition for sustainable agriculture in itself is sustainable land management (SLM) and rehabilitation of degraded lands. Community Based Integrated Watershed Management (CBIWSM) approach was adopted as one of the top climate change adaptation strategies in Ethiopia. Massive sustainable local community based natural resource management efforts have been undertaken to reverse this situation and there are a lot of success stories in the last 25 years in Ethiopia which includes: Water harvesting, Irrigation (crop diversification and intensification), Zero grazing, A (re)forestation, plantation, agro forestry, closure areas, protected forests, intensive and integrated watershed management approach/ SWC and conservation agriculture. Land degradation is primed to exacerbate climate change impacts. Conversely, SLM practices constitute key adaptation measures by resulting in reduced soil erosion, improved water retention, and improved land productivity. Sustainable Land Management (SLM) requires addressing of the underlying causes to land degradation. Environmental rehabilitation efforts in Ethiopia have brought about reclamation of waste lands, re-vegetation of degraded hillsides, restoration of damaged pasturelands, and adoption of improved soil and water conservation and management technologies in cultivated lands. SLM practices and climate change adaptation and mitigation strategies are mutually supportive and represent win-win options.

The Kyoto protocol was a lost opportunity for Africa and it has only benefitted 3% from carbon trading. The prevailing international prices for carbon credits range from \$3.50 per ton CO₂ at Chicago Climate Exchange to \$15.80 per ton CO₂ in various European markets. Carbon credits from carbon sequestration projects in Africa are therefore worth millions of dollars. At present, the Plan Vivo Project in Uganda and the Nhambita Community Carbon Project in Mozambique are already selling carbon credits to United Kingdom-based companies and sharing their carbon revenues with local farmers. There is also recent Humbo CSP in Ethiopia.

Carbon Sequestration Assessment Methods (Plot-National/Regional level): Spatial Analysis and Modeling

The accurate quantification of the various components in the carbon cycle forms a core need for its assessment, monitoring, modeling, and the mitigation of adverse climate effects and, in

the end, sustainability of livelihoods in many parts of the earth. Within the carbon cycle, forestry in the broad sense forms the principal scientific area for research including both emissions (sources) and sequestration (sinks). Due to size, inaccessibility of the land resources, uniform methodology, quantification of the carbon cycle components in both space and time leans heavily on remote sensing, GIS modeling and related statistical tools. Nevertheless, there are significant knowledge gaps in these fields. Still more knowledge gaps exist when facing the post-Kyoto situation with respect to assessment and monitoring of forest degradation and land cover change in general, and the relationships with biomass and carbon.

To assess the likely impacts of the changes in the carbon cycle, and thus its climatic effects on especially the local communities, there is also a high need for 'ground truthing' the climate scenarios and macro data. Specific research areas are equations for standing biomass and biomass growth modeling. Application of appropriate biomass estimation methods and transparent and consistent reporting of forest carbon inventories are needed in both scientific literature and the GHG inventory measures Somogyi et al. (2006). Different approaches, based on field measurements, remote sensing and GIS have been applied for AGB estimation Lu [10].

The traditional techniques based on field measurements only are the most accurate but have also proven to be very costly and time consuming de Gier (2003). The use of remote sensing (RS) techniques has been investigated, but as yet this approach has met with little success for multi-age, multi-species forests and only with limited success in forests with few species and age classes representing a broad range of biomass distributions Schroeder et al. (1997). Nevertheless, even where RS data are useful for estimating forest biomass/carbon, ground data is still necessary to develop the biomass predictive model (i.e. calibration) and its validation Zianis et al. (2005). A sufficient number of field measurements are a prerequisite for developing AGB estimation models and for evaluating the AGB estimation results. GIS-based methods require ancillary data such as land cover, site quality and forest age to establish an indirect relationship for biomass in an area Lu [10], Brown (2002), ITC (2008). Research needs also include the development of cost-effective biomass monitoring systems and developing and evaluating criteria for assessing sequestered, the identification and quantification of land-based sources and sinks; assessing the relationships between sustainable land management and biomass sequestration, as well as the relationship biomass-land degradation, RS, GIS-modeling, ground-based forest biomass assessment, carbon accounting, participatory tools, and the use of related statistical instruments in particular [11].

Framework of Carbon Assessment Methods (Figure 3)

Hierarchical approaches in carbon Assessment (Plot-National-Regional level Carbon balance)

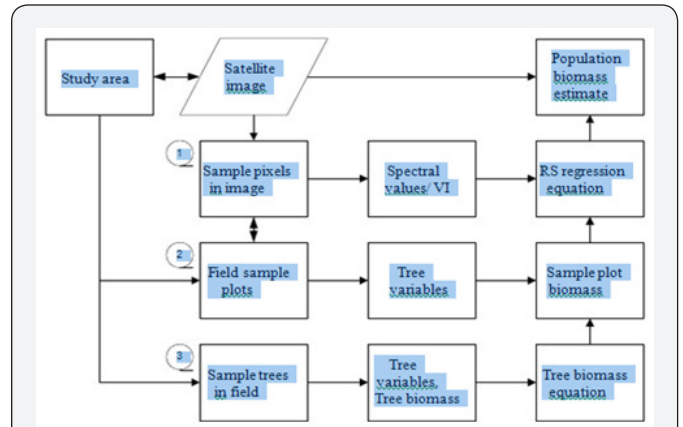


Figure 3: Multiphase sampling design for biomass assessment; 1, 2 and 3 indicate first, second and third phases.

Above ground Biomass

i. Remote Sensing Method

Remote sensing may thus provide an answer against such measurement and monitoring limitations. The remote sensing approach can meet the requirements of carbon sequestration such as permanent sample plots MacDicken (1997) achieved by means of fixed coordinates coupled with the systematic repetitive characteristic of most satellites; the economic realities of costs and benefits. Tucker (1979), (Richardson et al. (1983); and Christensen & Goudriaan (1993), demonstrated that the reflection of the red, green and near-infrared (NIR) radiation contains considerable information about plant biomass. However, they further found that the reflection coefficients determined are not stable because they do not represent the amount of dry matter but that of green foliage biomass that is phonologically affected.

Methods for estimating CO₂ sink from satellite imagery includes

Net Primary Production (NPP)

Experiments of Monteith showed that the increase of plant biomass net primary production (NPP) from well drained manuring crops can be represented by the following Eq. (i):

$$NPP=APAR..LUE \dots\dots\dots (i)$$

Where,

NPP=net primary production

APAR=Absorbed Photo-synthetically Active Radiation

LUE=Light Use Efficiency factor

PAR=Photo-synthetically Active Radiation

Seller , Asrar et al. and Frouin & Pinker have shown that PAR and APAR can be derived from remote sensing data by using the normalized difference vegetation index (NDVI) which uses the wavelength in the red (RED) and infrared NIR.

NDVI=NIR-RED/NIR+RED (ii.a)
 APAR/PAR~NDVI (ii.b)
 The biomass production per time step can be expressed as in Eq. (iii):

$$NPP = NDVI \times PAR \times LUE \dots\dots\dots (iii)$$
 Mathematical calculation for extraction of vegetation area Formula

$$\text{Area (m}^2\text{)} = \text{Numbers of pixels of clusters} \times \text{Resolution}^2 \text{ of the image} \dots\dots\dots (iv)$$

$$\text{Area (ha)} = \text{Area (m}^2\text{)} / 10000 \dots\dots\dots (v)$$
 Mathematical representation of the algorithms to be used -
 A theoretical summary of the steps involved in the calculation of biomass from remote sensing data is as outlined below Samarasingha (2000):

$$NDVI = f(\text{Band 4, Band 3}) \text{ Tucker (1979)} \dots\dots\dots (vi)$$

$$\text{Biomass} = f(\text{APAR}) \text{ (W/m}^2\text{)} \dots\dots\dots (vii)$$
 Kumar and Monteith, 1981 in (Samarasingha, 2000)

$$FPAR = f(NDVI) \text{ (Daughtry et al., 1992)} \dots\dots\dots (viii)$$

$$PAR = f(KL) \text{ (W/m}^2\text{)} \dots\dots\dots (ix)$$
 Christensen and Goudriaan (1993) for clear sky and Tropical countries PAR is 0.51

$$\text{Biomass} = \text{APAR} \times \epsilon \text{ (g/MJ)} \text{ Field et al. (1995)} \dots\dots\dots (x)$$
 Where,

$$\epsilon = \text{light use efficiency}$$

$$\epsilon = \epsilon^{\circ} \times T1 \times T2 \times W \text{ (g/MJ)} \text{ (Potter et al. (1993), Field et al. (1995))}$$
 Where

$$\epsilon^{\circ} = \text{globally uniform maximum (2.5g/MJ) and}$$
 T1 and T2 relate to plant growth regulation (acclimation) by temperature.
 Where,

$$T2 = 1.185 \times \{1 + \exp(-0.2(T_{opt} - 10 - T_{mon}))\} - 1 \times \{1 + \exp(-0.3(T_{opt} - 10 + T_{mon}))\} - 1 \text{ Field et al. (1995)} \dots\dots\dots (xi)$$
 Where,
 Top t = mean temperature during the month of maximum NDVI (constant for a certain vegetation type during the season),
 Tmon = mean monthly air temperature.

$$T1 = 0.8 + 0.02 \times T_{opt} - 0.0005 \times (T_{opt})^2 \text{ Field et al. (1995)} \dots\dots (xii)$$

$$W = 0.5 + (EET/PET) \text{ Field et al. (1995)} \dots\dots\dots (xiii)$$

$W = \Lambda$, the evaporative fraction from SEBAL. (Bastiaanssen and Ali, 2001),

Where

$$LUE = \epsilon \times T1 \times T2 \times \Lambda \dots\dots\dots (iv)$$

Applying all the values from above equations in Eq. (iii)

Therefore, Biomass = NDVI*PAR*LUE

PAR: Photosynthetically Active Radiation

Calculation of carbon for the entire scene = summation of pixel values for the entire scene.

Calculation of carbon for individual pixels = summation of pixel values for the entire scene / Number of pixel in the scene. Then total value of carbon sequestration from grid attribute table (Figure 3).

RS for the assessment of biomass in the framework are not restricted to forests rather; they assess the present biomass regardless of cover type. The biomass of all components of the ecosystem is considered: the live mass above and below ground of trees, shrubs, palms, saplings, etc., as well as the herbaceous layer on the forest floor and in the soil [12]. The greatest fraction of the total above-ground biomass is represented by these components and, generally speaking, their estimation does not represent many logistic problems. Remote sensing imagery can be extremely useful in carbon stock inventories in several ways:

- a. The estimation of above-ground biomass, indirectly, through quantitative relationships between band-ratio indices (NDVI, GVI, etc.) with measures of biomass or with parameters directly related to biomass (e.g. Leaf Area Index, LAI).
- b. Classification of vegetation cover and generation of a vegetation types map. This partitions spatial variability of vegetation into relatively uniform classes, which can be used as sampling framework for the location of ground measurement sites and the identification of plant species.
- c. As up scaling mechanism through spatial interpolation procedures for variables such as estimates of biomass, biodiversity and land degradation indices.

Field Measurement

Above-ground biomass is estimated from quadrat measurements by volume, through allometric calculations involving standard forestry measurements and procedures, (i.e. tree height -H-, diameter at breast height-DBH-, basal area-BA-, wood density -WD- and crown dimensions). Predictive equations, based on a regression approach are also used for estimation of biomass based on allometric and volume measurements Brown et al. (1989). To the tree biomass estimate in the 10 x 10m quadrat, the estimates from shrubs, deadwood and debris measured in the nested 5 x 5m quadrat are added [13]. The herbaceous layer, the litter and other organic debris

collected in the field from the 1x1m quadrat are taken to the laboratory, dried out and weighted [14]. The surface dry organic matter estimate per m² is added to the estimates of total above-ground biomass for each of the field sampling sites (10x10m quadrats). Below-ground biomass is estimated from root biomass as a function of above-ground biomass by non-destructive methods. These rely on calculations of below-ground biomass for similar types of vegetation and coefficients (e.g. 0.2 as the ratio of below-ground to above-ground biomass in forests, depending on the species) [15]. For agro-ecosystems the estimation of biomass makes sense only as the fraction of crop residues added back to the soil, used as animal feed, or for any other non-destructive use, discounting the harvest fraction. Crop growth models are used to project estimates of biomass into the future, when an estimate is required. Thus, average expected crop yields and crop residue production are used as indicators of biomass production in crops [16].

Field Surveys and Sampling Design

The sampling design for the collection of aboveground biomass data should be a multipurpose one in order to realize efficiencies in data collection and minimize costs. That is, the sites that are used to take measurements for aboveground biomass estimation should also be used for biodiversity and land degradation assessments through the observation of its indicators [17-22]. The multipurpose character of the sampling design demands that it should provide data for aboveground biomass estimation: morphometric measurements of standing vegetation; stem and canopy of various strata of trees and shrubs, as well as debris, deadwood, saplings, and samples of herbs and litter fall; Sampling quadrats of regular shape of dimensions 10 × 10 m, 5 × 5 m and 1 × 1 m, nested within each other, were defined as the units for sampling the landscape and measuring biomass, biodiversity and land degradation (Figure 4).

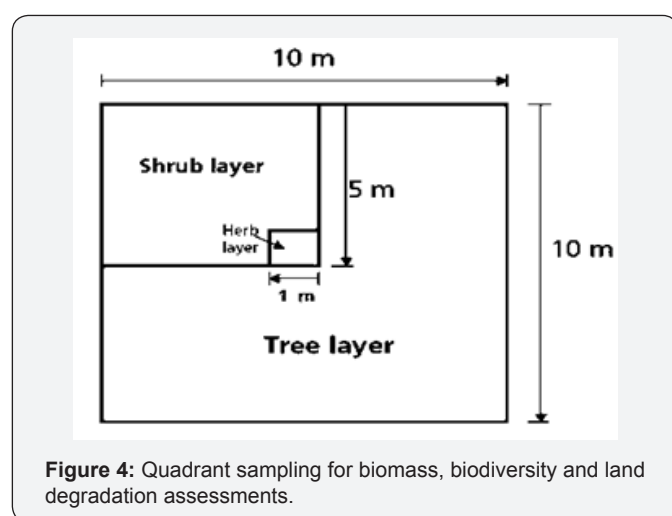


Figure 4: Quadrant sampling for biomass, biodiversity and land degradation assessments.

Below ground: Soil Organic Carbon (SOC) Assessment

SOC Sequestration potential is calculated based on the

following methods:

- i. Lab. analysis of samples.
- ii. Rapid perchloric acid method.
- iii. Spectroscopy method.
- iv. Ratio to above-ground method.
- v. Soil carbon dynamics modeling such as CENTURY and Roth-C Models.
- vi. Interpolation at land use scale.
- vii. Using the detailed sub-national scale data available in FAO, the IPCC indicator of the carbon stock of mineral and organic soil (separately) is calculated based on thermal climate and length of growing period map and soil type.

The traditional approach is labor intensive, slow, destructive, and, consequently, very limited in its utility and scope. Three newly emerging methods to measure carbon in soil *in situ* are a Laser Induced Breakdown Spectroscopy (LIBS) Cramers et al. (2001), near- and mid-infrared spectroscopy McCarty et al. (2002), and Inelastic Neutron Scattering (INS) method Wielopolski et al. (2004). While the first two methods present improvements over traditional core sampling. The percentage of soil mass stored as soil carbon is determined through combustion and analysis on a gas chromatograph [23-28]. The soil bulk density measurements are used to convert percent carbon to a ratio of mass of carbon per unit area, based on the known volume of the soil sample.

Formula:

$SOC (Mg C ha^{-1}) = WBC (\%) \times 10 \times Bd (g cm^{-3}) \times 2$, where WBC is the Walkley-Black carbon (Walkley - Black 1934) and Bd is the bulk density Wolde Mekuria et al. [11].

Total carbon stock for present land use

For carbon accounting purposes, the total carbon stock for a given area, which may be a soil or LUT polygon, or a PCC, present in the current landuse pattern, can be calculated from:

$$C_{stock\ total} = C_{ag} + C_{bg}$$

$$C_{bg} = C_{bg-biom} + C_{soil}$$

$$C_{stock\ total} = C_{ag} + (C_{bg-biom} + C_{soil})$$

Where $C_{stock\ total}$ is the total stock of C in the ecosystem, including aboveground (C_{ag}) and below-ground (C_{bg}) pools. The constituents of the belowground pool are the carbon content in roots and all below-ground biomass ($C_{bg-biom}$) and the C in the soil (C_{soil}) as organic C in SOM. The values of $C_{stock\ total}$ after the estimation of aboveground biomass, its conversion to C, the estimation of C in belowground biomass (roots, etc.), and the modeling of SOM turnover to establish SOC are calculated for particular sites where the biomass measurements have taken

place, in this case the 10 × 10 m quadrats [29-34]. Biomass estimates for below-ground biomass (BGB), i.e. roots, can be estimated as a fraction of aboveground biomass (AGB) by applying the same coefficients as in the estimation for present land use:

- i. BGB = 0.25 AGB for coniferous vegetation;
- ii. BGB = 0.30 AGB for broadleaf vegetation and crops.

In the case of crops, the coefficient 0.3 should be used. Then, for a given site or polygon:

$$\text{Biomass}_{(\text{total})} = \text{AGB} + \text{BGB}$$

The value of total biomass can be estimated from the equation above. Independently of the choice of model, the biomass estimates obtained, by necessity, will be referenced spatially to either a pixel or a polygon representing the land unit or ecozone or pedo-climatic unit from which the climate, soil and site data were extracted to run the model [35]. Therefore, biomass estimate values must be interpolated spatially.

Mapping Carbon stock in present land use: Up scaling procedures

Up scaling the estimates of biomass of PLUTs is a relatively straightforward procedure as suitability map layers have already been created for the “highly suitable” and “suitable” PLUTs. In this report, these were mapped out by assigning these two suitability ratings from the matching process to each one of the map objects, i.e. land unit polygons or PCCs evaluated.

The procedures for up scaling estimates of biomass consist of assigning the calculated value of Biomass_(total) calculated for a given LUT to the land unit polygon or PCC where this PLUT is assigned in the two scenarios of potential land use, either the “highly suitable” scenario or the “suitable” scenario. This will provide at least two mapping scenarios of biomass estimated by each of the estimation procedures above [36-39]. The up scaling procedure based on spatial interpolation or drawing average means per polygon was not necessary in this case. This is because the objects on which the biomass was estimated were already polygons and not the sampling quadrats used to estimate actual land use.

Estimation of carbon stock implicit in potential land use

$$\text{Carbon}_{(\text{in biomass})} = 0.55 \text{Biomass}_{(\text{total} = \text{AGB} + \text{BGB})}$$

Carbon in biomass and carbon in soils are added for the estimation of total carbon in present land use. The conversion of biomass to carbon is achieved through standard species-dependent coefficients reported in published work; e.g. Carbon = 0.55x biomass Mac Dicken (1998). Carbon stock is derived from:

$$\text{Carbon stock}_{(\text{total})} = C \text{ as biomass (above and below) + SOC. The}$$

soil Carbon (SOC) is estimated from analytical data of samples taken at the quadrat sites, or from reported data in soil survey reports of the area of concern. Conversion of SOM to SOC, when values of SOC are not reported, can be made through standard conversion factors (e.g. SOC=0.57xSOM). This may seem simplistic, but it is the best alternative, short of conducting an intensive and costly soil analytical and calibration effort [40-42].

Mapping Carbon stocks across the landscape is achieved through:

- a. Up-scaling estimates of biomass or Carbon from averages of quadrat sites within land cover polygons,
- b. Up scaling Carbon and biomass estimates by spatial interpolation, using Geostatistical techniques based on Regionalized Variable Theory, notably, the various forms of Kriging and Co-Kriging;
- c. Up scaling with interpolation of biomass estimates by bicubic splines or nearest neighbour methods;
- d. Exploiting the presence of co-variables of biomass or Carbon estimates (e.g. band-ratios of satellite images: NDVI or GVI) and then, either, apply co-kriging interpolation or a transfer function to convert the NDVI or GVI values into biomass or Carbon estimates across the landscape.

In summary, a reasonable course of action regarding up-scaling procedures of biomass estimates would be first, to decide on whether the quadrat sites are sufficient in number to compute reliable semi-variograms, and therefore interpolate with Kriging. If the decision is that there are insufficient sites (point-data) to estimate with this technique, then other interpolation algorithms (e.g. bicubic splines) should be used. Class or polygon averages should be used in the event of having only a few quadrat sites in the total area and within each polygon [43]. A band-ratio image (e.g. NDVI, GVI) can be converted into a map of biomass or total Carbon, when such variables are strongly correlated or co-regionalized, by fitting a regression model and then use it to convert NDVI or GVI values in each pixel to biomass or carbon. The summation of the estimates per grid cell or pixel, polygon or biomass class results in a total of biomass for the entire watershed or study area.

Data Acquisition and Analytical Approaches

Input Data

- a. Time series satellite imagery.
- b. Topomap.
- c. Land use dynamics (detailed data of each land use and land use type).
- d. Agro ecological map.
- e. SLM practices inventory for each land use type.

- f. Input use pattern.
- g. Detailed biophysical and socioeconomic data.
- h. Biophysical data (Climate, soil, topography, other land characteristics).
- i. Land characteristics and quality.
- j. Vegetation dynamics (forest density and species richness, type, degradation level)
- k. Vegetation parameters (Basal Area, DBH, Height, Canopy cover).
- l. Cropping systems data (Area, pattern, calendar, operation sequences, type, and yield and productivity data).
- m. Area cover by each land use and land use type.
- n. Socioeconomic data from interview and secondary data sources.
- o. Agricultural technologies and yield.
- p. Demography and settlement patterns.
- q. Miscellaneous.

Sampling procedure and sizes

Sample points from agro ecologies of different ages and spatial variability:

- i. Forested areas, reforested areas, wetlands, protected forests and woodlands.
- ii. Exclosures.
- iii. Agricultural land.
- iv. Open grazing areas and seasonally closed areas.
- v. Crop lands.
- vi. Waste lands and degraded areas.
- vii. Different species along slope gradient (topo-sequential sampling).
- viii. Irrigated and rainfed areas.
- ix. Watersheds and plots.

Data Collection Methods

Exploratory Field survey

- a. Collect relevant secondary information.
- b. Identify sample points from land use/cover classification.
- c. Stratify land use system in agro ecologies to identify sample points from each land use.
- d. Field validation of actual sample points through georeferencing using GPS.

Actual field survey

- i. Interview (Checklist).
- ii. Destructive and non-destructive sampling for direct estimation of C-stock and recording using relevee Sheet.
- iii. Measurement and observation (biophysical factors, georeferenced data using GPS).
- iv. Laboratory analysis.
- v. Soil and plant analysis exploring different methods for carbon.
- vi. Remote sensing data analysis: RS-based analysis of land uses to estimate, quantify and model C sequestration using time-series hyper spectral remote sensing.
- vii. Scenario development to estimate biophysical, social and economic potential of c-sequestration.
- viii. Comparison of methods.
- ix. "Ground truthing" (Validation) of models for accuracy and applicability.

Analytical tools

- a. Classical statistics.
- b. Regression Analysis.
- c. Principal Component Analysis (PCA).
- d. Spatial Analysis and Modeling.
- e. Geostatistics.
- f. AHP Method.
- g. Information value method.
- h. Integration (hybrid approach) of available tools (Exploration, testing, calibration, and validation in local context).

The way forward

Quantification at landscape and spatiotemporal pattern facilitates carbon trading at country, East Africa Region, and continental level [44]. This calls for establishing frameworks, integrated approaches and synergy among actors in modeling and predicting carbon sequestration potentials and promote best SLM practices to enhance marketing channels and institutional settings for effective carbon trading. Due attention should be paid to the following issues to enhance carbon accounting to optimize economic and ecological benefits of local communities in particular and Ethiopia at large [45].

Policy issues

- i. Local communities should be rewarded and empowered for their tireless local efforts in recognition of their contribution to mitigating global climate changes through carbon sequestration ("*Think Globally and Act Locally*" to achieve the

Kyoto protocol). To achieve this goal, there is a need to develop tools and cost-effective methods of C-sequestration assessment and C accounting (Carbon credit) system applicable at local and regional level.

ii. SLM to reach vast lowland (patal and agropastoral) areas of Ethiopia.

iii. Impact assessment studies MU and BOARD (2008), Abbadi (2014) have shown that these natural resource investments have brought about drastic positive changes in environmental changes and improved livelihoods. These efforts should be encouraged and enhanced through inter sectoral integration of stakeholders [46].

iv. Promotion of improved landuse systems and land management practices which provide win-win effects in terms of economic gains and environmental benefits to facilitate carbon trading systems to empower local communities for their contribution to mitigation global climate change.

v. National framework of implementation.

vi. Capacity building.

vii. M & E (inventory) of carbon trading in space and time.

viii. Marketing channels.

ix. Institutional setting (regulation, certification, standards, etc.)

x. Synergy at all levels.

Research priorities

a. Quantify/Estimate carbon stock in different land uses, land use types and SLM practices.

b. Model and predict regional carbon sequestration potential.

c. Identify best SLM practices to boost carbon sequestration.

d. Estimate the Economics (cost) of carbon sequestration of public efforts in the form of carbon trading for income generation.

e. Identify which carbon pool contributes most to carbon stocking at a given land use system and across land use dynamics [47].

f. Establish species, agro ecology, SLM practice, and carbon sequestration relationship.

g. Develop innovative and cost-effective method for regional level C-Sequestration (CS) assessment method through integration of RS, GIS, Statistical, direct field measurement, and laboratory analysis methods through space and time dimension.

h. Reliable Carbon Accounting System (CAS)/guideline for local communities to benefit from global carbon trading.

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DOI: [10.19080/IJESNR.2017.04.555631](https://doi.org/10.19080/IJESNR.2017.04.555631)

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