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Effect of precipitation, temperature, vegetation zone and soil order on carbon sequestration and cost implications for climate-smart agriculture in Africa

Abstract

This paper examines the effect of precipitation, temperature, vegetation zone and soil order on carbon sequestration in Africa and implications for climate-smart agriculture (CSA). This was predicated on the fact that the focus of upscaling CSA approaches have been principally dominated by socio-economic factors leading to reduced attention on biophysical factors such as precipitation, temperature, vegetation zone and soil order on carbon sequestration in Africa as in traditional agricultural adoption, the major influences on adoption concern household preferences, resource endowments, market incentives, biophysical factors, and risk and uncertainty. Data for this study were obtained from a meta-analysis of some SLM practices by converting their soil carbon sequestration rates to net climate mitigation benefits. The results show that from all the regions, arid, forest, Sahel, savanna and semi-arid, the forest region had the highest mean of soil carbon sequestered ($15990 \text{ kg C ha}^{-1} \text{ yr}^{-1}$). The highest amount of carbon was sequestered between 21–25 °C ($1566 \text{ kg C ha}^{-1} \text{ yr}^{-1}$). The highest amount of carbon was sequestered in oxisols. The trend of results has implication for the upscaling of climate-smart agriculture with proper attention to vegetation zones, amount of precipitation and soil order types.

Keywords: sustainable land management, climate-smart agriculture, abatement cost, carbon sequestration.

JEL Classification: Q01, Q05.

Introduction

The need for increase in agricultural production to meet expected demand for food and feed has been stressed by the prevailing climate change scenarios. To achieve food security and agricultural development goals, adaptation to climate change and lower emission intensities per output will be necessary. This transformation must be accomplished without depletion of the natural resource base. Climate change is already having an impact on agriculture and food security as a result of increased prevalence of extreme events and increased unpredictability of weather patterns. Enhancing food security while contributing to mitigate climate change and preserving the natural resource base and vital ecosystem services requires the transition to agricultural production systems that are more productive, use inputs more efficiently, have less variability and greater stability in their outputs, and are more resilient to risks, shocks and long-term climate variability. More productive and more resilient agriculture requires a major shift in the way land, water, soil nutrients and genetic resources are managed to ensure that these resources are used more efficiently.

Developing countries and smallholder farmers and pastoralists in particular are being especially hard hit by these changes. Many of these small-scale producers are already coping with a degraded natural resource base. They often lack knowledge about potential options for adapting their production systems and have

limited assets and risk-taking capacity to access and use technologies and financial services. However, agriculture, which accounts for nearly 14 percent of greenhouse gas emissions, also contributes to climate change (IPCC, 2007). Climate-smart agriculture (CSA) is an applied set of farming principles and practices that increases productivity in an environmentally and socially sustainable way (*adaptation*); strengthens farmers' capacities to cope with the effects and impacts of climate change (*resilience*); conserves the natural resource base through maintaining and recycling organic matter in soils (*carbon storage*); and, as a result reduces greenhouse gas emissions (*mitigation*).

CSA includes a number of technological, political, and institutional interventions (Aggarwal et al., 2004) revolving around seed, water, energy, and nutrients and some risk-averting and risk-insuring instruments that increase the resilience and stability of agriculture and thus help farmers adapt to and reduce the risk of climate change.

Climate-smart agriculture (CSA) emphasize the need for water-smart technologies such that land development, water conservation and harvesting measures in both rainfed and irrigated agriculture, crop planting, and irrigating techniques, among others, could form a package of practices to help overcome the climate-imposed stress (Sharma et al., 2006; Tyagi, 2009). Also, CSA underscore energy-smart technologies in a way that practices to overcome energy constraints are zero tillage and direct seeding. Although these technologies focus on reducing energy use and the cost of production, the measures simultaneously save irrigation water by improving the soil moisture provided by rainwater,

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decreasing soil moisture evaporation, and decreasing pre-sowing irrigation. Each of these technologies has the potential to reduce water demand between 10 and 20 percent and boost crop yields by a similar level. Conservation agriculture is an energy-smart emerging intervention for sustainability (Lumpkin and Sayre, 2009). Similarly, CSA underpin nutrient-smart technologies. These are agricultural practices that ensure soil and nutrient management and carbon management along with nitrogen management can contribute to the conservation of resources, sequestration of carbon, and safeguarding of future food security (Lal et al., 2011). Some of these practices reduce emissions of greenhouse gases and build organic carbon into the soil.

Furthermore CSA explores the sustained efforts in recent years that have led to the development of crop varieties that are resistant to biotic (pests and diseases) and abiotic (flood and drought, salinity and heat) stresses for irrigated and rainfed conditions (ICAR, 2009). Diversification of crops, cropping systems, and farming systems could be a potential response to overcome water scarcity and also to act as a mechanism to minimize weather-induced losses and stabilize incomes. These can be depicted as stress tolerant seeds and crop mix-smart technologies. CSA promotes weather-smart instruments due to the fact that the vagaries of weather events such as floods and drought are major reasons for fluctuating productivity and farm incomes which are expected to worsen under the current climate-change scenario. Risk management through the dissemination of weather advisories and climate information, together with weather-based insurance, is a nonstructural intervention to reduce production losses and stabilize farmers' income. Weather forecasting and advisory services and their dissemination through information and communication technology have made it possible to offset farming losses. Therefore, weather advisories and crop insurance have also been included as possible instruments to stabilize incomes and improve farmers' capacity to adopt other productivity-enhancing technologies.

In addition to the realization and development of technologies in response to CSA challenges, the process of

scaling up CSA approaches to improve adoption among end-users has been a dominant discourse and a race against time. The diffusion and dissemination of interventions have been analyzed in terms of adoption studies and have accumulated considerable evidence showing that demographic variables, technology characteristics, information sources, knowledge, awareness, attitude, and group influence affect adoption behavior (Oladele, 2013). Beyond adoption analysis are the issues of scaling up, up-scaling, scaling out which has the objective of leading to 'more quality benefits to more people more quickly, more equitably and more lastingly over a wider geographic area (IIRR, 2000). The terms scaling out and scaling up first appeared in rural development literature in the 1990s in relation to expanding the practice of participatory research and extension (PRE). Scaling up is a means of capacity building to plan and implement any development activity (Franzel et al., 2001) while to others it is considered as an end, – the assurance of lasting benefits to more people in a wider area (IIRR, 2000).

Scaling up means expanding, replicating, adapting, and sustaining successful policies, programs, or projects to reach a greater number of people; it is part of a broader process of innovation and learning (IFPRI, 2012). Scaling out and up are terms increasingly being used to describe a desired expansion of beneficial impacts from agricultural research and rural development. Scaling up refers to expanding beneficial institutional and capacity building practices within and across organizations and networks at local to international levels (Pachico and Fujisaka, 2004). It is a process for expanding learning and organizational or community capacities to identify and solve new and different problems, and adapt to changing situations. Scaling out and scaling up are often used jointly in rural development literature, whereas scaling out as the geographical spread of a technology, practice or systems change over time, scaling up is vertical within an entity. According to IIRR (2000), and Uvin and Miller (1996). the different types of scaling up are presented in Table 1.

Table 1. Typology of scaling up

Unwin's terms	Description	Alternative terms
Quantitative scaling up	Growth or expansion in their basic meaning increase the number of people involved through replications of activities, interventions and experiences	Dissemination, replication Scaling out or horizontal scaling up
Functional scaling up	Projects and programs expand the types of activities (e.g. from agricultural intervention to health, credit, training among others)	Vertical scaling up
Political scaling up	Projects/programs move beyond service delivery and towards change in structural/institutional changes	Vertical scaling up Institutionalization
Organizational scaling up	Organizations improve their efficiency and effectiveness to allow for growth and sustainability on interventions achieved through increased financial resources, staff training networking	Vertical scaling up Institutionalization development

Source: Uvin and Miller (1996).

The massive literature on innovation systems has established the basic hypothesis that farmers evaluate the costs and benefits of different practices in light of information accessed through social networks and other communication channels. The diffusion of innovation model provided critical insights into adoption decisions such that adoption of innovations follows a sequence of stages: knowledge, persuasion, decision, implementation and confirmation (Rogers, 2003). Innovations generated by agricultural research are communicated by extension agents to farmers. This approach has placed too much emphasis on traditional socioeconomic variables and ignores how other social factors, and uncertainty may be implicated by practices that are ostensibly consistent with CSA priorities (Kristjanson et al., 2009; Spielman, Ekboir and Davis, 2009; Vervoort et al., 2014). Effective outreach strategies will manifest with greater understanding of farmers' beliefs about climate change and their readiness to respond to climate change through mitigation and adaptation.

Despite the fact that improved land management technologies generate CSA 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. 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 non-permanence is lower when the adoption of soil carbon sequestration practices also leads to more profitable farming systems. Leakage occurs when a project displaces greenhouse gas emissions outside its boundary. Additionality implies that in order to attract compensation, emissions reduction must be in addition to what would have occurred under the business-as-usual scenario. Permanence, leakage, and additionality can be addressed through temporary crediting, ex ante discounting, and comprehensive accounting (Murray et al., 2007). Beyond these, there are a number of other implementation constraints. The absence of collective action will hinder successful uptake, diffusion, and impact of these land management technologies.

The focus of upscaling CSA approaches have been principally dominated by socioeconomic factors to reduced attention on biophysical factors such as precipitation, temperature, vegetation zone and soil order on carbon sequestration in Africa. As in traditional agricultural adoption, the major influences on

adoption concern household preferences, resource endowments, market incentives, biophysical factors, and risk and uncertainty. Also similarly to adoption of agricultural production innovations, agroforestry adoption follows the predictions of economic theory. Farmers will invest in a technology when the expected gains from the new system are higher than the alternatives for the use of their land, labor and capital. Early adopters will tend to be those relatively better-off households who have more risk capital available in terms of higher incomes or more resource endowments (land, labor, capital, and experience, education) to allow investments in uncertain and unproven technologies. This paper therefore examines the effect of precipitation, temperature, and vegetation zone and soil order on carbon sequestration in Africa and implications for upscaling climate-smart agriculture.

Methods

Data for this study were obtained from a recent analysis of some SLM practices important to soil carbon sequestration and thus of potential relevance to increasing crop yield, increasing the resilience of agroecosystems and mitigating greenhouse gas emissions (World Bank, 2012b). Estimates of the meta-analysis of soil carbon sequestration rates were converted to net climate mitigation benefits (abatement rates) by converting the C. sequestration rates to carbon dioxide equivalent and adjusting for emissions associated with the land management technologies (Eagle et al., 2010). To obtain these estimates searches were carried out using online database and search tools, including ProQuest, Scopus, Science direct, Springer Link, 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. This paper covered 850 estimates in Africa, 1313 in Asia and 931 in Latin America. The distribution of the estimates is provided in Figure 1. The estimates were taken into accounts and not the studies because a study can generate several estimates.

The inclusion-exclusion criteria were based on the fact that 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 non-experimental 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 at reasonable control. 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. The analysis considered the fact that 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 ha^{-1}) and sequestration rates ($\text{kg ha}^{-1} \text{yr}^{-1}$) 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 pedo-transfer 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.

The emissions associated with the technologies are classified as land and process emissions. Land emissions are the differences among conventional and improved practices for nitrous oxides and methane expressed in CO_2 equivalents, whereas process emissions are those arising from fuel and energy use. It is necessary to account for these emissions because achieving greater soil carbon sequestration through a change in land management practice does not automatically imply corresponding greenhouse gas mitigation potential. For instance, the benefits from increased soil carbon sequestration from fertilizer misuse may be, in part, out-weighted by fossil-fuel related or other greenhouse gas emissions.

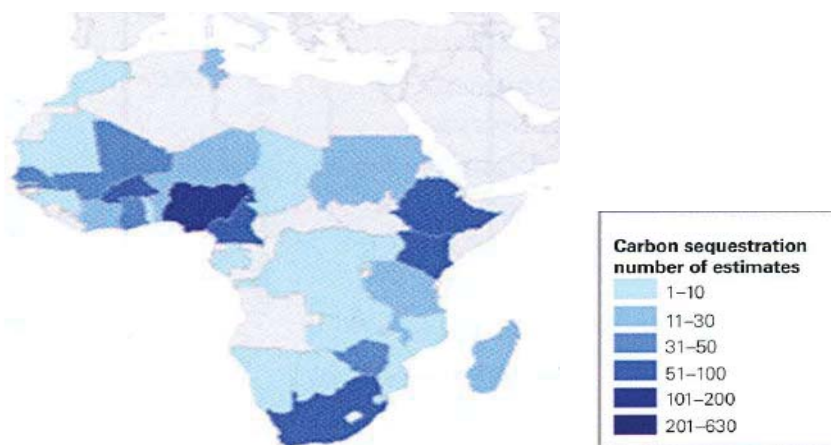


Fig. 1. Geographical distribution of carbon sequestration estimates

Carbon sequestration by regions. Figure 2 presents the different mean amount of carbon sequestered across the regions in Africa. The regions where the studies reviewed fell were arid, forest, sahel, savanna and semi-arid. From all the regions, the forest region

had the highest mean of carbon sequestered ($15990 \text{ kg C ha}^{-1} \text{yr}^{-1}$), possibly due to higher suitability of physical and the chemical interaction of the ecosystem compared to other regions. The forest region was followed by savannah region with a mean carbon

sequestration of 1264 kg C ha⁻¹ yr⁻¹, agreeing with the trend observed by Vagen et al. (2005). Tropical forests in humid and sub-humid regions of SSA cover about 366 million hectares (Mha), and play a major

role in the global C cycle (Bowman, 2000). Tiessen et al. (1998) reported that C storage in vegetation, litter and soils of dry tropical forests is approximately 150.3 and 70 Mg C ha⁻¹, respectively.

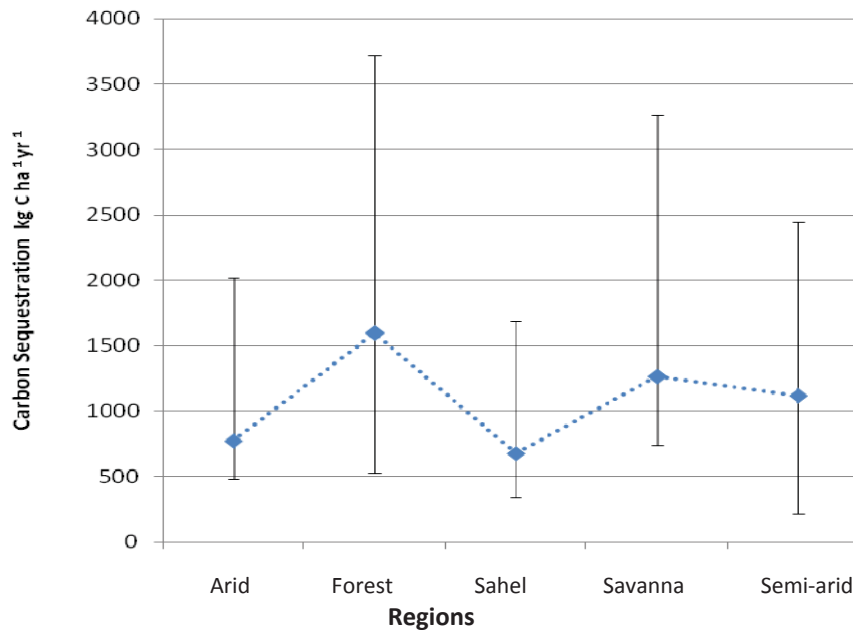


Fig. 2. Carbon sequestration by vegetation regions

Carbon sequestration by temperature. The rate of carbon sequestration varies with mean annual temperature; Figure 3 shows that the amount of carbon sequestered increased from less than 15°C until 25°C after which it declines. In this review, the highest amount of carbon was sequestered between 21- 25°C (1566 kg C ha⁻¹ yr⁻¹). Vagen et al. (2005) indicated that the SOC pool also varies widely among eco-regions, being

higher in cool and moist than warm and dry regions. Lal (2004) noted that soil temperature is the primary rate determinant of microbial processes. Therefore, increase in soil temperature will exacerbate the rate of mineralization leading to a decrease in the SOC pool. However, decomposition of by-products at higher temperatures may be more recalcitrant than those at lower temperatures (Dalias et al., 2001).

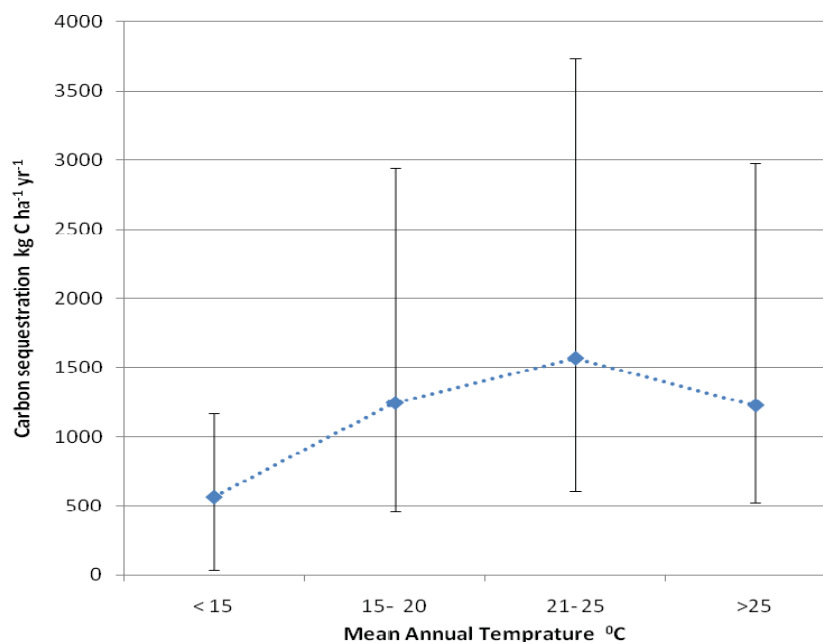


Fig. 3. Carbon sequestration by temperature

Carbon sequestration by precipitation. Figure 4 presents the different mean amount of carbon sequestered across the precipitation ranges in Africa.

The precipitation ranges were categorized into less than 500 mm, 500-1000 mm, 1001-1500 mm and greater than 1500 mm. From all the precipitation

ranges, the range of greater than 1500 mm had the highest mean of carbon sequestered (2368 kg C ha⁻¹ yr⁻¹). Lal (2004) noted that the rate of carbon sequestration was higher in wet areas due to high precipitation than non-wet areas. Chou et al. (2008) noted that C cycling in annual grasslands will be less sensitive to changes in rainfall quantity and more affected by altered seasonal timing of rainfall,

with a longer or later wet season resulting in significant C losses from annual grasslands. Knapp et al. (2002) stated that differences in precipitation patterns alone, independent of rainfall amount, can have a large impact on community composition and possibly ecosystem structure and function. The ecosystem interaction would have impact on the soil carbon.

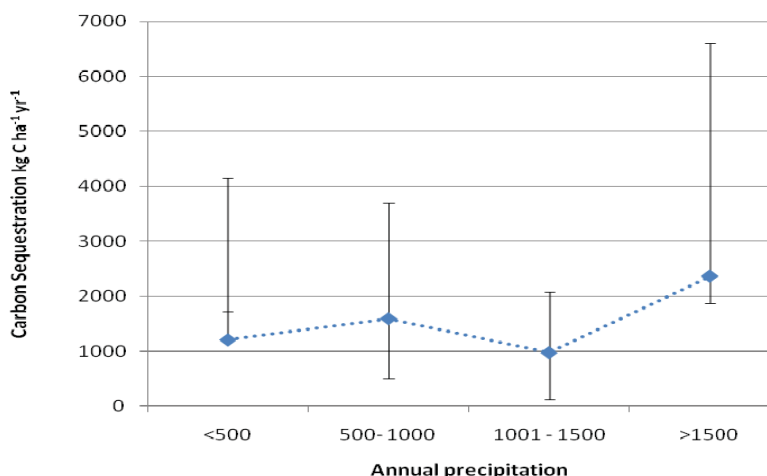


Fig. 4. Carbon sequestration by precipitation

Carbon sequestration by soil type. In Figure 5, the mean amount of carbon sequestered in different soil types was presented. The figure shows that the highest amount of carbon was sequestered in oxisols (2205 kg C ha⁻¹ yr⁻¹). The soil C pool comprises two components: SOC and the soil inorganic carbon (SIC) pool. The SIC pool is especially important in soils of the dry regions. The SOC concentration ranges from low in soils of the arid regions to high in soils of the temperate regions, and extremely high in organic or

peat soils. Vagen et al. (2005) stated that Africa soils are mostly ultisols and alfisols (south) and entisols (north), well-drained savannah soils of western Africa generally have low SOC contents. Ferralsols are highly vulnerable to loss of SOC following conversion to agricultural land use than acrisols, while SOC contents in cambisols may increase under permanent cropping relative to bush land. Albrecht et al. (1992) showed that andisols contain more SOC than ferralsols, ultisols and vertisols.

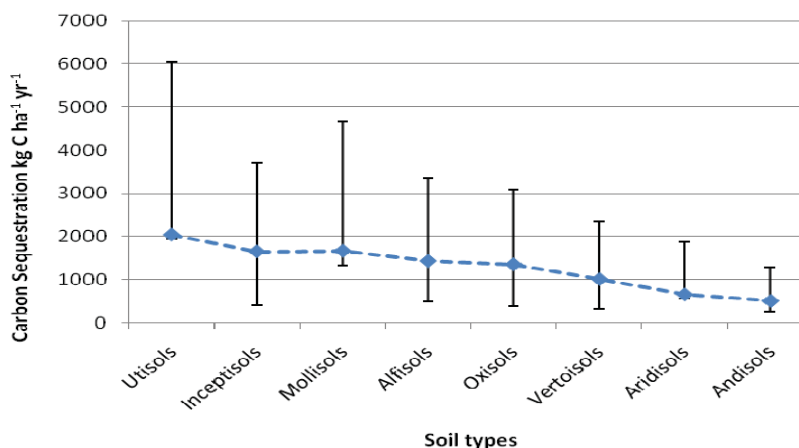


Fig. 5. Carbon sequestration by soil type

Conclusion

This review has revealed that there is high potential to sequester additional carbon through selected land management practices through proper monitoring precipitation, temperature, vegetation zone and soil order on which such land management

practices would be recommended. The potential of land management practices for climate change mitigation as found in the review should not be selectively considered but explored in the context of factors that may affect the application of each land management practice and the prevailing con-

ditions. There is need to integrate land management practices for carbon sequestration into larger sustainable development and livelihoods strategies and practices in order to enhance holistic approach and reduce some of the constraints that may inhibit these positive effect of land management practices for carbon sequestration.

In conclusion, the SOC estimates presented here provide a baseline to estimate future changes in soil C stocks due to variation in temperature, vegetation zone and soil order and to assess their vulnerability to key global change drivers. Likewise, they could be used to improve our ability to respond to environmental changes by informing. In addressing knowledge gaps with respect to the focus of this paper, a top priority is to make better use of existing data on land management impacts on soil C stocks as data limitations lead to large levels of uncertainty in some regions. Collection of new data should provide much needed baselines following rigorous, replicated sampling schemes that allow for future resampling and

coordinated collection of information about costs of adoption of practices, measurements or accurate assessments of effects on other GHGs as well as environmental co-benefits including water infiltration and storage capacity, increased biological diversity and adaptation to climate variation and change. The development of marginal abatement cost curves for a variety of practices feasible within important geographical regions could be very useful for demonstrating the benefits of C sequestration. Comprehensive local assessment of benefits (C sequestered, productivity enhancements, environmental co-benefits) versus costs (investment required, other GHG emissions among other indicators) would enhance the evaluation of the role of land management practices in C sequestration as a component appropriate for mitigation actions. There is a need for raising awareness for donors, policy-makers and consumers. Evidence for policy development at national and international level is necessary in order to promote good land management as instrumental to achieving agricultural and environmental goals.

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