World Soil Information

ISRIC SPRING SCHOOL

(22-26 April 2013)

World Soils and their Assessment

– Soil Carbon Benefits module –

Reader for the Soil Carbon Benefits module

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Contents

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Preamble

This document serves as a reader for the Soil Carbon Benefits module of the "World Soils and their Assessment" component of the ISRIC Spring School 2013. It is based on a paper[1] prepared by the author for an expert meeting on "Monitoring, Reporting and Verification systems for carbon in soils and vegetation in ACP countries" (Brussels, 26 January 2011), organized by EuropeAid Development and Co-operation Directorate-General (DG DevCo) and the Joint Research Centre (JRC). In places, the original document has been expanded with some newer text and materials. The reader is meant to provide background information and a list of references to the course participants; its aim is to be illustrative rather than comprehensive.

Within the scope of the ISRIC Spring School the focus will be on selected elements of the reader. These topics are summarised on the Soil Carbon Benefit (SCB) related webpages for the introductory/refresher course on "World Soils and their Assessment" (see: http://www.isric.org/training/soil-carbon-benefits). As indicated under the tab Objectives, after completion of this introductory course participants should have a broad understanding of: 1) main factors regulating the global distribution of soil organic matter (SOM), 2) options for enhancing SOM levels with improved management, 3) an insight in (new) approaches and techniques for measuring, monitoring and modelling SOC, 4) recognize the multiple benefits of soil organic carbon (SOC) as held in SOM, 5) be familiar with the Carbon Benefits Project (CBP) modelling system, and 6) have some hands-on-experience with at least the Simple Assessment Tool. Special attention will be paid to the on-line tools developed by the GEF co-funded Carbon Benefits Project (http://www.unep.org/climatechange/carbon-benefits/), including an exercise with the CBP's Simple Assessment.

Niels H. Batjes
Wageningen, 17 April 2013

[1] Batjes NH 2011. Research needs for monitoring, reporting and verifying soil carbon benefits in sustainable land management and GHG mitigation projects. In: De Brogniez D, P Mayaux and L Montanarella, (editors), *Monitoring, reporting and verification systems for carbon in soils and vegetation in African, Caribbean and Pacific countries*. European Commission, Joint Research Center, Brussels, pp 27-39 *http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR24932.pdf*

Introduction

The human-induced increase in atmospheric greenhouse gas (GHG) concentrations poses a threat to the global environment and human well-being. Carbon dioxide, but also nitrous oxide and methane, are most notorious in this regard. Mitigating GHG emissions is a major challenge and needed to curtail climatic change (Bouwman 1990; Smith *et al.* 2008; Watson 2003; Lal 2004).

GHGs and their elements carbon, nitrogen, oxygen and hydrogen are part of global biogeochemical cycles. They occur in the atmosphere, oceans, vegetation and soils. Some two thirds of all terrestrial carbon is contained in the soil; vegetation accounts for the rest (Batjes 1996). Soils are important long-term reservoirs of organic carbon; inorganic (carbonate) carbon can be important in semi-arid and arid regions (Lal *et al.* 2000). The amount of carbon in soil, present in soil organic matter, is strongly influenced by changes in land use and management.

Agriculture, land use change and forestry account for 25-30% of global anthropogenic GHG emissions to the atmosphere (IPCC 2007; World Resources Institute 2010). The agricultural sector alone is responsible for about 12% of total GHG emissions (Smith *et al.* 2007a; UNFCCC 2008). At present, agricultural lands occupy some 40-50% of the Earth's land surface, with agriculture causing an estimated emission of 5.1-6.1 Gt CO_2-eq yr^{-1} in 2015 (Smith *et al.* 2007a). This points at a significant potential for mitigation through improved land management, particularly in Non-Annex I countries (Figure 1).

According to the UNFCCC (2008), the global technical mitigation potential of agriculture, excluding fossil fuel offsets from biomass, by 2030 is estimated to be 5.5–6.0 Gt CO_2-eq per year. Some 89 per cent of this potential can be achieved by soil organic carbon (SOC) sequestration through cropland management, grazing land management, restoration of organic soils and degraded lands, bioenergy and water management (UNFCCC 2008).

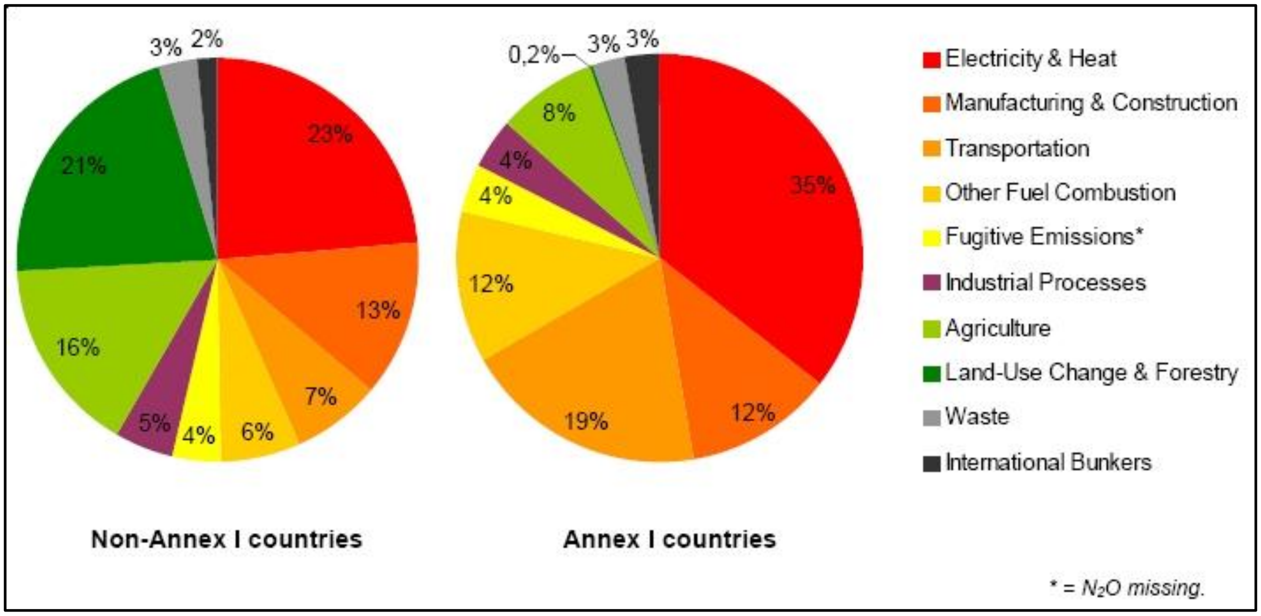

Figure 1. Emission sources in developing (non-Annex I) and developed (Annex I) countries (World Resources Institute 2010)

During the last decade, acceptance of the GHG mitigation potential of agricultural soils has increased. Various projects and other activities are being implemented worldwide. For example, a) in several countries, cropland activities have already been elected to officially account for SOC sequestration under the Kyoto Protocol (e.g., Canada, Denmark and Portugal); b) UN-REDD (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) and the on-going debate on REDD$^+$ have the potential to create new opportunities for agriculture and rural producers (e.g., food security, alleviating poverty, improving governance, conserving biodiversity and providing other environmental services); c) development of analytical solutions for field C (and GHG) measurement, monitoring and verification; d) development of tools for forecasting changes in C-balance respectively full carbon accounting, such as the GEF-CBP (Carbon Benefit Project) system (Milne *et al.* 2010a; Milne *et al.* 2010b) and FAO-EX-ACT tool (Bernoux *et al.* 2011); e) implementation of voluntary markets for trading C, such as the BioCarbon fund and the Chicago Climate Exchange (CCX). Nonetheless, there is a need for a robust technical and scientific information base to help translate policy frameworks and financial incentives into terrestrial carbon management.

The aim of this document is to point at important development and research needs for monitoring, reporting and verifying (MRV) soil carbon benefits in sustainable land management (SLM) and GHG mitigation projects. As such, its scope is more illustrative than comprehensive.

Soil organic matter and sustainable land management

Organic carbon is stored in the soil as organic matter, comprising decomposed parts of above and below ground biomass. Soil fauna, roots, microbes and fungi interact with mineral and fresh organic matter to gradually create stable humus. Brussaard *et al.* (2007) and others have discussed the importance of soil biodiversity to sustain (agro)ecosystem functioning.

Many managed agro-ecosystems have lost 30-55% of their original SOC pool since land use conversion (e.g., Mann 1986; Sampson and Scholes 2000) on a volume basis; without soil mass correction, however, land use change effects may have been underestimated by some 30% according to Don *et al.* (2011). The carbon sink capacity of the world's agricultural and degraded soils is estimated at 50 to 66% of the historic carbon loss of 42 to 78 Gt of carbon (Lal 2004). Generally, depleted SOC stores can be improved through rehabilitation or judicious soil and water management (Figure 2), but the possible gains are finite.

Under natural conditions, SOC levels remain at a certain equilibrium with the natural vegetation (Figure 2; baseline is set at 100, see Y-axis). A change in land use and management, such as deforestation for timber or conversion to pasture or agricultural lands, breaks the natural cycle. Less organic material becomes available and the soil gets more exposed to the sun and the atmosphere. As a result, the amount of SOC will rapidly decrease to a lower equilibrium, generally within 5 to 10 years. Consequently, CO_2 and other GHGs will be released into the atmosphere, contributing to global warming. In addition, such SOC losses will be associated with losses in soil quality, for instance a reduced capacity for holding water and retaining nutrient cations, with adverse impacts on food security and biodiversity.

In agricultural systems, the amount of SOC can be increased only when organic matter inputs are greater than decomposition. This can be achieved by implementing recommended management practices (RMP) that include an adroit combination of: (a) conservation tillage in combination with planting of cover crops, green manure and hedgerows; (b) organic residue and fallow management; (c) water conservation and management; (d) soil fertility management, including use of chemical fertilizers, organic manures and liming; (e) introduction of agro-ecologically and physiologically adapted crop/plant species, including agroforestry; (f) adapting crop rotations, with avoidance of bare fallow; and (g) stabilization of slopes and terraces to reduce risk of erosion by water (e.g., Batjes 1999; Bruce *et al.* 1999; Paustian *et al.* 1998; Smith *et al.* 2007a). The selection of RMPs should be site specific.

The build-up of SOC proceeds slowly and generally takes decades of continuous best management practices. The new steady-state may be lower, similar and sometimes even greater (Figure 2) than the antecedent SOC stocks. The latter has been the case, for example, with the Plaggen soils of Western Europe (Pape 1970) and Terra Preta dos Indios in the Amazon (Sombroek 1966) that have been historically enriched with organic materials and nutrients taken from surrounding locations.

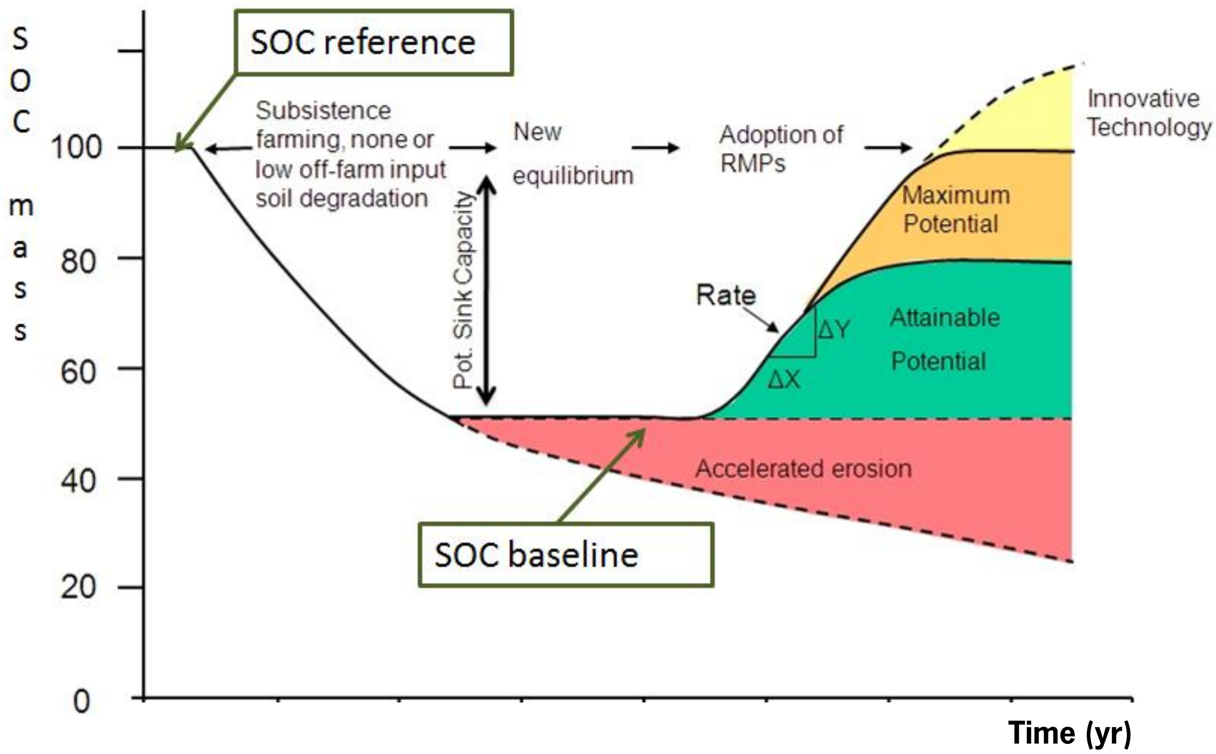

Figure 2. Adoption of recommended management practices (RMPs) can help restore SOC stocks and reduce GHG emissions (The reference level, on the Y-axis, is set at 100; X-axis not to scale; modified after Lal, 2008)

Sustained adoption of RMPs is necessary to maintain and improve the productivity of soils, prevent soil degradation, increase biodiversity and thereby improve the performance and resilience of agro-ecosystems. Generally, options that both reduce GHG emissions and increase productivity are more likely to be adopted than those which only reduce emissions (Smith *et al.* 2007a).

Regional differences in SOC sequestration potential

The amount and vertical distribution of organic carbon in boreal, temperate and tropical soils vary greatly (Figure 3, see Batjes and Sombroek 1997; Eswaran *et al.* 1995; Sombroek *et al.* 1993), due to regional differences in the intensity of the soil forming factors of climate, landscape position (relief), parent material, biological factors (plants, animals, micro-organisms, and mankind), and time (Jenny 1941). For example, for a given climate and vegetation type, soils formed on basic rocks will typically hold greater amounts of SOC than those developed over acid rocks. Global, area-weighted averages for SOC content range from about 4 kg C m^{-2} to 100 cm depth for soils of arid regions, where plant growth is limited, to about 24 kg C m^{-2} for soils from boreal regions (Batjes 1999).

For a given climate/soil stratum, the possible magnitude and rate of SOC sequestration will depend on: a) the baseline or reference level; b) antecedent SOC pool (land use history), c) soil properties, such as depth of soil, clay content and mineralogy, drainage/aeration conditions, and soil nutrient status; d) the type of RMPs adopted; and, e) socio-economic conditions/incentives.

Figure 3. The amount and vertical distribution of organic carbon varies greatly between and within boreal, temperate and tropical soils (Source: ISRIC World Soil Reference Collection)

High C-costs may be incurred in areas where natural processes do not effectively favour C sequestration, such as in arid regions (e.g., through fuel use for irrigation). As such, there is a need to identify regions and land management practices with a high potential for GHG emission reduction and SOC sequestration across the full range of world climate/soil/land use types. Although there are many different measures to protect/improve soils and SOM content, often their *net* GHG effects are not well documented and evaluated. Indicative rates of biophysically feasible SOC sequestration rates for defined land use activities and climatic zones, following adoption of specific RMPs, have been discussed in many papers. Overall, world croplands may sequester some 0.1-1.2 Mg C ha^{-1} yr^{-1} depending on climate, soil type, management practices and socio-economic conditions/incentives (e.g., Batjes 1999; Bruce *et al.* 1999; Sampson and Scholes 2000; Smith *et al.* 2007a). The maximum feasible C sequestration potential at any given location, however, will seldom be realized due to a series of biological, physical, social, and political constraints (Sanderman et al. 2010). In the absence of policy interventions, it will be rational for individual farmers in tropical countries to manage their soil carbon at socially sub-optimal levels since soil carbon is part of the national and world natural capital (Izac 1997).

Every measure that increases SOC content (sensu soil organic matter) is likely to have beneficial impacts on soil properties and functions (UNEP 2012), thereby providing important ecosystem services (Millennium Ecosystem Assessment 2005; Milne et al. 2012). In this context, it is especially important to evaluate the socio-economic feasibility of alternative management options, and their possible impact on human well-being through effects on e.g. food security. As observed by Janzen (2006), it is the biological turnover of organic C that is important for function, not just the amount accumulated in stable C-pools; for a critical examination see Powlson *et al.* (2011).

Measuring, monitoring and modelling SOC changes

Knowledge of how different land management strategies will affect agro-ecosystem carbon stocks and GHG changes, land degradation and sustainability remains far from complete (e.g., IPCC 2006; Kogel-Knabner *et al.* 2005; Powlson *et al.* 2011). The above reveals the need for a better understanding of the role of soils and the vegetation that grows on it as natural regulators of GHG emissions and climate change. Estimating SOC stock and GHG emission changes on any scale will require access to a wide range of databases: climate, terrain, soils and land use/vegetation, as well as the main socio-economic drivers. Managing, sustaining and utilising such databases, especially at the continental and global level, will require enduring efforts; the same applies for model development and testing.

Relationships between environmental/management factors and SOC dynamics can be established using experimental field-trials, chronosequence studies and monitoring networks. Soil monitoring networks (SMN), for example, can provide information on: direct changes of SOC stocks through repeated measurements at a given site; data to parameterise and test biophysical models at plot scale; a set of point observations that represents the variation in climate/soil/land use management at national scale, allowing for up scaling. As shown by a recent review (van Wesemael *et al.* 2011), many SMNs are in the planning or early stages. Within such networks, monitoring sites may be organised according to different sampling schemes, for example regular grid, stratified approach or randomized (e.g., ISO 2002; Ravindranath and Ostwald 2008; UNFCC 2009). Further, there are numerous protocols for field sampling and measuring SOC (e.g., GOFC-GOLD 2009; ISO 2002; McKenzie *et al.* 2002; Pearson *et al.* 2005; Stolbovoy *et al.* 2007), thereby providing a possible source of confusion also since C-projects may have different objectives.

Basically, there are two types of C-projects: climate change mitigation, with strict C and GHG reporting needs (e.g., CDM and REDD^{+}) and Sustainable Land Management projects the focus of which is on food security, farmer livelihood, resilience and biodiversity. Increasingly, SLM projects also need to assess broad impact of interventions on SOC and GHG fluxes, as is the case, for example, within the Green Water Credits (GWC) project (Geertsma *et al.* 2010). Overall, projects should be encouraged to use the most accurate methods possible, given the resources available and project objectives (Milne *et al.* 2010a; Milne *et al.* 2010b).

Because SOC levels are particularly sensitive to changes in land use practices, these can be regulated through land use policy interventions (e.g., Izac 1997; Koning *et al.* 2001; Smith *et al.* 2007b). Carbon-fixing projects that claim *environmental benefits* have paid most attention to carbon in vegetation rather than in the soil, primarily because of the relative ease of measurement. Compared with biomass carbon, SOC must be monitored over longer periods because the changes are small relative to the very large stocks present in the soil as well as the inherent variability; this requires sensitive measurement techniques. Methodological efforts are needed to ensure that SOC stock changes can be detected consistently (known accuracy, within defined permissible error) across complex landscapes. When assessing SOC stock at the landscape scale, one should focus on the precision of SOC analyses from the laboratory, reducing the spatial variation of SOC, and use equivalent masses for SOC stock comparison (Goidts et al. 2009; Wendt and Hauser 2013).

Studies of SOC dynamics have been hampered by the difficulty of sampling and observing processes beneath the earth's surface. Standard methods of soil analysis are often too expensive for continuous monitoring, in view of the large number of samples/analyses involved. Various promising techniques are under development (e.g., Gehl and Rice 2007; Viscarra *et al.* 2010). Inelastic Neutron Scattering (INS, e.g., Wielopolski *et al.* 2011), Infra-Red Reflectance Spectroscopy (Vis-NIR and Mid-IR, e.g., Ladoni *et al.* 2009; Reeves *et al.* 2002; Terhoeven-Urselmans *et al.* 2010) and Laser-Induced Breakdown Spectroscopy (LIBS, e.g., Ebinger *et al.* 2006; Martin *et al.* 2003), for example, can provide rapid, accurate measurements, once calibrated. Further, Gamma-spectroscopy appears promising for rapid measurement of bulk density (e.g., Mostajaboddavati *et al.* 2006), required to compute SOC stocks.

So far, mainly Vis-NIR and MIR reflectance spectroscopy have produced good results for the prediction of SOC content (McBratney *et al.* 2006; Shepherd and Walsh 2007; Viscarra *et al.* 2010) on a cost-effective basis. Airborne imaging spectroscopy has been used for mapping top soil properties (Ben-Dor et al., 2008). This technique provides good results for mapping the SOC content in the plough layer of bare soils (i.e., in seedbed condition) as shown by Van Wesemael et al. (2011). In all cases, however, conventionally measured SOC (dry combustion) in reference laboratories is necessary to calibrate the new techniques, and to build spectral libraries needed for the extension of spectral measurements in un-sampled areas. Further, as techniques and standards for soil analyses are evolving continuously, it is good practice to preserve soil samples from SMNs so that they may be re-analysed in the future.

Remote sensing (RS) provides direct observations of land surface features/processes, thereby increasing the accuracy of SOC change predictions. New RS techniques permit monitoring of changes in selected chemical and physical properties of soil, though only to a limited depth. Operational routine RS assessment of SOC stocks, however, is not yet considered possible according to the Terrestrial Carbon Group (2010). Anderson and Croft (2009) discuss the newest techniques within active, passive, optical and microwave remote sensing and consider multi-sensor approaches and the issue of scale. The accuracy and precision of such RS methods, however, is rapidly improving as more experience is gained (Mulder *et al.* 2011). According to Ge et al. (2011), a large array of agriculturally-important soil properties (including texture, organic and inorganic carbon content, macro- and micro-nutrients, moisture content, cation exchange capacity, electrical conductivity, pH, and iron) have been quantified with RS successfully to various extent for in-field soil property determination; the visible and near-infrared regions are most commonly used to infer soil properties, while the ultraviolet, mid-infrared, and thermal-infrared regions have been used occasionally.

The range of soil and ancillary data collated through SMNs and similar field sampling programmes should be stored in a (freely-accessible) information system to support geo-statistical analyses and modelling (e.g., Batjes et al. 2013). At present, however, external access to SMN data is often restricted to the metadata (e.g., Panagos et al. 2013), thereby greatly reducing their value to the scientific community and society.

Carbon offset markets

It remains difficult to assess the environmental benefits associated with SLM projects because these should be determined according to standardised criteria and procedures. Many different methodologies have been developed/tested in different countries; a co-ordinated effort is needed to ensure that these methods are comparable/cross-referenced. Feasible accounting respectively modelling tools are needed for all lands and carbon pools, and these should consider all GHGs. The GEF co-funded Carbon Benefits Project (CBP), for example, is developing a standardized, cost-effective methodology that is comprehensible, standardized, robust and applicable to all GEF-SLM projects to: (1) permit the GEF (and others) to monitor the net C impacts of its investments in AFOLU projects, and (2) provide an enhanced capacity of SLM-projects to engage with the emerging carbon-offset markets (see CBP-CSU 2009-2012; Milne *et al.* 2010a; CBP 2013). Overall, the "attractiveness" of a project will depend on the buyer's objectives, and requirements will be different for a "compliance" (e.g., CDM) or "voluntary" (e.g., CCX) buyer (Kollmuss *et al.* 2008). Alternatively, current low prices per ton CO2eq are unlikely to represent a sufficient financial incentive for smallholders in many regions to participate in a carbon sequestration programme (e.g., Smith et al. 2008; Grace et al 2011; Batjes 2012).

Concluding remarks

Many challenges remain to making agriculture part of the mitigation agenda, also in view of the many trade-offs between forestry approaches to mitigation and agricultural approaches (Campbell 2009). Irrespective of the climate debate, however, soil quality and its organic matter content must be restored, enhanced and improved (Global Soil Forum 2012), seen its importance in sustaining ecosystem services (UNEP 2012).

Based on the preceding overview, several issues for further research on monitoring, reporting and verification systems for carbon in soils and vegetation may be identified:

- Increase process-level understanding of carbon dynamics, subject to changes in land use management and climate
- Development of cost-effective techniques to measure and monitor all C pools (and GHGs) to reduce the need for conventional laboratory analyses; implementation of QA/QC procedures
- Creation of, and long-term support, for national scale MRV systems; capacity building
- Development and validation of scaling procedures (accounting and modelling) at field, landscape and broader scales, ultimately for all terrestrial C pools and GHG fluxes; also, quantified uncertainty.
- Development of a tier-based, global information system with main socio-economic and biophysical driving variables, at relevant scales, to support modelling; ideally, open-access through web-services.
- Streamlined processes for harmonizing definitions, standards and methodologies.
- For (groups) of small farmers, consider options for C-markets based on adoption of practices or management options known to sequester C rather than market mechanisms that are based on the

impact of a given practice/management option based on verified, measured or model-estimated results.

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