1. Introduction

NEED FOR SOIL CARBON ESTIMATES

Increasing greenhouse gas (GHG) concentrations in the atmosphere create a threat to the global climate system and the environment. Soil is related to this issue since it can affect atmospheric carbon dioxide concentration by causing net emissions or acting as a sink of carbon.

Forest soils constitute a large pool of carbon and releases of carbon from this pool, caused by anthropogenic activities such as deforestation, may significantly increase the concentration of GHGs in the atmosphere (IPCC, 2000). Tropical deforestation represents nearly 25 percent of total anthropogenic GHG emissions worldwide (Pan *et al.*, 2011). Estimating and reducing emissions from these activities have become timely issues. Mechanisms that are effective in reducing emissions are of particular importance for the mitigation of global climate change.

Countries have agreed internationally to monitor their GHG emissions and removals. In accordance with Article 4.1(a) and 12.1(a) of the United Nations Framework Convention on Climate Change (UNFCCC), each Party (country) shall communicate to the Conference of the Parties (COP) to the UNFCCC a national inventory of anthropogenic emissions by sources and removals by sinks of all GHGs not controlled by the Montreal Protocol using comparable methodologies. The required contents of the national communications and the timetable for the submissions are different for Annex I and non-Annex I Parties. Annex I Parties (industrialized countries) that have ratified the Kyoto Protocol must also include supplementary information in their national communications and their annual inventories of emissions and removals of GHGs to demonstrate compliance with the Protocol's commitments. In addition, Annex I Parties are required to submit information on their national inventories annually, and to submit national communications periodically, according to dates set by the COP. The non-Annex I Parties (non-industrialized countries) must provide updated inventory reports every two years.

A framework for Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+ mechanism) has been designed to reduce emissions and enhance forest carbon stocks, following the agenda of the 15th session of the COP to the UNFCCC held in Copenhagen in 2009. The REDD+ mechanism also has the potential to promote co-benefits, including alleviating poverty, improving governance, conserving biodiversity and securing forest ecosystem services. Moreover, REDD+ is a framework that Annex I Parties can use to meet their commitments under the Kyoto Protocol of the UNFCCC, notably through Clean Development Mechanism (CDM) projects on afforestation and reforestation. In the 2010 Cancun Agreements of the United Nations Climate Change Conference, the parties agreed to establish the Green Climate Fund, and projects aiming to decrease the rate of deforestation were accepted as CDM projects.

The soil carbon monitoring system will increase the ability of developing countries to enhance reporting in national communications to be submitted every four years to the UNFCCC as well as biennial reports with updates of national GHG inventories (UNFCCC decision 1/CP.16). It will assist countries to report on eligible activities under the REDD+ mechanism, including reducing emissions from deforestation and forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks (UNFCCC decision 1/CP.16).

The methods for soil carbon monitoring given in this paper are useful tools for estimating soil carbon pools in constructing the national forest reference emission level (UNFCC decision CP.17).

SOIL CARBON CYCLE

Soil plays an important role in the global carbon cycle. The carbon stock of soil equals some 1 500 Pg in the topmost 1 m soil layer (Eswaran, van den Berg and Reich, 1993; Jobbágy and Jackson, 2000), and approximately 506 Pg (32 percent) of this is in the tropics (Eswaran, van den Berg and Reich, 1993) and 160 Pg in Africa (Henry, Valentini and Bernoux, 2009). Globally, the soil carbon stock is nearly three times the amount in the above-ground biomass and about twice as large as the carbon stock of the atmosphere (e.g. Eswaran, van den Berg and Reich, 1993). In Africa, the soil organic carbon stock corresponds to 68 percent of the terrestrial carbon stock (Henry, Valentini and Bernoux, 2009). Carbon dioxide emissions resulting from the decomposition of organic carbon compounds in soil amount to 60–80 Pg carbon per year (e.g. Thum *et al.*, 2011). A somewhat similar amount of carbon is brought annually to soil in the form of plant residues. These carbon fluxes from and to the soil are seven to nine times as large as the current anthropogenic fossil carbon dioxide emissions to the atmosphere, equal to 9.1 Pg in 2010 (Peters *et al.*, 2012).

Changes in soil carbon result from an imbalance between the carbon fluxes into and out of the soil. When more carbon is brought to the soil than is released, carbon accumulates in the soil, and vice versa. Increments in plant productivity and input of plant residues to soil thus have an increasing effect on soil carbon stock, whereas more favourable conditions for decomposition have a decreasing effect. Land-use change may induce quite rapid changes in soil carbon as a result of altered carbon input to the soil or decomposition conditions or both (e.g. Post and Kwon, 2000; Vågen, Lal and Singh, 2005; Zingore *et al.*, 2005).

CHALLENGES IN MONITORING CHANGES IN SOIL CARBON

Typically, the soil carbon stock is large and small relative changes may have a remarkable influence on forest carbon balance. In tropical rain forests, soils contain nearly as much carbon as vegetation, but exceed the biomass in other ecosystems by a factor of two to ten (Sombroek, Nachtergaele and Hebel, 1993). The carbon stock of tropical soils is smaller than the global average, but the soil carbon turnover rate is very high (Raich and Schlesinger, 1992; Cao and Woodward, 1998), which underlines the importance of monitoring tropical soils as a part of global carbon balance. It is a challenging task to detect a change in a large stock, especially in the case of forest soils where between-site and within-site variations are considerable (Conen, Yakutin and Sambuu, 2003; Yanai *et al.*, 2003; Wang *et al.*, 2009; Häkkinen, Heikkinen and Mäkipää, 2011). Henry, Valentini and Bernoux (2009) reviewed soil organic carbon estimates reported for Africa and concluded that only a few precise country- or regional-scale studies exist. Because of the variation in soil properties, e.g. in the soil carbon stock, a large number of samples are required in order to provide soil carbon estimates that are accurate enough for monitoring purposes.

METHODS OF MONITORING CHANGES IN SOIL CARBON

Under the UNFCCC, countries must estimate and report GHG emissions and removals, including changes in carbon stocks in all five pools (above- and below-ground biomass, dead wood, litter and soil carbon) and associated emissions and removals from land use, land-use change and forestry activities according to the GPG (IPCC, 2003; 2006).

Earlier global efforts on soil studies have – to a large extent – been focused on assessment of soil properties including carbon stock rather than on soil carbon changes (Batjes, 1995; FAO, 1995; 2006; FAO/IIASA/ISRIC/ISSCAS/JRC, 2008). IPCC (2003; 2006) has developed standard methods for estimating soil organic carbon stocks and stock changes. These methods are characterized by flexibility, ranging from the Tier 1 default method prescribed by IPCC with fixed default values, to methods that incorporate local information to estimate carbon stock changes at Tier 2 level, and to more advanced modelling and measurement-based networks at Tier 3 level. Features of the tiers as well as their applicability and associated weaknesses are evaluated and discussed in detail by Smith *et al.*, 2012. Some developed countries have established or are planning to establish representative networks of sample plots for repeated measurements of soil carbon stock (e.g. Ståhl *et al.*, 2004). Since measuring soil carbon stock changes is a laborious and expensive undertaking (Mäkipää *et al.*, 2008), soil carbon modelling is often used as an alternative or a complement to repeated soil carbon inventories to estimate and report the changes in soil carbon stock (Peltoniemi *et al.*, 2007). However, if the pool is not a significant contributor (less than 5 percent) to the GHG balance, emission and removals can be assessed using the Tier 1 default value. On the other hand, when the soil compartment is considered to be a significant source of GHG emissions, accuracy of the method needs to be improved.

OBJECTIVE OF THIS REPORT

The objective of this report is to describe and evaluate methods to monitor soil carbon at national level. Two kinds of methods are described: field surveys and modelling-based methods. In addition to general descriptions, the application of both methods is described in specific detail for the United Republic of Tanzania.