Nutr Cycl Agroecosyst (2008) 81:107–112
DOI 10.1007/s10705-007-9134-2

ORIGINAL PAPER

Carbon sequestration in soils of cool temperate regions (introductory and editorial)

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Received: 9 May 2007 / Accepted: 21 August 2007 / Published online: 6 September 2007

Abstract The cool temperate climate, dominance of perennial land use, and relatively large proportion of peat and organically rich soils, make the northern European regions to have a large potential of soil organic carbon (SOC) sequestration. However, with predicted global warming soils in these areas may become sources of atmospheric CO_2. Quantitative and reliable assessment methods and understanding of the spatial variability of SOC pools are required to make accurate mean estimate of available C and integrate variability into predictive models of SOC reserves and sequestration potential. Advanced analytical methods such as near-infrared spectroscopy and carbon isotope techniques can be used to estimate retention time and C turnover rates in soils. The rehabilitation of peat lands has shown a potential for SOC sequestration ranging from 25 to 45 gCm^{-2} yr^{-1} in Scandinavian countries. The potential of SOC sequestration in agricultural and forestry ecosystems depends on the land use and management practice adopted. Furthermore, the proven land management practices (e.g. conservation tillage, reduced soil erosion, restoring wetlands and degraded lands) coupled with improved cultivation practices (e.g. judicious fertilizer use, crop rotations and cover crops) can make the soil of this region as C sink.

Keywords Assessment methods · Carbon sequestration · Carbon stocks · Land use · Peat lands · Temperate regions

Introduction

Ideal settings to sequester organic carbon in soils are found in the environments that promote minimum soil disturbance (Post et al. 2001). Thus the cool temperate climate, dominance of perennial land use, and relatively large proportion of peat and organically rich soils, make the northern European regions to have a large potential of soil organic carbon (SOC) sequestration, but it can also have a potential for large CO_2 emissions with increased global warming. In contrast to natural ecosystems, most of the agricultural soils have been source of atmospheric enrichment of carbon dioxide through mineralization of soil organic matter, accelerated soil erosion, and drainage of wetlands. However, recent changes in crop management, including incorporation of crop residues, may have reduced CO_2 emissions from these soils.

Soil carbon sequestration is governed by many factors such as ecosystem composition (land use systems), climatic conditions, and soil properties, which independently or combined can influence the

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rate and magnitude of soil carbon sequestration. Agricultural soils contain far less SOC than their counterparts in natural ecosystems. For example, 70–80 % of SOC in the United Kingdom is contained in peat soils (Howard et al. 1995) and 35% of the total C in European soils is held within high organic soils that cover only 13% of the area of the European Union (Smith et al. 1997). Generally, an increase in rainfall and a decrease in temperature lead to an increase in SOC sequestration.

Although, emphasis is focused on decreasing the rate of CO_2 emission from fossil fuel use, there is increasing recognition that the rate of emissions can be mitigated by transferring CO_2 from the atmosphere to the terrestrial biosphere (West and Marland 2002). Thus, one of the more promising ways to reduce the rate of rise in atmospheric CO_2 is to encourage management policies that promote plant growth and thus leading to C sequestration in vegetation and ultimately in soils (Idso and Idso 2002). Some of these policies deal with agro-ecosystems, where adoption of restorative land use and best management practices on agricultural lands can reduce the rate of enrichment of atmospheric CO_2.

Soil is considered the dominant pool of organic carbon as it is estimated to contain about 1500 Pg C (10^{15} g), which is nearly twice the amount found in the atmosphere and 2.5 times of that found in biotic pools (Schleisinger 1997). Soil organic C affects many key properties, such as nutrient and pollutant availability, and soil structure and erosivity (Gregorich et al. 1994). Furthermore, the quantity and quality of soil organic carbon (SOC) pools are strong determinants of soil quality in terms of biomass productivity and environment moderation capacity (Bezidicek et al. 1996). It is thus imperative that efforts be made to enhance and sustain SOC in soils through understanding of soil carbon dynamics along with that of soil nitrogen and water and temperature regimes under different management systems to identify mitigation options. In this special issue of Nutrient Cycling in Agroecosystems, 10 manuscripts address the issues pertaining to SOC stocks under present and future climate, assessment methods for carbon stock and changes, and carbon dynamics and stock management in mineral and organic soils. All manuscripts are based on research conducted in Northern Europe and especially in Nordic and Baltic countries. The objective here is not to provide the synthesis of the manuscripts included in this special issue of the journal but rather provide brief introduction to the four SOC issues dealt in this Nordic seminar.

Soil carbon stocks under present and future climate

The soil stores large amounts of organic carbon. Soils of northern latitude are important in this context. Present land use has turned many of these soils from sinks to sources of carbon. Predicted global warming and changes in precipitation amount and distribution can also change many areas from presently acting as sinks to become sources of atmospheric CO_2. It has been estimated that since the late 1700s, the CO_2 abundance has increased progressively and reached 377 ppm in 2004 with an overall increase of about 35% (WMO 2006). The increase in CO_2 along with other greenhouse gases (methane (CH_4) and nitrous oxide (N_20)) has led to increased global temperature by 0.6°C during the same period. (IPCC 2001).

Changes in land use can have important implications for local and global biogeochemical cycle and local vegetation dynamics. Thus land use conversion may lead to transfer of C to the atmosphere either through biomass burning or decomposition or through cultivation leading to mineralization of SOC and accelerated erosion. However, the proven land management practices, such as conservation tillage, reduced soil erosion, using buffer strips along waterways, restoring wetlands and degraded lands and eliminating summer fallows (Lal et al. 1999; Paustian and Cole 1998) and improved cultivation practices such as judicious fertilizer use, crop rotations and cover crops, and improved pastures with deep rooted crops can make the soil as C sink.

It is important to have good estimates of the size of the C stocks in soils of various systems in northern regions, how they behave and have behaved in past and how they are likely to respond to predicted climate change. Higher predicted increase in temperature in arctic and boreal regions, may render permafrost soil from a net sink to a net source of CO_2 if and when permafrost thaws. In contrast to soil C pool, the biotic C pool may increase primarily because of the CO_2 fertilization effect. However, the potential of this sink to mitigate CO_2 emission may be constrained by nutrients. For example, elevated CO_2 only causes sequestration of SOC, when N is added at rates above typical atmospheric N inputs. Similarly, elevated CO_2 only enhances N_2 fixation, when other nutrients (P, and Mo) are added (van Groenigen et al. 2006).

Assessment methods for carbon stock and changes

Quantitative and reliable assessment methods of SOC are required to characterize soil properties and ecosystem functions. Soil organic C is a dynamic pool, and net changes in C sequestration often are more informative than absolute quantities. It is important to quantify temporal changes, whether caused by ecosystem development or by management practices, because they manifest changes in crucial properties of ecosystems (properties of soils) and of the ecosphere (e.g atmospheric CO_2) (Ellert et al. 2002). The methods for assessing soil C inventories and fluxes have gained importance, as the ability to measure C stored in soils and above ground biomass is critical to understanding C cycling in terrestrial ecosystems (Ellert et al. 2001). The efforts to understand and address C management at the regional and global scale have summoned the development of more efficient methods for soil C determination (McCarty and Reeves 2001).

Soil based approaches typically integrate various pieces of information, such as (i) temporal changes in SOC at single point, (ii) spatial variation in SOC distribution and associated cycling processes within landscape, (iii) geographical data on key variable such as land use, plant cover, soil properties, and climatic regime. Traditional methods of quantifying (e.g. dry combustion) SOC by laboratory analysis of soil core samples have widely recognised limitations and can be both time consuming and labour intensive. Soil estimates using these methods are further complicated by the spatial and temporal variability inherent in soil horizonation, SOC concentration, and bulk density (Ellert et al. 2001). Wilding et al. (2001) stated that it is necessary to understand the spatial variability of SOC pools in order to make accurate mean estimate of available C and integrate variability into predictive models of SOC reserves and sequestration potential. Therefore, development of methods for SOC that address and minimize the uncertainties associated with conventional methodologies are important for improving estimates of terrestrial C inventories and fluxes. Advanced analytical methods such as near-infrared spectroscopy (McCarty et al. 2002; Reeves et al. 2001) have been used to determine SOC. Carbon isotope techniques have been used to estimate retention time and C turnover rates in soils (Paul et al. 2001). Research attempts to measure SOC in situ have included Laser Induced breakdown Spectroscopy (LIBS) (Ebinger et al. 2003) and Inelastic Neutron Scattering (INS) (Wielopolski et al. 2003). Gehl and Rice (2007) while presenting the emerging technologies for in situ measurement of SOC, concluded that conventional analysis for SOC determination (dry/wet combustion) will likely remain the predominant methods used by researchers in the near future. However, the use of portable, field applicable, or remote sensing tools for in situ SOC determination may provide an effective means to estimate C constituents that require expensive and time consuming analytical methods (e.g. litter decomposition rate, microbial biomass etc.) (Ludwig and Khanna 2001). The research has shown that these new methods are capable, with varying degree of success, of improving our understanding of SOC dynamics at a scale not previously feasible.

Carbon dynamics and stock management in organic soils

Most peat lands (86.4%) are found in temperate zones and of these 99.4% are located in the northern hemisphere. Most of these peat lands lie in the cool temperate zone, between 50° N and 70° N, in Russia, Fennoscandia, north west Europe, Canada and USA (Moore 2002). In many of these countries, especially in northern Europe, relatively large areas of peat lands have been drained for agriculture or forestry. For example, 15 M ha of peat lands have been drained for forestry in the boreal and temperate zones, more than 90% of which has taken place in Russia and Fennoscandia (Paivanen 1997). Of the 3.2 million ha (M ha) of peat lands in Norway, 0.15 M ha has been converted to agriculture and 0.6 M ha to forestry (Singh and Lal 2005). The total C pool in 3.2 M ha of peat lands in Norway is estimated at 941 million Mg C (Singh and Lal 2005), while 9.6 M ha of forest soils have a C pool of

1330 million Mg (de Wit and Kvindesland 1999) and thus peat lands have more than twice the SOC density than forest soils. The use of peat lands for agriculture or forestry purposes has resulted into increased C losses to the atmosphere, because drainage and cultivation of peat soils are known to lead to subsidence and carbon loss as CO_2. The CO_2 efflux from Swedish cultivated peat soils was reported to reach up to 70 Mg CO_2 ha^{-1} y^{-1} (Kasimir-Klemdtsson et al. 1997), while other studies reported a loss of 22 Mg CO_2 ha^{-1} y^{-1} in Norway (Grønlund et al. 2006), between 15 and 27 Mg CO_2 ha^{-1} y^{-1} in Finland (Maljanen et al. 2001). On the other hand, the rehabilitation of peat lands has shown a great potential for soil organic carbon sequestration. Carbon sequestration rates in Ombrotrophic peat lands were 34–45 gCm^{-2} yr^{-1} (Malmer and Wallen 1996) and 25.5 ± 0.5, in Finland (Tolonen and Turunen 1995). While in southern Finland, the restoration of Eriophorum vaginatum at a drained Ombrotrophic site led to its becoming a carbon sink with the capacity to absorb 54–101 gCm^{-2} yr^{-1} (Koulainen et al. 1999). At untreated site, C uptake was close to zero. This suggests that restoration and management of peat lands can therefore be an important mitigation method both by preventing CO_2 loss and enhancing C sequestration. Drainage and cultivation of peat lands leads not only to CO_2 losses but it also affect N_2O and CH_4 dynamics in these soils. Information on the options in C stock management of these soils can be crucial for policy makers with regard to paragraph 3.4 of the Kyoto protocol. The C loss due to drainage of peat land can have considerable impact on the outcome of national inventories to the climate convention (FCCC).

Carbon dynamics and stock management in mineral soils

Management practices can make soil a sink or a source of atmospheric carbon. Activities that lead to depletion of the terrestrial pool and enrichment of atmospheric pool include deforestation, biomass burning, ploughing and continuous cropping, removal of biomass for fuel and accelerated erosion (Lal 2004). In contrast, practices that make agricultural soil a sink are conservation tillage, judicious use of fertilizer, cover crops, crop rotation, and fallowing; improved pasture and growing deep-rooted crops. Based on long-term experiments in Canadian prairies, Janzen et al. (1998) concluded that the possibility of significant C sequestration exists with the adoption of practices such as elimination of summer fallow, increased use of forages, improved fertility management, and reduced tillage intensity. In Norway, the overall potential of adoption of improved practices for SOC sequestration was, on an average, 0.8 million Mg yr^{-1}, which was about 2% of the yearly C emission in year 2000. Of the total potential, 59% can be contributed to adoption of erosion control measures, 6% to restoration of peat lands, 21% to adoption of conservation tillage and residue management, and 14% to adoption of improved cropping systems (Singh and Lal 2005).

There are several bright spots of SOC sequestration in terrestrial ecosystems. While CO_2 fertilization will enhance biomass production in general (Kimball et al. 2002), SOC sequestration can be enhanced by restoration of degraded lands, caused by erosion, compaction, nutrient depletion or pollution. Restoring of wetlands has a large potential of C sequestration.

The objective of this special issue

This special issue of Nutrient Cycling in Agroecosystems, consists of 10 manuscripts addressing the issues pertaining to assessment methods, SOC stocks, carbon dynamics and management practices in mineral and organic soils. Three manuscripts (Lal, Andrén et al.; Kätterer et al.) describe soil carbon stocks under present and future climate, while the one by Kätterer and Andrén presents a model approach for estimating daily soil temperature profiles from air temperature and leaf area index in cold temperate regions. The manuscript by Slepetiene et al. presents a rapid and inexpensive photometric method for the determination of SOC. One manuscript (Grønlund et al.) describes carbon losses from cultivated peat soils and their subsidence rates. The remaining manuscripts by Kõlli et al., Smith, Shrestha et al. and Persson et al. presents results pertaining to carbon stocks and carbon dynamics under land use changes and management practices in mineral soils.

In spite of the progress made in assessing the carbon stocks and carbon dynamics in the cool temperate regions and the positive effect observed on

SOC sequestration of the practices mentioned in these manuscripts, quantification and verification of SOC potentials under varying soil and climatic conditions and management practices are still challenging issues. Information on subsidence rate of peat soils and fluxes of SOC from organic rich and mineral soils, and long term impacts of management practices are still limited. However, development of better assessment method for SOC determination, understanding of spatial and temporal variations in a landscape, up-scaling techniques of point source data to larger catchments or regional scales and the use of predictive models have further improved the estimates of SOC sequestration and fluxes. There is also a general consensus that SOC gains obtained under the practices mentioned above may be considered of finite magnitude and duration.

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