Soil carbon dynamics and climate change: current agro-environmental perspectives and future dimensions

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Abstract The management of soil organic carbon (SOC) has now been identified as the most imperative dimension for managing the global climate change as well as soil fertility. In this respect, various agro-ecological approaches such as organic and integrated nutrient management system have been proposed worldwide, though accepted with limited enthusiasm. The understanding of the different soil C pools and processes are of vital importance before the implementation of these agro-ecological management practices, as it determines the success of SOC management. In the present study, we tried to encompass various SOC pools and processes governing the SOC dynamics in the agro-ecosystems. In this paper, dry tropical ecosystems having a unique ecological behaviour (such as strong nutrient conservation mechanisms and potential C sink nature) have been discussed especially due to its potential role in global climate change and mitigation, and linked soil fertility. It is proposed that a multi-factorial experimentation involving quantitative and qualitative change in soil available N, microbial and aggregate attributes, which has been recently found to be of crucial significance, is required for the proper mechanistic understanding of SOC dynamics. It may also help in the identification of some

integrative functional indicators, which can be used to achieve a balanced SOC dynamics via suitable agro-management.

Keywords Carbon accumulation · Dry tropical ecosystems · Organic systems · Soil CO₂ efflux

1 Introduction

Human development since industrial revolution has dramatically increased the atmospheric greenhouse gases (GHGs) primarily due to fossil-fuel burning, and land use change and management (USEPA 2014). The concentration of atmospheric CO₂ has increased from 280.0 to 398.6 ppm between 1750 and 2014 and is increasing currently at a rate of 2.11 ppm per year (CO₂now.org; IPCC 2014). This anthropogenic increase in atmospheric CO₂ concentration led to a change in global climate which has been identified as one of the most important scientific and political challenges of the twenty-first century in addition to the closely associated problem of sustainable food production (Abhilash et al. 2016; Saraswat and Kumar 2016; Srivastava et al. 2016a) (Fig. 1). Moreover, soil carbon management is supposed as a most exacerbating area for managing the soil fertility and productivity on the one hand and soil C sequestration to mitigate the change in climate on the another hand (Lal 2006). It indicates the interrelated nature of various problems humans are facing at present (Chen 2016). Therefore, scientific understanding of pools of soil C and its efflux from soil ecosystem in relation to agro-management practices is essential for managing the global climate change and soil fertility (Lal 2010).

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Fig. 1 Major greenhouse gases (a) and their economic sector-wise (b) distribution (adapted and redrawn from IPCC 2014; USEPA 2014)

2 Carbon dioxide (CO₂) as a major greenhouse gas

The CO₂ is a major greenhouse gas (GHG) because of its atmospheric concentration (about 398 ppm) and strongest radiative forcing among all the known GHGs (Fig. 1), despite having relatively lower warming potential (Forster et al. 2007). It, along with atmospheric water vapours, contributes majorly to the greenhouse effect on the earth. Though other GHGs such as methane (CH₄), nitrous dioxide (NO_x) and chlorofluorocarbons (CFCs) are present at lower concentrations (about 2–6 orders of magnitude) than CO₂ in the atmosphere, their per molecule absorption of infrared (IR) radiation is many fold higher than CO₂. It is now known (Fig. 1) that the major contributors of the enhanced atmospheric GHGs are fossil-fuel combustion, land use changes and increased use of synthetic fertilizers in the agriculture. The deterioration of soil quality following land use change and agro-management practices has drawn global attention towards the soil ecosystem in general and soil organic carbon (SOC) dynamics in particular (FAO 2001; Srivastava et al. 2016a). It is believed that the increased atmospheric CO₂, in which land use change and management adds considerably in the form of soil CO₂ efflux, can be sequestered back as SOC through appropriate agro-management practices. It may help to mitigate the change in global carbon cycle and climate (Aswathanarayana 2012).

3 Soil and atmospheric CO₂: source–sink relationships

Soil, which holds around 1500 Pg C, is now being considered as a major sink of the atmospheric CO₂ (Post et al. 1982). It constitutes more than the combined C in the vegetation and the atmosphere (Batjes and Sombroek

1997). Tropical soil shares 32 % of this SOC stock (Eswaran et al. 1993). The various pools and fluxes of C on the Earth are depicted in Fig. 2. SOC plays a major regulatory role in biogeochemical cycles and biosphere functioning due to its complex interaction with soil physical, chemical and biological factors and thereby its effect on the soil multi-functionality. SOC plays a central role in defining the soil quality and agro-ecosystem productivity (Lal 2003). It is identified that an increase in SOC may help in alleviating the soil degradation and, thus, ensure sustainable food production for the growing world population (Swift 2001). Therefore, there has been an additional interest in the role of SOC as a potential sink for atmospheric CO₂ (Post and Kwon 2000).

Land use change (LUC), especially forest to agriculture conversion, has been identified as a major source of historical loss of SOC, primarily in the form of soil CO₂ efflux (Lal 2004; Poeplau and Don 2013). It strongly influences the balance of SOC dynamics which affects the soil CO₂ efflux and subsequent C sequestration (Lal 2003). Further, various agro-management practices differentially affect the SOC dynamics (Srivastava et al. 2016a). These management-induced changes in the SOC have been already studied well in agricultural systems in the context of conservation tillage, cropping, organic and synthetic fertilization, and residue incorporation (Lugato et al. 2010; Srivastava et al. 2016a). The intensive crop production practices to increase the crop productivity (i.e. conventional agriculture), which involves agro-chemicals, improved irrigation, high mechanization and high yielding seed varieties, enhance the soil C mineralization, but induce severe environmental problems (Pimentel et al. 1995). Consequently, it depletes SOC with the time because of continuous harvest and negligible organic input. Therefore, it is essential to understand various pools and processes related with SOC before devising the management policies.

Fig. 2 Global carbon cycle depicting various pools and fluxes of C (adapted and redrawn from Houghton 2007)

3.1 Soil carbon dynamics

Soil C dynamics comprise the study of the soil C pools, the rate of its exchange among them (turnover) and the associated regulatory variables (Trumbore 2009). Therefore, it encompasses the kinetics as well as the governing variables, which defines the temporal change in SOC pools among its various compartments. SOC dynamics generally shows a nonlinearity, and several years are required to reach a new equilibrium (Luo et al. 2004). Therefore, the short-term assessments misrepresent the SOC dynamics. However, the long-term datasets to derive the rate of change across the various SOC pools to better understand the SOC dynamics are often scarce (Vaccari et al. 2012).

3.1.1 Soil carbon pools

The depletion of the SOC pool leads to a downfall in the soil quality and productivity (Lal 2001). SOC consists of several pools, namely active, slow and passive, with

differential turnover rate ranging from months to over several hundred to thousands years (Silveira et al. 2008).

- (1) *Active SOC pool*, also called labile form of C, is primarily made up of fresh plant and animal residues that breakdown in a very short time, from a few weeks to a few years (Fig. 3). This kind of organic matter is associated with a lot of biological activity.
- (2) *Passive SOC pool*, also known as humus or non-labile form of C, is not biologically active, and thus it provides very little food for soil organisms. It may take hundreds or even thousands of years to fully decompose. It is a dark, complex mixture of significantly transformed organic substances which also contains substances synthesized by the soil organisms. Usually, humus represents the majority of soil organic matter (SOM), and it is relatively stable over time.
- (3) *Slow SOC pool* is somewhere in between active and passive SOM. It consists primarily of detritus (i.e.

Fig. 3 Characteristics of different soil organic C pools and soil CO₂ efflux (adapted and redrawn from Trumbore 1997)

partially broken down cells and tissues), which decomposes gradually. Slow SOM is somewhat resistant to decay than active pools and may take a few years to a few decades to breakdown completely.

In general, the turnover rate of labile C pool ranges from several weeks to months or years, whereas recalcitrant, non-labile pools have a turnover rate of centuries to millennia (Paul et al. 2001; Singh et al. 2015). Labile C pool comprises easily oxidizable forms of SOC such as microbial biomass carbon (MBC), water-soluble carbon (WSC), particulate organic carbon (POC), which responds more rapidly to the agro-management practices (Blair et al. 1995; Purakayastha et al. 2008). The decomposition of labile C by soil microorganisms helps to stabilize the soil aggregates, releases nutrients by mineralization and provides food for soil microbial activity. Thus, it can serve as the sensitive indicator of soil quality (Blair et al. 1995; Purakayastha et al. 2008). Additionally, it plays an important role in improving soil quality and thus can minimize the negative environmental impacts. The amount of these active fractions and their proportion to total SOM are the good indicators of soil health. Therefore, the identification of highly sensitive SOC fractions may help to elucidate changes and trajectories in the SOC pool at early stages of changes in land use and management (Yang et al. 2009). Active SOC pool plays a very different role than passive does. As labile (active) and non-labile (stable) SOC play differential roles in SOM dynamics and nutrient cycling, the pool size and turnover time of these two fractions in bulk soil and in aggregate size fractions may be

important to assess and evaluate the soil management practices for the monitoring of SOC (Lutzow et al. 2007; Srivastava et al. 2016b).

Dissolved organic C constitutes an important labile SOM fraction (Zsolnay 1996), which acts as a primary source of energy and nutrients for the soil microorganisms. Thus, its turnover is strongly linked to the soil microbial activity (Chantigny 2003) and soil nutrient availability. It affects the important soil functions, such as soil physical stability and C sequestration in multiple ways (Zsolnay 1996; Chantigny 2003). Therefore, understanding of temporal dynamics of quantity and quality of DOC and similar labile C fractions would help to better manage soil C sequestration in agroecosystems.

3.1.2 Soil carbon processes

Decomposition, a biogeochemical transformation process, releases major SOC portions as soil CO₂ efflux (Post and Kwon 2000). It defines the characteristics, storage, turnover and transfer of C among various aggregate and particle size fractions, and thus indirectly determines SOC sequestration and soil CO₂ efflux (Adams et al. 2011). Being a microbial mediated process, it is sensitive to land use and management. Soil microbes typically are C-limited (Smith and Paul 1990) and act as a source of plant nutrient in the dry tropical ecosystems (Singh et al. 1989). Changes in the SOC are highly related to the soil microorganisms due to their primary role in nutrient cycling and SOC turnover (Smith and Paul 1990; Ryan et al. 2009). During the microbial decomposition, organic residues are

converted to humic substances via a SOC sequestration process termed as humification (Guggenberger 2005; Stockmann et al. 2013). In humification, the aromatic and paraffinic C increases, while the O-alkyl C decreases (Inbar et al. 1990).

Further, SOC closely relates to the soil aggregate formation and stability (Tisdall and Oades 1982). It has been recently identified that not only the chemical recalcitrance but biophysical processes (i.e. aggregate formation and dynamics) also act crucially in the turnover and sequestration of SOC (Schmidt et al. 2011). Thus, SOC turnover is governed by the accessibility of organic substrates to decomposers (Dungait et al. 2012), as well as by the chemical nature of the stored material (Conant et al. 2011). Soil aggregate occludes the SOC physico-chemically from microbial decomposition. Its dynamics (size distribution and C characteristics) is found to be dependent on management (Singh and Singh 1995). It determines the efficiency of C protection from decomposition due to its strong impact on the extent and manner of soil aggregate development. The soil management practices in agriculture have shown a significant impact on soil aggregate stability and dynamics (Bhattacharya et al. 2010), which is now being identified as a major player in climate change and loss of soil fertility.

4 Soil carbon management

The content and distribution of SOC across depth, compartments and aggregate size fractions are reportedly more sensitive to the land use changes (Leifeld and Kögel-Knabner 2005). It is evident by a decrease in the SOC pools and associated soil quality following the anthropogenic conversion of native forest to agriculture (Brown and Lugo 1990). Therefore, the restoration of SOC via soil management has the potential to sequester significant amount of C from the atmosphere into the soil (Lal 2004). Agro-management practices determines the global C cycle and SOC dynamics affecting soil aggregates as well as microbial communities and their activities (Six et al. 2004).

Organic amendments have been proposed as a means to increase the soil C storage (Powlson et al. 2012). It may occur directly from the C inputs in the form of organic amendments and indirectly due to increased plant production due to amendment (Whalen and Chang 2002; Ryals and Silver 2013). It has also been found related to the enhanced soil water-holding capacity, decreased bulk density and improved soil fertility (Mader et al. 2002; Lynch et al. 2005). Moreover, organic amendments may also increase the organic nitrogen (SON) in soils, which could act as a slow release fertilizer and enhance the net

primary productivity of the ecosystem (Ryals and Silver 2013). Manure application increases the SOC concentration, aggregate stability and soil biological activities, which altogether relates to improved soil structure (Jarecki and Lal 2003). Long-term studies have shown an increase in the soil microbial biomass under fertilization (Yan et al. 2007). Most studies report that the application of organic manure with/without inorganic fertilizers can manipulate the soil microorganisms to improve the soil health and fertility (Chaparro et al. 2012). It influences the soil microbial biomass, activity and community (Singh and Singh 1993; Jimenez et al. 2002; Goyal et al. 1999). Soil microbial biomass and activity has been found higher in the organic than conventional management system (Tu et al. 2006). Moreover, integrated use of fertilizers has been reported to accumulate higher SOC and its fractions as compared to sole chemical fertilization in some studies (Lal 2003; Purakayastha et al. 2008). However, several studies under integrated amendment have shown either little or no effects on the SOC content (Purakayastha et al. 2008). These contrasting effects of the management practices can be attributed to the climatic conditions that influence the plant and soil processes, which determine SOC dynamics (Ogle et al. 2005).

Agricultural management defines the SOC dynamics affecting soil processes (Ogle et al. 2005). In agroecosystems, enhanced nutrient availability through chemical fertilization enhances the yield, but negatively affects the SOC with the time. More specifically, soil N is a crucial driver of SOM dynamics in the agroecosystems. For example, the differential dynamics of soil NH_4^+ -N and NO_3^- -N (which may shift the soil ammonium-N to nitrate-N ratio; ANR) may have an important ecological significance as it may affect the important ecosystem properties (Bijlsma et al. 2000; Srivastava et al. 2015, 2016b). Differential shift in the soil NH_4^+ -N and NO_3^- -N concentration may have important ecosystem consequences in the changing environment in different ways (Cruz et al. 2003; Srivastava et al. 2015, 2016b). The differential availability of soil NH_4^+ -N and NO_3^- -N may have implication on SOC turnover because of their contrasting effects (Currey et al. 2010; Srivastava et al. 2015). Literature findings (Min et al. 2011; Srivastava et al. 2015, 2016b) suggest that the forms of inorganic N (i.e. soil NH_4^+ -N or NO_3^- -N) could differentially influence the rate of SOC cycling and thus C mineralization via changes in the soil chemical and biological attributes. Jha et al. (1996) reported that soil moisture content affects the soil nitrification more than ammonification, importantly at low water tension, through dehydration and substrate limitation. A significant relationship between the soil CO_2 efflux and gross N-mineralization is well reported in the literature (Flavel and Murphy 2006).

Depending on the management, soil microbial behaviour may differentially define the qualitative and quantitative change in the availability of C substrate and nutrient, particularly of the available N (Srivastava et al. 2016b). These changes may further affect the downward processes via cascade effect which may lead to differential response in the distribution, composition and function of soil microbial community as well as C characteristics across aggregate size fractions (Srivastava et al. 2016b). It is supposed that these changes altogether would lead to a differential aggregate dynamics, which determines the nature of soil C dynamics and degree of C sequestration, depending on the applied management system.

Limited studies are available from the tropics which deal with the qualitative and quantitative effects of LUC on SOC across aggregate size fractions. The temporal effect of sustainable management practices (such as organic and integrated management) on the soil aggregate characteristics is limited (Nicolás et al. 2014), particularly in the dry tropical ecosystem (Singh et al. 1989). This ecosystem is potentially unique due to its significant coverage (41 %) and human population as well as potential C sink nature. In these ecosystems, conversion of forest to chemical fertilizer-based agriculture has already led to a significant decline in SOC (Srivastava et al. 2015). These ecosystems are in the core of discussion related to global climate change due to their potential as an important C sink nature (Lal 2004). If managed properly, these ecosystems may help in the reduction of atmospheric CO₂ with the added benefit of improvement in the soil quality. Therefore, temporal changes in soil C dynamics and sequestration under long-term organic amendments, either individually or in an integrated manner, are urgently required in the dry tropical ecosystems. These studies would help in the better mechanistic understanding for soil C dynamics for its improved management and in understanding the response of these ecosystems to the climate change.

5 Conclusion and future research needs

Carbon sequestration in soils as SOC through agro-management practices has been widely considered as a promising option for the mitigation of global climate change simultaneous to soil infertility. Therefore, a thorough understanding of SOC dynamics and its relationship with the management practices is highly required. It would help to fine tune the agro-management practices in a site-specific manner to potentially sequester SOC to reap sustainable benefits from the soil ecosystem. Long-term studies on the interaction between the soil aggregate dynamics, soil N availability and microbial attributes in

relation to SOC dynamics under sustainable nutrient management practices have been scarcely done, quantitatively as well as qualitatively. In a recent study, SOC dynamics has been found to be dependent on both qualitative and quantitative characteristics of these attributes. It was found related to the relative availability of soil inorganic-N pools, which is due to its relationship with soil aggregate physical and chemical stability as well as microbial quantitative and qualitative attributes. Therefore, a multi-factorial experimentation involving the qualitative and quantitative attributes of available soil inorganic-N, microbial and aggregates is needed under various proposed sustainable management practices for the identification of integrative indicator variable and for the mechanistic understanding of SOC dynamics for sustainable SOC management.

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