Catena 86 (2011) 178–191

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Organic carbon and nitrogen in soil particle-size aggregates under dry tropical forests from Guanacaste, Costa Rica — Implications for within-site soil organic carbon stabilization

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ARTICLE INFO

Article history:
Received 14 April 2010
Received in revised form 22 November 2010
Accepted 28 March 2011

Keywords:
Soil organic carbon
Nitrogen
Particle size fraction
Principal component analysis
Dry tropical forest

ABSTRACT

In this study we report results on the soil organic carbon (SOC) pool (0–50 cm) from a chrono-sequence of dry tropical forest (dTf) of increasing age and a yearly burned ancient pasture in the "Sector Santa Rosa" at the "Área de Conservación Guanacaste" (ACG) in northwestern Costa Rica, where intense human induced land-use modifications has occurred during the past century. The effects of land conversion on soil organic carbon (SOC) have mainly been conducted in the Atlantic humid forests while overlooking dTfs. We quantified the depth distribution of SOC concentration down to 50-cm and in physically separated mineral soil fractions, as these data are scanty from the dTf. Additional objectives were to identify the relationship with selected soil physical and chemical properties, including stabilized SOC fractions by means of multivariate ordination methods. Statistically significant differences were found for the main fixed factor ecosystem for all soil variables analyzed (ANOVA). SOC and N concentrations were significantly higher in the oldest dTf compared to the other dTfs. Soil physical properties like aggregate size distribution and bulk density changed with depth, and varied significantly among the three dTf stands sampled. The multivariate analysis, i.e. between-within class principal component analysis (PCA), revealed a significant ordination of dTfs ($P<0.0001$). The SOC concentration decreased in particle size fractions of <200 μm aggregates with increasing soil depth. The lowest and highest C concentrations were obtained in the fine sand (105–200 μm) and clay + silt (<20 μm) fractions, respectively. Mineral-associated and stable SOC pool increased with depth, and poorly crystalline Fe oxides and ferrihydrite were the most important minerals for SOC stabilization at 40–50 cm depth. The highest SOC pool was found in the old-growth and >80 years-old dTfs, i.e., 228.9 and 150.3 Mg C ha^{-1}, respectively, values similar to those obtained in the Atlantic humid forests of Costa Rica. Comparatively to other studies, soils under dTf at Santa Rosa store a considerable amount of SOC with potentially large CO2 emissions if this ecosystem is not preserved.

1. Introduction

The soil organic carbon (SOC) pool is the largest pool of terrestrial organic carbon, with an estimated 2100 Pg (1 Petagram = 1015 g) ca. 3 times larger than the amount of C stored in above-ground vegetation (Post et al., 1982). In tropical soils the SOC pool amounts to 30% of the global C pool, i.e., 384–506 Pg down to 1-m depth (Batjes, 1996; Eswaran et al., 1993; Kimble et al., 1990), and more specifically 119 Pg C is stored in the top 1-m in the dry tropical forest (dTf) (Jobbágy and Jackson, 2000). The SOC is thus relevant for the terrestrial ecosystem C balance and its potential to respond to the global C cycle.

Compared to other ecosystems worldwide, the dTf has experienced the greatest transformation to agriculture lands (Hoekstra et al., 2005), and the process still continues in the dTfs of South America (Grau et al., 2008). The conversion of tropical forests to agricultural land has decreased over the past 10 years but continues at an alarmingly high rate in many countries (FAO, 2010), resulting in depletion of the SOC pool as much as 75% in the tropical region (Lal, 2004). Tripathi and Singh (2009) reported SOC data (0–10 cm) from dTf in the Similipal Biosphere Tiger Reserve (India) to be 19.8 g kg^{-1} while in pasture and cropland a reduction of 46 and 54% was observed, respectively. Changes on SOC pool after conversion of natural tropical ecosystems to agricultural land have been assessed by several authors (Buschbacher et al., 1988; Cerri et al., 1991; De Moraes et al., 1996; García-Oliva et al., 1994, 2006; Groffman et al., 2001; Marin-Spiotta et al., 2009; Murty et al., 2002; Neill et al., 1997;

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doi:10.1016/j.catena.2011.03.011

Schwendenmann and Pendall, 2006; Tiessen et al., 1992; Trumbore et al., 1995; Veldkamp, 1994; Werner, 1984), with various responses observed, including increases, decreases, or no net long-term changes in SOC. When agricultural land is no longer under cultivation and allowed to return to the previous vegetation cover, C accumulates in the soil by processes that essentially reverse initial losses of SOC after land conversion. SOC accumulation rates and time lag broadly vary depending on the productivity of the re-growing vegetation, physical and biological conditions in the soil, and the past history of SOC inputs and physical disturbance (Post and Kwon, 2000). Full recovery of SOC pool following deforestation depends on the length of time allowed for recovery and intensity of land use, taking several decades to achieve a new equilibrium (Ramankutty et al., 2007).

In Costa Rica, historic conversion of the dTf has potentially caused considerable loss of above- and belowground C due to extensive deforestation for land clearance following land colonization in Costa Rica during the 1950's to establish traditional livestock and agricultural land use (Calvo-Alvarado et al., 2009). Research on SOC in the dTf, as indicated by the small number of published studies (Sánchez-Azofeifa et al., 2005) in the Pacific region (Johnson and Wedin, 1997; Powers et al., 2009), has not kept pace with those conducted in humid forests at the Atlantic region (Jiménez et al., 2007; Jiménez et al., 2008a, 2008b, 2008c; Powers, 2004; Powers and Schlesinger, 2002; Powers and Veldkamp, 2005; Veldkamp, 1994). Consequently, additional studies from the Pacific region are needed to increase our knowledge on SOC changes and the distribution and abundance of SOC in dTf, for which there are little published data, with comprehensive emphasis on the biological and physical factors involved.

Physical protection of soil C within aggregates is an important mechanism for C sequestration (Jastrow, 1996; Six et al., 2002). Assessment of SOC concentration within particle-size fractions from the dTfs and derived agro-ecosystems is not abundant in the literature either (García-Oliva et al., 1994, 1999b). Soil physical fractionation methods have been generally used to reveal the factors involved in C and soil mineralogy associations and in the study of the dynamics and turnover of organic matter (OM) (Christensen, 1992, 2001; Six et al., 2002). The dynamics of OM varies with soil aggregates size and physical fractionation techniques are, thus, useful to isolate C pools more sensitive to changes in land management or differences between ecosystems in order to elucidate processes and mechanisms involved in the storage of C (Six et al., 2002).

The stabilization of SOC is relevant for biogeochemical processes in ecosystems although the mechanisms are still poorly understood and a new framework has been proposed (Kleber et al., 2007a, 2007b). It is also important for global C cycling models to assess the effect of disturbance and recovery in the dTf in addition to identifying the processes of SOC stabilization. The main goal of this study was to increase our knowledge on the vertical distribution of SOC in size-class aggregates in the dTf, in addition to a better understanding of those factors that are correlated with soil C and the environmental between- and within-site control on SOC. Additional objectives were to: (1) assess C and N distribution associated with different soil mineral fractions of <250 μm aggregates, and (2) investigate SOC relationships with selected soil properties, including C stabilization data obtained from chemical extraction methods by applying multivariate ordination techniques in order to identify meaningful trends in dTf recovery. A forest chronosequence approach was used to infer SOC pool recovery after perturbation, which is a normal procedure in tropical ecology studies (Aide et al., 2000).

2. Materials and methods

2.1. Study area

The study was conducted during August 2005 in Sector Santa Rosa (85°36′54″W; 10°48′53″N) in the Área de Conservación Guanacaste (ACG, formerly Parque Nacional Santa Rosa), north-western Pacific region of Costa Rica (Janzen, 2000). The area is defined as a tropical dry zone. All the dTf of Costa Rica is located in ACG, and covers half the area of the total 120 × 103 ha of the park, while 3556 ha are dTf in Sector Santa Rosa (Maldonado et al., 1995; Kramer, 1997). The dTf is characterized by a well defined dry season (Mooney et al., 1995). Yearly average temperature and precipitation are 28 °C and 1530 mm, respectively, with a marked 6-month dry season between November and May (Janzen, 1993). Geologic substrate at Santa Rosa is Pleistocene aeolian ash. Soils at the study area are of volcanic origin (Guanacaste volcanic Cordillera), and major soil parent materials weathered in place are andesite to rhyolite ash-flow tuffs (ignimbrites) with intercalated fluvial deposits with high Fe content, and consisting mostly of plagioclase feldspar with biotite, hornblende, amphibole, and pyroxene (Weyl, 1980; PDX, 2005). Soils are classified as Inceptisols and Entisols (USDA taxonomy) defined as Typic Ustropept and Lithic Ustropept (Oficina de Planificación Sectorial Agropecuaria, 1999).

The dTf at Santa Rosa contains the highest number of plant families, genera, and species richness of all Central American dTfs (Gillespie et al., 2000). *Acacia collinsii* Saff. (Mimosaceae) (Spanish name “Cornizuelo”) and *Quercus oleoides* Schltdl. and Cham. (“Encino”) are two of the most abundant tree species (Allen, 2001; Janzen, 2000), although there is no single dominant species (Kalacska et al., 2004). Santa Rosa contains both evergreen forests dominated by live oak, *Q. oleoides*, but also a large number of other co-occurring species from the adjacent mixed deciduous forest where oaks are less common. These include *Tabebuia ochracea* Standl. (Bignoniaceae), the fern *Selaginella* sp., *Enterolobium cyclocarpum* (Jacq.) Griseb. (Mimosaceae), *Hymenaea courbaril* L. (Fabaceae), *Cecropia peltata* L. (Moraceae), *Bursera simaruba* (L.) Sarg. (Burseraceae), *Ficus* spp., and *Bromelia pinguin* L. (Bromeliaceae).

Within tropical forests the dTf represents 42% of the total (Brown and Lugo, 1982), and is among the most endangered ecosystems worldwide (Mooney et al., 1995). Currently, only 0.5% of the original dTf area in Pacific Mesoamerica is under protection (Calvo-Alvarado et al., 2009; Janzen, 1988a, 1988b) and remains in Costa Rica (Quesada and Stoner, 2004). During the 1950's and for more than 30 years severe deforestation reduced the area covered by dTf (Sader and Joyce, 1988). Land conversion and cattle grazing and human-induced fires, hugely reduced the area covered by the dTf in Guanacaste (Houghton et al., 1991; Maass, 1995; Toledo, 1992). This favored the invasion of the exotic pyrophite grass *Hyparrhenia rufa* (Ness) which fueled more fires and transformed drastically the original dTf physiognomy (Daubenmire, 1972). The area affected by this grass was reduced after cattle removal in addition to a fire-suppression active program (Janzen, 1988b; Kramer, 1997). Since 1979 the area covered by pastures in the ACG has decreased and, nowadays, natural fires are totally absent from ACG (R. Blanco, pers. comm.) Fire is an important disturbance for natural succession in the dTf (Vieira and Scariot, 2006). The management strategy of fire control has promoted oak passive regeneration of secondary dTf in Costa Rica.

As analyses are expensive, only a limited number of stands were selected on the same edaphological unit, i.e., three dTf stands and a pasture plot (Fig. 1): a) a remnant patch of old-growth forest >400 years old (Of), b) a secondary deciduous forest (Df), San Emilio (>80 years), c) a *Q. oleoides* forest of ca. 65 years old (Qu), and d) a yearly burned ancient pasture strip (Pa) (See list of plant species in Appendix A). The vegetation structure of the Of is similar to the original dTf, it was never cleared except some old individual trees in the mid-forties of the last century, i.e., *Swietenia macrophylla and Manilkara chicle* (Janzen, pers. comm.). Some fires occurred in the late 1970s and early 1980s, when the pastures came closer to the edge of this forest, as an occasional event during late April to early May when leaf litter was extremely dry and burned very low to the ground and detached branches were converted to charcoal. Even today fire scars