Forest Ecology and Management 261 (2011) 1170–1177

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Controls of litter quality on the carbon sink in soils through partitioning the products of decomposing litter in a forest succession series in South China

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ARTICLE INFO

Article history:
Received 15 September 2010
Received in revised form
19 December 2010
Accepted 24 December 2010
Available online 1 February 2011

Keywords:
C/N ratio
Lignin content
Litter decomposition constant (*k*-value)
Residence time of standing litter pool
Respiration
Dissolved organic carbon (DOC)
Fragment
Soil organic carbon (SOC)

ABSTRACT

Through the long-term measurement and development of a method for partitioning the products of decomposing litter, the impact of chemical components of forest debris on soil organic carbon (SOC) accumulation was studied in a forest succession series in South China. We quantified how litter quality is strongly correlated with the partitioning of respiration, dissolved organic carbon (DOC) and fragments of decomposing litter. In the succession sequence of 60-year-old pine forest (PF), to 80-year-old mixed pine and evergreen broadleaved forest (MF) to more than 400-year-old monsoon evergreen broadleaved forest (MEBF), the litter C/N ratios and lignin contents were gradually decreasing, which in turn were correlated with increasing litter decomposition constants (*k*-values), gradually shortening residence times of standing litter pool. And, 53.5%, 65.6% and 76.2% of the gravimetric litter mass losses were going belowground through both DOC and fragmentation. Correspondingly, the SOC accumulation rates in the top 20 cm of mineral soils for the three forests from 1978 to 2008 were 26 ± 4, 33 ± 5 and $67 \pm 5\,g\,C\,m^{-2}\,yr^{-1}$, respectively. Results of the study support the idea that in order to increase carbon sequestration in soils and long-term functional ability of forest ecosystems to act as carbon sinks, "Kyoto Forests" should be designed and reconstructed with a high diversity of broadleaved species, especially containing nitrogen-fixing trees.

1. Introduction

The mass of organic carbon in soils exceeds the mass of organic carbon in living vegetation by two or three times (Schlesinger, 1990), amounting to 1500 Pg in soil globally (Schlesinger, 1977; Post et al., 1982). Its residence time in the lower portion of the soil profile is frequently larger than 1000 years (Campbell et al., 1967). Thus soils could provide a substantial carbon sink to offset fossil fuel CO_2 emission as Prentice and Fung (1990) suggested. For this reason, afforestation is one of the strategies recommended within the Kyoto Protocol due its capacity to restore carbon not only in biomass but also in soil (Cerli et al., 2008). However, some evidence has shown that annual carbon sequestration in soils from the atmosphere is only about $0.4 \times 10^{15}\,g\,C\,yr^{-1}$, accounting for only 0.7% of global terrestrial net primary production (NPP) (Schlesinger, 1990); this indicates that the chain of organic carbon flowing from NPP to soil organic matter is impeded. Understanding the drivers that control the aboveground carbon flows into soil will be helpful in designing reforestation projects to maximize carbon sequestration.

Many studies have documented the concomitant development of soil carbon and vegetation in primary and secondary chronosequences, e.g., Bush (2008). Some studies have revealed that pioneer and transition forests have limited effects on soil organic carbon (SOC) accumulation even if the aboveground biomass accumulates rapidly and has attained a high level (Richter et al., 1999; Paul et al., 2002; Hooker and Compton, 2003; Johnson et al., 2003; Zhou et al., 2006a; Don et al., 2009), especially for pine forests (Richter et al., 1999; Paul et al., 2002; Zhou et al., 2006a). On the contrary, other evidences showed that broadleaved forests or those with nitrogen-fixing trees may allocate a higher fraction of NPP into soils (Paul et al., 2002; Resh et al., 2002; Mendoza-Vega et al., 2003; Bush, 2008; Kiser et al., 2009). A few studies even reported high organic carbon accumulation rate in mineral soils (Zhou et al., 2006b) or the whole ecosystem (Knohl et al., 2003) of matured broadleaved forest. Kiser et al. (2009) speculated that changes in forest species and cover influenced changes in mineral soil carbon. All these reports and findings have implied that chemical components of forest biomass may have deep impacts on SOC accumulation and thus

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doi:10.1016/j.foreco.2010.12.030

Table 1
Description of soil sampling for SOC measurements.

Year	Number of composite samples			Soil cores in each composite sample		
	Pine Forest (PF)	Mixed Pine and Evergreen Broadleaved Forest (MF)	Monsoon Evergreen Broadleaved Forest (MEBF)	PF	MF	MEBF
1978 and 1979	15	14	96	5	5	5
1983	16		16	5		10
1984	12		3	5		10
1985	12		2	5		10
1986	12		12	5		10
1990	6		6	10		10
1993			5			10
1996	1	1	1	20	20	20
1997	12	16	10	10	10	10
1998-2005 (annually)	20	20	20	10	10	10
2008	20	20	20	10	10	10

on the carbon sink in soils. However, the mechanisms have not yet been well addressed.

On a global average, 70% of the NPP in natural ecosystems flows to the ground through aboveground litterfall (Schlesinger, 1997). Organic carbon pools in mineral soil and vegetation are mainly connected through litter decomposition which can be divided into three interlinked processes of leaching, catabolism, and fragmentation (Swift et al., 1979). They are respectively responsible for the fluxes of dissolved organic carbon (DOC), respiration, and small fragments incorporating into soils due largely to activities of soil fauna. Leaching occurs largely in the early phase of decomposition, depending on the concentration of soluble compounds in decomposing litter. Catabolism is the process during which saprotrophic organisms use litter constituents for their growth and activities, releasing mineral carbon, for example, CO_2. Fragmentation is both a biotic process by some soil animals and an abiotic process through which litter is reduced into smaller fragments and then dissipated into the topsoil profile (Meentemeyer, 1984). Partitioning the three products of decomposing litter would be a method of addressing the relationship of NPP and SOC accumulation rates.

In this paper, we report our study of the relationships of litter qualities and carbon sinks in soils. This has been accomplished using SOC data, litterfall qualities and its components, litter decomposition constants (*k*-values), turnover rates and residence times of standing litter pools on the forest floors of three succession forests in Dinghushan Biosphere Reserve during 1978–2008. The three successional forests are pioneer forest-*Pinus massoniana* Lamb forest (PF); transition forest-mixed pine (*P. massoniana*) and evergreen broadleaved forest (MF); and climax-monsoon evergreen broadleaved forest (MEBF). We (1) present the long-term trends of SOC in top 20 cm soil layer along a successional forest chronosequence; (2) develop a method to partition the three interlinked fluxes (leaching, respiration and fragmentation) of decomposing litter; and (3) address the effects of litter quality on carbon sink in soils. This study advances our understanding of litter decomposition and its contribution to soil organic matter storage, which will be helpful in designing reforestation projects to maximize carbon sequestration.

2. Materials and methods

2.1. Site description

The three adjacent forests (at elevations ranging from 150 to 300 m, less than 500 m from one another and facing the same slope direction) are located in the Dinghushan Biosphere Reserve (DBR) (23°09′21″N–23°11′30″N, 112°30′39″E–112°33′41″E) in southern China, about 90 km west of Guangzhou city, covering an area of 1155 ha. The reserve was established in 1950 to protect natural monsoon evergreen broadleaved forests in the subtropics (Zhou et al., 2006b). The Southeast Asian subtropical monsoon climate has a distinctive hot-humid season (April–September) and a cool-dry season (October–March). The average annual rainfall is 1680 mm, of which almost 80% falls in the hot-humid season. The mean annual temperature is 22.3 °C and relative humidity is 80%. The bedrock is sandstone and shale. Soils are classified as ultisol with a pH of 4.0–4.9. A permanent plot of 10,000 m^2 was established for research purposes only in each of the three forests in 1978, and each plot was divided into 400 contiguous 5 m × 5 m sub-plots for biological monitoring and soil property measuring. The three forests, PF, MF and MEBF, respectively represent the pioneer, transition and climax succession stages of typical monsoon evergreen broadleaved forests in this region. The PF forest, approximately 22 ha, occupies the periphery of the reserve. The forest was initially planted in 1950s with a single species of *P. massoniana* and has been naturally invaded by other species, including *Evodia lepta* (Spreng) Merr, *Cratoxylum cochinchinense* (Lour.) Bl., and *Schima superba* Gardn. et Champ. The MF forest, approximately 557 ha, developed from the earlier established *P. massoniana* forest through natural succession, and is located between the central area and periphery of the reserve. The upper canopy of the community is dominated by *S. superba*, *Castanopsis chinensis* (Spreng.) Hance, and *P. massoniana.* The biomass of *P. massoniana* in MF has been in a continuous natural decline. Artificial disturbances have not occurred in PF and MF for more than 60 and 80 years, respectively. The MEBF forest, approximately 218 ha, is located in the central area of the reserve. The forest canopy consists of three distinct vertical layers. The upper canopy is dominated by species with fewer individuals, including *C. chinensis*, *Canarium tramdenum* Dai et Yakovlev, *S. superba*, *Cryptocarya chinensis* (Hance) Hemsl, *Cryptocarya concinna* Hance, *Aporosa yunnanensis* (Pax et Hoffm.), *Tsoongiodendron odorum* Chun, the sub-canopy is mainly composed of *C. concinna* and *Machilus chinensis* (Champ. ex Benth.) Hemsl, and the lowest canopy layer consists of shrubs. No disturbance was recorded for the past 400 years in the MEBF (Wang and Ma, 1982; Shen et al., 2001).

2.2. Soil carbon

Field measurements, conducted in September–October during the transition from the wet to dry season, were completed with an auger of 30 mm in diameter to the depth that included the entire top 20 cm soil layer. Excluding O layer material, soil samples were air-dried. Plant residues, including roots, were discarded, and soils were then triturated and sieved at 0.25 mm. SOC was determined using the wet oxidation method (Soil Plant Analysis Council, 1999). The data set used for this study was compiled from the temporal series shown in Table 1, spanning 31 years.