Catena 162 (2018) 141–147

Contents lists available at ScienceDirect

Catena

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

Effects of ageing and successive slash-and-burn practice on the chemical composition of charcoal and yields of stable carbon

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ARTICLE INFO

Keywords:
Chinese fir
Pyrogenic carbon
C stocks
Solid state ^{13}C nuclear magnetic resonance spectroscopy
Aryl-C

ABSTRACT

Chinese fir (*Cunninghamia lanceolata*) plantations cover over 12 Mha in the southeast provinces of China. The traditional conditioning of fields of this conifer involves the slash-and-burn practice. As a result of this practice, pyrogenic carbon (PyC) is produced by the incomplete combustion of organic matter; this includes a continuum of materials ranging from partially charred biomass and charcoal to soot. Owing to the structure and composition of PyC, it has traditionally been considered to have high chemical recalcitrance and resistance to degradation. Thus, PyC produced during slash-and-burn cultivation practices may profoundly alter the terrestrial carbon (C) cycle and soil chemical composition. Hence, this study aims to investigate the quantitative and qualitative composition of charcoal from the oldest Chinese fir plantation in China. Charcoal was sampled in soils from plots of different stand ages after one to four slash-and-burn rotations. This approach permitted an assessment of the effects of ageing and consecutive slash-and-burn rotations on the chemical composition of charcoal and the estimation of the stocks of stable C. The chemical composition of the PyC fraction was examined via elemental (CHN) and ^{13}C nuclear magnetic resonance spectroscopy (^{13}C NMR) analyses. These revealed some signs of degradation, such as a decrease in relative abundance of aryl-C and an increase in H/C_{at} values over time. The stocks of charcoal and yield of stable C in soil slightly increased with the number of fires, reaching a maximum of 1164 kg of PyC per hectare after four prescribed burns. Nevertheless, charcoal stocks decreased sharply with increasing stand age after each slash-and-burn event. In fact, over 25% of the charcoal stock was lost during the period from 12- to 21-years after the first slash-and-burn, and 85% was lost in the 97-year old stand. Our results together indicate that there has been a substantial loss of charcoal in soils following slash-and-burn rotations, on a time scale of decades associated with gentler slopes. Our results question the long-term persistence of charcoal in soils and highlight the necessity for periodic slash-and-burn rotation to maintain PyC stocks.

1. Introduction

China has the largest area of planted forests worldwide, with 36% (69 million ha) of the country's forests being represented by plantations (Chinese Ministry of Forestry, 2014). Chinese fir (*Cunninghamia lanceolata*) is an endemic, evergreen coniferous species cultivated as a commercial tree for its timber quality and fast growth. In recent years, the area under Chinese fir plantation rapidly increased covering over 12 Mha in the southeast provinces of China, accounting for about 80% of the total area where natural forests were converted to monoculture and mixed plantations (Bi et al., 2007; Chen et al., 2016).

In ancient times, natural broadleaved forests were not subjected to frequent prescribed burns; rather the conditioning of the fields of Chinese fir plantations involved the slash-and-burn practice. This practice resulted in the accumulation of PyOM, commonly called charcoal, at the soil surface. Incomplete combustion during fires in plantations transforms part of the biomass into charcoal, also referred to as pyrogenic carbon (Schneider et al., 2011). Pyrogenic Carbon (PyC) comprises a continuum of materials from partially charred biomass and charcoal to soot (Schmidt and Noack, 2000). The pyrogenic process, in general confers the charred materials, a longer mean residence time in the environment as compared to their unburned precursors (Santin et al., 2016; De la Rosa et al., 2008). Thus, PyC produced during slash-and-burn cultivation practices may profoundly alter the terrestrial

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https://doi.org/10.1016/j.catena.2017.11.028
Received 8 April 2017; Received in revised form 23 October 2017; Accepted 27 November 2017
0341-8162/

carbon (C) cycle. Chapin et al. (2002) reported that up to 40% of the terrestrial C cycle was affected by fires associated with natural or agricultural practices. It has been observed that the fires transform about 3% of the initial biomass to PyC (Forbes et al., 2006), and the latest estimates indicate that ~50% of the PyC produced by vegetation fires potentially sequester carbon over centuries. Nevertheless, PyC is exposed to degradation factors such as microbes, soil erosion, and transport through the breaking of soil aggregates (Kuzyakov et al., 2014; Berhe et al., 2007; Wang et al., 2013). Moreover, in order to satisfy the high demand for Chinese fir, logs have been harvested after a short rotation period of ~20–25 years since the late 1990s. Thus, contemporary fir plantations are dominated by young (~6 years) and middle-aged (~15 years) trees. Therefore, it is also essential to identify how the rotation period is affected by the slash-and-burn cultivation practice, which has a direct impact on charcoal stocks and its properties.

The potential significance of charcoal and other forms of PyC in C sequestration and soil properties has been clearly stated in several published reports (Lehmann, 2007; Cheng et al., 2008; Luo et al., 2016; De la Rosa and Knicker, 2011; Santin et al., 2016). Literature review provides a better understanding of the general properties and stability of charcoal under different conditions. Zackrisson et al. (1996) found no significant decline in charcoal levels over a 350-year post-fire chronosequence and also recorded large variability in charcoal stocks between sites. Anthropogenic charcoal in Amazonian black earths can be thousands of years old, as can charcoal in European chernozemic soils (1160–5040 years) (Schmidt, 2002) and coastal temperate rain forests (up to 12,000 years) (Gavin, 2003). Hammes et al. (2008) demonstrated that after grassland fires on the Russian Steppe in 1900, stocks of soil PyC declined by only 25% over the next century, and the turnover time was 293 years. Singh et al. (2012) concluded that the mean residence time (MRT) of PyC ranged in the order of centuries, similar to the MRT of slow-cycling pyrogenic organic matter (PyOM) (500–600 years) described by Knicker et al. (2013).

Until now, a few studies have investigated the long-term (i.e. decadal) fate of PyC in soils, and the results have been ambiguous, partly due to the different methodologies used in the characterisation and quantification of PyC (Schneider et al., 2011). Minor changes in the carbon pool have dominant effects on forest C dynamics. Therefore, there is an urgent need to examine the effect of successive prescribed burning on the abundance of charcoal in soils to achieve a general inventory of the stable pools of carbon and employ appropriate soil management.

Additionally, in the present work, the study area (Nanping) constituting the oldest documented plantation (planted in 1919) of Chinese fir in China (first rotation), which permitted us to cover a long period of time. In this study, PyC is used as a general term to describe the solid residues of incomplete combustion of biomass (including charcoal or char). We are conscious that this is only a fraction of the continuum of black carbon materials generated during pyrolysis (Schmidt and Noack, 2000). Nevertheless, studies on the chemical composition and stocks of PyC left in the soil after stubble burning are very scarce. Thus, the present study estimates the stocks, properties, and chemical composition of charcoal from different stand ages and rotations of Chinese fir plantations.

2. Materials and methods

2.1. Study area

The study area was located in a small watershed in Wangtai Town, Nanping City, Fujian Province, China (Fig. 1). The region has a subtropical monsoon climate, with a mean annual temperature of 19.3 °C and a relative humidity of 83% (Guo et al., 2014). The mean annual precipitation is 1699 mm, with most precipitation occurring from March to August. The mean annual evapotranspiration is 1413 mm. The altitude of the study area ranges from 150 to 250 m and ~30° slope. The soil is red earth derived from granite (Guo et al., 2005), equivalent to Hapludult based on United States Department of Agriculture (USDA) soil taxonomy (Soil Survey Staff, 2014). The soil texture of the sample site ranged from sandy clay to clay loam. The soil profile was well developed with charcoal deposition in the organic layer, due to slash-and-burn management practices. The thickness of the A horizon ranged from ~10 to 20 cm, while that of the B horizon was characterized by the accumulation of clay and iron oxides. Soil density ranged from 1.10 to 1.26 g cm^{-3}.

2.2. Chronosequence approach

Mature timbers of Chinese fir plantations are harvested at the age of 25–30 years. Before the saplings are planted, the area is cleared and the bark and other plant residues are subjected to slash-and-burn. The sampling campaign was performed in the year 2015. A total of 10 different sites were sampled. They consisted of first rotation stands of 12-, 21-, 40- and 97-years-old (slash-and-burned once); second rotation stands of 12-, 21- and 31-years-old (slash-and-burned twice); third rotation stands of 13- and 21-years-old (slash-and-burned three times); and fourth rotation stands of 10-years-old (slash-and-burned four times). Selection of the sites covered by 12-year old (first and second rotation), 13-year old (third rotation), and 10-year old (fourth rotation) stands was performed to permit the comparison of charcoals with similar periods of time since the last burn and from one to four cycles of slash-and-burn. The average time elapsed between each slash-and-burn cycle was 20 to 25 years.

2.3. Soil sampling

For each site, five subplots (20 × 20 m) with southeastern slopes were established, and three pits were systematically dug diagonally for each subplot. Soil samples were collected (0–20 cm depth) from each of the three sampling pits and mixed thoroughly to form a single composite sample per plot, resulting in a total of 50 samples, and stored in sealed bags. Buffer zones (4 m wide) were included in each direction to avoid edge effects. To minimize the effect of the slope position on soil characteristics, subplots were selected at a mid-slope position. Ohlson et al. (2009) determined that sampling to a depth of 20 cm in these environments is sufficient to estimate the majority of soil charcoal stocks. Two core soil samples were collected to determine soil bulk density (BD) at 0–20 cm depth using metal soil cores (200 cm^3). Bulk density cores were dried at 105 °C until a constant dry weight was reached. Coarse fragments (stones, rocks, and roots) were removed manually, and their masses were subtracted from the total weight (bulk density = mass at 105 °C/Vcore − Vcoarse fragments).

2.4. Charcoal analysis

Soil samples were air-dried and homogenized. Subsequently, five sets of 400 g dry soil were separated from each plot and passed through 1 mm, 0.5 mm, and 0.25 mm sieves. All charcoal particles were removed manually from the sieves. For the fraction of charcoal ≤ 0.25 mm, the remaining material was placed in a petridish and the charcoal was removed manually using tweezers with the aid of an optical microscope (SMZ18, Nikon Instruments Ltd., Hong Kong). The charcoal concentration was determined in g kg^{-1} soil (dry weight).

2.5. Elemental analysis

Carbon (C), hydrogen (H) and nitrogen (N) content were determined by using a CHNS Elementar Analyzer (Vario Elementar Analysensysteme, Hanau, Germany).