Agriculture, Ecosystems and Environment 236 (2017) 243–255

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France

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ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 1 December 2016
Accepted 5 December 2016
Available online xxx

Keywords:
Alley cropping
Soil organic carbon storage
Equivalent soil mass
Aboveground biomass
Belowground biomass

ABSTRACT

Agroforestry systems are land use management systems in which trees are grown in combination with crops or pasture in the same field. In silvoarable systems, trees are intercropped with arable crops, and in silvopastoral systems trees are combined with pasture for livestock. These systems may produce forage and timber as well as providing ecosystem services such as climate change mitigation. Carbon (C) is stored in the aboveground and belowground biomass of the trees, and the transfer of organic matter from the trees to the soil can increase soil organic carbon (SOC) stocks. Few studies have assessed the impact of agroforestry systems on carbon storage in soils in temperate climates, as most have been undertaken in tropical regions. This study assessed five silvoarable systems and one silvopastoral system in France. All sites had an agroforestry system with an adjacent, purely agricultural control plot. The land use management in the inter-rows in the agroforestry systems and in the control plots were identical. The age of the study sites ranged from 6 to 41 years after tree planting. Depending on the type of soil, the sampling depth ranged from 20 to 100 cm and SOC stocks were assessed using equivalent soil masses. The aboveground biomass of the trees was also measured at all sites. In the silvoarable systems, the mean organic carbon stock accumulation rate in the soil was 0.24 (0.09–0.46) Mg C ha^{-1} yr^{-1} at a depth of 30 cm and 0.65 (0.004–1.85) Mg C ha^{-1} yr^{-1} in the tree biomass. Increased SOC stocks were also found in deeper soil layers at two silvoarable sites. Young plantations stored additional SOC but mainly in the soil under the rows of trees, possibly as a result of the herbaceous vegetation growing in the rows. At the silvopastoral site, the SOC stock was significantly greater at a depth of 30–50 cm than in the control. Overall, this study showed the potential of agroforestry systems to store C in both soil and biomass in temperate regions.

1. Introduction

Soils play an essential role in the global carbon budget (Houghton, 2007). Currently, the land sink (including soil and vegetation) absorbs about 30% of the carbon (C) emitted to the atmosphere through the burning of fossil fuel and cement production (Le Quéré et al., 2014). Since 1850, the depletion of soil organic carbon (SOC) in cultivated lands has transferred about 70 Gt C to the atmosphere (Amundson, 2001; Lal, 2004a). The potential of these SOC depleted soils as future C sinks through SOC sequestration has now been recognized (Paustian et al., 1997; Freibauer et al., 2004; Smith, 2004). In France, SOC stocks have been estimated at 3.1-3.3 Gt C in the top 30 cm of soils (Arrouays et al., 2001; Martin et al., 2011). Based on the SOC saturation capacity (Hassink, 1997), assuming that the quantity of stable SOC is limited by the amount of fine particles, Angers et al. (2011) found that the median saturation deficit of French arable topsoils was 8.1 g C kg^{-1} soil. About 70% of French agricultural topsoils are, therefore, unsaturated in SOC and have the potential for additional

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http://dx.doi.org/10.1016/j.agee.2016.12.011
0167-8809/

SOC storage. Increasing SOC stocks is often seen as a win-win strategy (Lal, 2004a; Janzen, 2006) as it allows the transfer of CO_2 from the atmosphere to the soil while improving soil quality and fertility (Lal, 2004b).

Several agricultural practices have been developed to increase SOC stocks. For instance, the introduction of cover crops (Constantin et al., 2010; Poeplau and Don, 2015) or grasslands (Conant et al., 2001; Soussana et al., 2004) in the cropping sequence has proven effective. The effect of no-till farming on SOC stocks is disputed and highly variable (Luo et al., 2010; Virto et al., 2012; Dimassi et al., 2013) and seems to depend on the amount of C transferred from the crops to the soil (Virto et al., 2012). Agroforestry is a general term for agroecosystems in which trees are intercropped with crops or pasture (Nair, 1993). Silvoarable systems intercrop trees and arable crops and silvopastoral systems combine trees, pasture and livestock. These are recognized as possible land use management systems that can maintain or increase SOC stocks, both in tropical (Albrecht and Kandji, 2003) and temperate regions (Peichl et al., 2006; Bambrick et al., 2010; Wotherspoon et al., 2014). However, most studies only consider the surface soil layers (to a depth of <20 or 30 cm) whereas trees grown in agroforestry can be very deep rooted (Mulia and Dupraz, 2006; Cardinael et al., 2015a) and affect deep SOC stocks. A recent study in the Mediterranean region of France showed that an 18-year-old silvoarable system with hybrid walnuts intercropped with durum wheat increased SOC stocks by 0.25 ± 0.03 Mg C ha^{-1} yr^{-1} in the 0–30 cm layer and by 0.35 ± 0.04 Mg C ha^{-1} yr^{-1} from 0 to 100 cm compared to an adjacent agricultural plot (Cardinael et al., 2015b). Furthermore, although trees affect the spatial distribution of organic matter inputs to the soil (Rhoades, 1997), sampling protocols have not always taken account of the potential impact on the spatial distribution of SOC stocks. Some authors showed that SOC stocks were greater in the tree rows than in the inter-rows, and found no gradients within the inter-rows (Peichl et al., 2006; Upson and Burgess, 2013). Bambrick et al. (2010) found that the spatial distribution of SOC stocks varied with the time after tree planting. Few studies have estimated SOC storage in agroforestry systems in temperate conditions (Howlett et al., 2011; Mosquera Losada et al., 2011; Upson and Burgess, 2013) and these studies sometimes do not have control plots without trees for comparison, making it difficult to evaluate the precise effect of agroforestry on SOC stocks (Pellerin et al., 2013).

This study set out i) to quantify organic carbon stocks in soils and in the tree biomass in six agroforestry systems with adjacent agricultural control plots under different soil and climate conditions in France, ii) to study the spatial distribution of SOC stocks as a function of the distance from individual trees and the tree rows and iii) to estimate the SOC stock accumulation rates for these agroforestry systems.

2. Materials and methods

2.1. The six agroforestry sites

Each study site had an agroforestry system and an adjacent agricultural control plot. Before tree planting, the agroforestry plot was part of the agricultural plot, with the same soil use and management (crop rotation, fertilization, soil tillage). After tree planting, the soil management of the agroforestry inter-rows and of the agricultural plot remained identical. Rows of trees were planted in the agroforestry fields, with natural or sown grasses between the trees. Five sites, Restinclières (RE), Châteaudun (CH), Melle (ME), Saint-Jean d'Angely (SJ), and Vézénobres (VE), were silvoarable systems with no grazing. Only one site, Theix (TH), was a silvopastoral system with regular grazing. Four sites were owned and managed by farmers and Restinclières (RE) and Theix (TH) were experimental research sites.

The CH silvoarable site was located in Châteaudun (Fig. 1), in the department of Eure-et-Loir (longitude 1°17′58″ E, latitude 48°06′08″ N, elevation 147 m a.s.l.). The mean temperature was

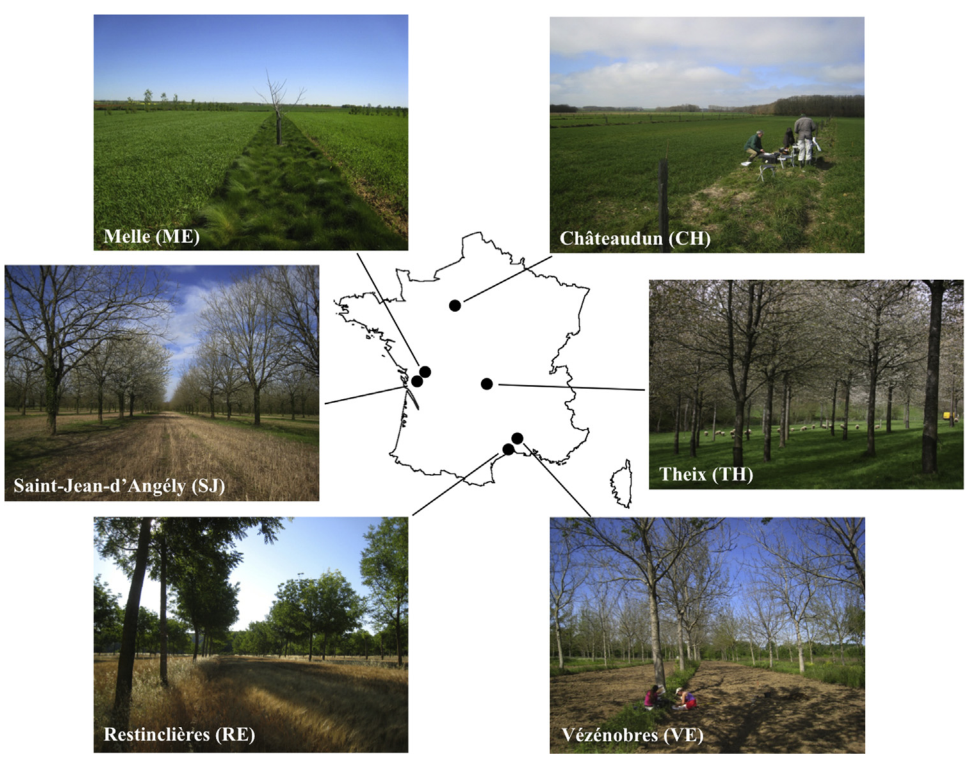

Fig. 1. Location and description of the six study cases under agroforestry systems sampled in France.