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How do management techniques affect carbon stock in intensive hardwood plantations?

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ABSTRACT

Recent studies in temperate regions have shown that agroforestry systems, especially silvopastoral systems, have greater carbon (C) sequestration potential than monocropping systems or pastures, or even forest plantations. In Europe, there is growing interest in establishing high quality wood plantations with intensive management comprising irrigation, fertilisation and chemical weed control to reduce rotation length. However, these operations can have major environmental impacts similar to the effects of intensive agriculture, such as impoverishment of soil C. The aim of this study is to identify optimum management practices for intensive systems of quality wood production to optimise soil C stock and plantation productivity. An experiment was conducted in Extremadura, mid-west Spain, from 2011 to 2014, in a 13-year-old hybrid walnut (*Juglans major* × *regia* mj 209xra) plantation with a density of 333 trees ha^{-1}. Two essays were established: one with three techniques to control competition from herbaceous strata beneath trees – mowing, ploughing and sheep grazing (1 sheep ha^{-1}) – and the other to test implementation of legumes (mixture of *Trifolium michelanium* and *Ornithopus compressus* complemented by the same quantities of phosphorous and potassium as mineral treatment) as an alternative to traditional mineral fertilisation (40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}). The C stock estimate was based on soil organic carbon (SOC) and aboveground (tree trunks and branches) and belowground biomass (tree and pasture roots). Most of the C stock was contained in SOC, at 50% in the uppermost soil layer (0–25 cm), followed by aboveground biomass. The response of SOC in each treatment was higher than the other parameters analysed, suggesting that SOC is a more sensitive pool to management techniques. Grazing as control of herbaceous vegetation and legume implementation as nitrogen supply are suitable techniques for optimising soil C stocks and also achieve adequate tree growth in the longer term.

1. Introduction

The importance of C sequestration in the land use scenario lies in its potential as a climate change mitigation strategy (Nair, 2012; IPCC, 2014). The Climate Change 2007 Synthesis Report (IPCC, 2014) proposed several management strategies in the agricultural sector to mitigate CO_2 concentrations in the atmosphere, including cropland and grazing land management and restoration of organic soils. The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and deforestation reduction, although their relative importance differs greatly across regions.

Europe has a shortage of quality wood, resulting in a growing interest in the establishment of hardwood plantations. In Spain, hardwood species are commonly harvested after long rotations of up to 50 or 60 years, although intensive management including irrigation, fertilisation and chemical weed control can reduce rotation length by half (to 20–25 years) (Rigueiro-Rodríguez et al., 2009). However, these operations can have major environmental impacts similar to intensive agriculture, such as impoverishment of soil C (Babcock et al., 2003). Sustainable forest management must be applied using multicriteria objectives that optimise both increasing biomass and C sequestration (Lal, 2005; Bravo et al., 2008). Management systems that maintain a continuous canopy cover and mimic regular natural forest disturbance are likely to achieve the best combination of high wood yield and C storage (Lal, 2005; Jandl et al., 2007).

Recent studies in temperate regions have shown that agroforestry systems, especially silvopastoral systems (integrated

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land-use systems combining wood production and pasture production) have greater C sequestration potential than open fields (crops or pastures) (Dube et al., 2012), mainly in the uppermost soil layer, due to increased C input with rhizodeposition and aboveground residue return (Ramesh et al., 2015). Agroforestry systems have attracted special attention in this regard because of the perceived advantages of the large volume of aboveground biomass and deep root systems of trees (Nair, 2012). Dube et al. (2012) observed that individual trees in silvopastoral systems sequestered nearly 30% more C in total biomass than in a pine plantation, as tree growth in the silvopastoral system was enhanced by lower tree competition, resulting in larger amounts of C being sequestered.

In intensive hardwood plantation, control of competing herbaceous vegetation is required to avoid tree-herbage competition for soil resources and fire risk. Grazing controls understorey vegetation. Its intensity may affect C stocks by modifying net C flows from the atmosphere to vegetation and soil as a result of changes to the amount, plant type composition and decomposition rates of residual plant material. Under grazing conditions, the residence time of aboveground C is very short (10–50 days). It varies according to the probability of defoliation and digestion of leaf tissues and the associated release of C into the atmosphere. In contrast, the residence time of belowground C is long (c. 1 to >1000 years) in grassland ecosystems (Soussana and Lemaire, 2014).

Implementation of forage legumes as an alternative to mineral fertilisation could lower the economic costs of high quality intensive wood plantations, increase the available nutrients in soil (especially N), improve pasture production and quality, and optimise the environmental functions of plantations, i.e. provide soil cover to control erosion (Gabriel and Quemada, 2011; McCartney and Fraser, 2010; O'Dea et al., 2015). López-Díaz et al. (2014) observed an improvement in N availability in soil by almost 200% compared to the control. No competition for soil water and nutrients by forage legumes was noted with legume presence.

Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all SOC (Montero et al., 2005). It is well known that soils are the largest reservoir of C in territorial ecosystems. Consequently, changes to soil C sequestration, whether positive or negative, could significantly alter atmospheric CO_2 concentrations and impact the global climate of the future (Lal, 2005; Ciais et al., 2013; Riggs et al., 2015). Forest soil C stock can be increased through forest management, which includes site preparation, fire management, afforestation, species management/selection, use of fertilisers and soil amendments. Changes in SOC due to management practices are difficult to quantify because they occur slowly, as claimed by Ramesh et al. (2015). Damien et al. (2015) observed that seven years of grazing at varied intensities modified vegetation but not soil C stocks. Soil C storage is important not only because of its role in the global C cycle, but also because it affects forest productivity, as soil C is a principal source of energy for nutrient recycling (Nave et al., 2010).

Patterns of aboveground biomass distribution in terrestrial ecosystems are reasonably well understood, whereas knowledge of belowground biomass and its distribution is still limited due to methodological difficulties in determining fine root biomass (Finér et al., 2011). Other researchers found that belowground biomass is a defined portion of aboveground biomass, reporting values of 25–40% depending on factors such as the nature of the plant and its root system and ecological conditions (Montero et al., 2005; Alías et al., 2015).

One aspect of the organic C pool that remains poorly understood is the vertical distribution of fine roots in the soil and accompanying relationships with climate and vegetation (Jobbágy and Jackson, 2000). Finér et al. (2011) reported that fine roots are very dynamic and play a key role in forest ecosystem C and nutrient cycling and accumulation.

The aim of this study is to evaluate the profitability of alternative techniques of control of competing vegetation and fertilisation in intensive hardwood plantations and the implications of these techniques in the C stock of the systems, raising the following research questions:

1. How does the type of treatment (traditional or alternative) affect SOC? The management system with least disturbance was expected to maintain highest soil C storage.
2. How does the type of treatment (traditional or alternative) modify the productivity of the system (i.e. quality timber production) in the short and long term? The productivity of alternative techniques would be similar to or better than traditional (and more intensive) practices in the medium and long term.
3. What is the importance of fine roots as a C sink under the various treatments? This parameter is not usually evaluated and could significantly increase C stock of forest plantations.
4. Which is the most important component (aboveground or belowground biomass, soil) as a C pool in an intensive forest plantation? Soil could be the most important C sink of agricultural and forestry systems.
5. Which treatments maximise the potential of silvopastoral systems as C sinks? Treatments that improve the most important C pool of these systems should primarily be taken into account to maximise their potential as C sinks.

2. Materials and methods

2.1. Study site characteristics

The experiment was conducted from 2011 to 2014 in northern Extremadura, mid-west Spain (ETRS89 Zone 20: X:298.303 Y:4.442326; 309 m a.s.l.), in a 13-year-old hybrid walnut (*Juglans major* × *regia* mj 209xra) plantation, characterised by fast growth and scarce fruit, with a density of 333 trees ha^{-1}. Trees were planted in 1998. Before planting, the land use was agricultural (maize). At the beginning of the essay, mean height and diameter at breast height (DBH) were 8.33 m and 17.8 cm, respectively.

The area is in the Mediterranean biogeographic region (European Environment Agency, 2006). Mean annual precipitation is 952 mm and mean annual temperature is 15.6 °C. A period of drought usually occurs from June to September. The experiment was performed in a sandy loam soil more than 140 cm in depth with less than 5% slope. Initial soil analyses revealed an acidic pH (pH 5 in water) and medium SOC levels (2.6%). Soil characteristics and history are similar.

2.2. Experimental design

Two essays were established: one experiment with three techniques to control competition from herbaceous strata beneath trees ("Grazed Walnut"), and the other to test alternatives to traditional inorganic fertilisation ("Fertilised Walnut").

The treatments (Table 1) to control competing vegetation (Grazed Walnut) were applied in early spring for three years (2012–14): a) mowing understorey vegetation (herbage); b) ploughing; and c) grazing (introducing a stock of 1 sheep ha^{-1}). In all plots mineral fertilisation was applied (NPK: 40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}) in autumn. Doses were based on tree requirements. Plots that were mowed and ploughed were fenced to prevent grazing.

In the Fertilised Walnut essay, three treatments (Table 1) were applied for four years (2011–14): d) inorganic fertilisation: application of 40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}, e) legume sowing (complemented by the same quantities of PK as a