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Carbon allocation dynamics one decade after afforestation with *Pinus radiata* D. Don and *Betula alba* L. under two stand densities in NW Spain

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ABSTRACT

Silvopastoral systems can contribute to the mitigation of climate change by functioning as sinks for greenhouse gases better than exclusively agricultural systems. Tree species, density, and an adequate management of the pasture carrying capacity contribute to the capacity of carbon sequestration. In this study, the capacities for carbon sequestration in silvopastoral systems that were established with two different forest species (*Pinus radiata* D. Don and *Betula alba* L.) and at two distinct densities (833 and 2500 trees ha^{-1}) were evaluated. Tree, litterfall, pasture and soil carbon storage determinations were carried out to deliver carbon sequestration in the different pools within the first 11 years of a plantation establishment. The results show that the global capacity for carbon sequestration in silvopastoral systems with pine canopy was higher than with birch cover. Independently of the forest species, the capacity for carbon sequestration increased when the systems were established at higher plantation densities. There were found strong differences in the relative proportions of carbon in each component of the system (litterfall, tree, pasture and soil). The soil component was found to be most important in the case of the broadleaf forest established at low density. The establishment of a silvopastoral system enhanced soil carbon storage, since afforestation was carried out, which results in a more enduring storage capacity compared with treeless areas.

1. Introduction

Carbon sequestration by forests is an important environmental issue since the Kyoto Protocol (article 3.3) was adopted in 1997 (http://unfccc.int/resource/docs/convkp/kpeng.pdf). That resolution included the removals by sinks that result directly from human-induced land use changes and forestry activities to meet the Kyoto carbon emissions commitments by the involved countries in the determined periods from 1990 onwards (Mosquera-Losada et al., 2009). These facts make reforestation and afforestation, as well as deforestation, very important for the global carbon balance accounting of different countries. Reforestation of agricultural land will not only contribute to an increase in carbon sequestration on a global scale; it will also increase the supply of lumber, reducing the need for the logging of old-growth forests that, consequently, releases high amounts of stored carbon (Nair et al., 2008).

To verify compliance with the Kyoto Protocol, it is vital to measure the carbon sequestration caused by land use changes from agricultural to forestland, as well as the management of these lands. Reforestation of agricultural land has recently been promoted in Europe and has resulted in the reforestation of more than one million hectares throughout Europe between 1994 and 1999 (EC, 2005), a result of the implementation of Regulation No. 2082/92 (EU, 1992). The establishment of agroforestry in forestlands were promoted through direct payments in the last European Union Rural Development Council Regulation 1698/2005 (EU, 2005), making it necessary to evaluate the gains and losses of carbon caused by changes in tree biomass, pasture production, soil organic matter content and livestock greenhouse carbon (GHC) emissions. This also highlights the importance of evaluating the balance of different alternatives of forest management in different environments, as described by Gordon et al. (2005).

Forest carbon stocks are affected by the previous land use, tree species, tree density and the interaction of all these variables with climate (Reynolds et al., 2007).). In an agroforestry system, edaphic carbon is considered the most important store from a quantitative perspective (Dixon, 1995). The capacity to increase the sequestration of carbon in the soil will largely depend on the tree species used in reforestation and their density. Carbon storage in a silvopastoral system is balanced by the

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emissions of greenhouse gases (CH_4 and N_2O) produced by the ruminants that feed on it. The amount of greenhouse gases, here called GHG emitted by livestock depends on the stocking rate, which depends on pasture production that is affected by tree development after afforestation. Thus, these should also be evaluated.

Agroforestry systems are not broadly extended within the Atlantic area of the European Union, where the important growth of trees could improve the European union carbon sequestration. Carbon sequestration studies carried out in the Atlantic region of Europe are related to grasslands or crops but not to forestlands, where aspects related to above and belowground carbon sequestration should be evaluated. Moreover, comparisons between tree species development and densities and their effect on livestock GHG emissions as well as on carbon sequestration should be carried out as pasture production and the chemical composition, and the quantity and rate of incorporation of carbon to soil from litterfall depends on tree species identity and density (Prescott et al., 2000). Compared with exclusively forest systems, carbon in silvopastoral systems should be evaluated. Some estimates assert that livestock production accounts for 18% of climate change, produces 9% of CO_2 emissions, 37% of CH_4 emissions, and 65% of the N_2O (Steinfeld et al., 2006). Moreover, long term studies should be carried out to quantify global carbon sequestration as tree canopy in the Atlantic region is fast developed, which affects to the global system biomass production (tree, pasture and therefore livestock), the inputs of organic matter into the soil and therefore the global carbon sequestration in the different pools of the agroforestry systems.

This paper aims to evaluate the amount of carbon sequestration in two silvopastoral systems that were established at two densities of *Pinus radiata* D. Don (pine) or *Betula alba* L. (birch) during the 11 years after trees were planted.

2. Materials and methods

2.1. Characteristics of the study site

The experiment was conducted in Castro Riberas de Lea (province of Lugo, NW Spain) at a latitude of 43.01′N and a longitude of 7.40′W. The study area is situated 439 m above sea level. The experiment was conducted in soil classified as an Umbrisol (FAO, 1998) with a sandy-loam texture (61.14% sand, 33.79% silt, 5.07% clay) that was previously designated for agricultural use (potato cultivation). The soil has an A horizon of 32 cm in depth, with some parts exceeding 40 cm. Argilic horizons began at a mean depth of 58 cm. According to the soil FAO classification system these soils are Umbrisol, with some horizon development, the eluviation of clay-sized particles to deeper horizons. These acidic and seasonally wet soils do not have accumulations of inorganic carbonates. The initial water pH (1:2.5) was nearly neutral (6.8), indicating to us a good availability of nutrients for plants (Porta-Casanellas et al., 2003). The edaphic contents of organic matter and nitrogen were 8.03% and 0.33%, respectively. Therefore, these would be considered elevated, though this is characteristic of soils used for cultivation in Galicia (Calvo de Anta et al., 1992). Furthermore the soil C/N ratio was 14.11, indicating a slow mineralisation rate and, consequently, favouring soil organic matter accumulation. The zone in which the experiment was conducted corresponds to what is considered an Atlantic bioclimatic region (EEA, 2003). The annual precipitation and the annual average temperature over the last 30 years were 1300 mm and 12.2 °C, respectively. Generally, moisture deficits that limit vegetative growth have been recorded in July and August due to drought.

2.2. Establishment, experimental design, and management

The experiment was initiated in 1995 and the results of the study were obtained for the period between 1995 and 2005. At the end of the winter of 1995, land ploughing was carried out. The results reported in this article pertain to a study involving 24 treatments. Some of the results have been previously reported in other publications (Rigueiro-Rodríguez et al., 2000; Mosquera-Losada et al., 2006; Fernández-Núñez et al., 2007). This article examines the results obtained for 4 of the treatments and 3 replicates (12 experimental units) that represent the typical forest management practices used in this area. The experimental design was random blocks with three replicates for each tree density. The treatments consisted of the evaluation of *P. radiata* (transplanted in soil from paperpots) and *B. alba* (bare rooted) that were established at two densities: (a) 2500 trees ha^{-1}, with a planting distance of 2 m × 2 m and an area of 64 m^2 per replicate, and (b) 833 trees ha^{-1}, with a planting distance of 3 m × 4 m and an area of 192 m^2 per replicate. In each experimental unit, 25 trees were planted with an arrangement 5 × 5 stems. After plantation, the plots were sown with a mixture of *Dactylis glomerata* L. var. Saborto (25 kg ha^{-1}) + *Trifolium repens* L. var. Ladino (4 kg ha^{-1}) + *Trifolium pratense* L. var. Marino (1 kg ha^{-1}). Fertiliser was not applied to replicate traditional reforestation practices for agricultural land in this area. A low pruning (at 2-m height) was performed on *P. radiata* at the end of 2001 and the *B. alba* was given a formational pruning with the objective of producing quality timber.

2.3. Field samplings

2.3.1. Soil

In order to determine the soil C content, a random sample was taken in January 2006 from each plot using a drill at a sampling depth of 25 cm, where the most organic matter accumulates. Once the samples were collected, they were taken to the laboratory, air-dried and sieved through a 2 mm screen. After this preparation, we determined the pH in water (1:2.5) and the total C content using the Saverlandt method (Guitián-Ojea and Carballás-Fernández, 1976).

2.3.2. Trees

Tree diameter measurements for *P. radiata* and *B. alba* were collected during the last year of the study (December 2005). The diameter of each inner plot tree was measured using a caliper at 1.30 m from the ground (diameter at breast height). Measurements were taken from nine inner trees in each plot. The biomass contents of the trees were determined via the implementation of allometric equations based on diameter (Table 1). These equations were determined by the National Institute of Agricultural Research and Technology and Food of Spain (Montero et al., 2005) in the region of the present study with tree densities similar to the experiment and have been used in the national carbon accounting system, as *P. radiata* stands are exclusively placed in the Atlantic Biogeographic Region of Spain, where the present study was developed.

2.3.3. Forest floor litter

The forest floor litter, hereafter litterfall, generated by the trees, which then accumulates on the soil surface, must be taken into account in estimates of a carbon cycle balance. The pine needle litterfall was hand separated from the same samples used for pasture production, as will be described in the next paragraph. No count was taken of the fallen birch leaves in the plot since the count of the birch leaves (being a deciduous species) was included in the estimate of the aboveground biomass of the tree (Table 1).