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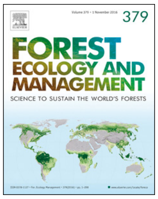

Above- and below-ground carbon accumulation and biomass allocation in poplar short rotation plantations under Mediterranean conditions

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ABSTRACT

Beside the production of biomass, short rotation coppice (SRC) poplar plantations can also contribute to carbon sequestration in the soil through their below-ground biomass. The present study evaluated the allocation of above and below-ground biomass at the end of the first rotation of four SRC plantations under Mediterranean conditions. The genotypes evaluated are commonly used for biomass plantations, i.e. genotypes 'AF2' and 'I-214' (*Populus* × *canadensis* Mönch), and 'Monviso' (*P.* × *generosa* Henry × *P. nigra* L.). No significant differences among genotypes were found with regard to below-ground biomass yield. The root:shoot ratio decreased in line with the growth in shoot basal diameter, with values ranging from 0.15 to 0.26. The accumulation of carbon in the below-ground fraction of the biomass ranged from 0.86 to 0.91 Mg C ha^{-1} yr^{-1}, whereas the above-ground carbon accumulation ranged from 3.89 to 6.48 Mg C ha^{-1} yr^{-1}. A general as well as a genotype-specific allometric model allowed to accurately predict the below-ground biomass yield using shoot basal diameter as the predictor variable. Both models provide an important tool to quantify the carbon accumulated in the below-ground fraction of the biomass.

1. Introduction

Research concerning poplar plantations under a short rotation regime has recently become prominent with the aim of maximizing the raw material both for bioenergy and more recently for bioproducts. Additionally, these plantations can play an important role in maintaining or sequestering carbon in the soil (Berhongaray and Ceulemans, 2015; Block et al., 2006) as well as in contributing towards the reduction of greenhouse gas emissions thereby helping to mitigate climate change (Agostini et al., 2015). Studies focusing on differences in yield based on the genotypes or on the management have led to much progress in this area, even though variation due to genotype-environment interactions (plasticity) makes it more difficult to attain the anticipated progress. Furthermore, the final tally in terms of carbon sequestration has also been the subject of research since the capacity of short rotation coppice (SRC) to sequester carbon remains unclear (Hillier et al., 2009; Walter et al., 2015). Some studies suggest a neutral carbon balance without emissions (Hansen, 1993; Johnson et al., 2007), although some recent studies reported that after successive rotations a point is reached at which the carbon balance becomes positive (Arevalo et al., 2011; Verlinden et al., 2013).

SRC crops are defined as high-density plantations of fast growing trees (such as poplars or willows), managed in rotations of 2–8 years (Berhongaray et al., 2017; Ferré and Comolli, 2018). This implies a different stage of development of the shoots (S) which regrow from the stool and the root (R) in successive rotations. Plant roots are an essential component of net primary productivity (NPP), which is the sum of visible growth and litter production of above- and below-ground components (Roy et al., 2001). Poplar root systems can account for around 25–35% of the total plant biomass (Heilman et al., 1994; Pregitzer and Friend, 1996), this percentage being higher (up to 63%) in juvenile trees (Block et al., 2006; King et al., 1999; Yin et al., 2004). In SRC plantations the roots can be of even higher importance given the expected rotations, which will imply that the above-ground and the below-ground parts are of different ages over the duration of the crop. Due to the difficulties in studying the root system, advancing the knowledge in this area is far from simple (Jha, 2017; Mokany et al., 2006). Despite this, some studies have focused on this fraction of the stool in relation to the whole SRC system (Berhongaray et al., 2015; Block et al., 2006). Although studies on poplar root systems are somewhat scarce, there are more that focus on fine roots given the ease of their extraction, as well as their importance in the assimilation of

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water and nutrients (Dickmann et al., 1996) and their important influence on carbon turnover (Mulia and Dupraz, 2006), despite the fact that fine roots only represent a small fraction of total tree biomass (Al Afas et al., 2008a,b; Berhongaray et al., 2013). There has not been much progress in the study of roots under irrigated short rotation plantations in Mediterranean areas, neither as regards fine roots nor as regards the radical system as a whole.

Root biomass can be directly measured using excavation techniques (Levillain et al., 2011) although these methods are costly and time consuming (Addo-Danso et al., 2016). A common approach for estimating not only above-ground biomass in highly diverse forests but also below-ground biomass, is to use allometric relationships based on an easily measurable variable (Clark et al., 2001; Kenzo et al., 2009; Saint-André et al., 2005). The use of allometric equations to predict root biomass is a generalized method (Cairns et al., 1997; Kurz et al., 1996; Snowdon et al., 2000; Vogt et al., 1995), since these relationships provide a simpler and more accurate means for estimating root biomass (Domenicano et al., 2011). However, few allometric relationships are available for below-ground biomass estimations in poplar SRC (Berhongaray et al., 2015; Coyle and Coleman, 2005; Fang et al., 2007), particularly as regards those growing under Mediterranean conditions where irrigation determines root development.

Poplar SRC plantations for the production of biomass provide an additional benefit in the form of carbon sequestration in the soil (Smith, 2004). To quantify the potential of carbon sequestration in the soil in SRC plantations, it is important to take both litterfall and fine root turnover into account (Walter et al., 2015), as well as the carbon accumulated in the below-ground woody biomass which remains in the soil during the successive coppices (Pacaldo et al., 2014). Hence, the accuracy of the allometric equations used to quantify the below ground biomass is of major importance.

The present study evaluated the allocation of the above and below-ground fraction in different short rotation poplar plantations under Mediterranean conditions at the end of the first rotation. Our main objective was to contribute towards furthering our understanding of the root system, providing accurate knowledge of the root system allocation in the first rotation of this type of plantations under Mediterranean conditions, which necessitate irrigation due to the severe summer drought. Therefore four plantations in Spain comprising three commonly used genotypes and with a range of different ages were evaluated. The specific objectives were: (i) to quantify the above and below-ground biomass, as well as the root:shoot relationship at genotype level, (ii) to develop allometric relationships based on shoot basal diameter or shoot basal area, from which root biomass could be estimated, and finally (iii) to compare the total and disaggregated amount of carbon accumulated in the biomass (above and below-ground) at plantation level, considering the genotype used.

2. Material and methods

2.1. Experimental field sites

Four experimental field sites in Spain (S1 to S4) were used in this study, covering different site conditions in the Mediterranean climate (Table 1). Three high-yielding genotypes were selected from the trial network. These were: 'AF2' (*Populus* × *canadensis* Mönch), 'I-214' (*P.* × *canadensis* Mönch) and 'Monviso' (*P.* × *generosa* Henry × *P. nigra* L.). The plantations were established in early spring using cuttings of 20–30 cm in length. Densities ranged from 5,555 cuttings ha^{-1} to 13,333 cuttings ha^{-1} in a design consisting of single rows 2.5 or 3 m apart. Three to four randomized replications were established for each genotype within each plantation. A similar management was applied in all plantations as regards fertilization during soil tillage according to the specific soil characteristics, weed control and irrigation (to field capacity) during the summer months (Sixto et al., 2013). A drip irrigation system was established to optimize water application.

Different rotation lengths were applied depending on the developmental status. The rotation length established at sites S2 and S4 was three years, while at sites S1 and S3 it was four years. Hence, the stages of development covered in this study at the end of the first rotation were: R3S3 or R4S4, denoting root age as R and shoot age as S. None of the stands were coppiced at the studied time; so the age in the above- and below-ground fraction was the same.

2.2. Above- and below-ground biomass

The sampling unit was considered the stool, which is the plant consisting of a stump, base or root from which one or several shoots are produced. Measurements of the above-ground fraction were taken at the end of each rotation on 16–25 stools per site, replicate and genotype. Shoot diameters over bark at 10 cm above ground (d_{basal}, mm), accounting for the size of the shoots at the usual harvesting height, were measured using a digital calliper (Absolute, Vogel Germany, Kevelaer, Germany) (accuracy to 1 mm). The basal area (BA_{basal}, mm^2) of the entire stool was calculated from basal diameters of all shoots. Total height of the highest shoot (H_{total}, cm) was also measured with a measuring pole to an accuracy of 1 cm. The number of shoots and the density of living stools were also recorded to quantify mortality. The above-ground woody biomass was assessed in all stools through destructive sampling after leaf fall. We considered above-ground woody biomass as the whole biomass above the harvesting height of these stools, which were cut back at 10 cm above the soil. Total above-ground dry woody biomass ($W_{above\text{-}ground}$, g DM (dry matter)) was determined for each sampling unit from the fresh weight and the estimated above-ground wood moisture by randomly selecting one entire stool from each of the plots and then oven-drying a randomly selected sample of each genotype to constant weight at 105 °C.

Five stools for each site, replicate and genotype were selected for below-ground biomass measurements. They were selected by covering the different diameter classes observed for each replicate. The root systems were extracted using a backhoe with manual assistance, exploring around 1 m^2 of soil for each stool (the dimensions were adapted to the different planting design in proportion to the density). All roots that we were able to retrieve within this area (up to a diameter of 0.10 mm) were manually collected, those roots belonging to the adjacent stools were excluded, although in some cases identification was not possible. The diameter of each broken root tip in each sample was measured to estimate the remaining biomass in the soil. We considered below-ground biomass as the whole biomass below the harvesting height of these stools, so it included the stump below the harvesting height, as well as the coarse roots and fine roots. Total dry biomass of the roots ($W_{below\text{-}ground}$, g DM) was determined for each sample from the fresh weight and the estimated below-ground wood moisture that was obtained using the same procedure as for the above-ground wood moisture.

The root:shoot ratio (defined as the below-ground biomass divided by the above-ground biomass) was calculated using the mean of the individual ratio of all samples (five stools per genotype and site). Below-ground (root) was considered as all biomass below the harvesting height and above-ground as all woody biomass above the harvesting height, i.e. all shoots produced by each stool.

$$root{:}\ shoot\ ratio = \frac{W_{below-ground}}{W_{above-ground}} \tag{1}$$

Dried above- and below-ground biomass was separated for subsequent carbon analyses through dry combustion using a CNS-2000 (TruSpec® CHNS, LECO, St Joseph, Michigan, USA). Above- and below-ground biomass values were converted to carbon accumulations using the average above- and below-ground carbon accumulations fractions, respectively.