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Root stock biomass and productivity assessments of reforested pine stands in northern Mexico

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ABSTRACT

Assessments of root biomass stock and rootstock productivity are critical for understanding ecosystem function and the cycles of several biogeochemicals, including carbon and nitrogen. An allometric equation provided a good model for measurements of coarse tree root ($d > 1.0$ cm) biomass, and a basal area growth and yield model was able to predict rootstocks and changes in rootstock biomass productivity. Independent spatial assessments and additional temporal measurements of coarse roots validated the empirical model, which predicted a wide range of rootstock and productivity values as a function of stand age, site index and tree dimension. In agreement with field measurements, the model predicted that the root to shoot ratio approach for estimating belowground biomass and productivity must include a correction factor in case forests under study miss measurements of stand age and site index parameters.

1. Introduction

Roots are the least studied component of forest biomass due to the amount of work needed to study them. In spite of this, root allometric equations are becoming common in the scientific literature for the evaluation of carbon stocks and fluxes (Cairns et al., 1997; Mokany et al., 2006; Kajimoto et al., 2006).

Beven and Germann (1982), Li et al. (2009) and Návar (2014) described the hydrological importance of roots. Living or decomposed tree roots create preferential pathways for water flow within the soil, which increase the velocity of subsurface flow beyond the thresholds of potential flow. They form porous structures and routes that convey water deep into the soil profile (Li et al., 2009; Návar, 2014). Therefore, evaluations of roots are important for assessing the size and total structure of water-flow pathways that are critical for the movement of soil water and for the potential transport of biogeochemicals and pollutants (Beven and Germann, 1982; Turton et al., 1995; Jarvis, 2008).

Rootstocks and tree dimensions are also critical for understanding the volume of soil occupied by trees or forests, particularly when this information is coupled with measurements of fine roots growing from coarse roots (Brunner et al., 2013). Nutrient availability shapes the productivity, composition, and diversity of biological communities, and root decay, decomposition and turnover are important sources of nutrient return to the soil (Vitousek, 2004). Hence, information about the change in root biomass stock over time, in the form of parameterized root data, is necessary for running complex productivity models that are being currently developed (Landsberg and Waring, 1997; Jourdan and Rey, 1997; Brunner et al., 2013). Furthermore, allometric functions that describe root biomass productivity are scarce in the scientific literature.

In spite of the ecological importance of coarse roots, most methods aiming root dynamics focus on the finest diameter classes. As a consequence, coarse rootstocks and rootstock productivity have not been accurately evaluated; mainly because the current methods for measuring, estimating, and monitoring belowground biomass are limited when coarse root distribution has high spatial variability. The conventional root assessment methods of fine roots include root excavation, monolith, soil cores, pits, and root to shoot ratio (Jourdan et al., 2008; Brunner et al., 2013). Coarse root growth and productivity have been assessed by monitoring roots over time. Some common techniques are: sequential coring, rhizotrons, ingrowth cores, root cross-section studies, root allometry, and maximum-minimum techniques (Brunner and Godbold, 2007). These methods and techniques must be carefully conducted, and estimates should be cautiously interpreted, because there is great variability in results for root productivity between them (Metcalfe et al., 2007; Jourdan et al., 2008; Gaul et al., 2009; Finér et al., 2012; Brunner et al., 2013).

Root growth rings, similar to stem analysis of coniferous tree boles, provide a way to assess growth and productivity that does not require continuous root measurements. However, root growth

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rings can be discontinuous and are often hard to measure or count when compared with shoot growth rings. False, missing, and discontinuous rings can skew root growth estimates (Fayle, 1975a,b). In general, missing rings are most common when there has been discontinuous growth or highly directional mechanical stress (Fayle, 1975b). It is difficult to obtain accurate ring counts because of false and incomplete rings in coarse root cross-sections due to growth irregularities, a strong radial tapering, and small radial growth in young roots (Reynolds, 1983).

Coupling data from a chronological forest inventory with root allometric equations is an alternative technique for predicting coarse rootstocks and rootstock productivity. This technique is typically used for forest growth and yield modeling (Alder and Synnott, 1992). However, it has not been applied to the tree communities of Mexico, and it is a scarcely reported approach in the scientific literature for estimating root biomass stocks and productivity (Brunner et al., 2013). Only Le Goff and Ottorini (2001) and Kajimoto et al. (1999, 2003) discuss this methodology, although for forests in northern France and eastern Siberia, respectively.

The aim of this research was (1) to develop an allometric coarse root equation; (2) to model, if possible, stand coarse root biomass according to tree age, site index, and stand parameters and (3) to assess coarse rootstocks and productivity of reforested pine stands in northern Mexico.

2. Materials and methods

2.1. Study area

I conducted this research in a temperate, reforested area in northern Mexico (Fig. 1). I established 133 experimental reforested stands in the mountain ranges of Durango, Nuevo Leon, and Coahuila. The Sierra Madre Occidental mountain range in Durango is characterized by a cold temperate climate (mean annual precipitation and temperature of 1000 mm and 12 °C), while the Sierra Madre Oriental mountain range in Nuevo Leon is temperate (mean annual precipitation and temperature of 800 mm and 14 °C), and the Sierra Madre Oriental mountain range in Coahuila is semi-arid (mean annual precipitation and temperature of 400 mm and 17 °C).

2.2. Sampling scheme

A chronosequence of 133 reforested plots (20 m × 20 m) was established with a random selection of the plots for conducting a forest inventory, as well as for excavating 59 trees during the period of 2002–2004. A forest inventory was carried out on at least one plot at each sampling site at Durango (Rio de Miravalles, Cielito Azul, San Jerónimo, Los Bancos, Alto de Latas, La Flor, Agua Blanca, Piloncillos, La Victoria, La Campana, and La Ciudad), Coahuila (Zapalinamé), and Nuevo León (El Potosí; La Loma, Las Adjuntas, and Santa Rosa). Thus, there were 42 stands in the cold temperate zone, 48 in the temperate zone and 43 in the semi-arid zone (Fig. 1). The sampled stands at Durango were reforested with the tree species *P. durangensis* Martínez, *P. cooperi* Blanco, *P. engelmannii* Carriere, and *P. arizonica* Engelmann. *P. pseudostrobus* Lindl., *P. pinceana* Gordon, *P. cembroides* Zucc., *P. nelsonii* Shaw, *P. brutia* Tenn. *Cupressus arizonica* Lindl. was reforested in Nuevo Leon. The sampling stands at Coahuila were mainly reforested with *P. halepensis* Mill. In Durango, the reforested species were native to the sites, with the exception of *P. arizonica*, which is a species distributed farther to the north and east. Pinyon pines (*P. pinceana*, *P. nelsonii* and *P. cembroides*) were exotic to the Nuevo Leon reforested sites; the first two are listed in the rare and endangered species list of Mexico (SEMARNAT, 2001). Moreover, *P. pinceana*, the weeping pinyon, is classified as near threatened on the International Union of Conservation Nature Red List (Perry, 1991; Farjon and Styles, 1997). *P. halepensis* is an exotic pinyon pine planted extensively in the uplands of the Zapalinamé mountain range near Saltillo, Coahuila, Mexico.

2.3. Coarse-root allometry

I harvested 59 trees of the following species: *P. cembroides* (6), *P. pinceana* (9), *P. pseudostrobus* (9), *P. brutia* (6), *P. durangensis* (15), and *P. cooperi* (14). The first four species were harvested from the temperate and the last two from the cold temperate forests. The semi-arid planted *P. halepensis* species was not harvested because of the conservation programs in the region and *P. cembroides*, *P. pinceana*, and *P. brutia* display similar semi-arid traits. These species may have accounted for the coarse root biomass versus basal diameter relationship of other semi-arid tree species as well. In general, a sufficient number of trees was harvested from each sampling site to cover all spatial and diameter variability. Prior to felling, the diameters of the standing trees were measured at the base of the stump and at breast height (1.4 m above ground level) using diameter tapes. The trees were then felled, measured for treetop height and separated into two main biomass components: branches and foliage, and stems. The soil beneath the stump was carefully removed using spades and hands, taking care to not damage the main roots. The stump and the roots were raised together gently and gradually with a chain and pulleys mounted beneath a steel tripod. The process of excavating the main roots continued until it was not possible to unearth the roots anymore. In general, the excavated parts of the root systems with a $d > 1.0$ cm were collected. The roots from each tree were weighed to determine their fresh weight, and sub-samples were oven-dried at 70 °C to a constant weight. I calculated the ratio of oven-dry weight to fresh weight of the samples multiplied by the total fresh weight to determine the total dry weight per biomass component, per tree. The relationship between dry coarse-root biomass (RB) and basal diameter (Bd) was assessed by fitting data to the allometric equation using nonlinear regression.

The forest inventory conducted on each of the 133 plots included measuring the tree dimensions: basal diameter, breast-height diameter, treetop height, and canopy area. Canopy area is the vertical projection of the canopy measured by four radiuses (north, south, east and west distances from the center of the trunk). The basal diameter was measured at ground level, excluding the buttress restricted to only a few individuals. The basal area was evaluated using the basal diameter instead of the conventional diameter at breast height. The reforestation age as measured from wood cores collected with the Pressler borer on three individual trees of each stand varied from 3 to 45 years. For the age I added two additional years as the seedlings was one-year at the time of planting. Because of the wide range of ages, I used age and site index at base age 15 years as well as stand density and mean stand basal diameter to predict basal area as independent variables fitted to models for stand-scale growth and for yield, to project changes in coarse-root biomass over time. I employed the chronosequence approach to develop a coarse-root stock and productivity model for the reforestation stands because trees and forests exemplify this approach (Alder and Synnott, 1992). Data on soils and climate (temperature and precipitation) were also collected at the stand scale from climatic maps. The Kjeldahl distillation method (Bremner, 1996) was used to evaluate the organic matter, organic carbon and nitrogen content of 15 stands.

In 2014, nine plots (1 × 1 m) were randomly assigned on 37-year-old reforestations with different basal areas, and the coarse ($d > 1.0$ cm) roots were excavated to 50 cm depth. Laboratory dried samples of coarse roots aided the evaluation of total, dry, coarse-