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Accuracy of tree root biomass sampling methodologies for carbon mitigation projects

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ABSTRACT

Tree root biomass contributes significantly to forest carbon pools but is difficult and costly to estimate. Accurate estimates of carbon fluxes from tree roots are required for specific mitigation projects, national accounts and global climate models. However, methodologies for the estimation of tree root biomass are varied and their effectiveness in terms of the precision of biomass and carbon estimates is difficult to evaluate. In this study tree root systems of 2 and 7 year old *Eucalyptus globulus* (Labill) trees were sampled volumetrically to a depth of 6 m using soil coring and excavation. These root mass data were used for Monte Carlo simulation of four different but typically used sampling strategies.

The uncertainty of estimates increased with tree age as a result of increased heterogeneity of root mass due to the presence of large diameter roots. Coring had the largest sampling uncertainty when applied to estimate coarse root biomass which did not include the root bole. Bulk excavation was the simplest and potentially the most time efficient method to attain a sampling uncertainty of 10%. Excavation to a root diameter limit enables better association of root biomass to individual sample trees however, more effort is required if roots are directly related to the sample tree by tracing of roots to a small diameter. Although root ball methods required the least amount of excavation and soil coring to attain a sampling uncertainty of 10%, this method requires sieving of excavated soil through a small mesh size and is more time consuming and difficult to apply in heavier textured soils. The efficiency of coring and precision of root mass estimates can be improved if coring is concentrated in closer proximity of the sample tree or within the boundary of the larger diameter proximal roots.

1. Introduction

Both the storage of carbon in biomass or production of biomass for bioenergy generation through the afforestation or reforestation of farmland are advocated as major climate mitigation strategies (Canadell and Raupach 2008; Pacala and Socolow 2004; Smith et al., 2014). Globally, renewable energy incentives and greenhouse gas emissions targets are drivers for the development of such systems. However, the efficacy of these mitigation strategies and efforts to restrict the rise of global temperature to 2 °C (UNEP, 2014) will rely on acceptable estimations of all carbon pools including tree root systems. Given that tree roots account for 20–40% of forest carbon (Brunner and Godbald, 2007; Finér et al., 2011; Mokany et al., 2006) this carbon pool is a significant component of the terrestrial carbon pool as forests contribute significantly to global carbon sinks and fluxes (Eamus et al., 2002).

Carbon in the above ground portion of trees can be relatively easily measured via destructive sampling and the subsequent data used to derive allometric equations (Snowdon et al., 2000). However, below ground biomass in tree roots is considerably more difficult to measure and the methodologies used are varied (Levillain et al., 2011). Estimates of tree root carbon pools based on empirical measurements are lacking; this is a direct reflection of the difficulty of measuring tree root systems and thus an encumbrance in the development of tree root allometric relationships. Consequently, understanding of tree root systems and their link with above ground biomass and the soil environment (Smithwick et al., 2014) is also limited. On a global scale, the lack of tree root biomass data impedes the understanding of forest biomass carbon and its effect on global carbon pools and fluxes (Vogt et al., 1996). For example, deforestation is one of the major sources of global carbon emissions (Smith et al., 2014) but the estimate of the root

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carbon stores is invariably based on default estimates (Aalde et al., 2006).

Vogt et al. (1998) suggest the measurement of large tree roots for carbon estimation can be easily derived via allometrics of above ground measurements but this is clearly not the case (Levillain et al., 2011) despite efforts made to develop methodology for tree root sampling (Snowdon et al., 2002). In particular, consistent measurement methodology of coarse roots which may account for over 70% of below ground biomass is lacking (Cairns et al., 1997; Herrero et al., 2014). Methods for sampling tree roots are varied depending on the needs of specific research, from fine root dynamics (Lopez et al., 1998; Makita et al., 2011) to total tree below ground biomass (Rey de Viñas and Ayanz, 2000). Common techniques used include volumetric sampling of tree roots via coring and soil pit methods (Levillain et al., 2011) monolith sampling (Makita et al., 2011) and voronoi polygons (Razakamanarivo et al., 2012; Saint-Andre et al., 2005), bulk root excavation (Niiyama et al., 2010; Ritson and Sochacki, 2003) and root ball excavation (Miller et al., 2006; Misra et al., 1998; Resh et al., 2003). Given the horizontal and vertical extent of tree root systems, a total estimate of tree root biomass is most likely to be an underestimate (Pinheiro et al., 2016; Stone and Kalisz, 1991).

Many factors affect tree root development and the morphology of tree root systems is determined by species, age, soil and hydrological properties and climatic variables (Tobin et al., 2007). There are limited detailed root biomass data and few species specific allometric relationships exist for below ground biomass (Jonson and Freudenberger 2011; Laclau 2003; Paul et al., 2014; Ritson and Sochacki 2003; Sochacki et al., 2007a). Indirect estimates of root biomass have been attempted based on relationships between above ground biomass and root biomass or root: shoot (r:s) ratios (Kuyah et al., 2012; Mokany et al., 2006; Snowdon et al., 2000). Generalized allometric equations based on mixed species data have been applied to circumvent the laborious task of sampling tree roots and developing allometric equations for individual species. However, the variability of estimates can be large when generalized data sets are applied to root biomass (Cairns et al., 1997).

The application of forest systems to mitigate climate change has resulted in the need to quantify carbon for both above and below-ground pools. This information is needed both for carbon offset (abatement) projects and also for national accounting. Given the heterogeneity of tree root systems and the variability of the soil in which roots grow, it is challenging to obtain precise biomass estimates in relation to below-ground tree biomass and consequent carbon storage. Currently, many carbon accounting approaches use default values for root biomass, based on ratios of above ground biomass (Aalde et al., 2006).

Typically, sampling for the development of tree root biomass allometric relationships would require sampling many tree root systems to reach acceptable levels of precision (Levillain et al., 2011). An alternative to such extensive sampling is the use of computer simulation. Monte Carlo simulations have been employed in forestry for issues relating to forest fire risk (Carmel et al., 2009), uncertainty of forest carbon flux (Verbeeck et al., 2006), forest carbon densities and uncertainties (Gonzalez et al., 2010) and forest sustainability (Luxmoore et al., 2002), and more recently by Paul et al. (2014) in testing allometric relationships for root biomass prediction. The use of Monte Carlo simulation for tree root sampling methodologies has not previously been reported.

A recent comprehensive review by Addo-Danso et al. (2016) on root sampling methods exemplified the range of root sampling methods that have been applied and recommended further studies to directly compare methods of tree root sampling on similar sites. In this study the approach of sampling many tree root systems was substituted with simulated sampling in order to investigate the effectiveness of different tree root sampling methods and sampling regimes. Complete tree root data sets from volumetric coring (Sochacki et al., 2007b) and detailed excavation were applied in conjunction with simulated sampling using the Monte Carlo technique. The aim of this study was to compare the precision and bias of tree root biomass estimates from a range of sampling methodologies to ascertain the most effective method of tree root sampling for below ground biomass and carbon estimation. Excavation and coring methods will be examined through a range of sampling regimes to determine the bias and precision of root biomass estimates and compare the effectiveness of these methods for tree root biomass sampling to past studies applying similar methods.

2. Methods

2.1. Site selection

Eucalyptus globulus (Labill.) is extensively used for reforestation in southern Australia and other regions globally. Two sites in southwestern Australia were selected for the purpose of this study (Fig. 1). The first site (Site 1; 34° 49′ 01.30″ S, 117° 59′ 37.93″ E) was a 2 year old *E. globulus* stand on a Eutric Cambisol (McArthur, 1991). This soil comprised 150 cm of sand overlying an abrupt boundary to a clay subsoil. The second site (Site 2; 34° 46′ 07.59″ S, 117° 22′ 49.81″ E) was a 7 year old *E. globulus* stand on a Xanthic Ferralsol (McArthur, 1991), comprising of 30 cm of gravelly loam horizon overlying clay. The gravel was ferricrete. Both stands had densities of 1250 trees ha^{-1}, with *E. globulus* being grown in a 10-year rotation in this region.

The two stand ages were chosen to be representative of a situation where root development was generally not restricted by competition between neighboring trees (2 years) and where the root dynamics were that of a stand nearing the end of a 10 year rotation (7 years).

2.2. Tree selection

One sample tree from each stand age was chosen. To characterize the stand around the sample tree a 20 × 20 m plot was demarcated to measure tree parameters of diameter and height. Using allometric equations developed by Brand (1999) the average tree biomass for the plot was calculated and a tree selected with approximately this value. This tree was also selected such that neighboring trees had a similar tree biomass estimate; this being to prevent bias in the sample tree root biomass estimates.

2.3. Soil coring

Sampling equipment was needed which could sample to depth (approximately 6 m) through hard soils with indurated layers or rock. It was also essential that large diameter roots be cut through cleanly and with minimal disturbance to the plot. The intensity of coring was high and therefore the equipment needed to be lightweight and maneuverable and not damage the sample plot. With these factors in mind a new apparatus was built specifically for intensive coring of tree root systems and designed to overcome limitations of current sampling equipment. This new apparatus which had an internal core diameter of 103 mm, was able to take soil-root samples of large diameter roots of any size and through soil of any hardness, including rock. A detailed description of this apparatus and testing is described by Sochacki et al. (2007b).

2.4. Coring layout

Roots were cored in a circular or Nelder array instead of a square or rectangular grid (Fig. 2a). This arrangement of sampling around a tree trunk has been applied to the study of spatial root distribution