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Estimating individual tree mid- and understory rank-size distributions from airborne laser scanning in semi-arid forests

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ABSTRACT

Limitations inherent to airborne laser scanning (ALS) technology and the complex sorting and packing relationships of forests complicate accurate remote sensing of mid- and understory trees, especially in denser forest stands. Self-similarities in rank-sized individual tree distributions (ITD), e.g. bole diameter or height, are a well-understood property of natural, non-plantation, forests undergoing density dependent self-thinning and thus offer an approach to solving this problem. Alternately, semi-arid conifer forests of the southwestern USA that experience episodic wildfires and herbivory tend to exist as open stands compared to forests where disturbances are less common. We found the ITD for semi-arid forest plots with ALS-estimated canopy cover < 50% had a low rate of omission error for mid- and understory ALS trees making distribution fitting of the mid- and understory ITD unnecessary. In dense semi-arid forest plots (>50% canopy cover) the ITD correlated significantly with a tapered Pareto distribution, a power law probability distribution that is not heavy right-tailed. Two-sample Kolmogorov–Smirnov tests confirmed that observed vs. ALS-estimated overstory ITD parameters were not significantly different regardless of canopy cover. Therefore an overstory ITD derived from ALS is sufficient for fitting a continuous distribution function to estimate the ITD of the forest understory when the scale parameter is established *a priori*. Foresters and ecologists interested in measuring and modeling stand dynamics from ALS can use this approach to correct for stand density effects when developing ALS-derived single-tree inventories. Canopy cover can be used as a proxy for stand density when developing a combined ITD with area-based approaches for estimating understory in semi-arid forests.

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1. Introduction

Conventional forest inventories are based upon plot-based field surveys which can be both economically and physically impractical across large areas and in complex terrain. In contrast, today foresters with access to the right technology and skill sets have the capacity to census nearly every single tree at the landscape level using airborne laser scanning (ALS) technology – known also as Light Detection and Ranging (LiDAR) (van Leeuwen and Nieuwenhuis, 2010; Maltamo et al., 2014). Producing a complete forest inventory at the landscape level was considered an impossible undertaking before the advent of ALS. Despite their utility, a current weakness of existing ALS inventory techniques is the inability to differentiate all trees in the stand, in particular understory trees (Maltamo et al., 2004; Hudak et al., 2009; Gatziolis et al., 2010; Frazer et al., 2011). Differentiation is difficult in understory trees which tend to be interconnected and obscured beneath the overstory trees (Kaartinen et al., 2012; Wing et al., 2012). Hybrid techniques involving individual tree crown (ITC) isolations (Breidenbach and Astrup, 2014) and area based approaches (Lindberg et al., 2010; Maltamo and Gobakken, 2014) have been developed to obtain precision and accuracy comparable to field measurements. Most of these ALS isolation and extrapolation techniques were developed in productive temperate forests, which tend to exhibit density dependent competition for space. Applicability of hybrid techniques is uncertain in semi-arid forests, which are by contrast resource limited, have low-productivity, and experience episodic disturbances.

To estimate tree size, e.g. biomass, biometricians measure trees first by their primary size measures, e.g. diameter at breast height (DBH), tree height, and canopy volume, and then apply allometric

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equations related to each measure. At the stand scale the critical density of plants in space can be linked to the size of individuals (Enquist et al., 1998, 2009; Deng et al., 2012). This behavior, termed as Reineke's (1933) stand density index (SDI) or the Yoda et al. (1963) '−3/2 self-thinning rule' (White, 1981; Westoby, 1984), assumes that as each tree grows to fill space with its canopy and roots it competes for limited resources. Metabolic Scaling Theory (MST) (Enquist et al., 1998) predicts competitive thinning to be the main source of tree mortality in the absence of exogenous processes, resulting in ranked-size individual tree distributions (ITD) following power laws (Enquist et al., 1998, 2009; West et al., 2009; Deng et al., 2012). MST principles are based on thermodynamic and hydraulic laws which extend from the individual tree to the forest scale (Enquist et al., 1998, 1999; Enquist and Niklas, 2001, 2002; Niklas and Enquist, 2001; Niklas et al., 2003; West et al., 2009; Deng et al., 2012). The allometry of a tree becomes predictable in part because each tree must maintain a bole diameter-height proportionality based on its elastic buckling strength to remain upright and support its branches (McMahon, 1973; McMahon and Kronauer, 1976). Canopy and roots must also fill enough volume space to support the tree's metabolic demand (Enquist et al., 2009; West et al., 2009; Savage et al., 2010; Kempes et al., 2011). We assumed in the current study that semi-arid forest trees compete chiefly for plant available soil water rather than light, although both constraints are possible at cooler higher elevations on more mesic sites.

Our chief aim was to determine whether the direct inventory limitation of ALS can be addressed by considering density-dependent relationships predicted to exhibit scale-invariant power-law forms in their ITD (Enquist et al., 1998, 1999; Enquist and Niklas, 2001; Niklas and Enquist, 2001; Niklas et al., 2003; Deng et al., 2012). Many semi-arid stands are open structured, and there was also the question of whether the ITC isolation techniques are accurate in such stands. The chief question revolves around whether the observed semi-arid forest stands exhibit density dependence and if so would we be able to estimate the ITD of the understory trees using a scale-invariant function, i.e. a power law probability distribution, after assuming an understory is present? If confirmed, such a technique could improve the accuracy of forest inventories over large semi-arid landscapes, with attendant implications for estimating standing biomass, carbon sequestration, and species composition.

There are various techniques for identifying ITC from ALS data using canopy height models (CHM) (Lefsky et al., 1999, 2002; Zimble et al., 2003; Zhao et al., 2009; Kaartinen et al., 2012; Koch et al., 2014), including: (1) local maxima [with filtering] (Dralle and Rudemo, 1996; Hyyppä et al., 2001, 2005; Persson et al., 2002; Monnet et al., 2010), (2) variable area window (Popescu et al., 2002; Popescu and Wynne, 2004; Swetnam and Falk, 2014), (3) hierarchical inverse watersheds (Chen et al., 2006; Zhao and Popescu, 2007), and (4) spatial wavelet technique (Falkowski et al., 2006, 2008).

1.1. Scale invariant rank-size frequency distributions

MST predicts that density-dependent forest ITD scale as inverse square laws:

$$\Delta n_k \propto x_k^{\alpha} \tag{1}$$

where Δn_k is the number of individuals in a standardized area in a given size class or bin, k, x is any primary size measure, and the exponent $\alpha < 0$ is negative, which for the example of bole radius is $\alpha = -2$ (Enquist et al., 2009). For linear binning a continuous function is given as:

$$f(x) \equiv dn/dx \propto x^{\alpha}. \tag{2}$$

Continuous ITD functions should be approximated using a probability distribution function because there is a minimum size limit $x > x_{\min}$ to the point at which the power law holds before the density diverges (as $x \to 0$) (Clauset et al., 2009); typically the $x_{\min}$ is the size of the smallest individual tree. A Pareto distribution: $S(x) = \Pr\{X \geq x\} = \left(\frac{x}{x_{\min}}\right)^{-\alpha}$, should be used with continuous data in this case (Newman, 2005; White et al., 2008; Clauset et al., 2009). In practical applications a power law Pareto is unlikely to be the best fit for a forest ITD because of divergence in both tails of the distribution due to stand dynamics, e.g. physiological tolerances and disturbance, and physiological limits to tree size. Exogenous impacts such as trampling, wind throw, wildfire and herbivory influence the ITD and result in both left- and a right-tail truncation of the canonical power law distribution (Seuront and Mitchell, 2008; Enquist et al., 2009; Swetnam, 2013). Examples of other continuous distributions that account for divergence in the right-tail include the tapered Pareto (Kagan and Schoenberg, 2001), truncated Pareto (White et al., 2008; Enquist et al., 2009), and negative exponential and stretched exponential functions (Clauset et al., 2009). In forestry applications ITD have been reported using a negative or stretched exponential function and in particular the Weibull distribution (Weibull, 1951; Dubey, 1967; Bailey and Dell, 1973; Maltamo et al., 2000, 2004). Truncated Weibull distributions tend to model the left tail of the distribution well (Maltamo et al., 2004); relatedly, both the two-parameter Weibull (with a shape parameter <1) and Pareto distribution are heavy right tailed (Newman, 2005). In the right tail of a forest ITD we expect a decline in abundance at an exponential rate. For our analyses we applied the tapered Pareto distribution (Kagan and Schoenberg, 2001; Schoenberg and Patel, 2012), a power law distribution that accounts for the observed behavior of the right-tail in forest rank-size ITD.

2. Methods

Maltamo and Gobakken (2014) suggest the combination of an ALS derived ITD and an area-based approach to estimate the full ITD of a stand. Here we follow that approach, evaluating first whether a tapered Pareto distribution (Pareto, 1896; Kagan and Schoenberg, 2001) describes the ITD in a defined area of interest, and then testing whether the ITD of the understory shares the same scale-invariant parameters as the ALS derived overstory ITD. We grouped our plots by canopy cover percentage to determine whether the self-similar properties of the ITD are a function of density dependence.

2.1. Study areas

We incorporated both field datasets and ITC from ALS for two semi-arid conifer-dominated forests in the southwestern USA. The Valles Caldera National Preserve is located in the Jemez Mountains west of Santa Fe, New Mexico at 35.9°N, 106.5°W (Fig. 1). Elevations range from 2300 m above mean sea level (amsl) in Redondo Meadow to 3431 m amsl atop Redondo Peak. The Valles Caldera is a collapsed volcanic caldera with a rim approximately 19 km wide; within the caldera are resurgent domes over 200 m high, locally referred to as *cerros*. Ponderosa pine (*Pinus ponderosa*) is common in the lowest elevations (2100–2400 m amsl), with some limber pine (*Pinus flexilis*) and Douglas-fir (*Pseudotsuga menziesii*) on mesic sites. Gambel oak (*Quercus gambelii*) is common in post-fire seral stands along with ponderosa pine and quaking aspen (*Populus tremuloides*). North aspects tend to be dominated by Douglas-fir and white fir (*Abies concolor*), with some subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). The highest elevation sites are dominated by Engelmann spruce.