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Detecting and quantifying standing dead tree structural loss with reconstructed tree models using voxelized terrestrial lidar data

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ABSTRACT

The structural loss rates of standing dead trees (SDTs) affect a variety of processes of interest to ecologists and foresters, yet the decomposition of SDTs has been traditionally characterized by qualitative decay classes, reductions in wood density as decay progresses, and sampling schemes focused on estimating snag longevity. By establishing a methodology to accurately and efficiently quantify SDT structural loss over time, these estimated structural loss rates would improve the performance of a variety of models and potentially provide new insight as to the manner in which SDTs undergo degradation in various conditions. The specific objective of this study were: 1) utilize the TreeVolX algorithm to estimate the volume of 29 SDTs scanned with terrestrial lidar; 2) develop a novel, voxel-based change detection algorithm capable of providing automated structural loss estimates with multitemporal terrestrial lidar observations; and 3) estimate and characterize the structural loss rates of *Pinus taeda* and *Quercus stellata* in southeastern Texas.

A voxel-based change detection methodology was developed to accurately detect and quantify structural losses and incorporated several methods to mitigate the challenges presented by shifting tree and branch positions as SDT decay progresses. The volume and structural loss of 29 SDTs, composed of *Pinus taeda* and *Quercus stellata*, were successfully estimated using multitemporal terrestrial lidar observations over elapsed times ranging from 71 to 753 days. Pine and oak structural loss rates were characterized by estimating the amount of volumetric loss occurring in 20 equal-interval height bins of each SDT. Results showed that large pine snags exhibited more rapid structural loss in comparison to medium-sized oak snags in southeastern Texas.

1. Introduction

Standing dead trees (SDTs) influence a variety of processes studied by researchers and forest managers, such as carbon storage and cycling dynamics in forests, nutrient cycling, species composition dynamics, wildland fire, wildlife habitat, and structural diversity of forest stands (Russell et al., 2015). In 2011 and 2012 a severe and extensive drought covered Texas, with precipitation values 50–75% below the long-term average (Hoerling et al., 2013). The drought increased tree mortality approximately 9-times above normal and translated to the estimated death of ~301 million trees statewide and the transformation of approximately 30 Tg of live tree C to a dead pool of C in one year (Moore et al., 2016). The regional C cycling effect of this tree mortality was the equivalent of nearly 50% of the average C annually emitted from forest fires in the continental United States (McKinley et al., 2011). Globally, the pool of SDTs and coarse woody debris (CWD) is estimated to be 36–72 Pg C, with the wide range in estimates reflecting that this C pool's dynamics are poorly constrained in terrestrial C cycling models (Cornwell et al., 2009). The performance of these models would be greatly improved if changes in tree structure could be linked to wood decay (Domke et al., 2011).

Nondestructive volume estimates for SDTs are typically calculated using various forms of allometric models, where parameters measured in the field (e.g., diameter at breast height (DBH) and tree height) serve

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as independent variables to species-specific equations designed to estimate volume based on empirically observed relationships (Brown et al., 1989). The United States Forest Service (USFS) Forest Inventory and Analysis (FIA) program currently estimates the volume of SDTs using the same allometric relationships designed for living trees, which only account for the volume of a tree's main stem, in the case of timber species, or the stem, large branches, and bark in the case of woodland species (Woudenberg et al., 2010). Since this approach does not distinguish between live or dead trees and focuses primarily on a tree's bole, these estimates fail to account for the structural losses and wood decay which occur in SDTs, as well as the woody material contained in branches and sections of the stem which are not accounted for in allometric equations.

Recent research has recommended the application of structural loss adjustments (SLAs) and density reduction factors (DRFs) to allometric volume estimations to better characterize the structural differences between SDTs and live trees (Domke et al., 2011). The incorporation of SLAs and DRFs provide an opportunity to differentiate between live and dead standing trees, but such estimates based on allometric relationships and qualitative decay class systems and would need to be developed and evaluated for a wide range of species and regions, possibly limiting their utility and accuracy when compared to the potential of emerging remote sensing methodologies.

As observed density reductions fail to completely account for the total amount of biomass lost during the decay process (Fraver et al., 2013; Harmon et al., 1987; Næsset, 1999; Zell et al., 2009), it is important for studies to quantify and incorporate structural losses when modelling the decay rates of SDTs. Laiho and Prescott (2004) reviewed 34 wood decomposition studies and found that only five had considered mass loss as a component of decay, while the remaining studies were based on observed density reductions.

The extent to which decay rates, estimated by reductions in wood density over time, affect the structural loss rates of SDTs is not clearly defined. A number of studies have observed the longevity of standing dead trees or modelled their transition through qualitative decay classes in different regions (Aakala et al., 2008; Cain, 1996; Cline et al., 1980; Conner and Saenz, 2005; Corace et al., 2010; Garber et al., 2005; Landram et al., 2002; Vanderwel et al., 2006), but these approaches often are focused on stand-level observations and not able to quantify the different ways in which SDTs lose volume and mass over time (i.e., structural loss vs. collapse), which could provide valuable contributions towards understanding the flux of woody debris from standing pools to downed pools among various species and regions. In a review of research concerning the decomposition and carbon storage of dead wood in various forms, Russell et al. (2015) conducted a sensitivity analysis and found that structural reductions had the greatest relative influence on the C content of standing dead trees, 59.1%, while wood density had a relative influence of 19.8%. This finding emphasizes the need for accurate volume estimations of SDTs, the increased development of SLAs for additional species and regions, and the development of methodologies which can precisely quantify structural losses of SDTs over time.

Light detection and ranging (lidar) is an active remote sensing technology which, by measuring the elapsed time between a laser pulse and its return after being reflected by an object, is capable of precisely recording the distance of objects from the lidar sensor and thus facilitating the capture of detailed 3D point clouds (Lefsky et al., 2002). Lidar sensors have been integrated into a wide variety of platforms and systems, such as: spaceborne (e.g., satellites), airborne (e.g., manned and unmanned aircraft), terrestrial (e.g., sensor fixed to a tripod), and mobile platforms (e.g., automobiles, all-terrain vehicles, handheld scanners) (Van Leeuwen and Nieuwenhuis, 2010).

Terrestrial laser scanners (TLS) in particular are capable of producing very dense point clouds of individual trees and have the advantage of being able to scan a tree from multiple vantage points, thus characterizing the fine details of an entire tree in terms of the structure, size, and orientation of its stem and branches, which are difficult to measure using other lidar platforms or traditional measurement approaches. TLS has been used in a wide variety of forestry applications (Dassot et al., 2011; Van Leeuwen and Nieuwenhuis, 2010) and recently has been utilized with the objective of reconstructing solid 3D models of trees derived from TLS point clouds, enabling accurate, nondestructive estimates of volume or biomass. Although this is a relatively new application of TLS, algorithms presented in the literature may be broadly grouped into two common approaches: (1) the fitting of geometric primitives, such as circular cylinders, to tree components (Calders et al., 2015; Côté et al., 2009; Dassot et al., 2012; Hackenberg et al., 2014; Raumonen et al., 2013); and (2) converting point clouds to a voxel-based representation and subsequently processing the voxels to derive a solid model (Bienert et al., 2014; Hosoi et al., 2013; Lefsky and McHale, 2008; Vonderach et al., 2012).

Despite the increasing interest in, and successful examples of, reconstructive tree modelling, the use of TLS to perform change detection analysis on individual trees, and structural loss in particular, has not been thoroughly tested in the literature. Kaasalainen et al. (2010) used TLS to quantify the defoliation of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) trees scanned in a laboratory environment. Three point cloud parameters were derived, for each tree, to estimate measured biomass changes after needles had been manually removed from the trees: (1) the total number of point cloud returns; (2) the ratio of tree returns to total returns; and (3) the number of ground returns. These parameters were used as predictors for biomass loss in linear regression models, resulting in Pearson correlation coefficients ranging from 0.929 to 0.977. A similar methodology was carried out in a field setting, but visual assessments were used as reference data and quantified linear relationships were not reported. While this study shows the potential of TLS to quantify biomass changes, it is unclear how well this particular methodology would work under a variety of field conditions with varying tree species and significant reductions in tree biomass, such as branch drops or stem breakage.

Srinivasan et al. (2014) used single-position scans with a TLS to estimate the biomass change of 29 loblolly pine (*Pinus taeda*) trees in a forested environment. The authors used linear regression techniques to model biomass change at the individual tree level in comparison to reference biomass changes estimated with allometric equations over a three year period. Out of several different approaches, the most accurate estimate of biomass change was based on the direct changes in two point cloud parameters between observations, volume beneath top of canopy and 90th percentile height, resulting in an R-squared of 0.50 and an RMSE of 10.09 kg. Kaasalainen et al. (2014) applied the quantitative structure modelling (QSM) methodology to detecting biomass changes in laboratory and field environments, with an accuracy of 12% in estimating the volume of a small branch following the manual removal of branch sections and an unknown accuracy in the field with regards to a estimating the volume of a single live tree over time, which was estimated to be approximately ± 10%. These estimates were the mean results of 10 modelling runs, which typically exhibited a standard deviation of 5–15% for estimated branch volume due to the stochastic nature of the algorithm. The accuracy of this study suggests that reconstructive tree modelling has the potential to reliably quantify biomass or volume loss in forest environments.

The methodology described in this study presents a novel, voxel-based approach to addressing the current knowledge gaps concerning the structural loss of standing dead trees by developing automated methods to detect, quantify, and characterize volumetric losses over time using solid, voxel-based reconstructed tree models. To the best of the author's knowledge, this study represents the first attempt to quantify and characterize the structural loss of SDTs in a forest environment with the use of multitemporal TLS observations at the individual-tree level.

The overall objective of this study is the development of a methodology capable of detecting, quantifying, and characterizing the