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Mapping individual tree health using full-waveform airborne laser scans and imaging spectroscopy: A case study for a floodplain eucalypt forest

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ABSTRACT

Declining forest health can affect crucial ecosystem functions, such as carbon storage in biomass and soils, the regulation of water regimes, the modulation of regional climate and conservation of biodiversity. Airborne laser scanning (ALS) and imaging spectroscopy (IS) are two potentially complementary remote sensing technologies capable of characterizing and monitoring regional forest health. However, the combined use of ALS and IS data to classify the health of individual trees has not yet been assessed. In this study we propose a new approach utilizing ALS and IS combined to characterize the health of individual trees. Firstly, we applied a recently developed bottom-up individual tree delineation algorithm across a structurally complex floodplain eucalypt forest that has experienced episodes of severe dieback over the past six decades. We further calculated ALS and IS indices for delineated tree crowns and used them as predictor variables in machine learning models. We trained and evaluated an object-oriented random forest classifier against field-measured tree crown dieback and transparency ratios, as indicators of eucalypt tree health and crown density, respectively. Our results showed that dieback levels of individual trees can be classified using ALS and IS with an overall accuracy of 81% and a kappa score of 0.66, while the classification of tree crown transparency levels had an overall accuracy of 70% and a kappa score of 0.5. Returned pulse width, intensity and density related ALS indices were the most important predictors in the tree health classification, as they accounted for >40% of the variance in the data. At the forest level in terms of dieback, 81.5% of correctly delineated trees were classified as healthy, 12.3% as declining and 6.2% as dying or dead. Dieback occurred primarily in areas that were flooded <5% of the time, as quantified by Landsat derived flooding frequency (1986–2011). Our results provide a novel application of ALS and IS to accurately classify the health of individual trees in a structurally complex eucalypt forest, enabling us to prioritize areas for forest health promotion and conservation of biodiversity.

1. Introduction

Globally, forests are being degraded or lost at alarming rates largely due to fire and intensive logging (Hansen et al., 2013; Trumbore, Brando, & Hartmann, 2015) posing the greatest threat to forest health (Castello & Teale, 2011). The forest growth reduction or actual mortality of trees is usually referred to as forest health decline and is caused by a variety of environmental and human-induced factors including biological, hydrological, and atmospheric sources (e.g. forest insects, fungi, physical forces, air pollution or climatic stress) (Coops, Goodwin, & Stone, 2006; Evans, 2014; Franklin, 2001; Stone, Kathuria, Carney, & Hunter, 2008). Core indicators of forest health usually include plant and site characteristics, such as dendrology, mensuration, biophysical attributes (e.g. crown density, dieback, change in leaf pigments, greenness and canopy water content), soil chemistry, root disease and presence or absence of bioindicator plants and could be estimated in the field or using remote sensing (Franklin, 2001; Townsend et al., 2012). Remote sensing studies can cost less than fieldwork and provide systematic characterization of large forested areas as the major outcome. However, fieldwork is essential for ground validation of remote sensing data and is particularly indispensable for measuring forest health indicators that cannot be observed through remote sensing technology within an acceptable range of accuracy (Kleinn, 2003). Therefore remote sensing, combined with field measurements, is usually the choice for forest health mapping (Trumbore et al., 2015).

Forest loss and degradation in Australia during the past 60 years has been attributed to deforestation, rapidly expanding invasive weed species, altered fire regimes, insect outbreaks and extended periods of drought (Allen et al., 2010; Bradshaw, 2012; Lindenmayer, 2005). Specifically, the iconic river red gum trees in many of the Murray Darling Basin riparian forests have been severely stressed by increase in tree

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mortality and growth reduction mostly caused by drought and high temperatures (Cunningham, Mac Nally, Griffioen, et al. 2009; Cunningham, Mac Nally, Read, et al. 2009; OEH, 2012). In 2008 the Murray Darling Basin Authority decided that a remote sensing approach was necessary to provide adequate monitoring of changes in forest health across the whole Murray River floodplain (Cunningham, Griffioen, White, & Nally, 2010).

At the outset of planning of any remote sensing campaign a choice must be made whether to adopt a full coverage or sample transect design (Hopkinson et al., 2013). Similarly, it is important to select sites for ground based survey to capture the tree health variability of the forest. Usually fieldwork targeting is based on existing data (Haavik & Stephen, 2010; Hopkinson et al., 2013), while remote sensing data acquired prior to fieldwork could substantially facilitate the selection of a representative sample of ground-based data. Here we showcase a procedure to prioritize areas for airborne remote sensing data acquisition that is further incorporated to target field campaign.

The application of remote sensing for monitoring different indicators of forest health have been discussed in great depth and spanned from using active, passive and a combination of active and passive remote sensing sensors. So far, a variety of different pixel-based remote sensing techniques such as application of airborne imaging spectroscopy (IS) derived vegetation indices (Evans, Lyons, Barber, Stone, & Hardy, 2012), airborne laser scanning (ALS) penetration variables (Solberg, 2010), spectral mixture analysis (Asner et al., 2007) and traditional classifications (Cunningham et al., 2010) have been used to assess forest health (Deshayes et al., 2006). Most commonly, forest health mapping is done by relating field measured forest health indicators (e.g. foliage reddening and yellowing or defoliation caused by insect activity) to remotely sensed spectral or structural response. Applications of this approach have predicted forest health decline with categorical accuracy for two or more classes of 60–99%, e.g. Franklin, Wulder, Skakun, and Carroll (2003), Pontius, Martin, Plourde, and Hallett (2008), Meddens, Hicke, and Vierling (2011), Garrity et al. (2013), Adelabu, Mutanga, and Adam (2014). Other researchers proposed methods that do not rely on field-measured data, for example, Mišurec et al. (2012) suggested a statistical method by z-normalizing values of remotely sensed health indicators and classifying them into classes using the standard deviation (σ) classification method. However, in this way the classification is relative to the particular input scene and cannot be generalized to other areas or other scenes.

While the above mentioned pixel-based remote sensing methods were valuable in assessing forest health at the stand level (Cunningham, Mac Nally, Griffioen, et al. 2009; Cunningham, Mac Nally, Read, et al. 2009; Samalens et al., 2012), we suggest that the integration of high density ALS and high resolution IS could allow object-oriented assessment of forest health at the individual tree level. Object-oriented approaches usually outperform traditional pixel-based methods for classification and dramatically enrich contextual information delivered by remote sensing products (Tochon et al., 2015). A tree health map resolving individual trees is a potentially powerful product that enables describing forest canopies in rigorous ways that field-based studies cannot match, demographic reporting on forest dynamics, and more reliable diagnosis of ecological processes linked to forest health (Asner, Jones, Martin, Knapp, & Hughes, 2008; Asner, Martin, Anderson, & Knapp, 2015; Canham et al., 2006). However, in previous studies individual tree health was assessed by either ALS (Wing, Ritchie, Boston, Cohen, & Olsen, 2015; Yao, Krzystek, & Heurich, 2012) or spectral imagery (Bhattarai, Quackenbush, Calandra, Im, & Teale, 2012; Guo, Kelly, Gong, & Liu, 2007; Polewski, Yao, Heurich, Krzystek, & Stilla, 2015) using binary classifications. To the best of our knowledge, there is no reference study for the object-oriented multiclass classification of individual tree health by integrating ALS and IS. Moreover, such classifications were never applied to estimate the health of individual trees in a structurally complex eucalypt forest.

Generally, the pixel-based remote sensing methods for mapping forest health are well suited for stand level studies, while individual tree level, object-oriented classifications were rarely implemented (Bhattarai et al., 2012; Coggins, Coops, & Wulder, 2008; Guo et al., 2007). The traditional pixel-based classification often leads to a "salt-and-pepper" effect if the mapping area has a diversity of health condition with a high spatial heterogeneity as it relies solely on the spectral information of a single pixel (Blaschke, 2010; Zhang et al., 2013). Moreover, a pixel-based classification is not readily applicable for forest health studies at the individual tree level, where mapping units represent objects such as tree crowns. Therefore, Guo et al. (2007) and Coggins et al. (2008) investigated the feasibility of using object-oriented classification of airborne imagery in mapping tree mortality and insect infestation spread at the individual tree level. Both studies reported high accuracies of individual tree delineation and health classification of a dominant forest overstory from airborne imagery. Bhattarai et al. (2012) also suggested that the object-oriented approach has more predictive capability when classifying tree health than similar analyses done at pixel level. However, only 56% of field measured trees were correctly delineated in their study due to limitations in the capacity of satellite imagery to detect suppressed trees that were not visible from above. ALS based methods have potential to delineate individual trees more accurately than IS, but so far ALS has only been used for estimating standing dead trees (Casas Planes et al., 2014; Wing et al., 2015; Yao et al., 2012). Building on above mentioned studies, we propose combining the 3D capability of ALS with IS capacity to assess chemical composition of vegetation canopies to characterize individual tree health (including suppressed trees) in a structurally complex forest.

Forest health is a function of both structure, reflecting such symptoms as tree crown dieback and defoliation (Doo-Ahn Kwak & Cho, 2007; Rossini, Panigada, Meroni, & Colombo, 2006; Turner, 2007), and foliar chemistry, particularly pigment content, which is strongly correlated with forest reflectance properties (Rossini et al., 2006; Solberg, Næsset, Lange, & Bollandsås, 2004). Therefore, in this study we investigate the potential of integrating ALS, providing detailed 3D information on tree structure, with IS, providing information on chemical composition of canopies, to quantify levels of individual tree health decline. In Shendryk, Broich, Tulbure, and Alexandrov (2016) we demonstrated a novel algorithm to delineate individual eucalypt trees in a structurally complex forest from ALS with up to 68% accuracy. In this study we propose the application of our tree delineation algorithm to classify levels of tree health in the same forest, which has undergone a range of recent stresses thought to be related to drought and changes in flooding frequency (OEH, 2012). Recognizing the signs of unhealthy forest and teasing out the causes are important both for sustaining the services that humans rely on and for the effective conservation of forest ecosystems (Sugden, Fahrenkamp-Uppenbrink, Malakoff, & Vignieri, 2015).

The overall aims of this project were to classify the health of individual trees by integrating full-waveform ALS, IS and field measurements and to demonstrate its application in diagnosing potential causes of forest decline. We addressed these aims by developing a quantitative assessment method for individual tree health based on ALS and IS and investigating spatial relation of forest health to flooding frequency. Although, the decrease in flooding has been frequently identified as the main cause of tree health decline, there is no reference study that provides quantification of the effects of flood reduction on individual tree health. To ensure efficient use of resources, we first adopt and refine a procedure for targeting airborne remote sensing and fieldwork surveys.

2. Study area

Barmah-Millewa Forest (BMF) (Fig. 1), which occupies 737 km^2, is the largest contiguous area of river red gums (*Eucalyptus camaldulensis*) in the world and represents a key site for the management of environmental flows - volumes of water released within regulated river systems for ecological benefit - in the Murray Darling Basin (Chong &