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Assessing very high resolution UAV imagery for monitoring forest health during a simulated disease outbreak

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ABSTRACT

Research into remote sensing tools for monitoring physiological stress caused by biotic and abiotic factors is critical for maintaining healthy and highly-productive plantation forests. Significant research has focussed on assessing forest health using remotely sensed data from satellites and manned aircraft. Unmanned aerial vehicles (UAVs) may provide new tools for improved forest health monitoring by providing data with very high temporal and spatial resolutions. These platforms also pose unique challenges and methods for health assessments must be validated before use. In this research, we simulated a disease outbreak in mature *Pinus radiata* D. Don trees using targeted application of herbicide. The objective was to acquire a time-series simulated disease expression dataset to develop methods for monitoring physiological stress from a UAV platform. Time-series multi-spectral imagery was acquired using a UAV flown over a trial at regular intervals. Traditional field-based health assessments of crown health (density) and needle health (discolouration) were carried out simultaneously by experienced forest health experts. Our results showed that multi-spectral imagery collected from a UAV is useful for identifying physiological stress in mature plantation trees even during the early stages of tree stress. We found that physiological stress could be detected earliest in data from the red edge and near infra-red bands. In contrast to previous findings, red edge data did not offer earlier detection of physiological stress than the near infra-red data. A non-parametric approach was used to model physiological stress based on spectral indices and was found to provide good classification accuracy (weighted kappa = 0.694). This model can be used to map physiological stress based on high-resolution multi-spectral data.

1. Introduction

Forest plantations provide a wide range of economic, social and environmental benefits in many parts of the world (Yao et al., 2014). In New Zealand, forestry exports provide the third largest source of export earnings, worth over NZ$5 billion per annum and forest industry directly employs 18,000 people (NZFOA, 2013). New Zealand's commercial plantation forest sector is dominated by the fast-growing conifer species *Pinus radiata* D. Don (*P. radiata*) which occupies 90% of the total plantation area (Watt et al., 2017). Such reliance on a single species means that the forest industry is particularly vulnerable to biosecurity incursions by plant pests and pathogens that pose a threat to *P. radiata*. Despite being an island nation with rigorous biosecurity protocols and monitoring programmes, incursions remain a serious threat with recent introductions estimated to have cost New Zealand's primary sector upwards of NZ$ 400 million (Hulme, 2014). In the context of forestry, *P. radiata* in New Zealand is currently affected by a number of pathogens including *Dothistroma septosporum*, *Cyclaneusma minus* and *Phytophtora pluvialis*. Infection by these organisms results in a significant loss in forest productivity. It is estimated that Dothistroma Needle Blight alone resulted in a cost of NZ $19.8 million per year to the New Zealand economy throughout the 2000s (Watt et al., 2011).

Forest health surveillance forms a significant part of biosecurity monitoring and effective pathogen management efforts (Bulman et al., 2016). Surveillance methods are based on the detection of infection symptoms; these are specific to each pathogen but for plantation trees these commonly include foliar discolouration followed by some degree of defoliation. Traditionally, regular ground-based surveys carried out by highly trained field technicians have

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formed the basis of monitoring efforts in many countries (Brown and Webber, 2008; Bulman et al., 2004; Smith et al., 2008). These surveys are commonly carried out on an annual basis (Coops et al., 2006) and are used both to identify new incursions and to plan control or damage mitigation measures (Bulman et al., 2016). Furthermore, information from these surveys contributes towards policy development, international reporting obligations, forest planning and investment decision making (Stone and Coops, 2004). The utility of traditional survey techniques are limited by the small spatial coverage that can be achieved and the inevitable subjectivity between assessors conducting ground surveys.

Modern remote sensing tools have the potential to complement ground-based surveys by expanding spatial coverage and offering objective assessments of tree and forest health. To realise these benefits it is important to correctly identify the survey techniques and data sources required to meet the surveillance objectives (Wulder et al., 2006a). An appropriate sensor choice and resolution can be defined by the desired sensitivity of the surveillance and the physiological impacts of the stressor on observable properties such as the spectral characteristics of foliage. With an appropriate sensor choice and resolution defined, the increased area that can be covered and assessed using remote sensing is typically large and complete coverage may even be achievable, greatly improving the accuracy and completeness of surveillance (Wulder et al., 2006b). Aerial survey (also referred to as aerial sketch mapping), which involves manual identification of disease outbreaks by a skilled observer on-board an aircraft, is a commonly used, affordable and flexible approach for large-scale mapping of disease outbreaks. This method provides an accurate means of detection of a wide-range of forest health symptoms but offers limited ability to resolve different levels of physiological damage (Stone et al., 2013) and often lacks spatial specificity for damage that occurs at a fine scale over a relatively narrow time-frame (Johnson and Ross, 2008).

The acquisition of digital spatial data has many, often complimentary, advantages compared with manual aerial surveys, including a high level of consistency, spatial accuracy and automation of subsequent analysis. Most research has used satellite imagery to quantify the spatial extent of insect outbreaks and tree mortality at regional and landscape scales using imagery of a moderate (5–30 m) resolution (Meigs et al., 2011; Fraser and Latifovic, 2005). Over the last decade a growing number of studies have used high resolution (<5 m) satellite imagery to characterise tree mortality at finer spatial scales on individual trees, or clusters of trees, within a stand (Stone et al., 2012; Dennison et al., 2010; Hicke and Logan, 2009; Guo et al., 2007; Coops et al., 2006). Generally, the use of satellite imagery with a finer spatial resolution (Coops et al., 2006; Hicke and Logan, 2009; White et al., 2005; Wulder et al., 2008) has been shown to more accurately classify mortality, resulting from insect outbreaks, than imagery with medium resolution (Franklin et al., 2003; Skakun et al., 2003; Wulder et al., 2006).

Pest and disease detection remains a key target for remote sensing technologies. To date, only a few studies have demonstrated successful disease detection in forests using high resolution multi-spectral imagery from aircraft (Leckie et al., 2004), satellites (Poona and Ismail, 2013) and hyper-spectral imagery from manned aerial platforms (Coops et al., 2003; Calderón et al., 2015; Pu et al., 2008). This is in contrast to agricultural research where a range of studies have examined the use of remote sensing data for detection of foliar pathogens in annual agricultural crops. This may be because disease symptoms in these crops are often expressed in the upper parts of the plant and agricultural cropping systems are structurally simple and small in scale by comparison to forests (Barton, 2012; West et al., 2003; Sankaran et al., 2010).

Change detection techniques provide a useful starting point for the identification of subtle changes in forest health based on spectral information. The aggregation of multi-temporal composite images can greatly improve the signal to noise ratio (Rullan-Silva et al., 2013) and using longer time periods can mitigate the detrimental impacts of environmental factors, such as cloud cover, on detection. Using this approach, acceptable accuracies have been demonstrated for detection of bark beetle attack on conifer species (Garrity et al., 2013; Meddens and Hicke, 2014; Havašová et al., 2015; Goodwin et al., 2008) and needle discolouration resulting from *Dothistroma pini* (Coops et al., 2003). Analysis of time-series data was also used by Eitel et al. (2011) who girdled a number of trees in a piñon-juniper woodland and then successfully detected tree stress using a dense sequence of multi-spectral images from the RapidEye satellite constellation (Eitel et al., 2011). Invoking stress symptoms in this manner provides superior experimental control and is well suited to testing and calibration of methods for the early detection of symptoms such as pathogen induced physiological changes in foliage.

Imagery from manned and satellite platforms provides coverage over large areas but is typically time consuming and relatively costly to acquire on a regular basis. This makes data from these platforms poorly suited as means for early detection of outbreaks, near-continuous monitoring of high-risk sites such as those frequently accessed for public recreation, or for identification of small, isolated outbreaks that could easily be missed in medium resolution imagery. The development of unmanned aerial vehicles (UAVs) may offer new platforms for the collection of very high resolution imagery, while also offering the ability to collect data at short intervals in a cost-effective manner.

Despite their potential advantages, studies using UAVs to detect biotic damage in forests are scarce. Hyper-spectral data were acquired from a UAV over a stand of Norway spruce (*Picea abies* L. Karst.) infested with the European spruce bark beetle (*Ips typographus* L.) (Näsi et al., 2015). Using this data, Näsi et al. (2015) were able to classify individual trees into classes of healthy, infested and dead with a reasonable accuracy (Cohen's kappa = 0.6.). Lehmann et al. (2015) used a UAV equipped with compact digital camera to characterise defoliation of oak trees by the oak splendor beetle (*Agrilus biguttatus*). A modified normalized difference vegetation index (mNDVI) derived classification was used to distinguish between five vegetation health classes with Kappa index of agreement ranging from 0.77 to 0.81 for the two study sites (Lehmann et al., 2015).

In this study, disease symptoms in a stand of *P. radiata* were simulated through careful application of herbicide to groups of trees of varying sizes. A UAV equipped with a multi-spectral sensor was used to regularly monitor changes in needle colour prior to treatment and for three months after herbicide application with the aims of (i) developing suitable data collection methods and processing procedures for UAV data acquisition and analysis to detect physiological stress, (ii) to test the sensitivity of specific spectral indices to provide an indication of the early onset of physiological stress and (iii) to determine the optimal spatial resolution of imagery for detection of a simulated disease outbreak across tree clusters of varying size.

2. Materials and methods

2.1. Study site

The study site was located in Kinleith Forest in New Zealand's Central North Island (Fig. 1) (latitude 38° 24′18.74S, longitude 176° 0′59.28E), approximately 28 km southeast of the township of Tokoroa. The site is around 230 m above sea level and slopes gradually up towards the south-eastern corner of the trial. The site experiences a temperate climate (total annual rainfall = 1238 mm, mean annual temperature = 13.4 °C) and the soils are loam