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A spatial and temporal analysis of forest dynamics using Landsat time-series

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ABSTRACT

Understanding forest dynamics at the landscape scale is critical given the demands of sustainable forest management and climate change mitigation. This study proposes an approach for holistically characterising and analysing forest dynamics across large areas and long-time periods using information derived from Landsat time-series. To achieve this, we first developed a two-phase classification process to predictively map (1) disturbance and recovery levels and (2) disturbance causal agents for multiple detected disturbance events. The model explanatory data included a range of trajectory-based metrics derived from Landsat time-series, while model training and validation data were derived from a human-interpreted reference dataset. While previous studies have often described forest dynamics using some specific spectral change metrics, we demonstrated an ensemble approach to map disturbance and recovery trends (by treating them as a single metric) and to characterise not only abruptly occurring change events (e.g., clear-fell logging and wildfire) but also events of low severity (e.g., prescribed burning and selective logging). In addition, we adopted a space-time data cube concept to simultaneously report both newly detected disturbance events (detected disturbances) as well as events that have previously occurred but are ongoing (ongoing disturbances). This ongoing element of forest dynamics is often under-reported. The method was tested over 3.7 million ha of public land sclerophyll forests, where multiple disturbance events have occurred over the last 30 years (1987–2016). Our models of disturbance and recovery levels obtained overall accuracies of 78.6% and 72.3% for primary and secondary disturbance events, respectively. The overall accuracies for the models of disturbance causal agents were 80.7% and 73.0%, respectively. The data cube reported an average annual disturbance rate of 4.2% per year. This was dominated by newly detected disturbance (2.7% per year) as distinct from ongoing disturbance that was, however, considerable (1.5% per year). Our approach presented herein can improve the understanding of forest dynamics over long time periods and large areas and has potential for supporting land managers.

1. Introduction

Forest dynamics can be summarized with two basic elements: disturbance and recovery. These are important ecological processes that have significant impacts on the global forest carbon budget and other ecosystem services such as the water cycle and energy balance (Hicke et al., 2012; Houghton, 1998). Thus, understanding forest dynamics is a priority for sustainable forest management and climate change mitigation (Anderson-Teixeira et al., 2013; Hansen and Loveland, 2012). In the context of long-term forest monitoring, investigating both disturbance and post-disturbance (subsequent) recovery associated with multiple disturbance events can provide a comprehensive framework for enhancing our understanding of forest dynamics (White et al., 2017). Given this context, land managers and policy-makers require a thorough understanding of change in forests in order to implement effective management and conservation techniques. Many national and international jurisdictions, in charge of both management and reporting activities, urgently need a robust and cost-effective approach for large area reporting. Multi-temporal remote sensing data, such as Landsat time series, has the potential to provide comprehensive baseline information on forest dynamics over regional or global scales (Cohen and Goward, 2004; Griffiths et al., 2014; Hansen and Loveland, 2012; Kennedy et al., 2010; Lehmann et al., 2013).

Among remotely sensed data sources, Landsat time series has been

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commonly used for forest change characterization over large areas. The Landsat archive provides the longest collection in standard format of satellite imagery (since 1972) at a spatial resolution capable of capturing changes caused by both human and natural activities (Cohen and Goward, 2004). The entire historic Landsat archive has been made available to the public since 2008 (Woodcock et al., 2008; Wulder et al., 2012). This has been accompanied by the development of automated change detection algorithms based on the Landsat time series such as Landsat-based Detection of Trends in Disturbance and Recovery or LandTrendr (Kennedy et al., 2010), Vegetation Change Tracker or VCT (Huang et al., 2010), and Breaks For Additive Season and Trend or BFAST (DeVries et al., 2015b). Of these, the ability of the LandTrendr segmentation algorithm to detect historical forest disturbance and recovery has been demonstrated in various contexts (Banskota et al., 2014; Cohen et al., 2010; Kennedy et al., 2012; Main-Knorn et al., 2013; Powell et al., 2013). An advantage of this algorithm is that the fitted vertices allow detection of both abrupt disturbance events (e.g., wildfire and logging) as well as long-term processes such as recovery and long-duration disturbance (e.g., drought and disease). The rich information in the Landsat archive and the advanced development of change detection algorithms allow us to describe the change of landscapes in a comprehensive manner.

Forest disturbance and recovery can be characterised by temporal and spatial patterns. Using the Landsat time series, temporal patterns such as the occurrence date and duration of change can be robustly derived through change detection analysis using the aforementioned algorithms (DeVries et al., 2015b; Griffiths et al., 2014; Hermosilla et al., 2015; Huang et al., 2010; Kennedy et al., 2010; Kennedy et al., 2012; Zhu et al., 2012). However, to characterise spatial patterns such as change levels and associated causal agents, further analysis that links the change in spectral signals with ground reference data is required. While previous studies have demonstrated different Landsat-based approaches to characterise forest dynamics (e.g., DeVries et al., 2015b; Hermosilla et al., 2015; Kennedy et al., 2015; Kennedy et al., 2012; Liu et al., 2017; Senf et al., 2015; Shimizu et al., 2017; White et al., 2017), few of them have considered both disturbance and subsequent recovery trends across large forest areas. A robust LandTrendr-based method for characterising disturbance and recovery patterns over large areas was developed by Kennedy et al. (2012). In that study, the raw spectral values of the Normalized Burn Ratio (NBR) were converted into percent vegetation cover using a regression model. The authors then defined three disturbance levels (high, medium, and low) corresponding with different estimates of vegetation cover. For mapping recovery trends, the study introduced the recovery indicator (RI), which scaled the post-disturbance recovery value to the loss of vegetation through disturbance. This metric was adapted by White et al. (2017) to describe post-disturbance regrowth across Canada's forest systems. In another study, Liu et al. (2017) stratified both disturbance and recovery into three levels of (serious/strong, moderate, and light) using defined spectral thresholds. Notably, all of these studies directly described the trends in recovery using metrics representing spectral change such as the RI, but none of them linked these metrics with reference data. Although it is widely known that recovery in spectral data is not a direct measure of actual forest recovery (Bartels et al., 2016), trends of forest recovery can nonetheless be quantified by linking spectral change metrics with an appropriate reference dataset. In this study, we determine the trends of recovery following disturbance by comparing current (or post-recovery) structural conditions of forests (defined as groups of canopy cover and height) with the pre-disturbance conditions.

A comprehensive characterization of forest dynamics requires an understanding of not only disturbance and recovery trends but also associated causal agents. As change processes (both natural and anthropogenic) normally occur and impact on forest areas larger than Landsat pixels, the prediction of disturbance agents was often performed at the patch (or object) level using ensemble approaches (Hermosilla et al., 2015; Kennedy et al., 2015; Shimizu et al., 2017). In these studies, disturbance patches were defined by grouping adjacent pixels experiencing a disturbance at the same date. In addition, previous studies (e.g., Kennedy et al., 2015; Schroeder et al., 2017; Senf et al., 2015) have demonstrated the importance of spectral change metrics in distinguishing among different disturbance causal agents, especially for those with a low frequency and low impact on forests.

Analysis performed on remotely sensed data provides us with a number of important characteristics of forest dynamics over long time periods. However, these characteristics are often individually represented as map-based products which may limit the ability of agencies and reserchers in utilising the derived information (Shafran-Natan and Svoray, 2006). One limitation relates to statistical analysis of forest dynamics. For instance, when reporting the forest disturbance rate for a given year, most studies consider only events which are newly detected to have occurred during that year. Forests, however, are impacted not only by events occurring within a given time period (hereafter, detected events) but also by events occurring before and ongoing throughout that time period (hereafter, ongoing events). Another limitation of map-based products is that it is normally required to examine a number of different single-attribute layers to temporally track the disturbance and recovery history of pixels of interest. Thus, we propose that information on forest dynamics should be analysed in a flexible data infrastructure, such as a data cube, which allows tracking forest history over time and provides ongoing information on land-use history.

In this study, we demonstrate an approach for holistically characterising and analysing forest disturbance and recovery across large areas and long-time periods using information derived from Landsat time-series. Our work exploits time series of Landsat imagery during three decades (1987 to 2016) and is tested over 3.7 million ha of public forest land in eastern Victoria, Australia. Our specific objectives are:

1. To develop methods for predictively mapping disturbance and recovery levels and associated causal agents at the landscape scale, using pixel-level temporal segmentation outputs.
2. To improve reporting of forest dynamics by adopting a space-time data cube concept in analysing the characteristics of forest disturbance and recovery.

2. Study area

The study area, shown in Fig. 1, is located in the eastern part of the state of Victoria, Australia, and is covered by four Landsat WRS-2 scenes (Path/Row 91/85, 91/86, 91/87, and 90/86). It comprises an area of over 5.3 million ha, which accounts for approximately 22.3% of the total land area of the state of Victoria. Within this boundary, public forest land represents 3.7 million ha and includes two main land tenures (state forest and parks and conservation reserves). Public forest in the study area extends across several bioregions (Interim Biogeographic Regionalization for Australia or IBRA), each of which has distinct ecological, geological and climatological features (Department of Environment and Primary Industries, 2014). Vegetation is dominated by wet and dry sclerophyll forests. The former are tall forest ecosystems with trees reaching 75 m or more in height while the later include relatively low and spreading trees that reach a maximum height of 25 m (Viridans, 2016).

According to Australian forest structural definitions (Australian Surveying and Land Information Group, 1990), forests within this area are stratified into three classes based on mature tree height (low, medium and high forest), and three classes based on crown cover (woodland, open and closed forest) (Fig. 2). Forests within the study area have been impacted by a series of disturbance events including fuel reduction burns, wildfires, logging and drought. For example, the area has experienced several severe wildfires over the last decade which led to high tree mortality (Department of Environment and Primary Industries, 2014). This has resulted in significant changes in carbon biomass stocks across the study area.