ARTICLE IN PRESS

RSE-09038; No of Pages 16

Remote Sensing of Environment xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Mapping forest growth and degradation stage in the Brigalow Belt Bioregion of Australia through integration of ALOS PALSAR and Landsat-derived foliage projective cover data

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A R T I C L E I N F O

Article history:
Received 18 November 2012
Received in revised form 26 October 2013
Accepted 1 November 2013
Available online xxxx

Keywords:
Brigalow
ALOS PALSAR
Landsat
Regrowth
Degradation
Carbon
Biodiversity

A B S T R A C T

Differentiation of forest growth stages through classification of single date or time-series of Landsat sensor data is limited because of insensitivity to their three-dimensional structure. This study therefore evaluated the benefits of integrating the Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) L-band HH and HV polarisation response from the woody components of vegetation with Landsat-derived foliage projective cover (FPC). Focus was on 12 regional ecosystems (REs) distributed across the Brigalow Belt Bioregion (BRB) of Queensland, Australia, where different stages of growth dominated by brigalow (*Acacia harpophylla*) were widespread. From remnant areas of brigalow-dominated forests mapped previously for each RE by the Queensland Herbarium through field visits and interpretations of aerial imagery, frequency distributions of all three channels were extracted and compared to those of image segments generated using FPC and PALSAR data. For woody vegetation (with an FPC threshold of ≥9%) outside of the remnant areas, mature (non-remnant) forests were associated with segments where the HH and HV backscatter thresholds were within one standard deviation of the mean extracted for remnant forest. Early-stage regrowth was differentiated using an L-band HH threshold of <−14 dB, common for all REs because of similarities in structure at this stage. The early-stage included forests regrowing over several decades and often occurred in areas recovering from recent clearing events. Objects falling between the early and mature stages were considered to be intermediate regrowth and/or degraded forest. All areas with an FPC <9% were mapped as non-forest.

Within the BRB, the Queensland Herbarium established that forests with brigalow as a dominant or subdominant component originally occupied over 7.3 million ha but were reduced to 586,364 ha by 2009, with 460,499 ha (78.5%) having brigalow as the dominant component. Using the Landsat FPC and ALOS PALSAR data, an additional 722,686 ha of brigalow-dominated regrowth forest were identified giving a total forested area (brigalow-dominated remnant and secondary forest) of 1,183,185 ha or 17.2% of the area of the 12 REs. Within this area, the greater proportion of regrowth (368,473 ha or 31.1%) was mapped as early stage primarily because of recovery following recent clearance events. 230,551 (19.5%) ha and 123,662 ha (10.5%) were mapped as intermediate and mature (non-remnant) stages respectively and the remainder (38.9%) was remnant forest. Users' and producers' accuracies were, respectively, 81% and 69% for early regrowth and 71% and 89% for mature and intermediate stage forests combined. The mapping, which used Queensland Herbarium's RE data to delineate brigalow extent, provided a structural, rather than age-based classification of growth stage, as is typically retrieved using time-series comparison of optical imagery. The regional estimates of growth/degradation stage generated for the

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http://dx.doi.org/10.1016/j.rse.2013.11.025
0034-4257/© 2014 Published by Elsevier Inc.

BRB provide a basis for optimising the use and recovery of these threatened brigalow ecosystems with benefits for biodiversity and carbon sequestration.

1. Introduction

The clearance of forests across the world has contributed to significant declines in both terrestrial carbon stocks and habitat, leading to increased levels of atmospheric greenhouse gases and losses of biodiversity (including species extinctions; Dirzo & Raven, 2003; Pan et al., 2011). Nevertheless, in many regions, forests are regenerating on abandoned and/or previously disturbed land, providing potential for the restoration of ecosystem structure, diversity and function (Bowen, McAlpine, House, & Smith, 2007; 2009; Ramankutty & Foley, 1999). Primary forests that have remained intact (often referred to as remnant) also contain substantial stocks of carbon (Gibbs, Brown, Niles, & Foley, 2007) and a high diversity of plant and animal species (Barlow, Gardner, Araujo, et al., 2007). Efforts focusing on conserving forest ecosystems for biodiversity and carbon values therefore rely on knowledge of the extent of remnant forests (which need to be conserved) and secondary forests at different stages of growth and degradation (which need to be protected and managed to facilitate ecosystem restoration and provide additional carbon sequestration). Spatial and quantitative information on forest extent, structural attributes (e.g., cover, height) and biomass, and changes in these is also critical for advising management strategies that aim to optimise the recovery of forest ecosystems to retain biodiversity and enhance terrestrial carbon stocks. However, for many regions of the world, such information is lacking. For this reason, increasing emphasis is being placed upon using remote sensing observations to fill these gaps, particularly as these forests are often scattered over vast areas and may be experiencing rapid change (Chambers et al., 2007; Goetz et al., 2009).

A common approach to mapping the growth stage of forests has been to use time-series of remote sensing (primarily optical) data to differentiate forests of differing age (e.g., Helmer, Lefsky, & Roberts, 2009; Prates-Clark, Lucas, & dos Santos, 2009; Yanesse et al., 1997). These methods are data intensive and assume stand age to be an indicator of the stage of development relative to that of the primary or mature forest, with older forests often considered the most similar in terms of structure and species composition (Bowen et al., 2007). However, the succession of forests may be influenced by a number of factors, such as clearing mechanisms, periods and types of use, the history of burning as well as physical factors such as soils, climate and topography (Prates-Clark et al., 2009). Degradation of forests within the same landscape, including those that are regenerating, is also not considered, with many forests assumed to be developing in one direction. For these reasons, forests of the same age may differ in their structure, species composition and biomass and rates of change in these attributes over time (Lucas, Honzak, do Amaral, Curran, & Foody, 2002). Whilst age information is important to retain, remote sensing efforts also need to be directed towards tracking the structural development or degradation of forests relative to the mature state and ideally quantifying the changes in biomass (carbon) over time. Such an approach is also advantageous as structure often relates to the way that fauna are distributed within and utilise a habitat (Bowen et al., 2007; Selwood, MacNally, & Thomson, 2009).

Using areas within the Brigalow Belt Bioregion (BRB) in Queensland, Australia, as an example, Lucas et al. (2006) proposed an approach to identifying regenerating forests at the earliest stage of structural development that combined single-date NASA JPL airborne Synthetic Aperture Radar (AIRSAR) L-band HH (~25 cm wavelength) polarisation data and Landsat-derived foliage projective cover (FPC). FPC is the percentage of an area occupied by the vertical projection of foliage, and is estimated routinely for the state of Queensland using a multiple regression relationship established between field measures of woody FPC and Landsat sensor visible (green and red), near infrared and shortwave infrared data. The FPC of woody vegetation is determined by accumulating measures of FPC retrieved from time-series of Landsat sensor data, which disaggregates the seasonal contribution from herbaceous vegetation (Armston, Denham, Danaher, Scarth, & Moffiet, 2009). The accuracy of retrieval was increased when vapour pressure deficit (VPD), defined as the difference in vapour pressure from a saturated atmosphere, was included in the regression because of the known correspondence between the evaporative potential of the atmosphere and FPC (Specht & Specht, 1999). Based on cross-validation comparisons (Armston et al., 2009), the regression model provided an adjusted R^2 of 0.80 and RMSE of <10.0% for the estimation of FPC. Lucas et al. (2006) identified the early stage of regeneration as areas supported an FPC associated with forests but an L-band HH backscattering coefficient more typical to non-forest. Clewley et al. (2012) expanded this approach to differentiate early stage from more intermediate and mature stages by referencing the characteristics of remnant forest, although instead used Japanese Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) HH and HV with Landsat-derived FPC data to facilitate regional applications. This study therefore sought to evaluate whether the methods of Lucas et al. (2006) and Clewley et al. (2012) could be used in combination to differentiate forests at progressive stages of structural development and/or degradation across the BRB given the diversity of ecosystems, environments and climates occurring, with focus on ecosystems dominated primarily by brigalow (*Acacia harpophylla*). By generating new maps of forest growth and/or degradation stage for the BRB, significant capacity to quantify biodiversity and carbon stocks and dynamics would be provided as well as knowledge on where future restoration activities might be targeted.

In Queensland, regional ecosystems (REs) are defined as vegetation communities that are associated with a particular combination of geology, landform and soil (Sattler & Williams, 1999). The extent of these REs, whether currently forested or otherwise, has been mapped through reference to the physical environment and consistent patterns detectable within time-series of aerial photography and satellite imagery over the whole region, with these supported by a limited number of known sample points to provide a description (Neldner, Wilson, Thompson, & Dillewaard, 2012). As few images are available across Queensland before the early 1960s and few sample points exist before the 1970s (apart from localised explorer and early settle records), what is often referred to as the pre-1750 or pre-European extent of the REs (i.e., prior to major impacts from non-indigenous populations) is difficult to ascertain, particularly as ecosystem boundaries might also have changed. Hence, the pre-clearing extent is defined, with this referring to REs present before known clearing (if occurring) but equating generally to the "pre-1750" or "pre-European" extent (Accad, Neldner, Wilson, & Niehus, 2008; 2012; Neldner, Wilson, Thompson, & Dillewaard, 2005, Neldner et al., 2012). In some cases, old survey records (e.g., from the 1940s and 1950s) have been used to determine the pre-clearing vegetation in areas already cleared (Fensham & Fairfax, 1997). Remnant forests are considered to be those that have remained intact before and throughout this period and have never been cleared. In many cases though, the earliest period when these forests were observed is the 1940s and 1950s when aerial photographs were first acquired.

This study focused particularly on 12 REs within the BRB where brigalow is dominant within the forest community, although within other REs mapped across the BRB, this species may be subdominant.

Please cite this article as: Lucas, R.M., et al., Mapping forest growth and degradation stage in the Brigalow Belt Bioregion of Australia through integration of ALOS PALSAR and Lan..., *Remote Sensing of Environment* (2014), http://dx.doi.org/10.1016/j.rse.2013.11.025