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Multi-resolution time series imagery for forest disturbance and regrowth monitoring in Queensland, Australia

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A B S T R A C T

High spatio-temporal resolution optical remote sensing data provide unprecedented opportunities to monitor and detect forest disturbance and loss. To demonstrate this potential, a 12-year time series (2000 to 2011) with an 8-day interval of a 30 m spatial resolution data was generated by the use of the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) with Landsat sensor observations and Moderate Resolution Imaging Spectroradiometer (MODIS) data as input. The time series showed a close relationship over homogeneous forested and grassland sites, with r^2 values of 0.99 between Landsat and the closest STARFM simulated data; and values of 0.84 and 0.94 between MODIS and STARFM. The time and magnitude of clearing and re-clearing events were estimated through a phenological breakpoint analysis, with 96.2% of the estimated breakpoints of the clearing event and 83.6% of the re-clearing event being within 40 days of the true clearing. The study highlights the benefits of using these moderate resolution data for quantifying and understanding land cover change in open forest environments.

1. Introduction

Globally, forest loss and degradation is the second largest contributor to the post-industrial revolution increase in atmospheric carbon dioxide (CO_2; van der Werf et al., 2009). Whilst much of the conversion from forest to non-forest (e.g., agriculture, urban areas, and infrastructure) over the past four decades has been observed using satellite sensor data, losses associated with degradation have been less discernable and consequently underestimated (Asner et al., 2005). Uncertainties also remain regarding the contribution to carbon emissions. Quantifying the extent and also magnitude of degradation is therefore important, particularly given that affected areas often do not recover or are eventually cleared.

Many studies investigating ways to map forest disturbance have focused on changes in the biophysical properties of forests, with these determined largely through the use of spectral data or derived indices such as the Normalised Difference Vegetation Index (NDVI; Tucker, 1979). For this purpose, and primarily because of the high temporal (near daily) coverage, coarse (~1 km) spatial resolution Advanced Very High Resolution Radiometer (AVHRR) and SPOT-VEGETATION or Terra-1 Moderate Resolution Imaging Spectrometer (MODIS; 1 km to 250 m) have been used (Running & Nemani, 1988; Schöttker, Phinn, & Schmidt, 2010; Verstraete & Pinty, 1996). In particular, these data allow for the detection of a) seasonal change (e.g. phenological behaviour influenced by temperature and rainfall pattern), b) gradual change (e.g. impacts of long term climatic or land management changes) and c) abrupt changes and disturbances (e.g. land clearing or fire), as shown by Verbesselt, Hyndman, Newnham, and Culvenor (2010). Finer (~30 m) spatial resolution data from the Landsat sensors have allowed detection of specific events, such as vegetation clearing, selective logging or fires (Kennedy et al., 2009). These data have not though been widely used for process monitoring because of the low temporal frequency (16 days for Landsat), which has been reduced further by cloud cover, adverse atmospheric conditions and sensor problems (Baumann et al., 2011; Kennedy et al., 2009). However, the release of the Landsat archive at no cost (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012) has provided new opportunities for assessing historical changes in landscapes.

To provide the option of high spatial resolution and high temporal frequency, a number of data fusion techniques have been developed that link MODIS and Landsat sensor data (e.g., Gao, Masek, Schwaller, & Hall, 2006; Roy et al., 2008; Zhu, Chen, Gao, Chen, & Masek, 2010). Of note is the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM), which has been applied successfully for a range of

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studies and purposes (Gao et al., 2006; Hilker, Wulder, Coops, Seitz, et al., 2009; Watts, Powell, Lawrence, & Hilker, 2011). For example, Walker, de Beurs, Wynne, and Gao (2012) demonstrated the usefulness of the STARFM algorithm for phenological studies in the drylands of Arizona by using 12 STARFM predicted images. Schmidt, Udelhoven, Gill, and Röder (2012) used STARFM to predict 333 Landsat sensor images over a 7.5 year time period, with these then used to study regional ecological and phenological processes in a heterogeneous Northern Australian savanna. ESTARFM (Zhu et al., 2010) and mESTARFM (Fu, Chne, Wang, Zhu, & Hilker, 2013) have been successfully applied as an improvement on STARFM, although findings of Emelyanova, McVicar, van Neil, and van Dijk (2013) are inconclusive in establishing whether this improvement is evident for all environments (e.g., with a dominant temporal variance, STARFM gave a superior performance). Hence, the less complex STARFM algorithm was applied here. Hilker, Wulder, Coops, Linke, et al. (2009) used a STARFM-based fusion model (STAARCH) for mapping forest disturbances. This algorithm computes a Disturbance Index (DI) based on a Tasselled Cap (Kauth & Thomas, 1976) transformation and NDVI data for each simulated image. A regionally adapted mask of mature forest is then used to scale and empirically threshold the DI time series. The pixel neighbourhood is included to reduce DI noise.

An environment where the STARFM algorithm has had limited evaluation is woody change in the open forests and woodlands of northern Australia (Bhandari, Phinn, & Gill, 2012; Schmidt et al., 2012). Nevertheless, temporal comparisons of Landsat imagery have been undertaken to allow detection of forest loss. In particular, the Queensland Department of Science Innovation Technology and the Arts (DSITIA) developed a program to monitor vegetation change using Landsat data; the Statewide Landcover and Trees Study (SLATS). In this program, annual state-wide maps of Foliage Projected Cover (FPC) have been generated using empirical relationships between ground-based estimates from a range of vegetation types and both Landsat data and climate variables (Armston, Denham, Danaher, Scarth, & Moffiet, 2009; Danaher et al., 2010). From these data, forest losses have been reported annually since 1999 and over longer time intervals between 1988 and 1999 (Danaher et al., 2010). The scale of the Landsat scale imagery has also proved adequate for describing the complex and spatially heterogeneous landscapes occurring across the state (Danaher et al., 2010). In this case, images captured during Queensland's dry season are preferentially selected, as these give best differentiation between the dry ground cover layer and the non-deciduous woody vegetation.

To evaluate the potential application of the STARFM algorithm for determining undisturbed forest phenology and detecting and spatially differentiating the date and magnitude of forest change, a 12-year time series (2000 to 2011; with an 8-day interval) of Landsat and STARFM simulated images was used. The study was conducted in the Injune Landscape Collaborative Project (ILCP) research area west of Injune in central southeast Queensland. A major benefit of using this area was that large scale (<1:4000) true colour aerial photography and Light Detection and Ranging (LiDAR) data were acquired in 2000 and 2009 over a well-defined grid of 150 500 m × 150 m Primary Sampling Units (PSUs), with 4 km between each in the north-south and east-west directions. Hence, these data could be used to establish reference sites that had experienced limited change as well as disturbance and regeneration at the stand level over the period of the time-series. The study sought to establish whether a) a baseline of vegetation phenology over the 12 year period could be described for undisturbed natural vegetation based on the NDVI, b) time-series analysis could be used to indicate the timing and magnitude of disturbance events, and c) an increasing trend in NDVI metrics (e.g., dry season minima) could be associated with the regeneration of forests.

2. Study area

The study focused on the ILCP research area, which is located approximately 100 km west of the township of Injune in central southeast Queensland (Fig. 1a, b). The landscape can be described as a southern savanna region characterised as having variable rainfall and an ecosystem that is generally water limited. The majority of the landscape consists of forests and agricultural lands, with some abandoned to regrowth. Scattered buildings (primarily farmhouses) and unsealed roads are the main urban infrastructures occurring. The 37 × 60 km area was selected for the initial study as extensive tracts of vegetation were being cleared in the late 1990s and the open forests and woodlands (wooded savannas) contained structural formations typical to many occurring in Queensland. The study area was divided into a large sample grid of 150 (10 columns × 15 rows) Primary Photo Plots (PPPs; Fig. 1c) over which large-scale 1:4000 aerial photographs were acquired in 2000. Within these, 500 m × 150 m PSUs (Fig. 1d) were located in the stereo overlap. Each PSU was further divided into 30 secondary sampling units (SSU) of 50 m × 50 m. The original study area was chosen to be at the centre of the Landsat satellite swath (Tickle, Lee, Lucas, Austin, & Witte, 2006), but was extended south by 20 km to include areas where a range of land clearing activities were occurring.

Between 2000 and 2011, changes in the structure, biomass and species composition of forests occurred within the study area. Changes were caused by natural events such as fires, and human activities including stock grazing, selective and complete tree clearing by landholders (primarily for agricultural purposes) (Goodwin & Collett, 2014). Changes in climatic conditions (e.g., drought and flooding) also impacted on the structure and composition of forests. For example, in 2006, many large and mature rough barked apple (*Angophora floribunda*) trees died as a consequence of a prolonged period of drought, but smooth barked apples (*A. leiocarpa*) were unaffected (Lucas, Bunting, Paterson, & Chisholm, 2008). Regrowth following clearing for agriculture or fires was also commonplace.

3. Data and methods

3.1. Spaceborne, airborne and field data

For the ILCP study area, 97 Landsat sensor data with a cloud cover of less than 20%, acquired from December 1999 to September 2011 were obtained, with 69 and 28 acquired by the Landsat Thematic Mapper (TM) and Enhanced TM (ETM+) respectively (Table 1a). The Scan Line Corrector (SLC)-off effect (which results in missing data in alternate groups of lines at the edge of the image) was evident within 11 ETM + scenes (Pringle, Schmidt, & Muir, 2009). For the same period, 525 MODIS images were available from which the MODIS Bidirectional Reflectance Distribution Function (BRDF) model parameters (MCDS43A1) and the BRDF/Albedo quality product (MCD43A2) had been derived. The latter is a quasi-roll-on version of the 16-day MODIS composites and is produced every 8 days (Roy et al., 2008).

Across the PSU grid, discrete return LiDAR (using an OPTECH ALTM1020) and 1:4000 scale colour aerial photographs had been acquired in 2000, with a repeat coverage colour aerial photographs and full waveform (RIEGL LMS-Q560) LiDAR obtained in 2009. Flight height and pulse densities were 150 m and 1 pulse per m^2 in 2000 and 400 m and 4 pulses per m^2 in 2009. Both LiDAR datasets were processed to a 1 m spacing. These data were used to obtain estimates of height and cover for each PSU for the years 2000 and 2009 based on the methods outlined in Tickle et al. (2006). A comparison of these data allowed areas that had remained undisturbed or otherwise to be identified. Through interpretation of the 2000 aerial photography, forest types were delineated and assigned with a community code, with these representing the primary dominant, co-dominant and/or sub-dominant tree species or genera. The interpretation of these data was assisted by forest inventory data collected in 2000 from selected (34) 50 m × 50 m SSUs located within the PSU grid (Tickle et al., 2006), with this including measures of vegetation structure (cover, height and diameter distributions) and species type. More limited field campaigns were conducted