bnhcrc.com.au

CALIBRATION OF WATER BALANCE USING DIGITAL PHOTOGRAPHY

Mana Gharun, Malcolm Possell, Tina Bell
University of Sydney
Bushfire and Natural Hazards CRC

Version	Release history	Date
1.0	Initial release of document	06/01/2017

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Programme

Publisher:
Bushfire and Natural Hazards CRC

January 2017

Cover: Sampling area in the Hawkesbury region NSW. Photo: Mana Gharun

TABLE OF CONTENTS

ABSTRACT

Prescribed fires impact the hydrological cycle in forested catchments because they remove vegetation and modify the amount of evapotranspiration (ET) that occurs. Evapotranspiration is the most important component of the hydrological cycle and perturbations to it can substantially affect the water balance of an ecosystem. However, our understanding of ET responses to disturbance is very limited and this makes post-fire assessment of water balance difficult.

In this study we used relationships between tree size and tree water use, and leaf area index (LAI) and forest water use to investigate the impact of fuel-reduction burning (FRB) on water availability. Leaf area index is an important input for estimating ET and measurement techniques such as digital photography can potentially be used by land managers as a means of rapidly quantifying the impact of FRB on water balance at both the plot- and catchment-scale. Our results will enable land managers to identify hydrologically sensitive areas in accordance with their management objectives.

END-USER STATEMENT

Felipe Aires, *Fire and Incident Management, Office of Environment and Heritage, NSW*

The ability to measure the impact of fuel reduction burning on forest water use at the catchment-scale using more accurate, faster and cheaper methodologies creates many possibilities for tailored strategies for landscape management.

Identifying hydrologically-sensitive areas and assessing post-burn impacts on catchment water availability is critical for securing water resources and for prevention of environmental degradation.

This study describes the further development of forest water use models through an investigation of water use of understorey species – an important biophysical component in the field. The validation of digital photography studies will improve model robustness and will ultimately benefit land management agencies.

INTRODUCTION

Evapotranspiration (ET) – the amount of water lost from forests due to surface evaporation combined with plant transpiration – is the most important component of catchment water balance. It can be estimated either directly using a range of measurement techniques or indirectly using modelling efforts that require climatic and plant physiological inputs and parameters.

Leaf area index (LAI) – the total leaf area (m^2) per unit ground surface area (m^2) – controls many biological and physical processes in water, nutrient and carbon cycles and is an important input for estimating ET and carbon stocks in forests (Waring and Running 1998; Brown 2002; Rosenqvist *et al*. 2003).

Measurement techniques for LAI differ in complexity and accuracy (Breda 2003), ranging from destructive sampling (the most accurate method but very time-consuming) to estimation from remotely sensed vegetation greenness (a method that requires calibration/validation but has greater spatial coverage). Leaf area index can also be measured using digital cover photography (see Macfarlane *et al*. 2007). Compared to time- and labour-intensive biomass measurements, automated processing of digital images is a rapid and cost-efficient technique which has a lower risk of human error than other methods.

While digital photography has been used and validated for measurement of the overstorey canopy of eucalypt forests, the method has not been rigorously tested as a method for measuring LAI of the understorey. The LAI of understorey vegetation is more difficult to determine from digital images because of greater heterogeneity of leaves compared to overstorey canopy and background soil and light conditions compared to the sky in the background of overstorey canopy images. As a result, LAI of the understorey is often neglected in overall estimations of forest LAI.

Fuel-reduction burning (FRB) impacts catchment water balance predominately by removing live fuel in the understorey and modifying the amount of vegetation water use (i.e. ET). Water use by vegetation is directly proportional to the amount of leaf area and changes in LAI are directly linked to patterns of burn severity (Boer *et al*. 2008). Evapotranspiration can be estimated from LAI either using physical models that require a range of climate and vegetation inputs and parameters or empirically from observations of ET within a known range of LAI. Changes in understorey LAI can therefore be used to assess the impact of FRB on catchment water balance.

Digital photography is a relatively rapid and easy technique for estimating leaf area at a range of scales. For example, measurements at 30 points within a forest stand can be collected in less than 15 minutes. To upscale this to catchment- and landscape-scales, ground-based measurements of LAI can be linked to remotely sensed vegetation indices (e.g. Normalized Difference Vegetation Index; NDVI) which are relatively easy to derive from surface reflectance values. The NDVI has been shown to have a strong positive relationship with LAI (Carlson and Ripley 1997; Coops *et al*. 1997).

In addition, sap flow measurements have been used to estimate individual tree water use and show that stand basal area and sapwood area (also related to the amount of leaf area) can be used as a proxy for estimating vegetation water use. Here we test an empirical approach for estimating changes in forest water balance at the catchment-scale using existing models of tree water use that researchers have developed in similar forests using sap flow measurements. A model is presented for sites measured in the ACT as a case study to map the impact of FRB on water availability. The usefulness of this approach for modelling of additional sites is discussed.

METHODS

STUDY AREA

The study area includes 13 FRBs distributed across the ACT and NSW. Four sites (each site corresponds to one FRB) were selected in the ACT and nine sites in NSW (five in the Hawkesbury region and four in the Nattai region, Figure 1). Each site includes three pairs of circular burnt/unburnt plots (each a 'burn unit'; see Gharun *et al*. 2015) selected to be at least 500 m apart. In total we selected 78 plots each 1590 m^2 in size.

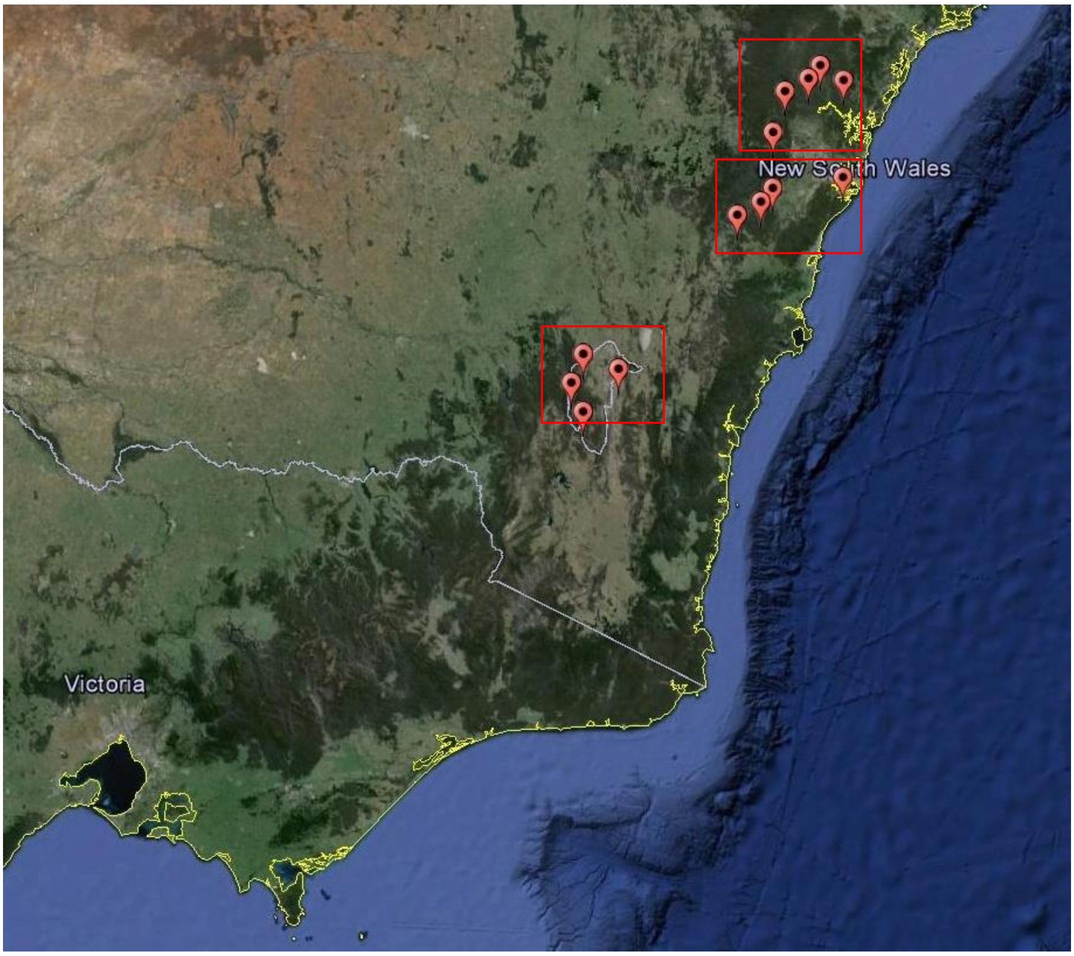

FIGURE 1 DISTRIBUTION OF STUDY SITES IN THE ACT (FOUR SITES, 24 PLOTS) AND NSW (NATTAI AND HAWKESBURY MANAGEMENT REGIONS; NINE SITES, 54 PLOTS). SITES IN NSW ARE GROUPED BASED ON THEIR SPATIAL PROXIMITY TO THESE MANAGEMENT REGIONS.

VEGETATION MEASUREMENT

Trees and shrubs are the main contributors to forest water use and one way to determine their water use is to use their basal area (a function of their diameter). For the overstorey trees, we measured the diameter of every tree (with a diameter of 10 cm or greater) within a 20 × 20 m subplot in the centre of each plot. For the understorey trees and shrubs, we selected four subplots (5 m radius) located at the north, east, south and west corners of the plot and measured the diameter of every tree or shrub less than 10 cm in diameter and more than 50 cm in height.

LEAF AREA INDEX MEASUREMENTS USING DIGITAL PHOTOGRAPHY

Images of overstorey and understorey cover were taken 2 m above ground level using a digital camera mounted on an extendable pole (Figure 2). A bubble level mounted on the side of the pole was used to position the camera horizontally and the shutter was operated by an infra-red remote control.

At least 30 images were taken in each plot. An example nadir image is shows in Figure 2. Cover images were analyzed in MATLAB (The MathWorks Inc., Natick, MA, 2014) using the automated procedure of Fuentes *et al*. (2008). For each image, the background (i.e. sky in overstorey images and soil in understorey images) were separated from the foreground (vegetation) pixels. The automated procedure calculates foliage cover (f_f, fraction of foreground pixels) using algorithms described in Macfarlane and Ogden (2012).

To estimate LAI for the understorey, it was assumed that foliage cover is related to crown cover (f_c) – as it is for the overstorey canopy – and a crown porosity (Φ) of 0.25 was used to calculate crown cover (Macfarlane and Ogden 2012):

$$f_c = \frac{f_f}{1-\Phi}$$

A light extinction coefficient (k) of 0.6 was used to estimate LAI from crown cover (Vertessy *et al*. 1996):

$$LAI = -f_c \ln(\Phi)/k$$

For each plot, the LAI of the understorey (LAI_{under}) was added to the LAI of the overstorey (LAI_{over}):

$$LAI_{total} = LAI_{over} + LAI_{under}$$

FIGURE 2 IMAGES OF UNDERSTOREY VEGETATION WERE TAKEN USING A DIGITAL CAMERA MOUNTED ON AN EXTENDABLE POLE (LEFT). IMAGES OF THE UNDERSTOREY (TOP RIGHT) WERE ANALYZED TO SEPARATE LIVING VEGETATION FROM BACKGROUND SOIL (BOTTOM RIGHT). A SIMILAR METHOD WAS USED FOR MEASUREMENT OF OVERSTOREY VEGETATION.

VALIDATION OF DIGITAL PHOTOGRAPHY OF UNDERSTOREY VEGETATION

The digital photography method was originally developed to estimate overstorey LAI and has not been validated for understorey LAI in eucalypt forests. For validation of the method, we used digital cover images of 70 pots containing six-month old glasshouse-grown seedlings of *Eucalyptus globulus*. Each pot contained at least seven seedlings. Images were taken 2 m above each pot (Figure 3) before biomass was harvested. For each pot, a specific area was marked around the pot to estimate leaf area per unit ground surface area. Images were cropped to this area before leaf area was digitally analysed (Figure 3). Once the digital photography had been completed, the aboveground biomass was removed and total biomass (leaves and stems) and fresh leaves were weighed. The amount of leaf area was measured using a leaf area meter (LI-3000 C, LI-COR, USA). For this, all leaves were carefully removed from their stems and fed through the leaf area meter. The process of measuring leaf area was very time-consuming (on average 40 minutes for each pot) and, while leaves were kept as fresh as possible, it was inevitable that wilted samples needed to be excluded from leaf area measures. However, leaf biomass included all of the leaves in each sample.

FIGURE 3 IMAGES OF SEEDLINGS OF *EUCALYPTUS GLOBULUS* BEFORE HARVESTING (LEFT AND BOTTOM RIGHT) AND DIGITAL ANALYSIS OF LEAF AREA (TOP RIGHT).

MODELLING VEGETATION WATER USE

Water use of individual trees (Q, L ha^{-1} day^{-1}) was inferred from sapwood area (SA, cm^2) using models developed by Pfautsch *et al*. (2010):

$$Q = 79.31 + \frac{7.44 - 79.31}{1 + (SA/367.16)^{4.58}}$$ for sapwood area >200 cm^2

$$Q = 0.63 + 0.06SA + 0.0002SA^2$$ for sapwood area <200 cm^2

Sapwood area was estimated from the basal area (BA) of the stem using the relationship developed by Mitchell *et al*. (2012):

$$SA = 0.88BA^{0.76}$$

The sum of individual tree's water use divided by the plot size gives an estimate of forest water use per hectare.

MODELLING LEAF AREA INDEX FROM LANDSAT IMAGERY

In this study, plots were located on flat to gently sloping terrain (<10˚) and the size of the plot used was compatible with stand structure of dry sclerophyll forest and Landsat pixel size (30 m). Cloud-free Landsat 8 imagery of the study area was obtained from the US Geological Survey (USGS) archive at: http://earthexplorer.usgs.gov/

Geographic coordinates of the corners of the plots were used to choose the corresponding scenes (each Landsat scene is identified with a path and row number which identifies the spatial coverage of the passing satellite) for the timeframe closest to our sampling time in the field. Details of the Landsat product used in this study are given in Table 1.

TABLE 1 DESCRIPTION OF THE LANDSAT DATA SELECTED FOR ESTIMATING NDVI AND MODELLING LEAF AREA INDEX. FRB = FUEL REDUCTION BURN

State	FRB name	Ignition date	Path-row	Measurement date	Landsat acquisition date
ACT	Googong	11/3/2015	90–85	1 Apr 2015	26 May 2015
ACT	Tidbinbilla	17/3/2015	90–85	1–2, 20–21 Apr 2015	26 May 2015
ACT	Cotter	30/3/2015	90–85	23, 29–30 Apr 2015	26 May 2015
ACT	Wrights Hill	18/3/2015	90–85	30 Apr 2015	26 May 2015
NSW	Joadja	5–22/4/2016	90–84	26–27 Apr 2016	28 Apr 2016
NSW	Martin Creek	8–10/3/2016	90–84	18–19 Apr 2016	28 Apr 2016
NSW	Lakesland	13–18/9/2015	90–84	21–22 Oct 2015	4 Dec 2015
NSW	Spring Gully	14–24/8/2015	90–84	16–17 Sep 2015	4 Dec 2015
NSW	Helicopter Spur	17–24/8/2015	90–83	24–25 Sep 2015	1 Oct 2015
NSW	Paterson	19/8/2015	90–83	30 Sep–1 Oct 2015	1 Oct 2015
NSW	Haycock Trig	19–24/8/2015	90–83	8–9 Sep 2015	15 Sep 2015
NSW	Left Arm	1–3/4/2016	90–83	17–18 May 2016	14 May 2016
NSW	Kief Trig	14–17/4/2016	90–83	4–6 May 2016	14 May 2016

Surface reflectance in the red (ρRED) and near-infrared (ρNIR) bands were extracted from the satellite images and NDVI calculated for each plot:

$$NDVI = \frac{(\rho_{NIR} - \rho_{RED})}{(\rho_{NIR} + \rho_{RED})}$$

Linear regressions were used to model LAI_{total} from Landsat NDVI. Regression coefficients of the models were specific to three main study areas in the ACT and Nattai and Hawkesbury management regions. A model is presented for sites in the ACT as a case study to map the impact of FRB on water availability.

RESULTS AND DISCUSSION

Plant biomass is directly related to the amount of leaf area (R^2 = 0.96; Figure 4). In the field, the variation in leaf area index was 31% for overstorey trees and 52% for the understorey. Values for LAI ranged from 0.45–2.68 with the highest being associated with sites near the coast of NSW (Table 2). Understorey LAI measured with digital photography correlated strongly with LAI measured for seedlings of *E. globulus* (R^2 = 0.92; Figure 5). Validation of digital photography indicated that the methodology developed for the overstorey can be used to estimate LAI of the understorey, by replacing parameters relevant to the understorey (i.e. crown porosity and light extinction coefficient in the LAI and f_c equations).

TABLE 2 TREE SIZE AND COVER OF OVERSTOREY AND UNDERSTOREY COMPONENTS OF FOREST MEASURED IN THE ACT AND NSW (BURNT AND UNBURNT). FRB = FUEL REDUCTION BURN; DBH = DIAMETER AT BREAST HEIGHT; LAI = LEAF AREA INDEX

State	FRB name	Overstorey trees		Understorey trees/shrubs	
		DBH (mean ± SD; cm)	LAI (mean ± SD)	DBH (mean ± SD; cm)	LAI (mean ± SD)
ACT	Googong	21.8 ± 12.3	0.85 ± 0.27	1.8 ± 0.9	0.11± 0.02
ACT	Tidbinbilla	27.7 ± 24.3	0.95 ± 0.24	1.8 ± 1.3	0.52 ± 0.45
ACT	Cotter	40.6 ± 19.7	0.75 ± 0.19	1.3 ± 1.0	0.37 ± 0.32
ACT	Wrights Hill	27.9 ± 15.0	0.91 ± 0.10	2.5 ± 2.0	0.31± 0.23
NSW	Joadja	22.6 ± 13.7	0.63 ± 0.28	2.0 ± 1.8	1.45 ± 0.64
NSW	Martin Creek	21.4 ± 11.0	1.28 ± 0.14	1.2 ± 1.1	2.95 ± 0.33
NSW	Lakesland	22.7 ± 11.9	1.42 ± 0.23	1.4 ± 1.2	3.27 ± 0.54
NSW	Spring Gully	16.9 ± 13.0	1.67 ± 0.31	3.2 ± 2.9	3.86 ± 0.73
NSW	Helicopter Spur	19.5 ± 9.3	1.09 ± 0.40	1.4 ± 1.4	2.51± 0.92
NSW	Paterson	18.0 ± 8.2	1.20 ± 0.43	1.1± 1.2	2.77 ± 1.00
NSW	Haycock Trig	21.2 ± 11.8	0.72 ± 0.20	1.6 ± 1.4	1.67 ± 0.47
NSW	Left Arm	21.4 ± 11.4	1.05 ± 0.24	1.5 ± 1.3	2.43 ±0.56
NSW	Kief Trig	25.4 ± 16.8	0.67 ± 0.21	1.4 ± 1.4	1.56 ± 0.49

At the plot-level, total water use (sum of overstorey and understorey tree water use divided by the plot area) was positively related to total leaf area (understorey and overstorey). We also found that NDVI was particularly sensitive to changes in the combined overstorey and understorey LAI (LAI_{total}), particularly for understorey LAI (Table 3). Because of this close relationship it was possible to relate the plot-level Q (L ha^{-1} day^{-1}) to LAI_{total} (Figure 6). We used the strong correlation between Landsat NDVI and ground measurements of LAI (Table 3) to model LAI across the landscape using Landsat NDVI (Figure 7). Landscape level maps of LAI, determined for the periods before and after fuel-reductions burns, were then used to upscale plot-level measurements of Q to the landscape-scale for the periods before and after fuel-reduction burns. This allowed us to investigate the potential impact of FRB on water availability in the forests investigated (Figure 8).

TABLE 3 PEARSON'S CORRELATION COEFFICIENT FOR GROUND BASED LEAF AREA INDEX (LAI), LANDSAT NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) AND VEGETATION WATER USE (Q, L HA^{-1} DAY^{-1}) FOR THREE MAIN STUDY AREAS SEPARATED ACCORDING TO THE SPATIAL PROXIMITY OF STUDY SITES (SEE FIGURE 1). ns = NOT SIGNIFICANT, OVER = OVERSTOREY, UNDER = UNDERSTOREY

Study area	LAI_{total}/ NDVI	LAI_{over}/ NDVI	LAI_{under}/ NDVI	Q_{total}/ LAI_{total}	Q_{over}/ LAI_{over}	Q_{under}/ LAI_{under}
ACT	0.83	ns	0.81	0.54	ns	0.67
Nattai, NSW	ns	ns	0.62	0.71	ns	0.89
Hawkesbury, NSW	0.52	0.39	0.39	0.60	0.48	0.82

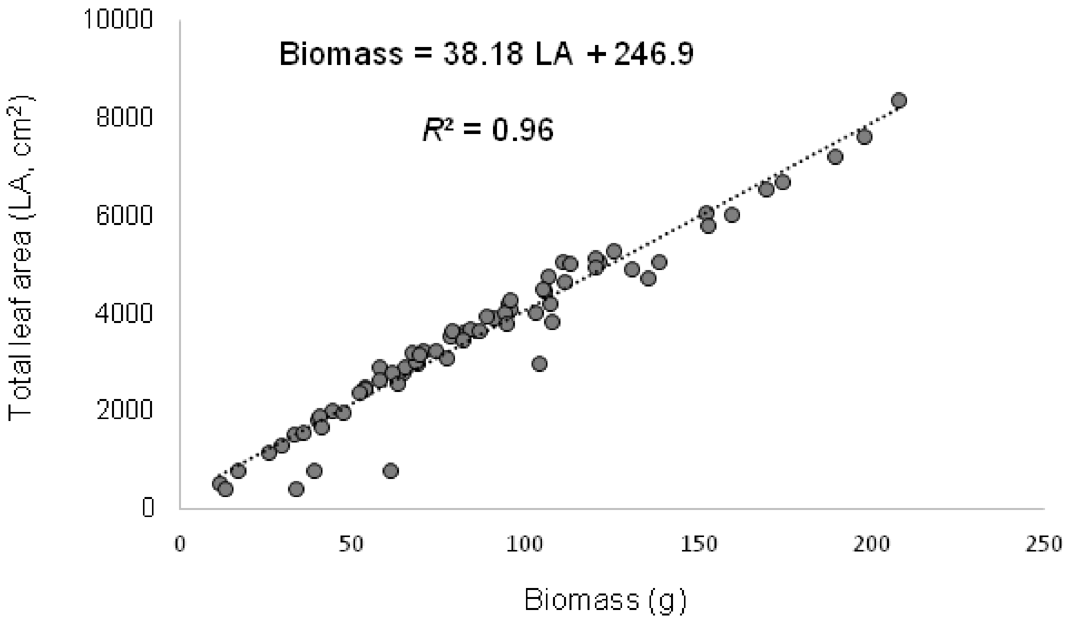

FIGURE 4 RELATIONSHIP BETWEEN BIOMASS AND LEAF AREA OF GLASSHOUSE-GROWN SEEDLINGS OF *EUCALYPTUS GLOBULUS*.

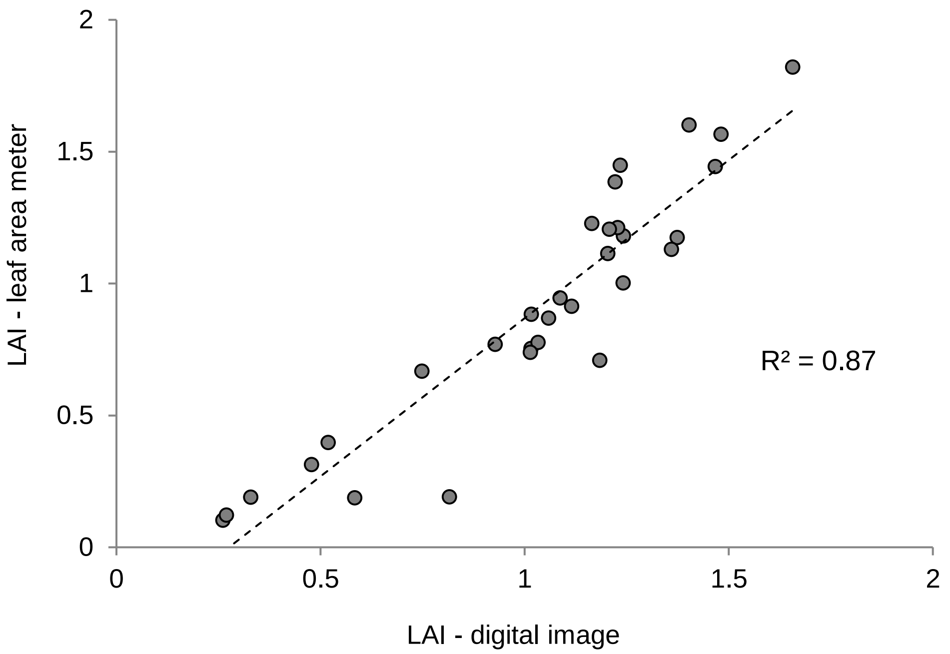

FIGURE 5 RELATIONSHIP BETWEEN LEAF AREA INDEX (LAI) MEASURED FROM DIGITAL IMAGES (LAI – digital image; x-axis) WITH LAI MEASURED FROM GLASSHOUSE-GROWN SEEDLINGS OF *EUCALYPTUS GLOBULUS* (LAI – leaf area meter; y-axis).

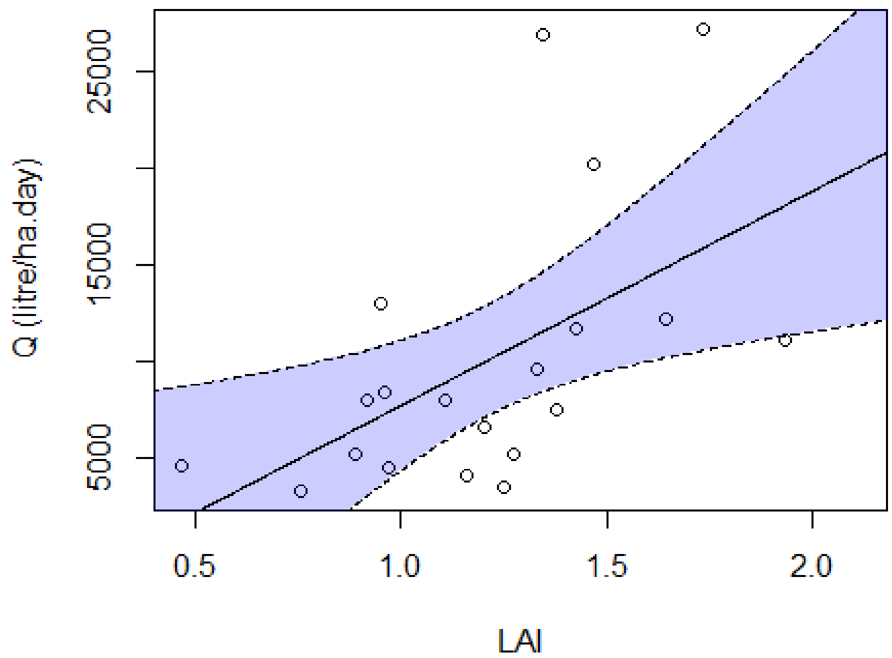

FIGURE 6 RELATIONSHIP BETWEEN MEASURED LEAF AREA INDEX (LAI_{total}) AND PLOT-LEVEL WATER USE DEVELOPED AS A CASE STUDY FOR SITES IN THE ACT (p <0.05, R^2 = 0.30; Q = 11107 LAI_{total} – 3410). THE SHADED AREA MARKS THE 95% CONFIDENCE INTERVAL (α = 0.05).

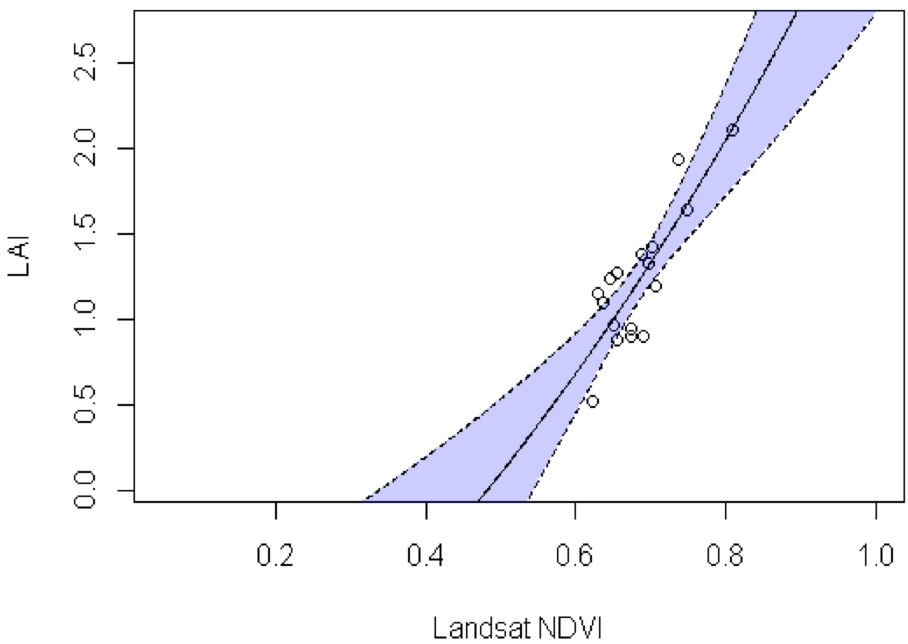

FIGURE 7 RELATIONSHIP BETWEEN LANDSAT NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) AND LEAF AREA INDEX (LAI) AS A CASE STUDY FOR SITES IN THE ACT WHICH ALLOWS FOR MODELLING OF LAI FOR BEFORE AND AFTER FUEL REDUCTION BURNING ACROSS THE CATCHMENT (p <0.05; R^2 = 0.69; $LAI_{total} = 0.04\ e^{4.88\ NDVI}$). THE SHADED AREA MARKS THE 95% CONFIDENCE INTERVAL (α = 0.05).

We used the relationship between plot-level tree water use and LAI to investigate the potential impact of FRB on water availability in forests. From the model developed as a case study using the sites in the ACT, a 1 unit reduction in total LAI will result in 11,100 L ha^{-1} day^{-1} reduction in forest water use across the landscape. Water that is not used by the vegetation as a result of its removal by FRB, contributes to the overall water stock. Modelled LAI based on NDVI was used to map Q and this provided useful detail about the distribution of the impact of low intensity fire at the catchment scale.

The average annual rainfall for the Googong area (the location of the case study) is 600 mm (for the years 2005–2011; Bureau of Meteorology). After mapping the impact of a FRB, we estimated a change in water availability of up to 400 mm in parts of the landscape (dark blue color in Figure 8). This is equivalent to 60% of the annual rainfall that is ultimately affected by the FRB (Figure 8). Areas of smaller decreases in LAI associated with areas of the landscape with greater topographic wetness (i.e. at the bottom of slopes and along drainage lines). For a given burn condition, an area where the vegetation uses more water is potentially more affected by a FRB. Using this methodology, land managers can identify hydrologically sensitive areas in accordance with their management objectives, as well as assess pot-burn impacts on catchment water availability.

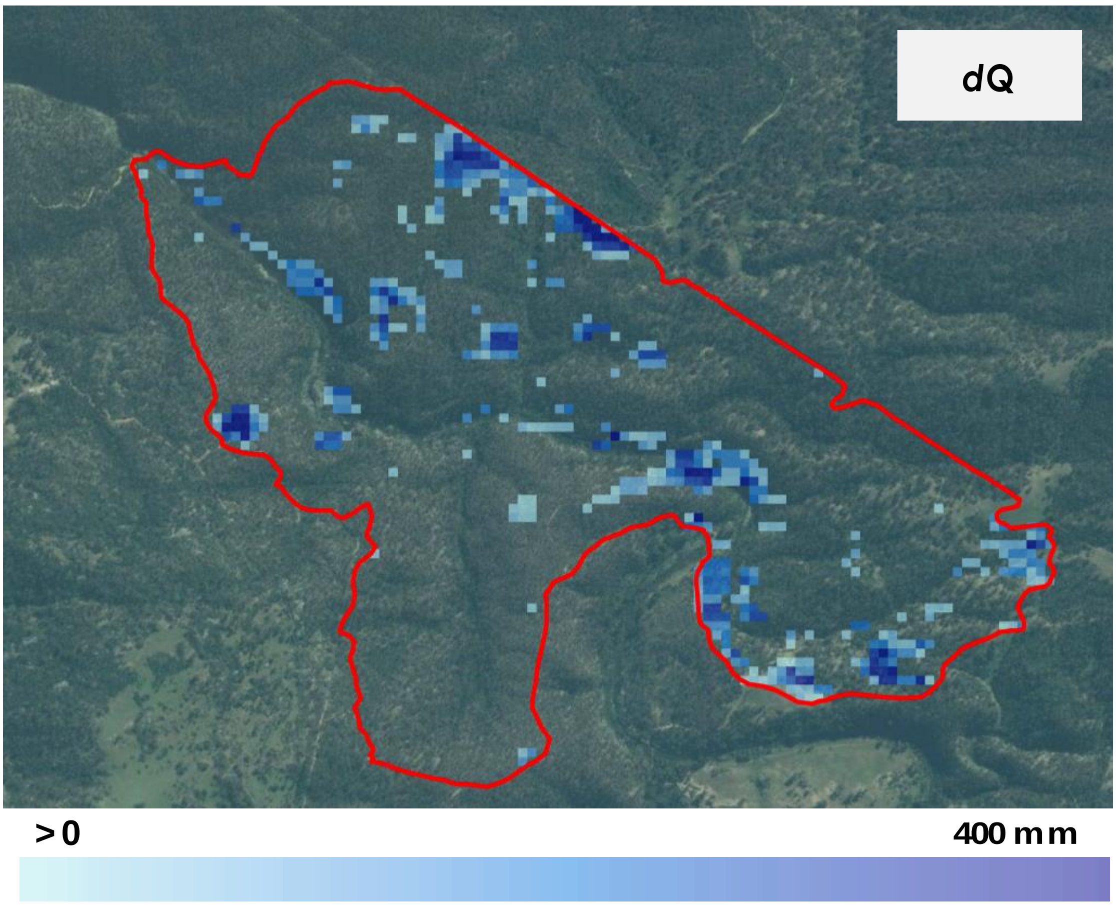

FIGURE 8 MAP OF CHANGES IN THE FOREST WATER USE AFTER FUEL-REDUCTION BURNING IN THE GOOGONG BURN (280 HA) IN THE ACT ($dQ = Q_{pre\ burn} - Q_{post\ burn}$). RED LINE MARKS THE BURN BOUNDARY.

While FRB can have an immediate impact on the hydrological cycle in a catchment, vegetation regeneration processes combined with predominant hydrological flows need to be considered to assess the longer term impact of FRB.

Uncertainty in the impact of FRB on water varies with the type of model developed. Such uncertainty can be reduced by using ancillary information about vegetation type and site conditions. While, at this stage, our approach is purely empirical, future steps will include collection of additional data related to our field sites including physical components of the catchment to improve the estimation of the impact of FRB on water availability.

Acknowledgements

We thank Erika De Almeida for validation of the digital photography method for measurement of foliage cover to provide a non-destructive estimate of biomass and leaf area index of understorey vegetation. Erika's research was part of the Study Abroad Internship Program for the University of Sydney from November 2015–January 2016. We also thank Dr Karanjeet Sandhu from the Plant Breeding Institute, University of Sydney for supplying seedlings for the validation project.

We thank Adam Leavesley from the ACT Parks and Conservation Service, and Raf Pedroza, Adrian Johnstone, Glenn Meade, Sarah Brookes and Vicki Elliott from the NSW National Parks and Wildlife Service for access to information and sites for fuel reduction burns and help with field work.

We thank Ariana Iaconis, Marco Harbusch, Vicky Aerts, Felipe Salvo Aires, Bonnie Cannings, Nicole Piaskowski, Mengran Yu, and Angela Gail Gormley for their help in the field.

REFERENCES

1. Bi H, Turner J, Lambert M J (2004) Additive biomass equations for native eucalypt forest trees of temperate Australia. *Trees* 18, 467-479.
2. Boer MM, Macfarlane C, Norris J, Sadler RJ, Wallace J, Grierson PF (2008) Mapping burned areas and burn severity patterns in SW Australian eucalypt forest using remotely-sensed changes in leaf area index. *Remote Sensing of Environment* 112, 4358-4369.
3. Breda N J J (2003) Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *Journal of Experimental Botany* 54(392), 2403-2417.
4. Brown S (2002) Measuring carbon in forests: current status and future challenges. *Environmental Pollution* 116(3), 363-372.
5. Carlson TN, Ripley DA (1997) On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment* 62(3), 241-252.
6. Coops N, Delahaye A, Pook E (1997) Estimation of eucalypt forest leaf area index on the south coast of New South Wales using Landsat MSS data. *Australian Journal of Botany* 45(5), 757-769.
7. Fuentes S, Palmer A R, Taylor D, Zeppel M, Whitley R, Eamus D (2008) An automated procedure for estimating the leaf area index (LAI) of woodland ecosystems using digital imagery, MATLAB programming and its application to an examination of the relationship between remotely sensed and field measurements of LAI. *Functional Plant Biology* 35(9-10), 1070-1079.
8. Gharun M, Possell M, Bell T (2015) Sampling schema for measurement of the impact of prescribed burning on load, fuel, carbon, water and vegetation. Bushfire and Natural Hazards CRC report.
9. Jenkins M E, Bell T L, Poon L F, Aponte C, Adams M A (2016) Production of pyrogenic carbon during planned fires in forests of East Gippsland, Victoria. *Forest Ecology and Management* 373, 9-16.
10. Macfarlane C, Arndt SK, Livesley SJ, Edgar AC, White DA, Adams MA, Eamus D (2007) Estimation of leaf area index in eucalypt forest with vertical foliage, using cover and fullframe fisheye photography. *Forest Ecology and Management* 242, 756-763.
11. Macfarlane C, Ogden G N (2012) Automated estimation of foliage cover in forest understorey from digital nadir images. *Methods in Ecology and Evolution* 3(2), 405-415.
12. Mitchell PJ, Lane P N J, Benyon R G (2012) Capturing within catchment variation in evapotranspiration from montane forests using LiDAR canopy profiles with measured and modelled fluxes of water. *Ecohydrology* 5(6), 708-720.
13. Pfautsch S, Bleby T M, Rennenberg H, Adams M A (2010) Sap flow measurements reveal influence of temperature and stand structure on water use of *Eucalyptus regnans* forests. *Forest Ecology and Management* 259(6), 1190-1199.
14. Rosenqvist A, Milne A, Lucas R, Imhoff M, Dobson C (2003) A review of remote sensing technology in support of the Kyoto Protocol. *Environmental Science and Policy* 6, 441-455.

15. Vertessy R A, Hatton T J, Benyon R J, Dawes W R (1996) Long term growth and water balance predictions for a mountain ash (*E. regnans*) forest subject to clearfelling and regeneration. *Tree Physiology* 16, 221-232.
16. Waring R H, Running S W (1998) Forest Ecosystems: Analysis at Multiple Scales (2nd edition ed.). San Diego: Academic Press.