

Australian vegetation phenology: new insights from satellite remote sensing and digital repeat photography

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Abstract

Phenology is the study of periodic biological occurrences and can provide important insights into the influence of climatic variability and change on ecosystems. Understanding Australia's vegetation phenology is a challenge due to its diverse range of ecosystems, from savannas and tropical rainforests to temperate eucalypt woodlands, semi-arid scrublands and alpine grasslands. These ecosystems exhibit marked differences in seasonal patterns of canopy development and plant life-cycle events, much of which deviates from the predictable seasonal phenological pulse of temperate deciduous and boreal biomes. Many Australian ecosystems are subject to irregular events (i.e., drought, flooding, cyclones and fire) that can alter ecosystem composition, structure and functioning just as much as seasonal change. We show how satellite remote sensing and ground-based digital repeat photography (i.e., phenocams) can be used to improve understanding of phenology in Australian ecosystems. First, we examine temporal variation in phenology at the continental scale using the Enhanced Vegetation Index (EVI), calculated from MODerate resolution Imaging Spectroradiometer (MODIS) data. Spatial gradients are revealed, ranging from regions with pronounced seasonality in canopy development (i.e., tropical savannas) to regions where seasonal variation is minimal (i.e., tropical rainforests) or high but irregular (i.e., arid ecosystems). Next, we use time series colour information extracted from phenocam imagery to illustrate a range of phenological signals in four contrasting Australian ecosystems. These include greening and senescing events in tropical savannas and temperate eucalypt understory, as well as strong seasonal dynamics of individual trees in a seemingly static evergreen rainforest. We also demonstrate how phenology links with ecosystem gross primary productivity (from eddy covariance) and discuss why these processes are linked in some ecosystems but not others. We conclude that phenocams have the potential to greatly improve current understanding of Australian ecosystems. To facilitate sharing of this information, we have formed the Australian Phenocam Network (<http://phenocam.org.au/>).

Key Words

Phenocam, OzFlux, remote sensing, climate change, MODIS, EVI

1 Introduction

Phenology is the study of the timing of periodic biological occurrences, from flowering and leaf emergence to animal migrations and breeding patterns, all of which vary between and within species and are influenced to a certain degree by the climate (Lieth, 1974; Richardson et al., 2013a). Phenological monitoring allows us to quantify and track seasonal cycles and irregular natural events,

as well as how vegetation phenology responds to meteorological events and climate change. At the ecosystem level, the timing of leaf emergence and senescence in plants has a major influence on the length of the growing season (Dragoni et al., 2011; Keenan et al., 2014b). At larger scales, phenological responses feed back to the climate system by altering the land surface energy balance and the coupled cycles of water, carbon and nutrients from an ecosystem (Peñuelas et al., 2009; Richardson et al., 2013a). Research suggests that contemporary warming has advanced spring onset in the northern hemisphere by *ca.* 2.8 days per decade since the 1970's (Parmesan, 2007), with even higher rates of change (4.8 days per decade) in more recent decades (Keenan et al., 2014b). Likewise, in the southern hemisphere, advancement in spring onset has been estimated at a rate of 2.2 days per decade (Chambers et al., 2013).

In response to increasing evidence of earlier spring onsets, the Intergovernmental Panel on Climate Change (IPCC) has placed a high importance on the gathering and interpretation of phenology observations to improve our understanding of the ecological impacts of climate change (Ciais et al., 2013). Understanding the processes that lead to modifications in phenology, as well as the complex links between phenological shifts and climatic variability and change at local, regional and global scales, requires more detailed field-based observations that underpin larger scale remote sensing and ecological modelling tools (de Jong et al., 2012; Migliavacca et al., 2012; Melaas et al., 2013).

Repeat photography with digital cameras (phenocams) has emerged as a powerful observational tool for ecological research and evaluation of remote sensing data products and model simulations (Richardson et al., 2007; Migliavacca et al., 2011; Hufkens et al., 2012; Wingate et al., 2015; Brown et al., 2016). Digital images collected from phenocams typically provide red-green-blue (RGB) colour channel information that can be partitioned and converted to quantitative indices (Woebbecke et al., 1995; Gillespie et al., 1987; Sonnentag et al., 2012). These indices have been shown to closely track vegetation colour changes, such as canopy greenness, and are indicative of different plant development stages in a variety of ecosystems (Sonnentag et al., 2011; Inoue et al., 2014; Keenan et al., 2014a; Peichl et al., 2014; Toomey et al., 2015). A loosely organized global phenocam network is emerging with regional networks including the PhenoCam Network (Richardson et al., 2009a) and the National Ecological Observatory Network (NEON) in the USA (Keller et al., 2008), the EUROPhen network in Europe (Wingate et al., 2015; Brown et al., 2016), the Phenological Eyes Network (PEN) in Japan (Nasahara and Nagai, 2015) and most recently, the Australian Phenocam Network (Brown et al., 2016). These networks provide support for phenocam data collection and sharing in the wider scientific community and are a platform for the development of open data and data sharing standards.

Phenology information can also be derived from satellite remote sensing imagery. Satellite data provides spatially explicit time series of vegetation phenology proxies such as the enhanced vegetation index (EVI, Huete et al., 2002), and the normalised difference vegetation index (NDVI,

Tucker, 1979), as well as estimates of canopy cover fraction, the fraction of absorbed photosynthetically active radiation and leaf area index (LAI) derived from optical remote sensing (Gonsamo and Chen, 2014). In addition, vegetation optical depth and biomass can be derived from radar or passive microwave remote sensing (Andela et al., 2013;Liu et al., 2013;Liu et al., 2011;Liu et al., 2007). Such remotely sensed vegetation phenology proxies can be analysed to estimate temporal changes in the vegetation characteristics at the landscape scale and contribute toward the development of satellite phenology products, such as the MODerate resolution Imaging Spectroradiometer (MODIS) Land Cover Dynamics product (Ganguly et al., 2010), and the Australian satellite land surface phenology product (Broich et al., 2015).

Satellite-derived phenology can be compared to changes observed at smaller scales with phenocams. For example, Hufkens et al. (2012) and Klosterman et al. (2014) used phenocams to evaluate the MODIS MCD12Q2 product for deciduous forests in the north-eastern USA. Despite discrepancies related to spatial scale and site representativeness, the results showed good agreement between the phenocam- and satellite-derived timing of phenological events (i.e., phenophases). For various temperate and boreal forest, grassland and peatland ecosystems, time-series data of canopy greenness derived from phenocam imagery have been used to analyse seasonal changes of net ecosystem exchange (NEE) and gross primary productivity (GPP) (Ahrends et al., 2009;Richardson et al., 2007;2009b;Zhu et al., 2013;Toomey et al., 2015). Characterising changes in plant physiology (Keenan et al., 2014a), modelling of canopy development (Wingate et al., 2015) and quantifying inter-annual variation in phenology (Inoue et al., 2014) have also been achieved using phenocams. Despite the promising applications of phenocam data in North America, Europe and Asia, there has been a slow uptake of phenocam research in Australia; a continent characterized by diverse ecosystem types often with distinctly different phenological characteristics compared to temperate and boreal deciduous ecosystems (Chambers et al., 2013).

The diversity of Australian ecosystems, and their marked differences to northern hemisphere temperate deciduous and boreal biomes, poses the challenge of how to best define and quantify vegetation phenology signals, especially due to their responses to irregular natural events such as rainfall, flooding, fire and extreme temperatures. While the traditional definition of the term *phenology* as the “*timing of recurrent biological events*” (Lieth, 1974) is generally assumed to apply to seasonally cyclical events, such as canopy bud burst and senescence in winter-deciduous forests, a closer look at life patterns in many Australian biomes yields a more complex picture of non-seasonal, yet still periodic, events as the major drivers of phenology (Specht and Brouwer, 1975;Pook et al., 1997;Ma et al., 2015).

In this synthesis, we examine the drivers of plant phenological cycles across Australia, illustrate the potential measurement tools available, and suggest future avenues of required research. At the

national scale, we demonstrate how satellite observations can be used to characterize broad-scale phenological variability across the continent, and discuss the major drivers underlying these patterns. At the ecosystem scale, we highlight the value of using digital image archives obtained from phenocams installed at a selection of contrasting OzFlux sites (Australian and New Zealand flux tower network, see Beringer et al. (2016)), for examining the phenology of canopies and individual plants in Australian ecosystems. We discuss how greenness information obtained from phenocam imagery can be compared with flux tower estimates of GPP and why such relationships are stronger from some Australian ecosystems than for others. Finally, we assess the feasibility and effectiveness of phenocams for continuously observing Australia's diverse ecosystems.

2 Drivers of phenology in Australia

Australian ecosystems include a diverse range of biomes spanning from tropical savannas and rainforests in the north, to arid and semi-arid shrublands and grasslands in the centre and finishing with temperate evergreen forests and woodlands in the south (see Beringer et al. (2016) in this issue for more climate and biome information). Stern and Dehani (2013) recently identified the major climate zones in Australia as ranging from equatorial and tropical in the north, through to subtropical, desert, grassland, temperate and polar in the south. This wide-ranging climatic variability results in long-term mean annual rainfall ranging from 134 to 2804 mm and mean annual air temperature ranging from 3.8 to 29.0 °C (from 1961-1990 data gridded at 0.1 degrees (Australian Bureau of Meteorology, 2013)). Therefore, Australian vegetation has adapted a number of unique phenologies to respond to these climatic drivers.

Temperature is an important phenological driver in Australian ecosystems (Chambers et al., 2013), just as it is in temperate deciduous and boreal ecosystems in the northern hemisphere. However, Australian ecosystem dynamics are arguably influenced more strongly by the availability of water, because 70 % of its land mass is classified as arid or semi-arid (Chambers et al., 2013). The response of LAI and vegetation cover to rainfall events, mean annual rainfall and the corresponding soil water availability is well documented (Pook, 1985; Specht and Specht, 1989; Ellis and Hatton, 2008; Donohue et al., 2009; 2013; Andela et al., 2013; Duursma et al., 2016). Similarly, vegetation density closely follows climate gradients in average rainfall (Ellis and Hatton, 2008; Donohue et al., 2009; Hutley et al., 2011; Ma et al., 2013). Large-scale variability in climatic conditions governs vegetation distribution across the continent and most Australian vegetation has adapted in some form around the need to maintain a balance between water access and water loss.

Among the exceptions to this concept are temperate and tropical rainforest ecosystems found along the east coast of the continent, where rainfall is almost continually in excess of water requirement. In contrast, C4 grass phenology is driven by wet season rainfall across Australia's tropical savanna ecosystems whilst the C3 eucalypt overstory remains relatively static throughout the year, supported

by access to deeper soil water reserves (Walker and Langridge, 1997; Eamus et al., 2002; Hutley et al., 2011). Recurrent dry spells and droughts are often associated with high mortality events in south-western Australia (Evans and Lyons, 2013; Matusick et al., 2013) and in both riparian (Davies et al., 2008; Gehrke et al., 2006) and non-riparian trees (Semple et al., 2010) in south-eastern Australia. Over longer timescales, non-seasonal shifts in temperature and rainfall, as well as second order effects on soil water availability, have been attributed to forest declines (Evans et al., 2013) and mortality (Evans and Lyons, 2013).

Fire events commonly occur in Australia and are often triggered by drought and dry conditions, which are not traditionally regarded as phenological drivers but nonetheless have a cyclical character in many Australian ecosystems (Maier and Russell-Smith, 2012). Most eucalypt forests in Australia suffer periodic burning and have adapted strategies to allow prompt regrowth after fire (epicormic growth) to obtain a rapid photosynthetic advantage over other vegetation competing for light (Hodgkinson, 1998; Burrows, 2008). Drought can also trigger insect attacks, which have been observed to result in rapid canopy defoliation and ecosystem carbon loss in a eucalypt forest in south-eastern Australia (Keith et al., 2012; van Gorsel et al., 2013). Seasonal grazing due to insects and other arboreal browsers is another periodic disturbance in Australian ecosystems that can inhibit new leaf production and greatly modify the canopy, thus thwarting phenology responses observable in these ecosystems (Lowman, 1985; Specht, 1985; Melzer et al., 2000).

Temporal variations in leaf colour, although not as pronounced as in temperate deciduous forests, do occur in evergreen species that dominate Australian ecosystems. For example, eucalypt leaves can contain large amounts of anthocyanin, causing a reddening of the leaf surface (Sharma and Crowden, 1974). While there is no general consensus on why anthocyanins are present in leaves (Gould et al., 2000), their accumulation is associated with the expansion and subsequent predation of young foliage (Close and Beadle, 2003), nutrient deficits that affect photosynthesis (Terashima and Evans, 1988; Sugiharto et al., 1990) or as a protection against solar radiation (Gould, 2004). Accumulation of foliar anthocyanin has been observed in leaves of many Australian plant species (Nittler and Kenny, 1976; Hodges and Nozzolillo, 1996; Kumar and Sharma, 1999; Close et al., 2000; 2001a; 2001b), as well as reddening of adult leaves due to a changing anthocyanin to chlorophyll ratio when exposed to stressors such as cold or drought (Close et al., 2001a; Stone et al., 2001; Barry et al., 2009). In other cases, exposure to stressful processes can result in a decrease in leaf chlorophyll content, accompanied by or the precursor to, visible chlorosis (Coops et al., 2004). Such leaf reddening events are visible and often occur in a cyclical manner, therefore they can be considered as phenological in nature and may be identified by phenocams. The examples listed in this section illustrate the wide ranging drivers of vegetation phenology in Australian ecosystems and highlight the need for continued research to better understand how phenology may respond to climate change in the future.

3 Continental scale phenology from satellite sensors

To characterize the phenological diversity of Australian ecosystems at the continental scale, we used satellite remote sensing observations to map land surface seasonal variability in measures of vegetation greenness. For this, we used EVI as a phenology indicator to construct an EVI seasonality map for Australia using 8-day composites of spectral reflectance observations from MODIS (MCD43C4.005 product) at 0.05 degree (c. 5 km) resolution for the period 2000-2012. We calculated EVI (Huete et al., 2002) as Eq. (1):

$$EVI = G \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + L + C_1 \rho_{red} - C_2 \rho_{blue}} \quad (1)$$

where ρ_{NIR} , ρ_{red} , and ρ_{blue} are atmospherically corrected spectral reflectance in near-infrared, red and blue wavelength ranges, respectively; G is a gain factor ($G = 2.5$); C_1 and C_2 are aerosol resistance coefficients ($C_1 = 6$, $C_2 = 7.5$); and L is a soil-adjustment factor ($L = 1$). Values of EVI below 0 and above 1 were removed, as these pixels were either contaminated by cloud or open water.

The mean seasonal pattern for each pixel, based on variability in EVI from 2000-2012, was calculated as the mean annual pattern in 8-day values over the 13 years. Subsequently, this seasonal pattern was subtracted from the time-series for each pixel to yield seasonally adjusted anomalies. We then calculated (i) the standard deviation in these seasonally adjusted anomalies ($n=585$), as well as (ii) the overall mean EVI and (iii) the standard deviation of the mean seasonal pattern ($n=45$). Combining these three measures allowed us to distinguish areas in Australia where the phenological signal was primarily ‘non-seasonally dynamic’ (EVI varied but not in accordance with seasons), ‘constantly high’ (EVI remained high year-round), or ‘seasonally dynamic’ (EVI showed regular seasonal variability).

To explore phenological variability in more detail around Australia, EVI is displayed by time series plots for selected sites (Fig. 1; A – F). Our continental phenological response map shows the tropical region of northern Australia (Fig. 1; A & B) experiences a predictable seasonal phenology, as it receives reliable summer monsoon rainfall (Cook and Heerdegen, 2001). In contrast, large areas of Australia are characterised by non-seasonal variability in vegetation cover (Fig. 1, C). These areas primarily fall within the arid interior, as well as in the south-western and south-eastern subhumid regions, where rainfall variability has been particularly strong during the observation period, including the worst multi-year drought on record (Van Dijk et al., 2013; Broich et al., 2014).

Tropical savanna ecosystems in northern Australia depict both seasonal (monsoon driven) and non-seasonal changes (fire driven), represented by EVI for Howard Springs (location A), which has a high level of variability as shown by the highest amplitude in EVI for all sites (i.e., amplitude of 0.31, Fig. 1; A). In contrast, the tropical rainforest at Cape Tribulation (location B) shows a regular but low level

of seasonal variability where the amplitude varies much less than that for site A (i.e., amplitude of 0.15, Fig. 1; B). An exception to this regular cycle is the impact of cyclone Larry in early 2006. Cape Tribulation is located nearby and within the same tropical rainforest as the Cow Bay OzFlux site (Fig. 1; B). Both sites show the same seasonal trend and these changes in EVI can be related to changes in NEE that are observed at the OzFlux towers at both sites (Beringer et al., 2016).

Further inland, floodplain vegetation in the arid Channel Country (location C) responds primarily to infrequent and irregular flood events produced in the large upstream catchment. For a flood event in 2010, the time-series shows an initial reduction in EVI (open water produces negative EVI (Huete et al., 2002)) with a subsequent green flush (i.e., amplitude increases from 0.1 to 0.48, Fig. 1; C). The Western Australian wheat belt (location D) shows a winter peak in vegetation (i.e., Jun-Sep in the southern hemisphere), corresponding with maximum leaf area before the cropping of winter wheat (i.e., EVI amplitude of 0.41, Fig. 1; D). In contrast to location C, the year 2010 was the driest on record with poor harvests, recognisable as a lower EVI signal for that year at location D. Sub-tropical evergreen forests on the central New South Wales (NWS) coast (location E) show a seasonal cycle (i.e., amplitude of 0.20, Fig. 1; E) more like that of tropical rainforests further north (location B), which is most likely a phenological adaptation to rainfall during both summer and winter (Bowman, 2000). Highland vegetation in Tasmania (location F) shows a summer green phenology that is more reminiscent of temperate forest ecosystems in the northern hemisphere. These selected examples suggest that for most, but not all, of Australia's ecosystems it is not temperature or radiation but water availability and extreme events that drive vegetation phenology. Furthermore, in addition to the more or less predictable seasonal variations in precipitation, there is very strong variability in rainfall between years due to the strong influence of ocean circulation modes such as the El Niño Southern Oscillation, Indian Ocean Dipole, Southern Annular Mode and Pacific Decadal Oscillation (Van Dijk et al., 2013; Broich et al., 2014; Cleverly et al., 2016).

4 Ecosystem scale phenology from phenocams

Digital repeat photography has already been shown to provide high temporal resolution phenology information throughout many vegetation biomes in the northern hemisphere (i.e., Richardson et al. (2007); Migliavacca et al. (2011); Sonnentag et al. (2012); Keenan et al. (2014a); Klosterman et al. (2014); Toomey et al. (2015)). Images collected by phenocams are typically stored in JPEG format with red, green, blue (RGB) digital numbers (DN) for each pixel in the image. Raw image format can also be used, which is discussed in detail by Richardson et al. (2013b) and Brown et al. (2016). Variability in scene illumination can affect the RGB brightness levels (Woebbecke et al., 1995; Richardson et al., 2007), which can be minimised by using a transformation of the RGB numeric values to chromatic coordinates (Gillespie et al., 1987; Woebbecke et al., 1995; Sonnentag et al.,

2012). Of these indices, the green chromatic coordinate (GCC) has been identified as the most relevant to green vegetation phenology, given by Eq. (2):

$$GCC = G / (R + G + B) \quad (2)$$

where R, G and B are the per-pixel DN stored in the image, recorded as arbitrary units of intensity by the camera's charge coupled device. GCC is calculated for each pixel of the image, and then averaged over a user-defined region of interest (ROI). The red (RCC) and blue (BCC) chromatic coordinates were also calculated, in the same way as GCC in Eq. (2). We calculated chromatic coordinates using only images collected between the hours of 10 am and 4 pm, based on local site time, to reduce the bias of seasonal solar radiation change on the 'daily' values, which is a common phenocam analysis technique (Sonnentag et al., 2012; Filippa et al., 2016).

An advantage of being able to transform the phenocam images into these quantitative indices is that it allows for automated quality control of the data. This is important when a large network of automated measurements is being considered at a continental and global scale (Brown et al., 2016). Automated quality assurance and quality control (QA/QC) routines are regularly used for large-scale processing of other network data, including ecosystem flux data such as OzFlux (Beringer et al., 2016; Isaac et al., 2016), and continental scale observatories such as NEON (Taylor and Loescher, 2013) and TERN (Karan et al., 2016). Furthermore, these automated routines can allow for the fast calculation of online summary metrics that can be used for diagnosing instrument problems and highlighting potential flaws in data collection (Smith et al., 2014). As a result, instrument downtime can be minimized and data collection can be optimized across a large network of sensors.

4.1 Insights from existing phenocams

To demonstrate the utility of phenocams for monitoring *in-situ* vegetation phenology in Australian ecosystems, we calculated GCC from image data sets from four contrasting ecosystems in Australia; Cow Bay (AU-Cow, Fig 1; site 1), Howard Springs (AU-How, Fig 1; site 2), Tumbarumba (AU-Tum, Fig 1; site 3) and Whroo (AU-Whr, Fig 1; site 6). We used R software (R Core Team, 2013) to extract and calculate chromatic coordinates (Eq. 2) from phenocam images collected between the hours of 10 am and 4 pm at local site time (i.e. AEST or ACST). Temporal coverage varied for each camera, so we analysed all available images within the 10 am to 4 pm timeframe and calculated a daily average value of GCC, RCC and BCC.

4.1.1 Tropical rainforest

In the EVI phenology map, the Daintree tropical rainforest region (Fig. 1; B) displays constantly high EVI, as greenness varies little throughout the year compared with other sites. Overstory phenology at the evergreen Cow Bay rainforest OzFlux site (AU-Cow) showed GCC of the entire tree canopy was not seasonally dynamic either (Fig. 2). However, six individual tree crowns selected as ROIs and

1 analysed individually revealed a more dynamic variability in GCC (Fig. 2), which fluctuated in line
2 with leaf shedding and flushing events in some trees (Tree 1, Species *Wrightia laevis* and Tree 2,
3 *Acmena graveolens*) or remained relatively constant in others (Tree 3, *Dysoxylum alliaceum* and Tree
4 4, *Cerbera floribunda*). These events were determined via visual inspection of images that clearly
5 revealed leaf loss (Fig. 3). Species-rich ecosystems can include a wide range of phenologies (Wright
6 and van Schaik, 1994; Reich et al., 2004) that become indistinguishable when averaged over the entire
7 ecosystem. In contrast to temperate deciduous and boreal ecosystems in the northern hemisphere,
8 where seasonal dynamics of the canopy are largely temperature-controlled, the changes evident from
9 Cow Bay suggest that the different species respond to a variety of cues, resulting in an apparent
10 evergreen canopy despite significant individual phenological variability (Wu et al., 2016).

11 Tropical rainforests in nearby southeast Asia often show little or no clear seasonal dynamics in
12 canopy cover and productivity (Kho et al., 2013), but are well known for synchronous mast fruiting
13 with a return frequency of around 2-10 years (Visser et al., 2011). The general flowering in these
14 forests that is associated with these mast fruiting events has been shown to be triggered by irregular
15 droughts (Sakai et al., 2006). More recently, phenocams have been used to analyse the phenology of a
16 dipterocarp canopy, a forest type associated with mast events in Borneo (Nagai et al., 2016). This
17 study confirmed that indices such as %RGB and GCC can be used to track flowering and leaf flushing
18 at the individual tree level.

19 Less understood are similar ‘masting’ events in the forests of the wet tropics of north Queensland (M.
20 Bradford, *pers. comm.*). These masting events occur with a return frequency of around 7 years and the
21 trigger appears to be drier than normal conditions. Another characteristic of the Wet Tropics area is
22 cyclone activity during the wet season, where the coastal forests are known colloquially as ‘cyclone
23 scrub’. The return frequency of low intensity cyclones is around 5 years (Australian system: Category
24 1-for a coastal crossing) while more intense cyclones have longer return frequencies (Turton and
25 Stork, 2008). To date, no long-term phenology studies have been published for the rainforests of Far
26 North Queensland. The combination of phenocams and weather stations on the Cow Bay (AU-Cow),
27 Cape Tribulation (AU-Ctr) and Robson Creek (AU-Rob) OzFluz towers, all parts of the FNQ
28 Rainforest SuperSite (Fig. 1), will allow the timing and the drivers of synchronous masting events and
29 effects of cyclone activity to be studied in detail over the next few decades.

30 To highlight the utility of phenocams for identifying individual phenological variability in FNQ, we
31 looked at one of the trees (Tree 1, *Wrightia laevis*, the most variable tree in Fig. 2) in more detail (Fig.
32 3). This species, *Wrightia laevis*, may be found further north in semi-deciduous and deciduous
33 vegetation communities that are connected floristically to the rainforests of the Daintree region. When
34 leaf shedding occurred, GCC rapidly decreased with an associated rapid increase in BCC. The
35 analysis also showed a slower rate of leaf flushing compared to the swift leaf fall event. At the onset

to the rapid decrease in GCC, RCC increased markedly (Fig. 3). This increase in redness may be due to the build-up of anthocyanin pigments that cause the red colouration of senescing leaves, also a distinct feature of deciduous forest canopies in autumn (Hoch et al., 2001; Lee et al., 2003; Gould, 2004). The RCC response shows that phenocams can capture leaf reddening at fine spatial and temporal resolution, thereby opening up opportunities for understanding the causes and effects of such changes in more detail.

4.1.2 Tropical savanna

Unlike the constantly high EVI of Australia's tropical rainforests, savannas display seasonally dynamic EVI at the regional scale (Fig. 1; A). Extraction of GCC for understory images revealed a strong seasonal phenological response at the Howard Springs site, evident by a sharp increase in GCC at the onset of the wet season (i.e., October-November, Fig. 4). In contrast, similar comparison of these indices for the overstory images showed that overstory dynamics varied much less than those of the understory (Fig. 4). Therefore, the seasonality in EVI (Fig. 1; A) is primarily driven by the highly seasonally dynamic growth of the C4 grassy understory and less by the comparatively consistent evergreen overstory tree canopy. Fractional overstory cover at Howard Springs is approximately 50 % (Kanniah et al., 2009) and while the understory is homogenous at the landscape scale, it can vary at the phenocam scale (i.e., field of view (FOV) of several meters) (Moore et al., 2016). To account for this, GCC was calculated from four phenocams installed at the site and averaged to obtain a single daily GCC estimate.

There are two main strategies employed by plants growing in seasonally dry savannas; drought avoidance through deciduous or die-back (i.e., annual/perennial) phenology and drought tolerance through evergreen phenology (Williams et al., 1997; Tomlinson et al., 2013). We observed both strategies, as annual grasses displayed a boom-bust cycle in GCC whereas the eucalypt dominated overstory maintained its leaf cover without major variability in GCC. However, the savanna overstory at this site also includes a small portion (c. 20 %) of semi-, brevi- and fully deciduous species that shed their leaves primarily in the dry season (i.e. mid April - mid October, Williams et al., 1997; Hutley et al., 2011). The phenocams at this site did not capture these species, highlighting the need to consider phenocam positioning and FOV when installing in complex ecosystems.

The strong seasonal changes seen in the understory (Fig. 4) are a characteristic phenological response of savanna grasses to the onset of the dry season (i.e., April-May). Each year, the commencement of the dry season triggers understory C4 grass senescence (Andrew and Mott, 1983) and canopy leaf fall (Williams et al., 1997) as the plants prepare to survive through the rainless months of May to September (Cook and Heerdegen, 2001). This phenological change results in a transition from green to brown in the understory, as evidenced by reduced GCC and a reduction of savanna GPP (Whitley et al., 2011; Ma et al., 2013; Moore et al., 2016).

The reduction of leaf water content associated with senescence also causes an increase in fire susceptibility. During the dry season, the senesced understory is consumed in fire events at 1-5 year intervals (Beringer et al., 2015). Fire can affect phenology in the short term through its impact on canopy area (Cernusak et al., 2006; Beringer et al., 2007) and over longer timescales through feedbacks to plant demography (Beringer et al., 2011; Werner and Franklin, 2010; Werner and Prior, 2013). In addition to fire, cyclone activity can disturb Australia's savannas with wind throw from severe tropical storms resulting in patches of defoliation (roughly every 5 years) and extreme cyclones causing up to complete destruction (once every 500-1000 years) (Hutley et al., 2013). In Australian savannas, pronounced spatio-temporal variability exists in this phenology, which still requires further examination in fine detail so it can be more accurately understood (Ma et al., 2013). The coupling of phenocam imagery with MODIS phenology information (i.e., EVI) may assist in exploring the effects of disturbance in more detail, and whilst outside the scope of this study, it offers exciting opportunities for future research.

4.1.3 Temperate evergreen forest

We calculated GCC for the Tumbarumba OzFlux site (AU-Tum), a wet (i.e., high rainfall) temperate evergreen forest that represents another key Australian biome. Two phenocams were installed at this site, one on the flux tower at 60 m with a nadir view angle (i.e., TimeLapseCam, Wingscapes, Calera, AL, USA) and the other at 1.5 m with an oblique view angle (i.e., Raspberry Pi RGB camera, Raspberry Pi Foundation, UK). As a result, the cameras measured different ROI's. Despite the differences in orientation and view, GCC values from both phenocams at Tumbarumba clearly increased from November 2014 to January 2015, showing a flush of the understory leading into summer (Fig. 5).

For wet temperate evergreen ecosystems in Australia, like the forest at Tumbarumba, flushing events in summer are a common occurrence (Restrepo-Coupe et al., 2015), as temperature and light tend to be the primary drivers of phenology, with water availability a secondary factor (van Gorsel et al., 2013; Rawal et al., 2014). Tumbarumba is situated in a subalpine zone where winter minimum temperatures often drop below zero, with occasional snow events (van Gorsel et al., 2013). Low temperature and incoming solar radiation in winter result in reduced vegetation cover and activity in alpine and subalpine regions, whereas increased radiation and temperature in summer promotes rates of vegetation emergence, flowering and cover (Law et al., 2000; Venn and Morgan, 2007; Green, 2010). A recent study from Rawal et al. (2014), looking at environmental effects on eucalypt phenology, found that photoperiod length and temperature were key variables controlling the growth rates of several eucalypt species in wet and dry temperate evergreen forests in south-eastern Australia. While this notion holds true for wet temperate forests such as Tumbarumba (Keith et al., 2012; van Gorsel et al., 2013), water availability increases in importance as a phenology driver in dry temperate forests (Rawal et al., 2014; Duursma et al., 2016). Continued phenocam monitoring at Tumbarumba

and other dry temperate sites (i.e., Whroo (site 6) & Cumberland Plain (site 12), Fig. 1), as well as the addition of more cameras in wet and dry temperate forests, will improve our understanding of the phenological processes occurring at temperate evergreen sites over longer timescales in Australia.

4.2 Phenocams and ecosystem productivity

Whilst phenocams are clearly useful for identifying fine scale phenological changes in terrestrial ecosystems often missed by larger scale satellite indices, the extracted indices can also provide a useful comparison with productivity estimates, such as GPP. Toomey et al. (2015) compared phenocam derived GCC to eddy covariance derived estimates of GPP at several sites within North America and Canada and found correlations between some ecosystem GCC indices and GPP. They concluded that phenocams can be a valuable tool for independently verifying variability in GPP attributable to phenology. To demonstrate the potential of this idea for Australian ecosystems, we plotted GPP data from two contrasting Australian ecosystems against phenocam derived GCC. At the first site, Howard Springs tropical savanna (GPP data from Moore et al. (2016)), GCC varied in line with that of GPP, both of which reach a maximum at the peak of the wet season (Fig. 4). The GCC signal rapidly decreases once the predominant understory grasses senesce at the end of the wet season, and is also reflected by a reduction in GPP (Fig. 4). Whitley et al. (2011) attributed increased LAI in the understory to the rapid increase in savanna GPP. Likewise, Moore et al. (2016) attribute the seasonal dynamics of savanna GPP to be largely determined by understory flushing, with a more steady contribution from the overstory throughout the year. Fig. 4 supports the conclusions of Whitley et al. (2011) and Moore et al. (2016) as it shows a much more dynamic understory when compared with the overstory, the cycles of which are reflected in the ecosystem GPP estimate.

At the second site, Whroo dry temperate evergreen woodland (GPP data from Beringer et al. (2016)), GCC and GPP do not track each other over time like at Howard Springs (Fig. 6). While GCC remains relatively constant, there is a clear growing season displayed by GPP in the summer months (i.e., Dec-Feb, Fig. 6). In evergreen ecosystems such as Whroo, productivity is driven more by vegetation responses to meteorological drivers (i.e., solar radiation, air temperature, rainfall) rather than to phenological variability (Restrepo-Coupe et al., 2015). Leaf area at Whroo is maintained at approximately $1.0 \text{ m}^2 \text{ m}^{-2}$ throughout the year (I. McHugh, *pers. comm.*) and being evergreen in nature, the phenocam is not able to discern phenological variability related to greenness at the ecosystem scale. For temperate evergreen ecosystems in Australia, phenocams are not as useful for linking with GPP (Restrepo-Coupe et al., 2015), but still likely hold value for identifying individual phenology signals within the evergreen canopy.

5 Expanding the Australian Phenocam network

We have shown the value of phenocams for ecosystem monitoring in Australia, how they can be used to inform on species level changes, supplement large scale satellite remote sensing data and aid in

interpreting ecosystem GPP. In Australia, phenocams have primarily been installed at several pre-existing Terrestrial Ecosystem Research Network (TERN) supported OzFlux sites (<http://www.ozflux.org.au/>), at which eddy covariance flux towers are used to study carbon, water and energy exchanges between ecosystems and the atmosphere. Phenocams are currently being deployed across TERN and the Australian SuperSite Network (<http://www.tern-supersites.net.au>), where a comprehensive set of co-located measurements of vegetation, faunal biodiversity, soil/water and remote sensing are being made. Despite these recent deployments, the spatial and temporal coverage of phenocams in Australia remains limited (Fig. 1).

Several of the phenocams in Australian ecosystems are either in the early stages of operation or have experienced issues with long-term stability in data collection (i.e., FOV shifts, lack of timestamp standards; loss of data) and some ecosystems in Australia are missing altogether (i.e. alpine ecosystems, managed agricultural land, mangroves, Fig. 1). Phenocams are one of few observing methods that can bridge across spatial and temporal scales, from individual plants to the ecosystem and continental scales, and between biophysical function and ecological condition and composition. They can capture seasonal trends (Fig. 4, 5 & 6) and short lived events (Fig. 2 & 3) that are often missed by coarse scale techniques (i.e., satellite sensors, Fig. 1). As such, establishment of a national phenocam network in Australia will be an extremely valuable contribution to help integrate data products between TERN Facilities addressing different ecosystem questions at different scales (i.e., the SuperSites, OzFlux, LTERN, AusCover and eMAST).

5.1 Data standardisation and sharing

Standardization and quality control in phenocam data collection is essential to support cross-site and cross-ecosystem comparisons. There is a clear need for standards in measurement in Australia, with a wide range of phenocam hardware currently in use. Brown et al. (2016) provide recommendations for improving phenocam datasets and improving comparability between sites, including:

- maintaining metadata and data management standards (i.e., image naming, FOV, camera settings) for all camera-based data
- registering all publicly available phenocams with a regional phenocam network
- making datasets available online wherever possible

Analysis of some of the datasets revealed that camera quality and installation issues (i.e., sun glare, inappropriate image acquisition times, power consumption) play a role in data quality. However, the single greatest challenge was found to be changes in data quality and characteristics over time that limit or prevent automated analysis. In particular, changes in the FOV over time due to intentional or unintentional reorientation of the camera, creates a major obstacle to the collection of a sufficiently long time series and to automated data analysis. Slight or gradual changes can be dealt with through

additional image co-registration efforts, but they can be arduous and reduce the area effectively available for analysis. Solid mounting of the camera and, when necessary, accurate re-alignment after removal (i.e., for maintenance) or unintentional reorientation, can help alleviate such issues. Maintaining a consistent FOV is critical. For all but the most homogeneous environments, the FOV of the phenocam is the dataset. Each time the camera moves, the usable pixels for which there is long-term monitoring data become increasingly constrained.

Data publication and sharing are also important factors to consider. We have formed the Australian Phenocam Network (<http://phenocam.org.au/>) to provide a platform for phenocam data sharing, storage and publication to the wider scientific community. This network is continually evolving, with data made available under the TERN 'By Attribution' license based on the Creative Commons framework (<http://www.tern-supersites.net.au>). As for other national and global multi-site data sets, open access to phenocam data will enhance the reproducibility and extensibility of research and the combined value of such data (Brown et al., 2016).

6 Conclusion

We see considerable potential for the developing Australian phenocam network. Existing infrastructure, supported by TERN, will assist in the establishment of this network, the implementation of more phenocams around the country and the standardisation of data collection, analysis and sharing. An Australian phenocam network would also provide valuable data for monitoring networks such as OzFlux, SuperSites, AusPlots and eMAST. Currently, there are only a small number of continuously operating phenocams in Australia, with even fewer uploading data to the Australian phenocam website. Expansion of the currently sparse distribution of Australian phenocams will help improve our understanding of the diversity of phenological strategies employed by Australian ecosystems. Combined with satellite remote sensing techniques, phenocams can improve our ability to quantify and predict the functioning of Australia's ecosystem within the Earth system.

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Authorship Note

This paper was conceived and outlined at the ACEAS 2014 Phenocam Workshop led by Brown and Keenan. Moore created the first draft and was the primary editor for subsequent drafts. Keenan and Brown provided oversight and additional edits. All authors provided additional text, edits and review. Liddell provided data for the Cow Bay analysis, van Dijk provided analysis of the remote sensing data, and Duursma provided primary analysis for the Cow Bay and Tumbarumba data. Moore provided data and analysis for the Howard Springs data and Culvenor provided data for Tumbarumba. Restrepo-Coupe and provided data and analysis for Cow Bay, Whroo and Tumbarumba dataset.

Figure Credits: 1: van Dijk & Moore; 2&3: Duursma; 4: Moore; 5: Culvenor & Moore; 6: Moore & Restrepo-Coupe

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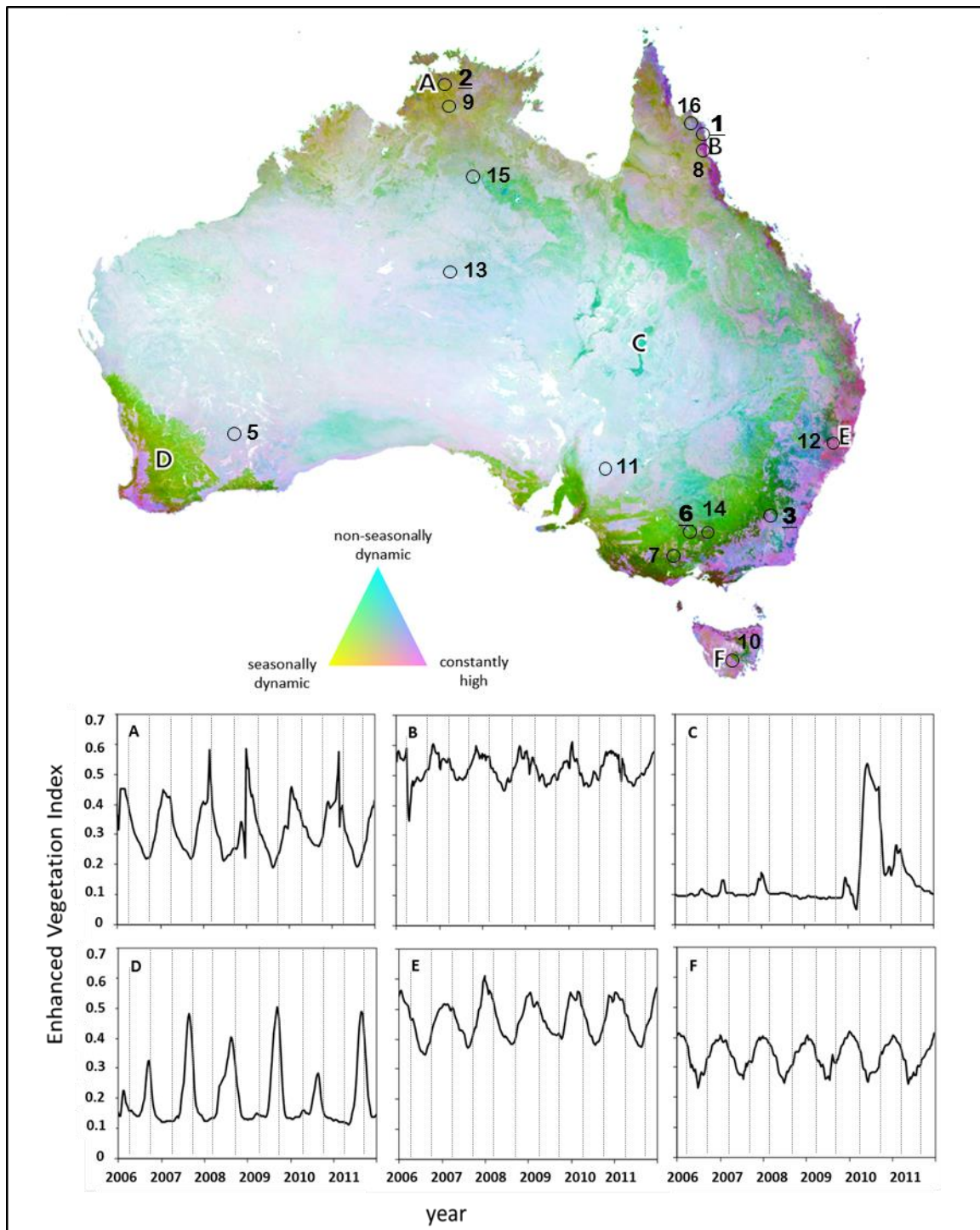


Figure 1: Enhanced Vegetation Index (EVI) map of Australia obtained from MODIS global 0.05 degree 8-day reflectance composites for 2000-2012 (MOD09) with a selection of six pixels to demonstrate the following: Yellow areas have a strong seasonal cycle, such as Howard Springs at point A. Cyan areas have a relatively strong, but non-seasonal variations in EVI, such as Channel country at point C. Magenta have a more constant moderate to high EVI with less temporal variability compared with other sites, which include sites such as Cape Tribulation at point B, the central coast at point E and the Tasmanian highlands at point F. Green areas have both seasonal and non-seasonal variation, such as the wheat belt of Western Australia at point D. Blue areas have relatively high greenness but strong non-seasonal variation. The SD in seasonally adjusted anomalies (yellow) was scaled from 0-0.1; SD in mean seasonal cycle (cyan) from 0-0.1; and mean EVI (magenta) from 0-0.6. Also included are the locations (and Fluxnet codes where applicable)

of currently operating phenocams in Australia. Numbers refer to; 1. Cow Bay (AU-Cow), 2. Howard Springs (AU-How), 3. Tumbarumba (AU-Tum), 4. Karawatha, 5. Great Western Woodlands (AU-GWW), 6. Whroo (AU-Whr), 7. Wombat (AU-Wom), 8. Robson Creek (AU-Rob), 9. Litchfield (AU-Lit), 10. Warra (AU-Wrr), 11. Calperum (AU-Cpr), 12. Cumberland Plain (AU-Cum) & EucFACE, 13. Alice Springs (AU-ASM), 14. Riggs Creek (AU-Rig), 15. Sturt Plains (AU-Stp), 16. Cape Tribulation (AU-Ctr). Phenocam data used in this paper are from sites 1, 2, 3 and 6.

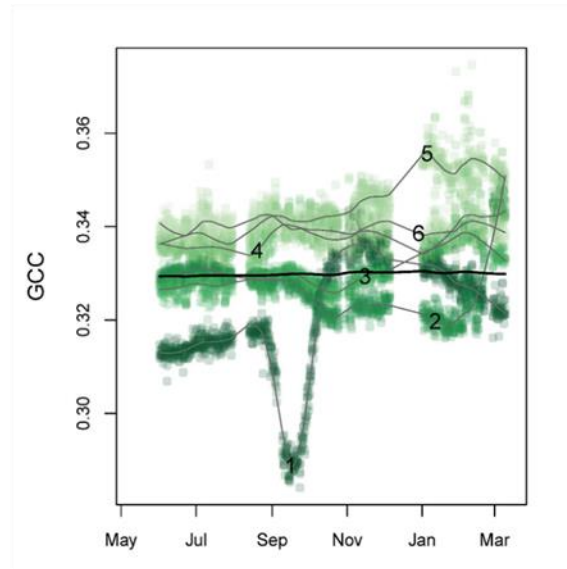
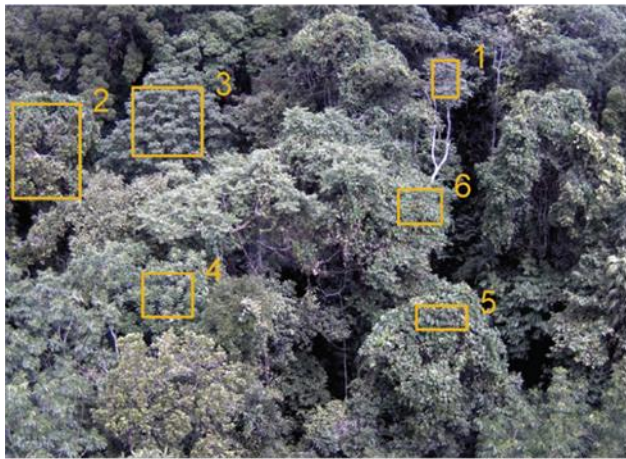


Figure 2: Green chromatic coordinates (GCC) for six individual tree crowns (indicated by orange regions of interest) at the Cow Bay tropical rainforest OzFlux site (Fig. 2; site 1, AU-Cow), Queensland, Australia. Leaf shedding and flushing events (note especially Tree 1, *Wrightia laevis* and Tree 2, *Acmena graveolens*) are highly specific to individual trees. Black line represents GCC from the full camera field-of-view. See Fig. 4 for example region of interest variability over time.

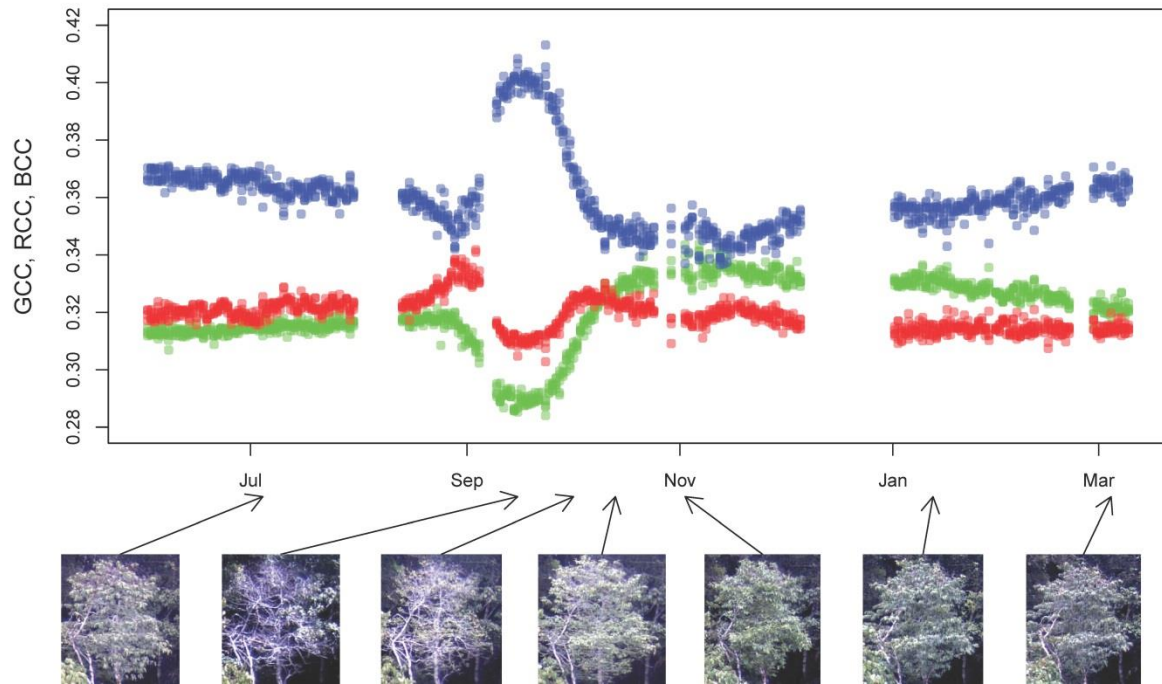


Figure 3: Green (GCC), red (RCC) and blue (BCC) chromatic coordinates for a single tree (*Wrightia laevis*) at the Cow Bay tropical rainforest OzFlux site (Fig. 2; site 1, AU-Cow), Queensland, Australia. Quick leaf shedding and flushing events are well captured by the phenocam.

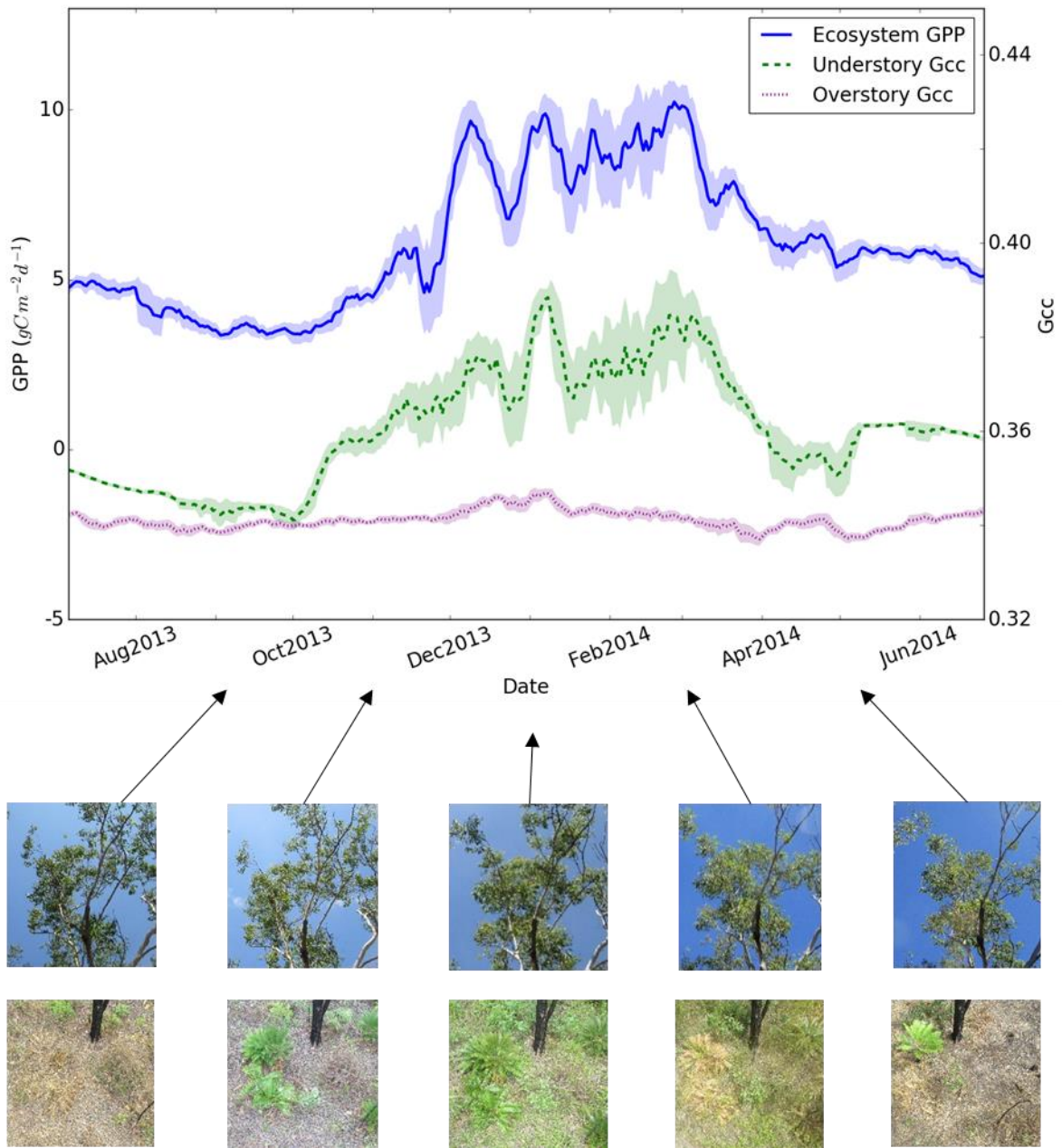


Figure 4: Ecosystem gross primary productivity (GPP) and green chromatic coordinates (GCC) for the overstory and understory, with region of interest (ROI) image examples, at the Howard Springs tropical savanna OzFlux site (Fig. 2; site 2, AU-How), Northern Territory, Australia. Data are shown as an 8-day centred running mean with $\pm 90\%$ confidence shading.

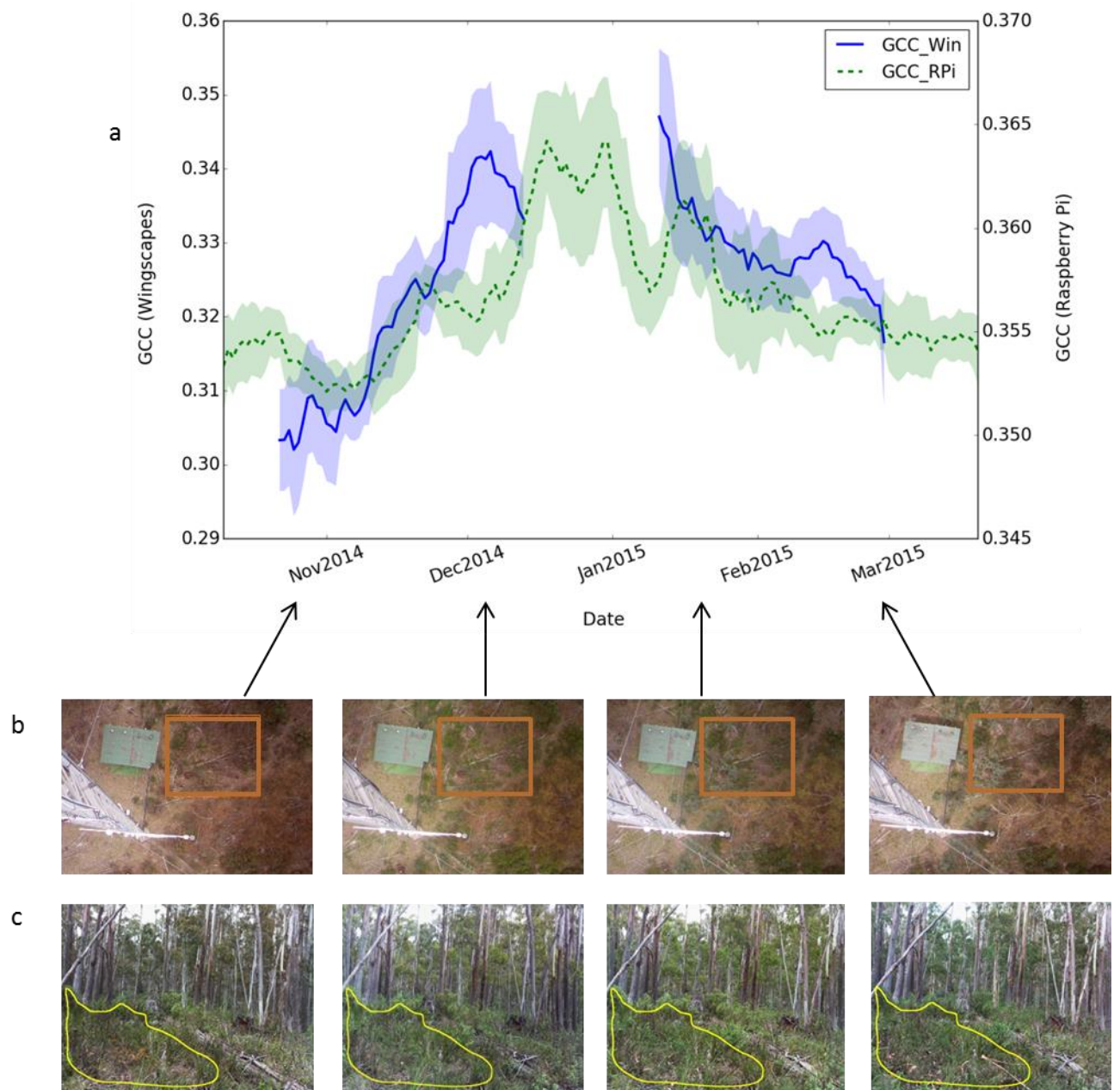


Figure 5: Phenocams in use at the Tumbarumba wet temperate OzFlux site (Fig. 2; site 3, AU-Tum), New South Wales, Australia. Figure a) shows green chromatic coordinates (GCC) for understory vegetation from two individual understory phenocams; that of b) a downward facing TimeLapseCam wingscapes (GCC_Win) phenocam (region of interest inset) and c) an oblique facing raspberry pi (GCC_RPi) phenocam (region of interest inset). GCC data are shown by an 8-day centred running mean with $\pm 90\%$ confidence shading.

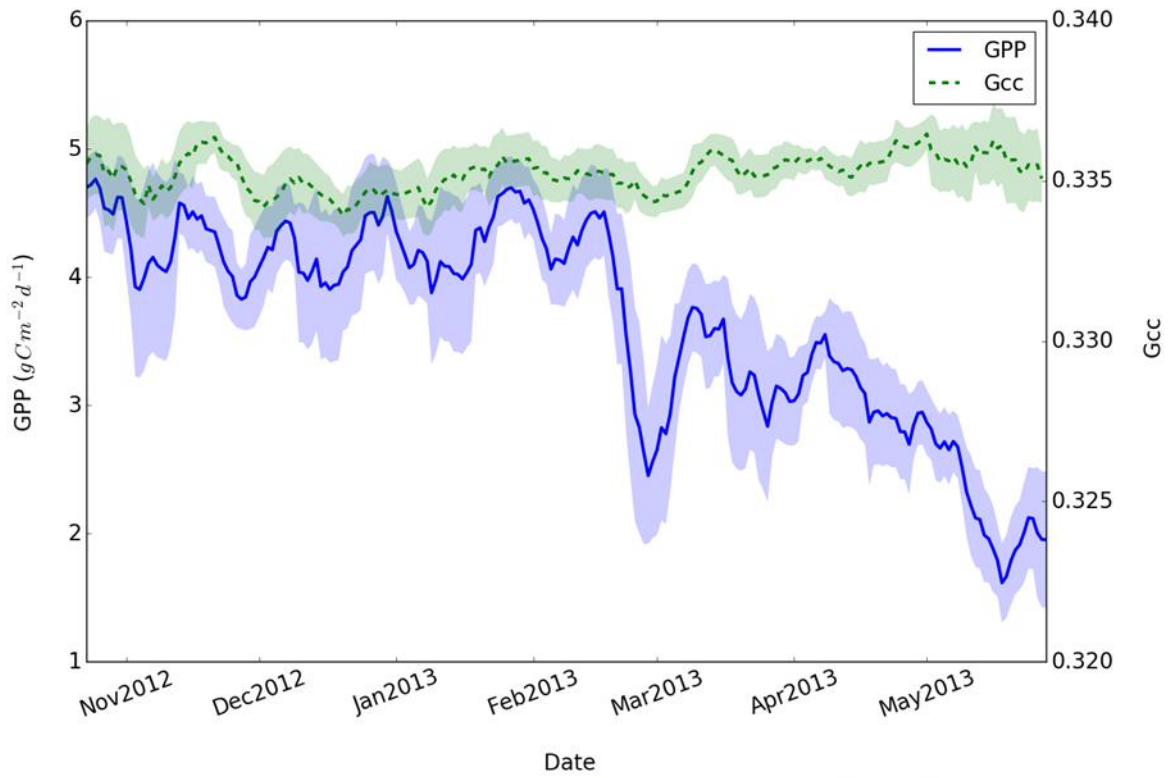


Figure 6: Ecosystem gross primary productivity (GPP) and green chromatic coordinate (GCC) index for the Whroo dry temperate OzFlux site (Fig. 2; site 6, AU-Whr) in south-eastern Victoria, Australia. Both GPP and GCC data are shown by an 8-day centred running mean with $\pm 90\%$ confidence shading. The region of interest (ROI) for GCC calculation is indicated by the orange box in the three images that represent different times throughout the year.