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

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1 **Abstract**

2 Phenology is the study of periodic biological occurrences and can provide important insights into the

3 influence of climatic variability and change on ecosystems. Understanding Australia's vegetation

4 phenology is a challenge due to its diverse range of ecosystems, from savannas and tropical rainforests

5 to temperate eucalypt woodlands, semi-arid scrublands and alpine grasslands. These ecosystems exhibit

6 marked differences in seasonal patterns of canopy development and plant life-cycle events, much of

7 which deviates from the predictable seasonal phenological pulse of temperate deciduous and boreal

8 biomes. Many Australian ecosystems are subject to irregular events (i.e., drought, flooding, cyclones

9 and fire) that can alter ecosystem composition, structure and functioning just as much as seasonal

10 change. We show how satellite remote sensing and ground-based digital repeat photography (i.e.

11 phenocams) can be used to improve understanding of phenology in Australian ecosystems. First, we

12 examine temporal variation in phenology at the continental scale using the Enhanced Vegetation Index

13 (EVI), calculated from MODerate resolution Imaging Spectroradiomter (MODIS) data. Spatial

14 gradients are revealed, ranging from regions with pronounced seasonality in canopy development (i.e.,

15 tropical savannas) to regions where seasonal variation is minimal (i.e., tropical rainforests) or high but

16 irregular (i.e., arid ecosystems). Next, we use time series colour information extracted from phenocam

17 imagery to illustrate a range of phenological signals in four contrasting Australian ecosystems. These

18 include greening and senescing events in tropical savannas and temperate eucalypt understory, as well

19 as strong seasonal dynamics of individual trees in a seemingly static evergreen rainforest. We also

20 demonstrate how phenology links with ecosystem gross primary productivity (from eddy covariance)

21 and discuss why these processes are linked in some ecosystems but not others. We conclude that

22 phenocams have the potential to greatly improve current understanding of Australian ecosystems. To

23 facilitate sharing of this information, we have formed the Australian Phenocam Network

24 (http://phenocam.org.au/).

25 **Key Words**

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

27 **1 Introduction**

28 Phenology is the study of the timing of periodic biological occurrences, from flowering and leaf

29 emergence to animal migrations and breeding patterns, all of which vary between and within species

30 and are influenced to a certain degree by the climate (Lieth, 1974;Richardson et al., 2013a).

31 Phenological monitoring allows us to quantify and track seasonal cycles and irregular natural events, as

32 well as how vegetation phenology responds to meteorological events and climate change. At the

33 ecosystem level, the timing of leaf emergence and senescence in plants has a major influence on the

34 length of the growing season (Dragoni et al., 2011;Keenan et al., 2014b). At larger scales, phenological

35 responses feed back to the climate system by altering the land surface energy balance and the coupled

36 cycles of water, carbon and nutrients from an ecosystem (Peñuelas et al., 2009;Richardson et al., 2013a).

1   Research suggests that contemporary warming has advanced spring onset in the northern hemisphere

2   by *ca.* 2.8 days per decade since the 1970's (Parmesan, 2007), with even higher rates of change (4.8

3   days per decade) in more recent decades (Keenan et al., 2014b). Likewise, in the southern hemisphere,

4   advancement in spring onset has been estimated at a rate of 2.2 days per decade (Chambers et al., 2013).

5   In response to increasing evidence of earlier spring onsets, the Intergovernmental Panel on Climate

6   Change (IPCC) has placed a high importance on the gathering and interpretation of phenology

7   observations to improve our understanding of the ecological impacts of climate change (Ciais et al.,

8   2013). Understanding the processes that lead to modifications in phenology, as well as the complex

9   links between phenological shifts and climatic variability and change at local, regional and global

10   scales, requires more detailed field-based observations that underpin larger scale remote sensing and

11   ecological modelling tools (de Jong et al., 2012;Migliavacca et al., 2012;Melaas et al., 2013).

12   Repeat photography with digital cameras (phenocams) has emerged as a powerful observational tool

13   for ecological research and evaluation of remote sensing data products and model simulations

14   (Richardson et al., 2007;Migliavacca et al., 2011;Hufkens et al., 2012;Wingate et al., 2015;Brown et

15   al., 2016). Digital images collected from phenocams typically provide red-green-blue (RGB) colour

16   channel information that can be partitioned and converted to quantitative indices (Woebbecke et al.,

17   1995;Gillespie et al., 1987;Sonnentag et al., 2012). These indices have been shown to closely track

18   vegetation colour changes, such as canopy greenness, and are indicative of different plant development

19   stages in a variety of ecosystems (Sonnentag et al., 2011;Inoue et al., 2014;Keenan et al., 2014a;Peichl

20   et al., 2014;Toomey et al., 2015). A loosely organized global phenocam network is emerging with

21   regional networks including the PhenoCam Network (Richardson et al., 2009a) and the National

22   Ecological Observatory Network (NEON) in the USA (Keller et al., 2008), the EUROPhen network in

23   Europe (Wingate et al., 2015), the Phenological Eyes Network (PEN) in Japan (Nasahara and Nagai,

24   2015) and most recently, the Australian Phenocam Network (Brown et al, 2016). These networks

25   provide support for phenocam data collection and sharing in the wider scientific community and are a

26   platform for the development of open data and data sharing standards.

27   Phenology information can also be derived from satellite remote sensing imagery. Satellite data

28   provides spatially explicit time series of vegetation phenology proxies such as the enhanced vegetation

29   index (EVI, Huete et al., 2002), the normalised difference vegetation index (NDVI, Tucker, 1979), as

30   well as estimates of canopy cover fraction, the fraction of absorbed photosynthetically active radiation

31   and leaf area index (LAI) derived from optical remote sensing (Gonsamo and Chen, 2014). In addition,

32   vegetation optical depth and biomass can be derived from radar or passive microwave remote sensing

33   (Andela et al., 2013;Liu et al., 2013;Liu et al., 2011;Liu et al., 2007). Such remotely sensed vegetation

34   phenology proxies can be analysed to estimate temporal changes in the vegetation characteristics at the

35   landscape scale and contribute toward the development of satellite phenology products, such as the

1   MODerate resolution Imaging Spectroradiometer (MODIS) Land Cover Dynamics product (Ganguly

2   et al., 2010), and the Australian satellite land surface phenology product (Broich et al., 2015).

3   Satellite-derived phenology can be compared to changes observed at smaller scales with phenocams.

4   For example, Hufkens et al. (2012) and Klosterman et al. (2014) used phenocams to evaluate the

5   MODIS MCD12Q2 product for deciduous forests in the north-eastern USA. Despite discrepancies

6   related to spatial scale and site representativeness, the results showed good agreement between the

7   phenocam- and satellite-derived timing of phenological events (i.e. phenophases). For various

8   temperate and boreal forest, grassland and peatland ecosystems, time-series data of canopy greenness

9   derived from phenocam imagery have been used to analyse seasonal changes of net ecosystem exchange

10   (NEE) and gross primary productivity (GPP) (Ahrends et al., 2009;Richardson et al., 2007;2009;Zhu et

11   al., 2013;Toomey et al., 2015). Characterising changes in plant physiology (Keenan et al., 2014a),

12   modelling of canopy development (Wingate et al 2015) and quantifying inter-annual variation in

13   phenology (Inoue et al 2014) have also been achieved using phenocams. Despite the promising

14   applications of phenocam data in North America, Europe and Asia, there has been a slow uptake of

15   phenocam research in Australia; a continent characterized by diverse ecosystem types often with

16   distinctly different phenological characteristics compared to temperate and boreal deciduous

17   ecosystems (Chambers et al., 2013).

18   The diversity of Australian ecosystems, and their marked differences to northern hemisphere temperate

19   deciduous and boreal biomes, poses the challenge of how to best define and quantify vegetation

20   phenology signals, especially due to their responses to irregular natural events such as rainfall, flooding,

21   fire and extreme temperatures. While the traditional definition of the term *phenology* as the "*timing of*

22   *recurrent biological events*" (Lieth, 1974) is generally assumed to apply to seasonally cyclical events,

23   such as canopy bud burst and senescence in winter-deciduous forests, a closer look at life patterns in

24   many Australian biomes yields a more complex picture of non-seasonal, yet still periodic, events as the

25   major drivers of phenology (Specht and Brouwer, 1975;Pook et al., 1997;Ma et al., 2015).

26   In this synthesis, we examine the drivers of plant phenological cycles across Australia, illustrate the

27   potential measurement tools available, and suggest future avenues of required research. At the national

28   scale, we demonstrate how satellite observations can be used to characterize broad scale phenological

29   variability across the continent, and discuss the major drivers underlying these patterns. At the

30   ecosystem scale, we highlight the value of using digital image archives obtained from phenocams

31   installed at a selection of contrasting OzFlux sites (Australian and New Zealand flux tower network,

32   see Beringer et al. (2016)), for examining the phenology of canopies and individual plants in Australian

33   ecosystems. We discuss how greenness information obtained from phenocam imagery can be compared

34   with flux tower estimates of gross primary productivity (GPP) and why such relationships are stronger

35   from some Australian ecosystems than for others. Finally, we assess the feasibility and effectiveness of

1   phenocams for continuously observing Australia's diverse ecosystems.

2   **2 Drivers of phenology in Australia**

3   Australian ecosystems include a diverse range of biomes spanning from tropical savannas and
4   rainforests in the north, to arid and semi-arid shrublands and grasslands in the centre and finishing with
5   temperate evergreen forests and woodlands in the south. Temperature is an important phenological
6   driver in Australian ecosystems (Chambers et al., 2013), just as it is in temperate deciduous and boreal
7   ecosystems in the northern hemisphere. However, Australian ecosystem dynamics are arguably
8   influenced more strongly by the availability of water, because 70 % of its land mass is classified as arid
9   or semi-arid (Chambers et al., 2013). The response of LAI and vegetation cover to rainfall events, mean
10   annual rainfall and the corresponding soil water availability is well documented (Pook, 1985;Specht
11   and Specht, 1989;Ellis and Hatton, 2008;Donohue et al., 2009;2013;Andela et al., 2013;Duursma et al.,
12   2016). Similarly, vegetation density closely follows climate gradients in average rainfall (Ellis and
13   Hatton, 2008;Donohue et al., 2009;Hutley et al., 2011;Ma et al., 2013). Large-scale variability in
14   climatic conditions governs vegetation distribution across the continent and most Australian vegetation
15   has adapted in some form around the need to maintain a balance between water access and water loss.

16   Among the exceptions to this concept are temperate and tropical rainforest ecosystems found along the
17   east coast of the continent, where rainfall is almost continually in excess of water requirement. In
18   contrast, C4 grass phenology is driven by wet season rainfall across Australia's tropical savanna
19   ecosystems whilst the C3 eucalypt overstory remains relatively static throughout the year, supported by
20   access to deeper soil water reserves (Eamus et al., 2002;Hutley et al., 2011;Ma et al., 2013). Recurrent
21   dry spells and droughts are often associated with high mortality events in south western Australia (Evans
22   and Lyons, 2013;Matusick et al., 2013) and in both riparian (Davies et al., 2008;Gehrke et al., 2006)
23   and non-riparian trees (Semple et al., 2010) in southeast Australia. Over longer timescales, non-seasonal
24   shifts in temperature and rainfall, as well as second order effects on soil water availability, have been
25   attributed to forest declines (Evans et al., 2013) and mortality (Evans and Lyons, 2013).

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

1   Temporal variations in leaf colour, although not as pronounced as in temperate deciduous forests, do
2   occur in evergreen species that dominate Australian ecosystems. For example, eucalypt leaves can
3   contain large amounts of anthocyanin, causing a reddening of the leaf surface (Sharma and Crowden,
4   1974). While there is no general consensus on why anthocyanins are present in leaves (Gould et al.,
5   2000), their accumulation is associated with the expansion and subsequent predation of young foliage
6   (Close and Beadle, 2003), nutrient deficits that affect photosynthesis (Terashima and Evans,
7   1988;Sugiharto et al., 1990) or as a protection against solar radiation (Gould, 2004). Accumulation of
8   foliar anthocyanin has been observed in leaves of many Australian plant species (Nittler and Kenny,
9   1976;Hodges and Nozzolillo, 1996;Kumar and Sharma, 1999;Close et al., 2000;2001a;2001b), as well
10   as reddening of adult leaves due to a changing anthocyanin to chlorophyll ratio when exposed to
11   stressors such as cold or drought (Close et al., 2001a;Stone et al., 2001;Barry et al., 2009). In other
12   cases, exposure to stressful processes can result in a decrease in leaf chlorophyll content, accompanied
13   by or the precursor to, visible chlorosis (Coops et al., 2004). These leaf reddening events are visible and
14   often occur in a cyclical manner, therefore they can be considered as phenological in nature and may
15   be identified by phenocams.

16   **3 Continental scale phenology from satellite sensors**
17   To characterize the phenological diversity of Australian ecosystems at the continental scale, we used
18   satellite remote sensing observations to map land surface seasonal variability in measures of vegetation
19   greenness. For this, we used EVI as a phenology indicator, whereby we constructed an EVI seasonality
20   map for Australia using 8-day composites of spectral reflectance observations from MODIS
21   (MCD43C4.005 product) at 0.05 degree (*c*. 5 km) resolution for the period 2000-2012. We calculated
22   EVI (Huete et al., 2002) as Eq. (1):

23   $$EVI = G \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + L + C_1 \cdot \rho_{red} - C_2 \cdot \rho_{blue}} \tag{1}$$

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

28   The mean seasonal pattern for each pixel, based on variability in EVI from 2000-2012, was calculated
29   as the mean annual pattern in 8-day values over the 13 years. Subsequently, this seasonal pattern was
30   subtracted from the time-series for each pixel to yield seasonally adjusted anomalies. We then calculated
31   (i) the standard deviation in these seasonally adjusted anomalies (n=585), as well as (ii) the overall
32   mean EVI and (iii) the standard deviation of the mean seasonal pattern (n=45). Combining these three
33   measures allowed us to distinguish areas in Australia where the phenological signal was primarily 'non-

1   seasonally dynamic' (EVI varied but not in accordance with seasons), 'constantly high' (EVI remained

2   high year-round), or 'seasonally dynamic' (EVI showed regular seasonal variability).

3   Our continental phenological response map shows the tropical region of northern Australia (Fig. 1; A

4   & B) experiences a predictable seasonal phenology, as it receives reliable summer monsoon rainfall

5   (Cook and Heerdegen, 2001). In contrast, large areas of Australia are characterised by non-seasonal

6   variability in vegetation cover (Fig. 1, C). These areas fall largely within the arid interior, as well as in

7   the south-western and south-eastern subhumid regions, where rainfall variability has been particularly

8   strong during the observation period, including the worst multi-year drought on record (Van Dijk et al.,

9   2013;Broich et al., 2014).

10   To explore phenological variability in more detail around Australia, EVI is displayed by timeseries plots

11   for selected sites (Fig. 1). Tropical savanna ecosystems in northern Australia depict both seasonal

12   (monsoon driven) and non-seasonal changes (fire driven), represented by EVI for Howard Springs

13   (location A). In contrast, the tropical rainforest at Cape Tribulation (location B) shows a regular but low

14   level of seasonal variability where the maximum EVI is in the late dry season, and the minimum EVI

15   is in the wet season (Fig. 1). An exception to this regular cycle is the impact of cyclone Larry in early

16   2006. Cape Tribulation is located nearby and within the same tropical rainforest as the Cow Bay OzFlux

17   site (Fig. 1). Both sites show the same seasonal trend and these changes in EVI can be related to changes

18   in NEE that are observed at the OzFlux towers at both sites (Beringer et al., 2016).

19   Further inland, floodplain vegetation in the arid Channel Country (location C) responds primarily to

20   infrequent and irregular flood events produced in the large upstream catchment. For a flood event in

21   2010, the time-series shows an initial reduction in EVI (open water produces negative EVI (Huete et

22   al., 2002)) with a subsequent green flush. The Western Australian wheat belt (location D) shows a

23   winter peak in vegetation, corresponding with maximum leaf area before the cropping of winter wheat.

24   In contrast to location C, the year 2010 was the driest on record with poor harvests, recognisable as a

25   lower EVI signal for that year at location D. Sub-tropical evergreen forest on the central NSW coast

26   (location E) show a strong seasonal cycle that is most likely a phenological adaptation to summer-

27   dominant rainfall (Bowman, 2000). Highland vegetation in Tasmania (location F) shows a summer

28   green phenology that is more reminiscent of temperate forest ecosystems in the northern hemisphere.

29   These selected examples suggest that for most, but not all, of Australia's ecosystems it is not

30   temperature or radiation but water availability and extreme events that drive vegetation phenology.

31   Furthermore, in addition to the more or less predictable seasonal variations in precipitation, there is

32   very strong variability in rainfall between years due to the strong influence of ocean circulation modes

33   such as the El Niño Southern Oscillation, Indian Ocean Dipole, Southern Annular Mode and Pacific

34   Decadal Oscillation (Van Dijk et al., 2013;Broich et al., 2014;Cleverly et al., 2016).

1   **4 Ecosystem scale phenology from phenocams**

2   Digital repeat photography has already been shown to provide high temporal resolution phenology

3   information throughout many vegetation biomes in the northern hemisphere (i.e. Richardson et al.

4   (2007);Migliavacca et al. (2011);Sonnentag et al. (2012);Keenan et al. (2014a);Klosterman et al.

5   (2014);Toomey et al. (2015)). Images collected by phenocams are typically stored in JPEG format with

6   red, green, blue (RGB) digital numbers (DN) for each pixel in the image. Raw image format can also

7   be used, which is discussed in detail by Richardson et al. (2013b) and Brown et al. (2016). Variability

8   in scene illumination can affect the RGB brightness levels (Woebbecke et al., 1995;Richardson et al.,

9   2007), which can be minimised by using a transformation of the RGB numeric values to chromatic

10   coordinates (Gillespie et al., 1987;Woebbecke et al., 1995;Sonnentag et al., 2012). Of these indices, the

11   green chromatic coordinate (GCC) has been identified as the most relevant to green vegetation

12   phenology, given by Eq. (2):

13   $GCC = G / (R + G + B)$ (2)

14   where R, G and B are the per-pixel DN stored in the image, recorded as arbitrary units of intensity by

15   the camera's charge coupled device. GCC is calculated for each pixel of the image, and then averaged

16   over a user-defined region of interest (ROI). The red (RCC) and blue (BCC) chromatic coordinates

17   were also calculated, in the same way as GCC in Eq. (2).

18   An advantage of being able to transform the phenocam images into these quantitative indices is that it

19   allows for automated quality control of the data. This is important when a large network of automated

20   measurements is being considered at a continental and global scale (Brown et al., 2016). Automated

21   QA/QC routines have been regularly used for the large-scale processing of network data (Taylor and

22   Loescher, 2013;Beringer et al., 2016). Furthermore, these automated routines can allow for the fast

23   calculation of online summary metrics that can be used for diagnosing instrument problems and

24   highlighting potential flaws in data collection (Smith et al., 2014). As a result, instrument downtime

25   can be minimized and data collection can be optimized across a large network of sensors.

26   **4.1 Insights from existing phenocams**

27   To demonstrate the utility of phenocams for monitoring *in-situ* vegetation phenology in Australian

28   ecosystems, we calculated GCC from image data sets from four contrasting ecosystems in Australia;

29   Cow Bay (AU-Cow, Fig 4; site 1), Howard Springs (AU-How, Fig 4; site 2), Tumbarumba (AU-Tum,

30   Fig 4; site 3) and Whroo (AU-Whr, Fig 4; site 6). We used the R software package (R Core Team, 2013)

31   to extract and calculate chromatic coordinates (Eq. 2) from the phenocam images. Temporal coverage

32   varied for each camera, so we analysed all images and calculated a daily average value of GCC, RCC

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

Tropical rainforests in nearby southeast Asia often show little or no clear seasonal dynamics in canopy cover and productivity (Kho et al., 2013), but are well known for synchronous mast fruiting with a return frequency of around 2-10 years (Visser et al., 2011). Less understood are similar 'masting' events in the forests of the wet tropics of north Queensland (M. Bradford, *pers. comm.*). These masting events occur with a return frequency of around 7 years and the trigger appears to be drier than normal conditions. Another characteristic of the Wet Tropics area is cyclone activity during the wet season, where the coastal forests are known colloquially as 'cyclone scrub'. The return frequency of low intensity cyclones is around 5 years (Australian system: Category 1-for a coastal crossing) while more intense cyclones have longer return frequencies (Turton and Stork, 2008). To date, no long-term phenology studies have been published for the rainforests of Far North Queensland. The combination of phenocams and weather stations on the Cow Bay (AU-Cow), Cape Tribulation (AU-Ctr) and Robson Creek (AU-Rob) OzFluz towers, all parts of the FNQ Rainforest SuperSite (Fig. 1), will allow the timing and the drivers of synchronous masting events and effects of cyclone activity to be studied in detail over the next few decades.

To highlight the utility of phenocams for identifying individual phenological variability, we looked at one of the trees (Tree 1, *Wrightia laevis*, the most variable tree in Fig. 2) in more detail (Fig. 3). When leaf shedding occurred, GCC rapidly decreased with an associated rapid increase in BCC. The 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,

1 thereby opening up opportunities for understanding the causes and effects of such changes in more

2 detail.

4.1.2 Tropical savanna

4 Unlike the constantly high EVI of Australia's tropical rainforests, savannas display seasonally dynamic

5 EVI at the regional scale (Fig. 1; A). Extraction of GCC for understory images revealed a strong

6 seasonal phenological response at the Howard Springs site, evident by a sharp increase in GCC at the

7 onset of the wet season (Fig. 4). In contrast, similar comparison of these indices for the overstory images

8 showed that overstory dynamics varied much less than those of the understory (Fig. 4). There are two

9 main strategies employed by plants growing in seasonally dry savannas; drought avoidance through

10 deciduous or die-back phenology and drought tolerance through evergreen phenology (Williams et al.,

11 1997;Tomlinson et al., 2013). We observed both strategies, as annual grasses displayed a boom bust

12 cycle in GCC whereas the eucalypt dominated overstory maintained its leaf cover without major

13 variability in GCC. However, the savanna overstory at this site also includes a small portion (*c.* 20 %)

14 of semi-, brevi- and fully deciduous species that shed their leaves primarily in the dry season (Williams

15 et al., 1997;Hutley et al., 2011). The phenocams at this site did not capture these species, highlighting

16 the need to consider phenocam positioning and field of view (FOV) when installing in complex

17 ecosystems.

18 The strong seasonal changes seen in the understory (Fig. 4) are a characteristic phenological response

19 of savanna grasses to the onset of the dry season. Each year, the commencement of the dry season

20 triggers understory C4 grass senescence (Andrew and Mott, 1983) and canopy leaf fall (Williams et al.,

21 1997) as the plants prepare to survive through the rainless months of May to September (Cook and

22 Heerdegen, 2001). This phenological change results in a transition from green to brown in the

23 understory, as evidenced by reduced GCC and a reduction of savanna GPP (Whitley et al., 2011;Ma et

24 al., 2013;Moore et al., 2016). The reduction of leaf water content associated with senescence also causes

25 an increase in fire susceptibility. During the dry season, the senesced understory is consumed in fire

26 events at 1-5 year intervals (Beringer et al., 2015). Fire can affect phenology in the short term through

27 its impact on canopy area (Cernusak et al., 2006;Beringer et al., 2007) and over longer timescales

28 through feedbacks to plant demography (Beringer et al., 2011;Werner and Franklin, 2010;Werner and

29 Prior, 2013). In addition to fire, cyclone activity can disturb Australia's savannas with wind throw from

30 severe tropical storms resulting in patches of defoliation (roughly every 5 years) and extreme cyclones

31 causing up to complete destruction (once every 500-1000 years) (Hutley et al., 2013). In Australian

32 savannas, pronounced spatio-temporal variability exists in this phenology, which still requires further

33 examination in fine detail so it can be more accurately understood (Ma et al., 2013).

4.1.3 Temperate evergreen forest

We calculated GCC for the Tumbarumba OzFlux site (AU-Tum), a 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 and the other at 1.5 m with an oblique view angle. As a result, the cameras measured different ROI's. Despite the differences in orientation and view, GCC values from both phenocams at the Tumbarumba wet sclerophyll forest clearly increased from November 2014 to January 2015, showing a flush of the understory leading into summer (Fig. 5).

For wet sclerophyll 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 sclerophyll forests in southeast Australia. While this notion holds true for wet sclerophyll forests such as Tumbarumba (Keith et al., 2012;van Gorsel et al., 2013), water availability increases in importance as a phenology driver in dry sclerophyll forests (Rawal et al., 2014;Duursma et al., 2016). Continued phenocam monitoring at Tumbarumba and other dry sclerophyll sites (i.e. Whroo & Cumberland Plain, Fig. 1), as well as the addition of more cameras in wet and dry sclerophyll 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 correlation 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

1   a reduction in GPP (Fig. 4). Whitley et al. (2011) attributed increased LAI in the understory to the rapid

2   increase in savanna GPP. Likewise, Moore et al. (2016) attribute the seasonal dynamics of savanna GPP

3   to be largely determined by understory flushing, with a more steady contribution from the overstory

4   throughout the year. Fig. 4 supports the conclusions of Whitley et al. (2011) and Moore et al. (2016) as

5   it shows a much more dynamic understory when compared with the overstory, the cycles of which are

6   reflected in the ecosystem GPP estimate.

7   At the second site, Whroo evergreen dry sclerophyll woodland (GPP data from Beringer et al. (2016)),

8   GCC and GPP do not track each other over time like at Howard Springs (Fig. 6). While GCC remains

9   relatively constant, there is a clear growing season displayed by GPP in the summer months (i.e. Dec-

10 Feb, Fig. 6). In evergreen ecosystems such as Whroo, productivity is driven more by vegetation

11 responses to meteorological drivers (i.e. solar radiation, air temperature, rainfall) rather than to

12 phenological variability (Restrepo-Coupe et al., 2015). Leaf area at Whroo is maintained at

13 approximately 1.0 m^{-2} m^{-2} throughout the year (I. McHugh, *pers. comm.*) and being evergreen in nature,

14 the phenocam is not able to discern phenological variability related to greenness at the ecosystem scale.

15 For temperate evergreen ecosystems in Australia, phenocams are not as useful for linking with GPP

16 (Restrepo-Coupe et al., 2015), but still likely hold value for identifying individual phenology signals

17 within the evergreen canopy.

18 **5 Expanding the Australian Phenocam network**

19 We have shown the value of phenocams for ecosystem monitoring in Australia, how they can be used

20 to inform on species level changes, supplement large scale satellite remote sensing data and aid in

21 interpreting ecosystem GPP. In Australia, phenocams have primarily been installed at several pre-

22 existing Terrestrial Ecosystem Research Network (TERN) supported OzFlux sites

23 (http://www.ozflux.org.au/), at which eddy covariance flux towers are used to study carbon, water and

24 energy exchanges between ecosystems and the atmosphere. Phenocams are currently being deployed

25 across TERN and the Australian SuperSite Network (http://www.tern-supersites.net.au), where a

26 comprehensive set of co-located measurements of vegetation, faunal biodiversity, soil/water and remote

27 sensing are being made. Despite these recent deployments, the spatial and temporal coverage of

28 phenocams in Australia remains limited (Fig. 1).

29 Several of the phenocams in Australian ecosystems are either in the early stages of operation or have

30 experienced issues with long term stability in data collection (i.e. field-of-view shifts, lack of timestamp

31 standards; loss of data) and some ecosystems in Australia are missing altogether (i.e. alpine ecosystems,

32 managed agricultural land, mangroves, Fig. 1). Phenocams are one of few observing methods that can

33 bridge across spatial and temporal scales, from individual plants to the ecosystem and continental scales,

34 and between biophysical function and ecological condition and composition. They can capture seasonal

35 trends (Fig. 4, 5 & 6) and short lived events (Fig. 2 & 3) that are often missed by coarse scale techniques

1   (i.e. satellite sensors, Fig. 1). As such, establishment of a national phenocam network in Australia will

2   be an extremely valuable contribution to help integrate data products between TERN Facilities

3   addressing different ecosystem questions at different scales (i.e. the SuperSites, OzFlux, LTERN,

4   AusCover and eMAST).

5   **5.1 Data standardisation and sharing**

6   Standardization and quality control in phenocam data collection is essential to support cross-site and

7   cross-ecosystem comparisons. There is a clear need for standards in measurement in Australia, with a

8   wide range of phenocam hardware currently in use. Brown et al. (2016) provide recommendations for

9   improving phenocam datasets and improving comparability between sites, including:

10   • maintaining metadata and data management standards (i.e. image naming, FOV, camera
11   settings) for all camera-based data

12   • registering all publicly available phenocams with a regional phenocam network

13   • making datasets available online wherever possible

14   Analysis of some of the datasets revealed that camera quality and installation issues (i.e. sun glare,

15   inappropriate image acquisition times, power consumption) play a role in data quality. However, the

16   single greatest challenge was found to be changes in data quality and characteristics over time that limit

17   or prevent automated analysis. In particular, changes in the FOV over time due to intentional or

18   unintentional reorientation of the camera, creates a major obstacle to the collection of a sufficiently long

19   time series and to automated data analysis. Slight or gradual changes can be dealt with through

20   additional image co-registration efforts, but they can be arduous and reduce the area effectively

21   available for analysis. Solid mounting of the camera and, when necessary, accurate re-alignment after

22   removal (i.e. for maintenance) or unintentional reorientation can help alleviate such issues. Maintaining

23   a consistent FOV is critical. For all but the most homogeneous environments, the FOV of the phenocam

24   *is* the dataset. Each time the camera moves, the usable pixels for which there is long term monitoring

25   data become increasingly constrained.

26   Data publication and sharing are also important factors to consider. We have formed the Australian

27   Phenocam Network (http://phenocam.org.au/) to provide a platform for phenocam data sharing, storage

28   and publication to the wider scientific community. This network is continually evolving, with data made

29   available under the TERN 'By Attribution' license based on the Creative Commons framework

30   (http://www.tern-supersites.net.au). As for other national and global multi-site data sets, open access to

31   phenocam data will enhance the reproducibility and extensibility of research and the combined value

32   of such data (Brown et al., 2016).

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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.

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 Daintree analysis, van Dijk provided analysis of the remote sensing data, and Duursma provided primary analysis for the Daintree and Tumbarumba data. Moore provided data and analysis for the Howard Springs data and Culvenor and provided data for Tumbarumba. Restrepo-Coupe and provided data and analysis for Daintree, 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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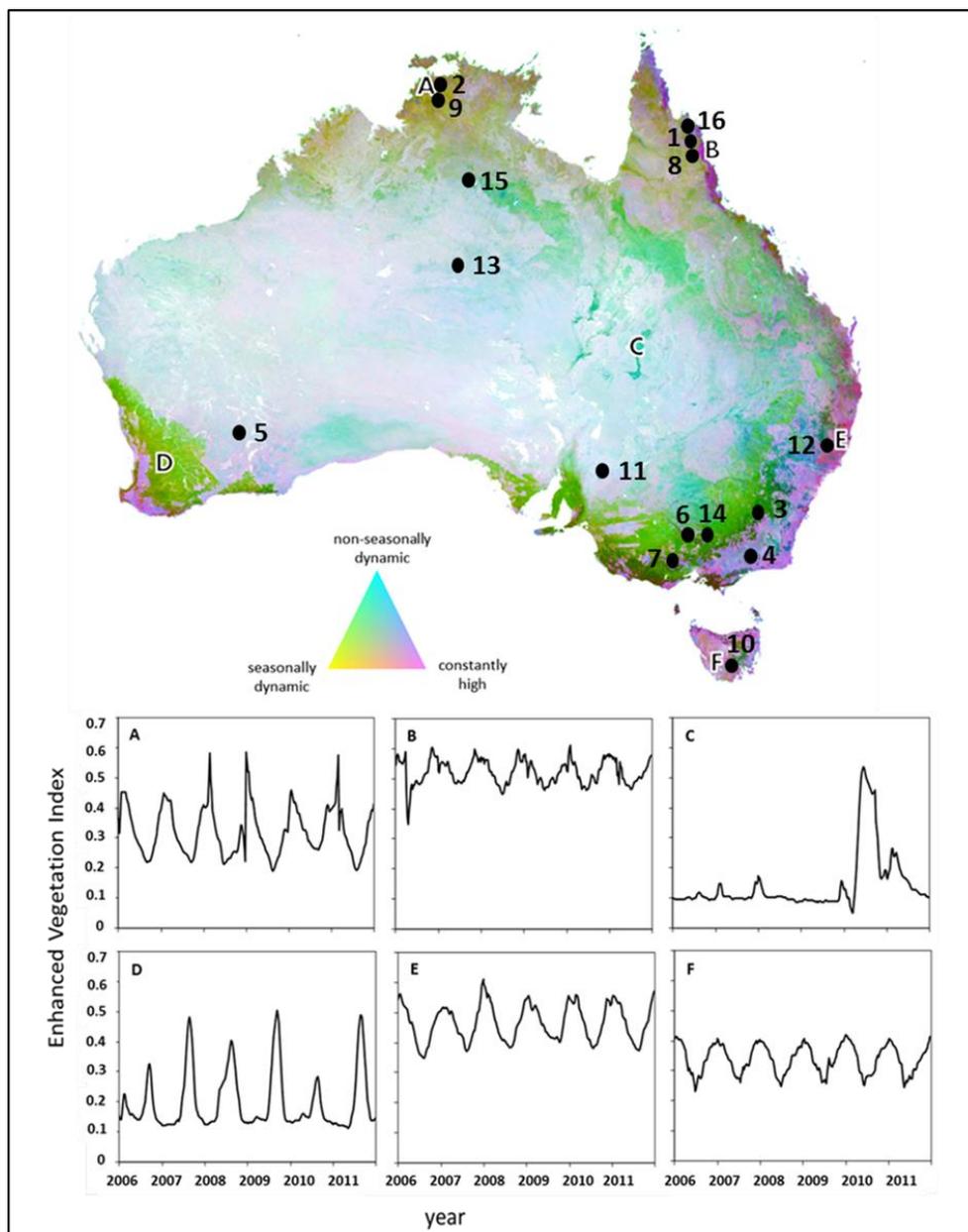31 observations, PLoS ONE, 8, 2013.

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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 strong, but non-seasonal variations in EVI, such as Channel country at point C. Magenta have constant moderate to high EVI with relatively little temporal variability, such as Cape Tribulation at point B and the central coast at point E. Green areas have both seasonal and non-seasonal variation, such as the wheat belt of WA at point D. Orange areas have relatively high greenness but also a seasonal component, such as the Tasmanian highlands at point F. Blue areas have relatively high

greenness but strong non-seasonal variation. The paler colours of the map centre show weaker EVI signals. 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).
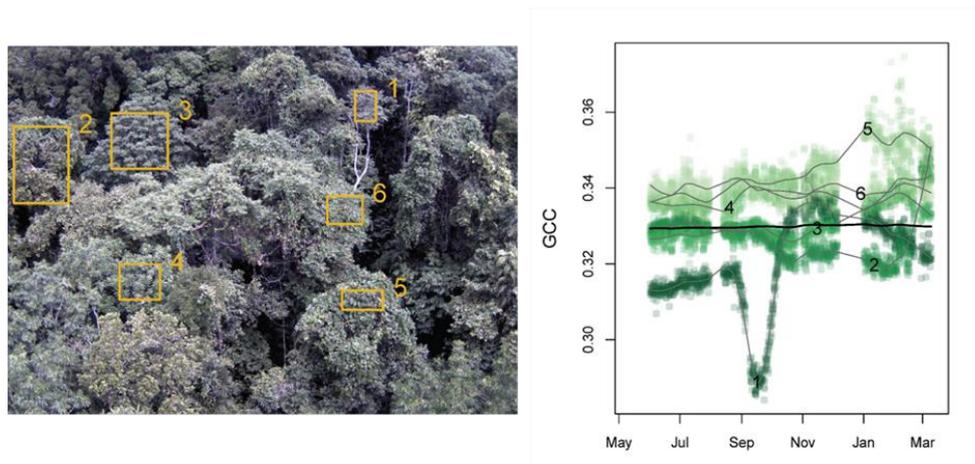
Figure 2: Green chromatic coordinates (GCC) for six individual tree crowns (indicated by orange regions of interest) at the Cow Bay tropical forest OzFlux site, Queensland, Australia. Leaf shedding and flushing events (note especially Tree 1, *Wrightia laevis* and Tree 2, *Acmena graveolens*) are highly specific to individual trees. Black line represents GCC from the full camera field-of-view.
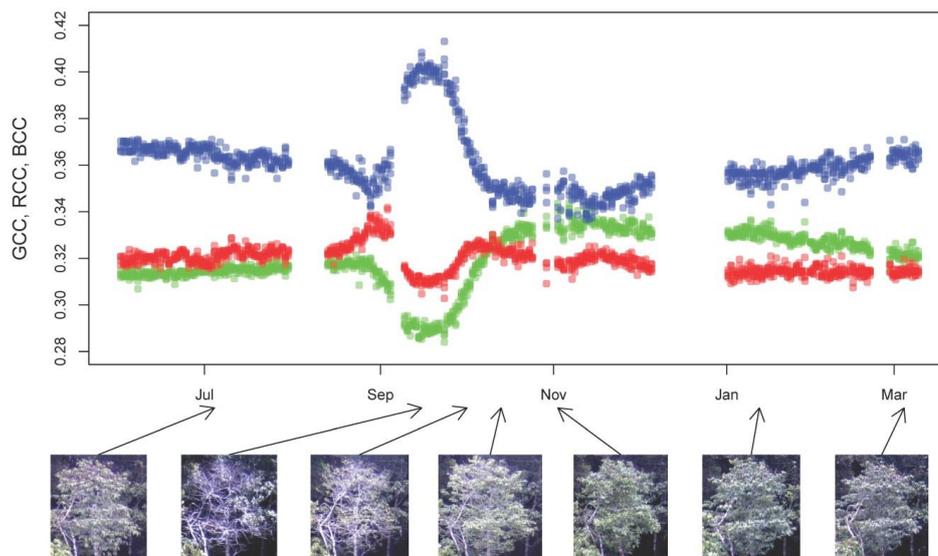
Figure 3: Green (GCC), red (RCC) and blue (BCC) chromatic coordinates for a single tree (*Wrightia laevis*) at the Cow Bay tropical forest OzFlux site, Queensland, Australia. Quick leaf shedding and flushing events are well captured by the phenocam.
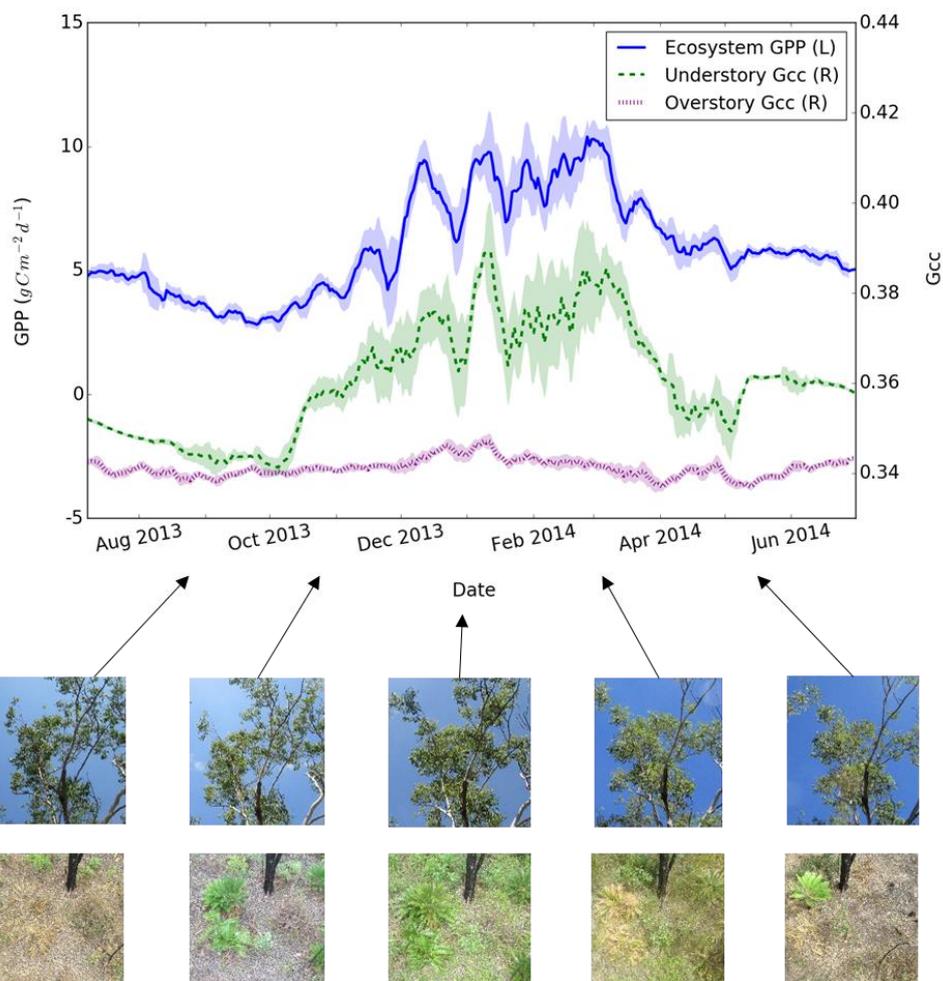
Figure 4: Savanna ecosystem gross primary productivity (GPP) and green chromatic coordinates (GCC) for the overstory and understory, with region of interest (ROI) image examples, at Howard Springs OzFlux site, Northern Territory, Australia. Data are shown as an 8-day centred running mean with ± 90 % confidence shading.
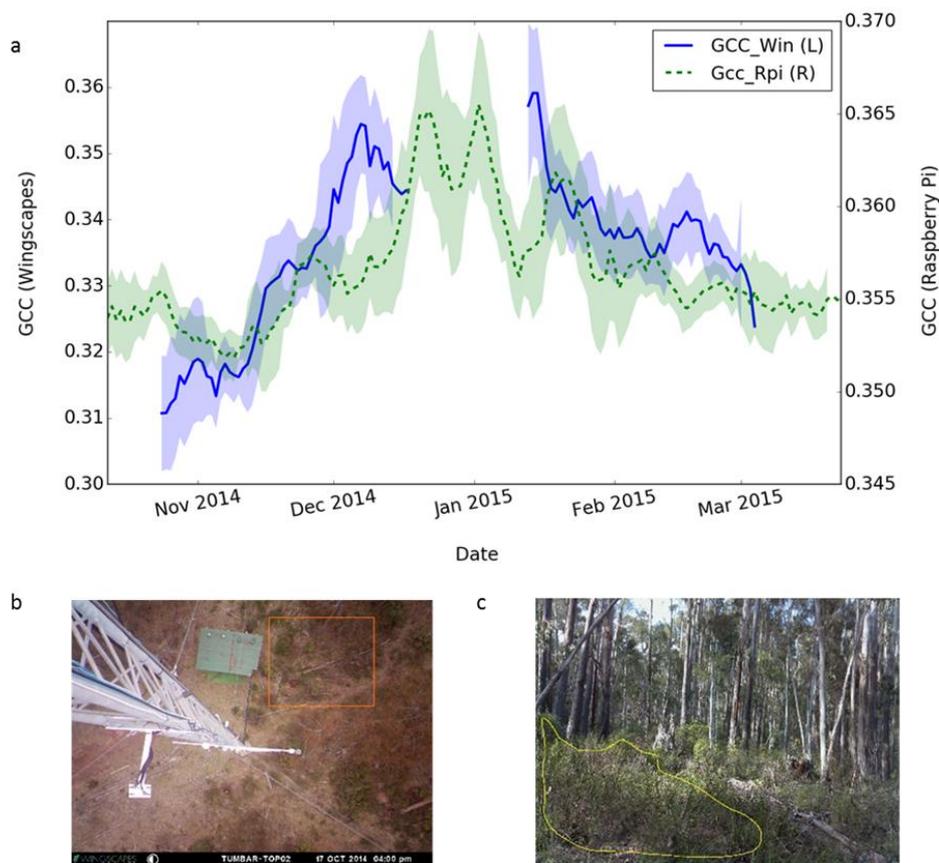
Figure 5: Phenocams in use at Tumbarumba (AU-Tum), New South Wales, Australia showing a) green chromatic coordinates (GCC) for understory vegetation from b) a downward facing wingscapes phenocam (region of interest inset) and an oblique facing raspberry pi (Rpi) phenocam (region of interest inset). GCC data are shown by an 8-day centred running mean with ± 90 % confidence shading.
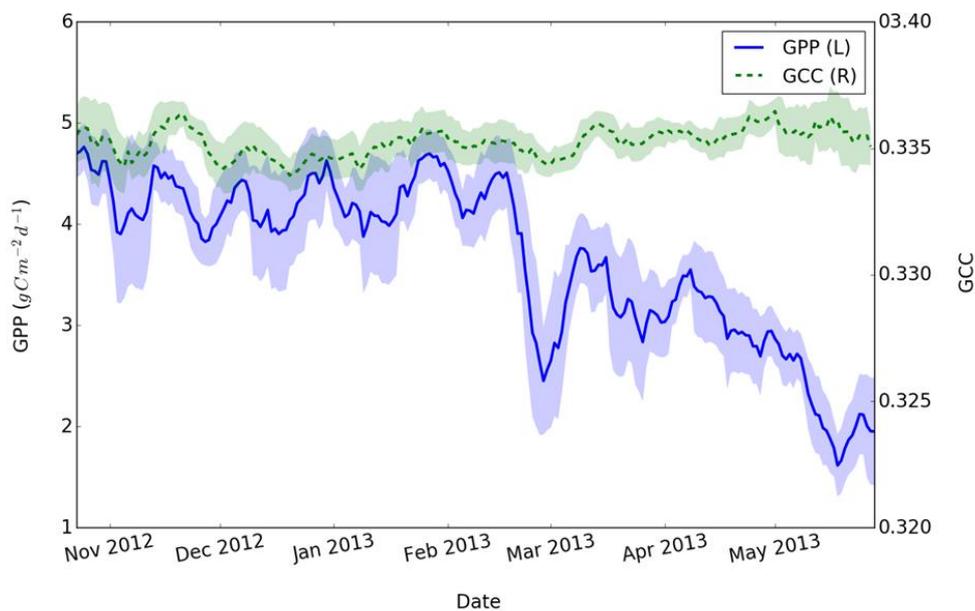
Figure 6: Ecosystem gross primary productivity (GPP) and green chromatic coordinate (GCC) index for a temperate eucalypt woodland (Whroo Conservation Reserve) in southeast Victoria, Australia. Both GPP and GCC data are shown by an 8-day centred running mean with ± 90 % confidence shading. The region of interest (ROI) for GCC calculation is indicated by the orange box in the image.