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Research paper

Climate phase drives canopy condition in a large semi-arid floodplain forest

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ABSTRACT

To maintain and restore the ecological integrity of floodplains, allocating water for environmental benefits (i.e. environmental water) is widely practised globally. To efficiently manage the always limited environmental water, there is pressing need to advance our understanding of the ecological response to long-term climate cycles as evidence grows of intensification of extreme climatic events such as severe drought and heat waves. In this study, we assessed the alleviating effects of artificial flooding on drought impact using the canopy condition of the iconic river red gum forests in Australia's Murray Darling Basin (MDB). To achieve this, we jointly analysed spatial-temporal patterns of NDVI response and drought conditions for the period of 2000–2013, during which the MDB experienced an extreme dry–wet cycle. Our results indicated that while NDVI-derived canopy condition was better at the sites receiving environmental water during the dry phases, both watered and unwatered sites displayed great similarity in seasonality and trends. Furthermore, we did not find any significant difference in NDVI response of the canopy between the sites to suggest significant differences in ecosystem stability and resilience, with watered and unwatered sites showing similar responses to the extreme wet conditions as the drought broke. The highly significant relationship between long-term drought index and NDVI anomaly suggest that climate phase is the main forcing driving canopy condition in semi-arid floodplain forests.

1. Introduction

Changes in the flow regimes of major rivers worldwide have contributed to the decline of flood-dependent biota, and to the dieback of floodplain forests in arid and semi-arid regions (González et al., 2010; Mac Nally et al., 2011). The situation is expected to deteriorate with the intensification of extreme climatic events such as severe droughts and heat waves (Thornton et al., 2014). The interception of flows in large storages, and water diversion for irrigation and town water supply combine to reduce the frequency, magnitude and duration of flows required to sustain the flood-dependent biota in many river systems (Kingsford, 2000). Water delivery strategies in support of irrigated agriculture can also change the seasonality of flow, with adverse ecological impacts (Bunn and Arthington, 2002). While the hydrological alterations caused by water resource development are profound (Wen et al., 2013), they occur in the context of a naturally variable flow regime, and adaptation to cycles of wet and dry are a feature of the growth and reproductive strategies of biota occupying these landscapes (Rogers and Ralph, 2010). It can therefore be challenging to differentiate between the ecological effects of water development and the over-riding signal of natural variability, particularly at the inter-decadal and inter-annual scales favoured by most monitoring programs (Colloff et al., 2015).

High inter-annual and inter-decadal variability in flow is a characteristic of the rivers of the Murray Darling Basin (MDB), Australia's largest river system. In the northern catchments, river flows are amongst the most variable of all the world's rivers (Puckridge et al., 1998), and the timing and volume of discharge are strongly controlled by decaying tropical lows during the monsoon. The southern catchments supply a large and more reliable flow than the northern tributaries of the MDB, though here phases of the El Niño-Southern Oscillation (ENSO) (Allen, 1988) and the Indian Ocean Dipole (Ummenhofer et al., 2009) exert a strong influence on the timing and duration of droughts. The Pacific Decadal Oscillation appears to modulate the frequency and intensity of the ENSO (Power et al., 1999) and associated flooding patterns in the northern

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and central Murray-Darling Basin (Ralph and Hesse, 2010).

Complicating the assessment of the relative significance of natural and anthropogenic impacts on flow regime is the potentially over-riding signal of climate change. The best case scenario of the impact of climate change on the MDB is a projected decrease of 12% of available surface water to 2030, an estimate which combines the impact of water resource development, climate variability and climate change (CSIRO, 2008). However, variation in climate change assessments of projected surface water flow is high, as models are driven by circulation patterns sensitive to small changes in temperature. Further, the links between global radiative forcing the operation of large oceanic-atmospheric circulation cycles like ENSO, are poorly represented in the current models, and debate continues as to the influence of climate change on this source of variability (van Oldenborgh et al., 2005).

Recent conditions in the MDB, illustrate well the confounding interactions between the multiple stressors of water resource development, climate change and climate variability. The "Millennium Drought" (1997–2009) was the most severe drought on record for southeast Australia with the longest uninterrupted series of years with below median rainfall since 1900 (BOM, July 2012). Floodplains in the MDB were among the most severely impacted ecosystems, with large areas of floodplain forest dieback throughout the basin widely observed and reported (Gawne et al., 2011), and attributed to a lack of flood events (Leblanc et al., 2012). The below average rainfall conditions reached greatest severity in 2007, but continued to 2009. Studies at this time reported substantial declines in tree condition in the southern MDB over the preceding decades (MDBC, 2005; Cunningham et al., 2007, 2009). Cunningham et al. (2010) reported that 79% of red gum forests on the Murray River floodplains experienced some degree of dieback with tree canopy less than 80% of potential crown. This figure, consistent between 2006 and 2009, was significantly higher than the period between 1990 and 2003 for which there was little change (Mac Nally et al., 2011).

To alleviate the impacts of the extreme dry condition, targeted environmental watering was practised across the MDB. The investment of substantial resources in environment water by Federal and State government jurisdictions has focussed management attention on the development of monitoring methods capable of testing the efficacy of environmental water as an intervention strategy. The broad spatial scale of watering actions (with investment across 20 catchments within a 1 million km^2 river system) favours the application of remotely-sensed metrics linked to key environmental targets. The river red gum (*Eucalyptus camaldulensis*) dominates the rivers, watercourses and wetlands of the inland regions of Australia across all climatic zones (Colloff, 2014), providing important ecosystem services including the provision of habitat for a range of biota (Leslie, 2001), and the cycling of carbon (Robertson et al., 1999). River red gum stand condition is commonly used as a metric of environmental monitoring because of the perceived link with resilience and dieback. Stand condition has been defined as 'the amount of canopy present relative to the maximal potential canopy, considering stand age, and natural abiotic and biotic limitations' (Cunningham et al., 2007). Forest dieback, has been defined as a progressive reduction in the crowns of individual trees leading to widespread mortality (Cunningham et al., 2009). Cunningham et al. (2009) tested several stand-level structural and morphological variables to identify consistent indicators of stand condition, finding that percentage live basal area (an index of mortality), plant area index, crown depth and crown vigour (the percentage of the potential crown that contained foliage) were all highly correlated. Importantly, they found that all variables closely correlated with remotely-sensed NDVI (Normalized Difference Vegetation Index), allowing for broad-scale assessment of stand condition.

While previous studies have documented the relationships between declining water availability and declining tree stand condition (Cunningham et al., 2009; Mac Nally et al., 2011), they have been limited by a largely uni-directional trend (i.e. decreasing) in both metrics in the MDB until the end of the last decade (i.e. within a drought event). The resilience of rive red gum to drought is best tested by post-drought recovery, and for the MDB the return of wet conditions following 2009 provides a unique natural experiment into factors limiting recovery. In particular, the efficacy of environmental watering actions during dry periods in promoting survival and recovery of tree stand condition can be tested by incorporating the history of watering actions into the experimental design. The absence of suitable hydrological models for the Murray River floodplain forests prevented this in the study of Cunningham et al. (2009).

In this study, we focus on the assessment of the alleviating effects of artificial flooding on drought impact – or footprint – on the canopy conditions of the iconic river red gum forests by jointly analysing spatial-temporal patterns of canopy NDVI response and drought conditions between 2000 and 2013. Furthermore, we evaluate the appropriateness of the freely available MODIS NDVI as an indicator of forest stand condition for environmental water monitoring. The study period encompasses two climatic extremes; the longest and most intense drought on record (2000–2009), followed by the wettest year on record (2010) and several successive above-average rainfall years. We used the standardised precipitation and evaporation index (SPEI) computed from monthly climatic records (1900–2013) to evaluate drought condition. We used NDVI time series (2000–2013, during which MDB experienced an extreme drought – flooding cycle) to assess the vegetation cover response by trend and change-point analysis for sites with high canopy coverage. The underlying hypothesises include: (i) artificial flooding through environmental water application could enhance NDVI as the improved soil moisture conditions will trigger vegetation responses (Breshears et al., 2005) and promote the vigour of tree stand (Wen et al., 2009; Doody et al., 2014) reflected in the dynamics of NDVI time series (Asner and Alencar, 2010; Hlásny et al., 2015); (ii) the repetitive artificial flooding could prolong the functioning wet phase (Colloff and Baldwin, 2010) and maintaining a more vigorous vegetation cover, hence the NDVI time series would exhibit a higher time persistence, which can be expressed as the degree of temporal dependency (Dakos et al., 2012; de Keersmaecker et al., 2014), and the effects of SPEI on NDVI would be smaller; and (iii) ecosystems with longer functional wet phase could be more resilient to major stress (such as drought) and have higher rate of recovery after disruption (Pimm, 1984), which might be quantified as the magnitude of NDVI increase (decrease) during the transition of returning to wet (dry) phase.

2. Method

2.1. Study area – Yanga National Park

The study site is Yanga National Park, part of the Lowbidgee Wetland Complex at the western end of the Murrumbidgee River (Fig. 1). With an area of over 200,000 ha, the ecological value of Lowbidgee is recognised as critical fish and waterbird habitats and refuge in arid and semi-arid Australia (Maher, 1990; Wen et al., 2009), and is listed in the Directory of Important Wetlands in Australia (Australian Nature Conservation Agency, 1996). The area has a semi-arid climate with low rainfall, hot summers and mild winters. The average annual rainfall (1900–2011) is about 320 mm, and there is little seasonal variation (Wen et al., 2009). The mean