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Quantifying Australia's dryland vegetation response to flooding and drought at sub-continental scale

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ABSTRACT

Vegetation response to flooding across large dryland areas such as Australia's Murray Darling Basin (MDB) is not understood synoptically and with locally relevant detail. We filled this knowledge gap by quantifying vegetation dynamics, defined here as greening and browning due to changing chlorophyll content and leaf area index, in response to flooding and rainfall across the floodplains of the entire MDB. We quantified vegetation and flooding dynamics using the same data source, namely 26 years of high resolution, wall-to-wall satellite data, in a top down statistical modeling approach, where we controlled for rainfall. Our time series (1986–2011) covered a period of extreme hydroclimatic variability, including the South East Australian Millennium Drought, thus providing a research opportunity to investigate how the relationship between vegetation and flooding changed during wet and dry periods. Our results showed that besides rainfall, flooding plays a key role in driving floodplain vegetation dynamics, yet the role of flooding varied across the MDB floodplains. We quantified a change in the relationship of how vegetation responds to rainfall and flooding with an unprecedented level of spatial detail. The change in the relationships coincided primarily with the onset of the Millennium Drought, yet local and regional differences in the timing of the change did occur, suggesting that the beginning of the Millennium Drought did not impact all floodplain areas at the same time. Our synoptic while locally relevant quantification of the changing response of vegetation to rainfall and flooding is a first step to help underpin Australia's investment into environmental water allocations.

1. Background

Quantifying vegetation dynamics, defined here as greening and browning due to changing chlorophyll content and leaf area index, in response to hydroclimatic events such as drought and flood, climate variability and change is important for global change research, as vegetation and its dynamics play a key role in greenhouse gas fluxes, water, and runoff regulation (Daily, 1997; Reid et al., 2005). Recent studies suggest that carbon turnover in semi-arid biomes is important for inter-annual variability of the global land carbon sink. For example, the 2011 record global land carbon sink was driven by semi-arid vegetation greening in the southern hemisphere, with almost 60% of the 2011 sink anomaly attributed to increases in vegetation greenness due to large precipitation amounts over Australia, associated with a strong la Niña event (Ahlström, 2015; Poulter et al., 2014). Quantifying how vegetation dynamics are driven by climate variability is important (Seddon et al., 2016) and in semi-arid areas, vegetation chlorophyll content and leaf area index undergo abrupt changes, so called ‘boom and bust’ periods, as a time-lagged response to rainfall pulses (Broich et al., 2015; Broich et al., 2014; Seddon et al., 2016).

Specifically, floodplain ecosystems of semi-arid areas undergo, are shaped by, tolerate, and are maintained by distinct dry and wet periods, which are key factors driving vegetation dynamics (Colloff and Baldwin, 2010; Wen et al., 2012; Westbrooke and Florentine, 2005). These wet and dry periods occur inter- and intra-annually as a product of variability in local rainfall and flooding. Flooding is triggered by both local rainfall and rainfall over the upstream catchment. The resulting amounts and timings drive a heterogeneous spatial-temporal pattern of floodplain vegetation dynamics (Chen et al., 2016; Murray-Hudson et al., 2014; Neuenschwander and Crews, 2008; Udelhoven et al., 2015; Wen et al., 2012).

The overall dependency of floodplain vegetation on wet and dry periods makes floodplain ecosystems sensitive to climate variability (Capon et al., 2013), and this variability is projected to increase under

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climate change (Pricope, 2013; Sheffield and Wood, 2008; Stromberg et al., 1996; Vörösmarty et al., 2010). Quantifying floodplain vegetation dynamics as a function of climate and flooding variability is important given that carbon and methane emissions (Borges et al., 2015; Harms and Grimm, 2012) and their change under a future climate are thought to have significant impacts on biogeochemical cycles (Cao et al., 1998; Mitsch et al., 2013; Shindell et al., 2004).

The recent quarter century of climatic history over South Eastern Australia features extreme hydroclimatic variability, specifically variability in rainfall and flooding, including pre-drought variability, the rapid establishment of the El Niño Southern Oscillation-related (ENSO) Millennium Drought in 2001, with intra-drought variability until 2009 when a switch to La Niña led to record-breaking floods (Australian Bureau of Meteorology, 2014; Heberger, 2011; Leblanc et al., 2012; van Dijk et al., 2013). The Millennium Drought impacted the Murray-Darling Basin (MDB), the country's semi-arid breadbasket that extends across ~1,000,000 km^2 (van Dijk et al., 2013). The MDB is subject to competing demands over limited and fluctuating surface water resources for agriculture and the maintenance of floodplain vegetation and conflicts over water escalated during the Millennium Drought.

To better manage surface water resources while preserving or restoring floodplain vegetation, quantitative spatial-temporal information is needed. Specifically, information on how floodplain vegetation dynamics depend on rainfall and flooding as well as how this relationship changed through periods of drought is paramount (Cunningham et al., 2013; Murray Darling Basin Authority, 2014; Pricope, 2013; van Dijk et al., 2013).

The MDB is covered by the publically available, high spatial resolution remote sensing time series systematically acquired by the U.S. Landsat program with a temporal image density second only to the North American continent (Wulder and Coops, 2014; Kovalskyy & Roy, 2013). The Landsat time series provided us with the research opportunity to conduct retrospective, spatially explicit analysis and model the temporal response pattern of floodplain vegetation dynamics to climate variability and flooding across the entire MDB. No previous study (Table 2 in Appendix A) has synoptically used Landsat-observed flooding and Landsat-observed vegetation dynamics time series to model the vegetation response across an area as large as the MDB with local and management relevant detail. This type of analysis and modeling effort has until recently been prohibitive due to computational constraints, and is a first within the existing literature. The goal of this paper was therefore to synoptically quantify vegetation dynamics as a function of rainfall and flooding and assess how these relationships changed over time using Landsat and rainfall time series covering the decade prior to and during the Millennium Drought.

2. Methods

2.1. Study area

The MDB covers 14% of the Australian continent, and extends across five climate zones (Köppen, 1884). The average annual rainfall decreases from 1500 mm at higher altitudes along the Southern and Eastern boundaries of the MDB to < 300 mm towards the Northwest into the interior of Australia (Leblanc et al., 2012). Regional rainfall seasonality and runoff differ across the MDB, with larger rainfall totals and smaller runoff variability in the wetter south, which is drained by the Murray River and smaller rainfall totals and larger variability in the drier northern basin, which is drained by the Darling River (Murray–Darling Basin Authority, 2012; Fig. 1).

The MDB contains 50% of the Australian sheep population and 25% of its cattle and accounts for almost 50% of Australia's wheat production, 75% of irrigated land and approximately 40% of the country's agricultural production. For these reasons, it is frequently referred to as Australia's breadbasket (Prasa and Khan, 2002). As a result of agricultural development, > 90% of the MDB's floodplain ecosystems have already been lost or permanently altered by agricultural development (Rogers and Ralph, 2010). The modification of historical flow regimes affects the entire system, including over 200 wetlands of national importance and 16 RAMSAR-listed wetlands (Australian Department of the Environment and Energy, 2017). The MDB's remaining floodplain ecosystems are threatened by ongoing competition over limited water resources under a changing regional climate (Leblanc et al., 2012; Murray Darling Basin Authority, 2014). As a consequence, the National Water Initiative requires that surface water is appropriately managed, and that over-allocated systems are returned to environmentally sustainable levels of take (Council of Australian Governments, 2004). In this context, the Australian government has invested into improving irrigation efficiency and buying back of water previously allocated to agriculture and using it as environmental water to mimic the natural floodplain inundation regime (Murray Darling Basin Authority, 2014; Office of Parliamentary Counsel Canberra, 2012). Yet, balancing the maintenance of riparian ecosystem integrity with the extraction of scarce water resources for agriculture necessitates a greater understanding of relationships between riparian vegetation dynamics and flooding (Cunningham et al., 2013; Pricope, 2013).

2.2. Datasets

2.2.1. Remote sensing datasets

In this work we used a time series of over 25,000 Landsat 5 and 7 images, covering the entire MDB from 1986 to 2011. After applying the cloud-flagging method developed by Tulbure et al. (2016) and Tulbure and Broich (2013), we calculated the Enhanced Vegetation Index (EVI; Huete et al., 2002) for each pixel and seasonal time step (26 years $*$ 4 seasons = 104 time steps). We used EVI to quantify floodplain vegetation dynamics as the response signal under a changing rainfall and flooding regime. EVI is commonly used to quantify vegetation dynamics, such as green up timing, magnitude changes and disturbances, through a property referred to as vegetation greenness which correlates with sub-pixel chlorophyll content and leaf area index (Huete et al., 2014;Broich et al., 2015, Broich et al., 2014; de Jong et al., 2011). We quantified flooding using the surface water extent dynamics product developed by Tulbure et al. (2016). Alternatively we could have used the surface water extent dynamics provided by Pekel et al. (2016) yet decided against it given that the Tulbure et al. (2016) product was designed specifically for the MDB. Tulbure et al. (2016) was also the only published product with a statistical accuracy assessment that created confidence for its use in follow on applications (e.g. Bishop-Taylor et al., 2015, Bishop-Taylor et al., 2017a, 2017b, Bishop-Taylor et al., 2018; Heimhuber et al., 2015, 2017; Shendryk et al., 2016b). The statistical accuracy assessment met two key criteria. It was representative for the entire study area and it was framed by standard error envelopes, which provided a quantified level of confidence in the product's accuracy. The surface water extent dynamics product has been derived from the same time series of Landsat imagery as the EVI.

2.2.1.1. Seasonal aggregation of Landsat data. Given the presence of clouds and shadows, gap free observations of the land surface are not always available at the nominal temporal resolution of Landsat (16 days). To reduce the amount of missing data per time step, we derived seasonal composites (southern hemisphere winter, spring, summer and fall starting in June, September, December and March, respectively) by calculating the maximum EVI per pixel, season and year. The maximum value compositing approach is a long established method to avoid residual cloud contamination as well as cloud shadows (Gutman, 1991; Solano et al., 2010). In drylands, green up events are characterized by rapidly occurring, short lived increases in vegetation greenness of low amplitude. Therefore the peak greenness does not only show the vegetation's maximum productivity relative to the hydrometeorological conditions but also provides more contrast over