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Detecting microrefugia in semi-arid landscapes from remotely sensed vegetation dynamics

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ABSTRACT

Microrefugia are sites with stable, high quality habitat within landscapes characterized by dynamic environmental conditions driven by climate variability or ecological disturbances. There is considerable interest in the potential of microrefugia to provide climate change resilience to landscapes and to biodiversity conservation. Although attractive conceptually, there is yet little guidance on how to identify climate change microrefugia in order to study and protect them, and the data required to do so are often lacking. This study demonstrates how time series remote sensing, using all available Landsat images of a study area, can be used to directly detect microrefugia maintained by water subsidies in a semi-arid landscape in southwest Western Australia.

Microrefugia were identified as pixels with abundant vegetation and consistent vegetation dynamics between wet and dry years. At every pixel, a harmonic model was fit to the intra-annual time series of vegetation index values compiled from the wettest years in the Landsat-5 Thematic Mapper (TM) archive. This model was then used to predict the phenological cycle of the driest years at that pixel. Candidate microrefugia were defined to be those pixels with (1) high vegetation activity in dry years and (2) highly predictable phenologies that are consistent regardless of the weather conditions experienced in a given year. Spatial relationships between candidate microrefugia and landscape features associated with elevated moisture availability (thought to drive climate microrefugia in these semi-arid landscapes) were assessed. The candidate microrefugia show great promise. Evaluations against high-resolution imagery reveal that candidate microrefugia most likely buffer against drought, although refugia from other disturbances, especially fire, were also detected. In contrast, spatial proxies of the physical features expected to maintain microrefugia failed to adequately represent the distribution of microrefugia across the landscape, likely due to data quality and the heterogeneity of microrefugia. Direct detection of microrefugia with Earth observation data is a promising solution in data limited regions. Landsat time series analyses are well suited to this application as they can characterize both the habitat quality and stability aspects of microrefugia.

1. Introduction

Refugia are increasingly seen as essential conservation assets. Refugia, and especially microrefugia, are small sites with stable, high quality habitat in a regional context of change and adverse conditions (Dobrowski, 2011; Keppel et al., 2012); they provide landscape-level resilience to environmental variation (*sensu* Bengtsson et al., 2003). The refugia concept derives from biogeographical and paleoecological investigations of species' responses to glacial-interglacial cycles. Unlike macrorefugia (or simply ‘refugia’), which are large areas of suitable habitat for many species during a time of widespread climate-driven range contractions, microrefugia are isolated sites of benign microclimates that allow species persistence within a broad region of formerly suitable habitat (Rull, 2009). Microrefugia exist because of buffering processes that decouple the site's microclimate from regional climate (Dobrowski, 2011; Morelli et al., 2016). Because microrefugia allow *in situ* persistence within the species' former range, they facilitate species responses to climate change *via* distribution dynamics, reducing the migration speeds necessary to track climatically suitable habitat (Corlett and Westcott, 2013). Numerous lines of evidence, including fossils, distribution models, and patterns of genetic diversity, support the importance of microrefugia during past climate change (Birks and Willis, 2008; Gavin et al., 2014; Stewart et al., 2010). In Australia, which was not glaciated but experienced widespread conditions of extreme aridity during glacial phases (Byrne et al., 2008), biodiversity appears to have been maintained primarily in microrefugia (Byrne, 2008).

Because of the emphasis on glacial-interglacial cycles in the

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development of the refugia concept, attention is generally focused on the sites and processes that buffer temperature extremes. However, axes such as moisture availability (hydrologic refugia; Davis et al., 2013; McLaughlin et al., 2017) or disturbance (e.g., fire refugia; Ouarmim et al., 2014; Wilkin et al., 2016) are equally important (Reside et al., 2014). In addition, refugia can operate over multiple time frames, determined by their size and permanence (i.e., the degree to which they are decoupled from regional conditions). Evolutionary refugia allow population persistence over long time scales, such as glacial phases, while ecological refugia provide stable suitable habitat when processes such as extended drought render the broader area unsuitable for multi-year time frames (Davis et al., 2013; Morton et al., 1995). In arid and semi-arid systems, microrefugia provide critical contemporary habitat. Deserts are highly variable, with vegetation and wildlife populations exhibiting boom-bust dynamics driven by patchy, unpredictable precipitation (Morton et al., 2011). Water supplies that are decoupled from regional precipitation, such as accessible groundwater or springs, maintain consistent resource availability during bust phases. Wildlife populations retreat to these microrefugia, persisting locally despite extended periods of poor conditions regionally (Dickman et al., 2011; Pavey et al., 2014). Conservation strategies may be most effective if they focus on microrefugia, by targeting the sites crucial for population persistence when they are most vulnerable (Pavey et al., 2014).

Similarly, protection of refugia features prominently in general recommendations for climate change adaptation (Groves et al., 2012; Jones et al., 2016). However, while arid-zone refugia provide stable habitat during contemporary climate fluctuations, climate change microrefugia are expected to maintain relictual habitat within larger regions that climate change has rendered unsuitable (Dobrowski, 2011; Keppel et al., 2012; Reside et al., 2014). Such microrefugia may be most valuable as stepping stones facilitating species range shifts, even if they do not provide permanent suitable habitat (Hannah et al., 2014). Modeling studies have found that the availability of microrefugia can substantially reduce predictions of extinction risk due to contemporary climate fluctuations (Céré et al., 2015) and historical (Patsiou et al., 2014) and anthropogenic (Lenoir et al., 2017; Meineri and Hylander, 2017; Randin et al., 2009; Slavich et al., 2014) climate change.

While the conservation of refugia is an intuitive and appealing concept, conservation practitioners are currently unable to operationalize it. There exists much uncertainty over how to identify refugia within landscapes to target management spatially (Ashcroft, 2010). Putative refugia (micro- and macrorefugia) are typically located using simple heuristics, most commonly that areas with high topographic heterogeneity are likely to function as refugia (Ashcroft, 2010; Carroll et al., 2017; Dobrowski, 2011). There is less guidance about identifying refugia in areas of modest terrain (Reside et al., 2014). Another guideline, especially in arid systems, is that sites with access to permanent water sources are refugia (Davis et al., 2013; McLaughlin et al., 2017; Reside et al., 2014).

Refugia may also be determined empirically as areas that are relatively constant bioclimatically. Such sites display reduced contemporary variability or are forecast to experience less climate change relative to their surroundings, and thus meet the condition that refugia are decoupled from regional climate. However, there is uncertainty over how best to quantify this consistency. Measures of the velocity of climate change are becoming popular indicators of refugia (Ackerly et al., 2010; Hamann et al., 2015). Other approaches focus more explicitly on habitat, identifying refugia from species distribution or macroecological model projections (Carroll et al., 2015; Keppel et al., 2015). However, a critique of both of these strategies is that the spatial resolution of the climate data that exists to support them, typically 1–100 km, is too coarse to capture the important microclimates of microrefugia (Franklin et al., 2013; Potter et al., 2013). There is growing interest in developing fine-scale grids of micro- or topo-climate, often with ~30 m pixels, *via* downscaling techniques (Davis et al., 2016; Dingman et al., 2013; McCullough et al., 2016) or interpolation from dense sensor arrays (Ashcroft, 2010; Frey et al., 2016) to identify microrefugia. An important source of uncertainty is that different measures and different methodological choices identify different sites as candidate refugia (Ashcroft, 2010; Ashcroft et al., 2012; Carroll et al., 2015, 2017).

But a persistent challenge to the mapping of microrefugia is a widespread lack of suitable data. General guidelines about water subsidies, for example, have little use without spatial environmental data of relevant hydrological features. Likewise, bioclimatic data needed to quantify environmental variability at the local scales relevant for microrefugia are vanishingly rare, as fine-scale climate surfaces from dense sensor arrays may often be prohibitive. An alternative strategy that has received little attention is the direct detection of microrefugia with remote sensing.

By collecting repeated, spatially comprehensive observations of Earth over relevant spatial and temporal scales, remote sensing is an excellent means by which to resolve environmental data limitations (Pettorelli et al., 2014). Remotely sensed time series of vegetation activity may indicate stable habitat—sites with high temporal consistency that are decoupled from the larger fluctuations of the surrounding region—and thus the presence of microrefugia, especially in arid regions where patterns of vegetation activity and abundance are related to water availability (O'Grady et al., 2011). To date, there have been several studies to remotely detect ecosystems receiving groundwater subsidies (Barron et al., 2014; Contreras et al., 2011), but only one application of remote sensing to detect refugia (Mackey et al., 2012), using relatively coarse MODIS data. The current data policy allowing free use of the 40 + year archive of Landsat image data (Wulder et al., 2012) and the novel applications of dense Landsat time series (LTS) that it has stimulated (Kennedy et al., 2014) may support the detection of microrefugia at finer spatial resolution.

The objectives of this study are (1) to demonstrate how LTS data can be used to identify candidate microrefugia, especially hydrologic refugia, in a low-relief semi-arid landscape; and (2) to test the effectiveness of heuristics about physical proxies of microrefugia by evaluating associations between the refugia identified from LTS and landscape features expected to influence water availability. We also assess the robustness of the detected microrefugia to the choice of methods to quantify habitat stability.

2. Methods

2.1. Spatial & temporal extents

This study was conducted over four conservation stations in Western Australia (Fig. 1a; 5300 km^2) – Charles Darwin Reserve (formerly Whitewells Station), and Mt. Gibson, Ninghan, and Wanarra Stations. These reserves are former pastoral lands that have been destocked and are now managed for conservation by state government, aboriginal groups, and land management conservation NGOs. Dominant land covers in the study area are open woodlands and shrublands of *Eucalyptus* and *Acacia* species, as well as ephemeral salt lakes. Most of the study area is within the southwestern Australia global biodiversity hotspot, and includes a variety of species and communities of conservation concern. There is little topographic variation across the study area; elevations range from 244 m to 685 m (97% of the area is below 400 m). Some local relief is provided by Mt. Singleton, the Mt. Gibson Range, and numerous granite tors and outcrops. Elsewhere, granite sheets lie beneath shallow soils or are exposed.

Contrasts between vegetation activity in wet and dry conditions provide a measure of temporal consistency that is related to the availability of more permanent sources of water in arid and semi-arid areas (Barron et al., 2014) and is expected to provide an indicator of microrefugia (Griffin and Pearce, 1995). As well, observed changes between wet and dry years are more ecologically meaningful than the generic statistical measures of variability used to detect microrefugia