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Fragmentation metric proxies provide insights into historical biodiversity loss in critically endangered grassland

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ABSTRACT

Landscape transformation causes habitat loss and fragmentation, which poses the greatest threat to biodiversity globally. In a fragmented landscape the persistence of species is affected by the amount of habitat and the spatial attributes of individual habitat patches. As baseline biodiversity information is often unavailable to assess the effects of transformation on biodiversity, quantifying changes in patch metrics over time could be a useful indicator of biodiversity changes in fragmented landscapes. We investigate historical land cover changes due to increased anthropogenic land uses in a highly fragmented, critically endangered grassland, the Woodbush Granite Grassland, South Africa. We test how the spatial attributes of habitat patches were affected by habitat loss and fragmentation over two extended time-periods, and use these results to infer likely threats to biodiversity over these periods. We used repeat aerial photography to analyse the drivers and extent of land cover loss and the changes in five fragmentation metrics over a 60 year period. The overall grassland extent decreased significantly over the 60-year period, mainly due to increased timber plantations, with an estimated 6.1% of the original extent of the grassland remaining in 2008. Increases in patch isolation due to habitat loss were most pronounced between 1948 and 1977, while between 1977 and 2008 patch sizes decreased and edge effects increased. This extensive habitat loss and increase in fragmentation are likely to have had considerable impacts on the biodiversity of the region, which is supported by anecdotal evidence of species extinctions and local extinctions. Because so little of the vegetation type remains, it is imperative that the last vestiges of this vegetation type are protected from transformation and further habitat degradation. In summary, we show how, faced with a lack of biodiversity data, fragmentation patch metrics can be used to quantify threats to biodiversity.

1. Introduction

One of the consequences of land cover change is that natural vegetation, and thus the habitat for native species, diminishes and becomes fragmented (Ellis et al., 2010). When this occurs three processes which are closely intertwined take place: habitat loss, *i.e.* there is considerable reduction in the total amount of original habitat; division of the remaining habitat into smaller units, often patches (habitat fragmentation); and the formation of new land-use types which replace the former vegetation (Fahrig, 2003; Bennett and Saunders, 2010).

Of the different impacts of humans on the environment, habitat loss is often considered the most detrimental to biodiversity, with negative effects reported across many taxa, including amphibians (*e.g.* Cushman, 2006), bats (*e.g.* Ethier and Fahrig, 2011), birds (*e.g.* Smith et al., 2011), small mammals (*e.g.* Nupp and Swihart, 2000), wetland species (*e.g.* Quesnelle et al., 2013), coral reef fishes (*e.g.* Bonin et al., 2011) and plants (*e.g.* Collins et al., 2009). Habitat fragmentation results in loss of biodiversity, population connectedness and gene flow, and can increase habitat susceptibility to invasions, although the effects of fragmentation *per se* are thought to only become pronounced when the extent of the original habitat is reduced below a critical threshold (Fahrig, 2003).

As landscapes become increasingly fragmented, the spatial attributes of individual patches (see McGarigal et al., 2012 for list of metrics) in the landscape, such as the number of remaining patches in the landscape, the size of patches (patch area), isolation of patches, and the shapes of patches which affect the ratio of interior habitat to edge length (Fahrig, 2003; Bennett and Saunders, 2010), are affected. Accordingly, negative effects of habitat fragmentation on biodiversity may arise due to changes in

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these spatial attributes. As patch size decreases, species richness may decline (Bennett and Saunders, 2010) because patches have become smaller than the minimum area required for sustaining populations or individuals of species with larger range requirements (Nol et al., 2005); consequently, in smaller patches many species may be absent. It is expected that an increase in patch isolation causes a reduction of species diversity (Fahrig, 2003). It has been shown that all patch isolation metrics are strongly negatively related to habitat amount in the adjacent landscape (Fahrig, 2003, 2013). Therefore, patch isolation describes the absence of original habitat in the adjacent landscape (Fahrig, 2003). Patch edges are important structural features as well as functional components of habitat patches in the landscape (Ewers and Didham, 2006; Peyras et al., 2013). As the edges of individual patches increase, the interior of these patches decreases which results in a reduction and even loss of core species within these patches (Ewers and Didham, 2006). Edges often support a different suite of organisms than the more intact interior of patches due to different abiotic conditions; thus, community structure and diversity are characteristically altered at habitat edges (Ewers and Didham, 2006).

Therefore, the persistence of species and their population dynamics in remnant habitat patches is affected by the size, shape, and arrangement of these patches (Bennett and Saunders, 2010;). Several patch metrics have proven to be effective indicators of biodiversity in fragmented landscapes (Lindenmayer et al., 2002; Honnay et al., 2003; Schindler et al., 2008, 2013; Prugh, 2009; Uuemaa et al., 2009, 2013; Bailey et al., 2010; Walz, 2011). Thus, the use of patch metrics could be effective surrogates of both fauna and flora biodiversity as it is often financially and logistically challenging to estimate biodiversity at the landscape scale (Gardner et al., 2008). In addition, such surrogates are especially valuable in studies assessing fragmentation patterns over time, as biodiversity information for past time periods are often unavailable. Therefore, the advancement and usage of surrogates simplifies and assists the management of complex ecosystems, especially when biological data are limited (Mallinis et al., 2011; Pitkänen et al., 2014). Surrogates can thus be used as proxies of biodiversity patterns in a data-deficient landscape. Consequently, rapid assessment of biodiversity responses to habitat loss and fragmentation could be achieved by quantifying patch metrics.

In any highly transformed landscape with high biodiversity potential, it is essential to acquire spatially detailed data to quantify land cover changes (Mallinis et al., 2011; Pitkänen et al., 2014). Only once the causal factors responsible for changes in land cover are defined and understood can essential management policies be developed for local and/or regional areas to mitigate and minimise further disturbances and degradation of the natural ecosystem (Marcucci, 2000). Geographical Information System (GIS) and historical aerial photographs and/or remote sensing satellite images can be used as fast and reliable tools to measure and capture data for thorough analysis of land cover changes (Honnay et al., 2003; Mallinis et al., 2011; Pitkänen et al., 2014). Although satellite data provide a rich supply of spatial and spectral information (Mallinis et al., 2008), such information is temporally restricted as satellite data only became available from 1972 onwards and initially at low resolution. Consequently, spatially specific studies over long time periods showing land cover changes are limited. However, historical aerial photographs have been acknowledged as a rich source of information to quantify spatial processes and changes in a natural ecosystem over longer time periods (Corrigan et al., 2010; Mallinis et al., 2011; Pitkänen et al., 2014).

In this study, we used aerial photography to analyse the drivers and extent of land cover loss and changes in fragmentation metrics in a highly fragmented grassland system. Globally, grasslands are amongst the most threatened and transformed biomes: they support large human populations and are subject to ever-expanding resource needs (Hoekstra et al., 2005). In South Africa, grasslands cover approximately 28% of the country's land surface and support a rich flora high in endemism (Mucina and Rutherford, 2006). These grasslands provide a range of essential ecosystem services such as erosion control, carbon sequestration, water supply and purification, productive soils, medicinal plants, and they are utilised for tourism and recreation (Egoh et al., 2009, 2011; Dzerefos et al., 2016), and support the majority of South Africa's human population, resulting in high resource demands which have serious environmental repercussions for grassland biodiversity (Reyers and Tosh, 2003). Yet grasslands comprise the least protected biome in South Africa, with less than 2% formally protected (Neke and du Plessis, 2004; Reyers et al., 2005; Carbutt et al., 2011). South Africa's grasslands continue to face growing risks of transformation due to the establishment of exotic timber plantations, agriculture, overgrazing, mining and urbanisation (O'Connor, 2005; Reyers et al., 2005; O'Connor and Kuyler, 2009; Carbutt et al., 2011).

South Africa's Woodbush Granite Grassland (WGG) is amongst the most threatened and transformed grasslands in the country (Mucina and Rutherford, 2006). However, no baseline biodiversity data are available to assess the effects of habitat loss and fragmentation on its biodiversity. We have thus set out to quantify the habitat loss and fragmentation of the WGG. This will provide a better understanding of the threats that have faced the native biodiversity of the region, and provide clues about how its native biodiversity may have been impacted by its transformation. The first objective of this study was to investigate the amount of anthropogenically-driven habitat loss experienced by the WGG over 60 years, by quantifying its extent in 1948, 1977 and 2008. In addition, we examined what the drivers of habitat loss in the WGG have been. Second, we tested how the spatial attributes of grassland patches have been affected by habitat loss and fragmentation over time. We specifically quantified changes in five grassland patch metrics: patch size, isolation from the main grassland patch, isolation from nearest neighbour patch, isolation from any large patch and edge effects. Finally, we tested to what extent edge effects are affected if roads intersecting otherwise contiguous patches are considered. Little attention has been given to the effect of fragmentation of continuous and remnant habitats by highways and roads (Goosem, 1997). However, recent fragmentation research has highlighted the importance of incorporating the effects of roads on natural ecosystems (Goosem, 2007; Freitas et al., 2010; Marcantonio et al., 2013; Newman et al., 2014), as it may further increase edge effects. This study thus quantifies how landscape transformation and fragmentation have progressed over time and in space in the WGG, by specifically measuring patch metrics, which are useful proxies for changes in biodiversity within the remaining habitat patches in the absence of historical diversity data.

2. Methods

2.1. Study area

The WGG vegetation unit (Mucina and Rutherford, 2006) occurs in the Limpopo Province of South Africa (Fig. 1) and was defined based on vegetation surveys, geology and expert consultations. The extent of the vegetation unit is thus a description of the potential distribution of the vegetation type independent of current land use types. Its original extent was approximately 340 km^2 (Mucina and Rutherford, 2006). It is estimated that 661 plant species (36 of which are considered threatened; Dzerefos et al., 2016), 237 birds (8 threatened), 62 mammals (19 threatened), 38 reptiles (7