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Original Articles

Grazing reduces the capacity of Landscape Function Analysis to predict regional-scale nutrient availability or decomposition, but not total nutrient pools

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ABSTRACT

The Nutrient Cycling Index (hereafter 'Nutrient Index') derived from Landscape Function Analysis (LFA) is used extensively by land managers worldwide to obtain rapid and cost-effective information on soil condition and nutrient status in terrestrial ecosystems. Despite its utility, relatively little is known about its reliability under different management conditions (e.g. grazing) or across different climatic zones (aridity). Here we correlated the Nutrient Index, comprising measures of biocrust cover, plant basal cover, soil roughness and three attributes of surface litter cover, with empirical data on measures of soil total nutrient pools (C and N), nutrient availability (labile C, inorganic N and P), and decomposition-related enzymes at 151 locations from eastern Australia varying in grazing intensity and climatic conditions. Grazing intensity was assessed by measuring current grazing (dung production by the herbivores cattle, sheep/goats, kangaroos and rabbits), and historic grazing (the total area of livestock tracks leading from water). We used aridity (the relationship between precipitation and potential evapotranspiration) as a measure of climate. On average, the Nutrient Index was positively associated with total nutrient pools, nutrient availability and decomposition enzymes. However, further statistical modelling indicated that grazing intensity strongly reduced the link between the index and decomposition enzymes, labile C and inorganic P, but not with total nutrient pools. This grazing effect was predominantly due to cattle. Conversely, aridity had no significant effect on the predictive power of the index, suggesting that it could be used across different aridity conditions in natural ecosystems as a reliable predictor of soil health. Overall, our study reveals that the Nutrient Index is a robust predictor of total nutrient pools across different aridity and grazing conditions, but not for predicting nutrient availability or decomposition in environments heavily grazed by livestock.

1. Introduction

Rapid methods of assessing soil nutrient status have gained increasing popularity over the past few decades, particularly in arid and semi-arid environments (drylands) where monitoring extensive areas is prohibitively expensive, and where sophisticated laboratories are not always available. The use of indices or surrogates for assessing soil quality is widespread, particularly under cultivated agriculture (e.g. Granatstein and Bezdicek, 1992; Sojka and Upchurch, 1999; Li et al., 2013; Izquierdo et al., 2005; Zornoza et al., 2015; Raiesi and Kabiri, 2016) but also in drylands (Li et al., 2013; Raiesi, 2017). The attributes used to assess quality vary substantially, from soil physical, biological, chemical and biochemical, to microbiological assays, and the advantages of different indices vary with land management type, soil type, environmental setting and available resources. Consequently, there is no universally accepted measure for assessing soil quality (Karlen, et al., 1997).

The use of simple soil indices has many advantages over traditional physical and chemical methods. First, they are relatively rapid, and more sites can be assessed without the need for expensive and detailed laboratory analyses such as soil enzymes activities (Bell et al., 2013) or mineralization rates (C or N; e.g. Picone et al., 2002). Second, data collection, and assessment and interpretation of indices or surrogates require only low levels of expertise. Third, indices are typically focussed on specific management objectives that may be closely aligned to soil policy (e.g. Griffiths et al., 2016). Notwithstanding their limitations

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(Blecker et al., 2012; Sojka and Upchurch, 1999), the use of indices or proxies of soil health provide valuable insights into the processes driving soil function by focussing on tangible soil and ecological attributes that are appropriate and relatively well understood by operators with only minimal training.

Landscape Function Analysis (LFA: Ludwig and Tongway, 1995) is a widely accepted technique for assessing soil nutrient status in terrestrial environments. It incorporates a quadrat-based module (Soil Surface Condition) that assesses the capacity of the soil to resist erosion, cycle nutrients and infiltrate water (Tongway, 1995). One of these indices, the LFA Nutrient Cycling Index (hereafter 'Nutrient Index'), provides information on the nutrient status (e.g. nutrient availability and mineralization) of soils (Maestre and Puche, 2009; Tongway, 1995). It is based on the close relationship among 12 readily identifiable soil surface features and underlying processes of nutrient mineralisation. These relationships have been quantified using extensive field and laboratory studies (Holm et al., 2002; Ata Rezaei et al., 2006; Maestre and Puche, 2009; Zucca et al., 2013). The practicality of the Nutrient Index is based on the assumption that functional, healthy landscapes regulate critical resources such as sediment, water and organic material, which are all important components of the Nutrient Index (Sarre, 1998). Worldwide studies indicate that the values obtained from this index are highly related to laboratory and field measurements of their related processes (Maestre and Puche, 2009; McIntyre and Tongway, 2005; Holm et al., 2002; Ata Rezaei et al., 2006; Tongway, 1995; Zucca, et al., 2013). Consequently, the soil Nutrient Index has been used widely, across diverse landscapes, community types, climatic zones, management scenarios and land use intensities (e.g. Eldridge et al., 2011; Eldridge et al., 2016a), and often in developing countries (Ata Rezaei et al., 2006; Zucca et al., 2013). Given its largely global adoption, particularly in semi-arid rangelands, it is assumed that the Nutrient Index is globally relevant under a range of ecosystem conditions. Lacking, however, is an assessment of the effectiveness of the index under different land use intensity scenarios and climatic drivers, the strongest of which are grazing and increasing aridity.

Grazing is a major global change driver, and overgrazing has been described as one of the most destructive landuses on the planet because of its negative effect on ecosystem processes and functions (Steinfeld et al., 2006; Eldridge et al., 2015). However, grazing provides millions of peoples and their cultures worldwide with essential goods and services. Aridity is also a significant driver and reflects potential changes that might occur under hotter and drier global climates (Maestre et al., 2015, 2016). Increasing aridity will reduce the efficiency with which plants carry out essential soil processes such as the mineralisation of organic matter (Maestre et al., 2016), and has been demonstrated to decouple nutrient cycling in global drylands (Delgado-Baquerizo et al., 2013). Both grazing and aridity are expected to increase in response to a changing climate. With increases in aridity, human cultures that rely on livestock grazing for their livelihoods will be forced to exploit less suitable environments or increase their stocking rates to maintain productivity in the face of declining rainfall (Steinfeld et al., 2006; Prăvălie, 2016).

Here we evaluate the robustness of the LFA Nutrient Index in response to increasing grazing and aridity. Our intention is not to evaluate the strength of correlations between individual soil attributes and the index *per se* (Ata Rezaei et al., 2006; Maestre and Puche, 2009) or to debate the merits or otherwise of the many indices currently used in agriculture (Zornoza et al., 2015), but rather, to examine the utility of this index in response to the two major environmental drivers. Put simply, we assess the usefulness of the index under a drier climate and a more intensively managed world. The specific components of the Nutrient Index: surface roughness, biocrust cover, plant basal cover, plant litter cover, plant litter origin, and plant litter incorporation, are expected to vary naturally across aridity gradients, providing an indication of naturally co-occurring changes in soil nutrient availability. For example, a mesic environment with a greater incorporation of litter would be expected to have a higher amount of organic C than an arid ecosystem with a much lower amount of litter incorporation. Because of this, we hypothesized that increases in aridity, naturally accompanying changes in LFA components, should have little effect on the predictability of the LFA Nutrient Index. Conversely, however, we hypothesized that grazing would strongly influence the correlation between the index and multiple empirical measures of soil function, particularly those related to nutrient availability (i.e. inorganic N and P, and labile C) and measures of organic matter decomposition (i.e. extracellular enzyme activity). However, grazing may not influence the correlation with total nutrient pools. Our reasoning is that grazing would likely influence the availability of nutrients and enzymes *via* direct additions of nutrients as urine and dung, but may not alter components of the Nutrient Index such as litter incorporation, thereby disrupting the natural capacity of the index to predict nutrient availability. Conversely, grazing would be expected to alter plant components such as vascular and non-vascular plant cover and total nutrient pools in parallel, thus maintaining the links between the index and total nutrient pools. For example, a high grazing intensity would be expected to reduce plant basal cover and soil C (Eldridge and Delgado-Baquerizo, 2017), hence plant cover would still be a good predictor of total C under high grazing scenarios.

Clarifying the extent to which grazing by different herbivores might reduce the utility of soil chemical surrogates in drylands is critically important because governments and their resource management agencies need rapid, reliable and cost-effective measures to assess changes in soil function as the planet gets warmer and drier into the next century. This is particularly important in drylands because: (1) drylands mostly occur in developing countries, which have a more limited capacity to assess nutrient availability over extensive areas; (2) the effects of increases in aridity are likely to be most strongly felt, and (3) about 40% of Earth's human population currently reside in drylands (Prăvălie, 2016). The work is also important because increasing intensities of different herbivores would be expected to have different effects on surrogates of soil chemical status. For example, cattle and sheep have been shown to have strong negative effects on soil health, but kangaroos (*Macropus* spp.), which have co-evolved with soils and vegetation in Australia, have relatively benign effects (Eldridge et al., 2016b). The ability to predict soil nutrient pools, therefore, might be stronger in environments supporting low levels of livestock grazing or where kangaroos are the principal herbivores. Knowing how these different herbivores might affect the relationships between nutrient indices and different soil nutrients and enzymes is important because it provides land managers with vital information that will improve their ability to make decisions on how their management alters soil function using relatively rapid, cost effective methodologies that are readily accessible to non-professionals.

2. Methods

2.1. Study area

The study was undertaken in a woodland community in south-eastern Australia dominated by white cypress pine (*Callitris glaucophylla* Joy Thomps. & L.A.S. Johnson; Fig. 1). The climate is typically Mediterranean and semiarid (Aridity Index = 0.26–0.39; see below), with slightly greater rainfall in the east-central areas during the six warmer months, and in the south and south-west during the six cooler months. Average annual rainfall (385–460 mm yr^{-1}) and average temperatures (~18 °C) varied little across the sites.

2.2. Assessment of groundstorey cover and grazing intensity

We surveyed 151 woodland sites characterised by the presence of the community dominant *Callitris glaucophylla*. At each site we positioned a 200 m long transect within which were placed five 25 m^2