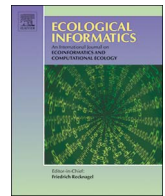




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Integrating remote sensing and demography for more efficient and effective assessment of changing mountain forest distribution



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ABSTRACT

Species range shifts have been well studied in light of rising global temperatures and the role climate plays in restricting species distribution. In mountain regions, global trends show upward elevational shifts of altitudinal treelines. However, there is significant variation in response between geographic locations driven by climatic and habitat heterogeneity and biotic interactions. Accurate estimation of treeline shifts requires fine-scale patterns of forest structure to be discriminated across mountain ranges. Satellite remote sensing allows detailed information on forest structure to be extrapolated across mountain ranges, however, variation in methodology combined with a lack of information on accuracy and repeatability has led to high uncertainty in the utility of remotely sensed data in studies of mountain treelines. We unite three themes; suitability of remote sensing products, ecological relevance of classifications and effectiveness of the training and validation process in relation to the study of mountain treeline ecotones. We identify needs for further research comparing the utility of different remotely sensed data sets, better characterisation of treeline structure and incorporation of accuracy assessment. Collectively, the improvements we describe will significantly improve the utility of remote sensing by facilitating a more consistent approach to defining geographic variation in treeline structure, improving our ability to link processes from stand to regional scale and the accuracy of range shift assessments. Ultimately, this advance will enable better monitoring of mountain treeline shifts and estimation of the associated to biodiversity and ecosystem function.

1. Introduction

Climate plays a key role in limiting plant species' distribution (Pearson and Dawson, 2003). Changes in temperature and precipitation will, therefore, lead to the exacerbation or alleviation of plant stress resulting in alterations to recruitment, growth rates, and adult mortality at climate-limited range edges (Lenoir et al., 2009; Peñuelas et al., 2007). Climate change scenarios predict a mean global temperature increase between 0.3 and 4.8 °C by 2100 compared to the 1985–2005 mean (IPCC, 2013). Consequently, shifts in the geographical distribution of a wide range of species are expected as climate change contributes to range expansion, retraction or fragmentation (Lenoir and Svenning, 2013; Masek, 2001). Regional variation in temperature anomalies means mountain ranges are expected to experience a higher than average temperature increase than other areas of the globe, making them particularly important for research into impacts of climate change (Dirnböck et al., 2011; IPCC, 2007).

Understanding the role that contemporary climate change has

played in species range shifts has been the focus of much activity over recent decades (Chen et al., 2011a; Gottfried et al., 2012; Lenoir and Svenning, 2015; Parmesan and Yohe, 2003). In mountain ranges across the globe, average elevational range shifts have been estimated between 6.1 m (Parmesan and Yohe, 2003) and 12.2 m (Chen et al., 2011a) per decade. Although global average values demonstrate a general uphill shift of species, they hide important variation in this response between species and geographical locations. For example, Chen et al. (2011a) report that 25% of species showed downhill shifts of elevational range limits whilst Harsch et al. (2009) report that of 166 treeline sites investigated 52.4% showed upward treeline shifts, 46.4% showed no change and 1.2% showed movement downslope. The scientific literature on this topic shows a significant bias in research effort towards North American and European mountain ranges. Southern hemisphere and Asian ranges are less well studied and, consequently, strongly under-represented in the literature (Chen et al., 2011a; Harsch et al., 2009). The underrepresentation and omission of large mountain ranges combined with interspecific variation in range shifts results in

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high uncertainty in the extent and impacts of species distribution shifts in mountain ranges at a global scale.

The altitudinal treeline has been used as an indicator for assessing species range shifts in mountainous regions for decades. The separation between closed-canopy subalpine forest and open vegetation at higher altitudes and the sensitivity to climatic change make mountain treelines ideal candidates for monitoring species range shifts across wide geographic areas. Changes in altitudinal treeline position such as those reported in the meta-analysis of Harsch et al. (2009) tell only part of the story of how mountain forests respond to changes in climate. In areas where mountain treelines have not advanced upward, forests have been shown to respond to climatic change through increased tree density below the upper tree limit or by lateral expansion across mountain slopes (e.g. Bharti et al., 2012; Klasner and Fagre, 2002). Consequently, when assessing mountain forest range shifts there is a need to identify both lateral and altitudinal movement in the treeline.

Non-uniformity in species range shifts is partly driven by high habitat heterogeneity in mountain areas. Temperature is routinely noted as the key limiting factor in plant species distribution (Chen et al., 2011a; Gottfried et al., 2012; Lenoir and Svenning, 2015; Parmesan and Yohe, 2003). At a global scale treeline position can be approximated by temperature alone with a mean growing season temperature between 5.5 and 7.5 °C limiting tree growth (Körner and Paulsen, 2004) and winter temperatures playing a key role in juvenile survival (Kullman, 2007; Rickebusch et al., 2007). However, in mountainous systems, topographic and geological controls play important roles alongside climate in limiting species distribution (Chen et al., 2011b; Forero-Medina et al., 2011; Pounds et al., 2006). Topography alters local temperature and precipitation regimes resulting in cooler conditions on poleward facing slopes (Malanson et al., 2011; Suggitt et al., 2011). Rain shadows created on the leeward side of mountains may result in a moisture limited system where the response to climatic change would be expected to differ from systems where temperature is the primary limiting factor (Foden et al., 2007). Topographic modification of regional climate regimes leads to a variable treeline position in mountain regions that differs with slope and aspect at a landscape scale (e.g. Butler et al., 2007; Case and Buckley, 2015; Germino et al., 2002; Greenwood et al., 2014; Fig. 1). Furthermore, at the plot level, differences in micro-climate arising from sheltering caused by slight topographic differences and neighbouring vegetation influences seedling establishment, leading to complex patterns of treeline advance or stasis (e.g. Germino et al., 2002; Greenwood et al., 2015).

Non-thermal regulators lead to significant variation of within-species range shifts where 42–50% of species show inconsistencies in the direction of range shifts between different geographic regions despite similar warming trends (Gibson-Reinemer and Rahel, 2015). At the mountain treeline, non-thermal controls may restrict treeline response to climatic change or cause a downslope retreat due to local differences in resource availability (e.g. McNown and Sullivan, 2013; Sullivan et al., 2015), radiative stress (Bader et al., 2007), drought stress (e.g. Johnson and Smith, 2007; Leuschner and Schulte, 1991; Millar et al., 2007), competitive dynamics (Wardle and Coleman, 1992) and disturbance regimes (e.g. Cullen et al., 2001; Daniels and Veblen, 2003) despite increased temperatures. In some cases, the stand structure of the treeline itself can modulate response to climatic change through constraint or facilitation of tree establishment, growth, and mortality within the ecotone (Camarero et al., 2016). We cannot, therefore, assume that treeline shifts will be uniform within or between mountain ranges.

1.1. The impact of treeline advance

Shifts in mountain forest distribution, whether due to climatic change or release from a non-thermal control, are expected to impact on local biodiversity (Greenwood et al., 2014). The relative isolation of mountainous areas and highly heterogeneous habitats means that

mountain systems can harbour disproportionately high numbers of endemic species and retain many rare species (Steinbauer et al., 2016). Encroachment of forest into non-forested areas will threaten mountain plant species through alterations to competitive dynamics where grassland species are likely to be out-competed for space and substrate by tree species as the forest advances (Grabherr et al., 1994) resulting in loss of species with narrow environmental tolerances (Jump et al., 2012).

In addition to the loss of biodiversity, shifts in high altitude forest distribution are expected to impact on ecosystem function (Greenwood and Jump, 2014). High altitude forests are important areas for carbon storage and sequestration (Peng et al., 2009; White et al., 2000). However, there has been little research into the impacts mountain treeline advance will have on carbon storage potential (Greenwood and Jump, 2014). Increased tree growth rates, density, and forest expansion is expected to increase biomass in mountain forests and their ability to act as carbon sinks may be increased as a result (Devi et al., 2008).

Ultimately, variation in mountain forest distribution shifts and the associated impacts are driven by the speed and spatial distribution of establishing juveniles at a plot scale. However, changes in forest distribution accumulate across the landscape and as such the impacts are manifested to a greater degree across an entire mountain range (hereafter referred to as regional scale). Accurate estimation of treeline shifts and the impacts, therefore, requires complex patterns of treeline advance or stasis at the plot level to be discriminated at regional scales. The biggest challenge to characterising mountain treeline heterogeneity at a regional scale is the generally poor accessibility of mountain ranges. The best estimation of species range shifts would come from multiple fixed monitoring sites across a mountain range (e.g. Global Observation Research Initiative in Alpine Environments; Grabherr et al., 2000). However, poor access means many studies have been based on incidental historical records covering a limited number of sites (Gottfried et al., 2012). Regional estimations based on limited field surveys alone in highly heterogeneous systems increase the risk of highly inaccurate estimates of change in forest distribution.

Remote sensing, a technique by which observations can be made without direct contact with a feature of interest, is ideally suited to capturing information across large geographic areas and its potential for studying environmental change is well recognised (Buchanan et al., 2015; Donoghue, 2002; Kennedy et al., 2014; Kerr and Ostrovsky, 2003). Considerable investment has been made over recent decades to improve precision and global coverage of remotely sensed data to aid monitoring of environmental change. Whilst the use of remotely sensed data in studies of mountain treeline shifts is not yet extensive, studies that have incorporated remotely sensed data have shown considerable potential for the characterisation of structural variation in the treeline (e.g. Allen and Walsh, 1996; Hill et al., 2007), assessment of distribution change (e.g. Bharti et al., 2012; Luo and Dai, 2013; Mihai et al., 2017), and to better understand how environmental factors act to influence variation in treeline position and structure over differing geographic scales (Weiss et al., 2015).

The integration of spatially explicit data, derived from remotely sensed data, on treeline structural variation and location across entire mountain ranges has significant benefits to better understand patterns and processes that govern treeline movement or stasis. Bader and Ruijten (2008) identified the mountain treeline from a Landsat ETM image and subsequently modelled the role of topography to predict forest cover. By linking a classified map with a digital elevation model Bader and Ruijten (2008) identified altitude as the main determinant of forest cover, with aspect also having a significant effect and areas where water and cold air accumulate resulting in inverted tree lines. Greenwood et al. (2014) used a time series of aerial photographs to identify patterns of treeline advance, highlighting the major role of topography in controlling treeline advance and subsequently, the micro-site characteristics influencing variation in tree establishment identified from remotely sensed data (Greenwood et al., 2015). Work

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