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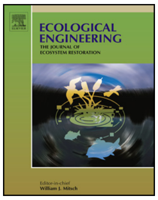

Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region

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ABSTRACT

Predicting climatic niche of species and projecting their potential range shifts in geographic distribution under future climate scenarios is essential for assessing impacts of climate change. Ecological niche-based models are widely used to map habitat suitability of current and future potential distribution of species, using precise coordinates of species occurrences, along with climatic and various environmental variables. Despite the importance of high dependence on forest resources in the Himalayan region, the direct impacts of climate change on major forest tree species is not well-documented. In the present study, we used MaxEnt (or maximum entropy) modelling to predict current distribution and changes in the future distributions of four ecologically and economically dominant forest tree species (*Quercus leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *Pinus roxburghii*) in the central Himalayan region. Future predictions were based on representative concentration pathways (RCPs) for two time periods (2050s and 2070s). We demonstrated the use of MaxEnt by combining different climatic, geomorphologic, and pedologic variables as predictor variables to model the potential climatic niches. We evaluated the model performance with an average AUC value varying as 0.809 (±0.020), 0.982 (±0.008), 0.966 (±0.006), and 0.803 (±0.025) for *Q. leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda* and *P. roxburghii*, respectively. Depending upon the RCPs, the results show both increase and decrease in suitable habitat range of these species across all future climate scenarios. The shifts in geographic distributions of climatic niches show unusual patterns, implying the need for urgent adaptive forest management strategies. Our approach can be used as a baseline database for broad-scale applicability in forest tree species restoration and conservation planning.

1. Introduction

Despite great uncertainty surrounding climate change-induced impacts, global estimates show marked influences on species extinction rates and distribution patterns, vegetation phenology, and ecosystem structure and composition (Chen et al., 2011; Jewitt et al., 2015; Mantyka-Pringle et al., 2015; Trumbore et al., 2015; Urban, 2015). Associated with climate change, several other concurrent stressors, such as invasive species, degradation, over-exploitation, pollution and plant diseases, which either act independently or in combination, further aggravate the impacts due to climate change (Lewis et al., 2015; Mantyka-Pringle et al., 2015). Over the next century, with expected changes in projected global climate as a result of increasing atmospheric CO_2 levels and other greenhouse gases (GHGs) (Friend et al., 2014), it is anticipated that it will lead to loss of individual species with substantial changes in their optimal conditions for growth and survival (Dirnböck et al., 2011; Gallagher et al., 2013), especially as climate change progresses towards the extremes.

In plant ecology, one of the oldest observations is the relationship between geographic patterns of species and climate (Chakraborty et al., 2013; Reu et al., 2011), with climate acting as a primary factor which regulates spatial distribution patterns of many tree species (Woodward and Williams, 1987). Most forest tree species are particularly sensitive to climate change (Hansen and Phillips, 2015), and are adapted to a range of climatic conditions, which is referred to as their climatic niche (Pearson and Dawson, 2003; Peterson, 2011). Due to the long life-span of tree species as well as their slow migration rates (Lindner et al., 2010; Pearson, 2006; Zhu et al., 2012), unprecedented rapid climate change will not allow immediate adaptation to newer climatic conditions in their current locations (Aitken et al., 2008). In such cases,

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species exposed to climate conditions outside their climatic niches will likely have three possible fates: migrating to other locations by tracking their ecological niches spatially, adapting to different conditions in current locations, or eventually leading to local extinction. This will invariably result in profound shifts in the distribution and abundance of species making them highly vulnerable, with range of possible impacts so far that have been underestimated (Lindner et al., 2014; Moritz and Agudo, 2013). Therefore, understanding the spatial distribution of climatic niches of forest tree species and projecting their potential range shifts for future climate change scenarios is important for assessing their vulnerability so as to develop appropriate adaptive forest management strategies under a rapidly changing climate, including assisted migration (Koralewski et al., 2015).

Hutchinson's (1957) fundamental niche defines 'climatic niche' as the climatic component within which species survive and grow, constituting a bioclimatic envelope which has its foundations in ecological niche theory (Pearson and Dawson, 2003). Most bioclimatic models are based on empirical relationships between observed species distribution and environmental variables (Araújo and Williams, 2000; Elith et al., 2006; Guisan and Zimmermann, 2000; Miller et al., 2007; Peterson, 2003). Such correlative models represent the *realized niche* since observed species' distributions are constrained by non-climatic factors, including biotic interactions (Pearson and Dawson, 2003). On the contrary, other bioclimatic models look for physiological representation based on mechanistic relationship between climate parameters and species responses (González-Moreno et al., 2015; Kearney and Porter, 2009), thereby, identifying the *fundamental niche* by modelling physiological limiting mechanisms in a given environment or geographic space (Monahan, 2009). The crucial issue in ecological niche-based modelling is the selection of explanatory variables to create species-environment profile that supposedly predicts distribution and abundance of species (Dormann, 2007). Nonetheless, since the causal mechanism of geographic distribution of species is not readily quantifiable, we often resort to substitute and proxies (Minor and Urban, 2007). With poorly studied taxa, correlative models are more advantageous since they require little knowledge of mechanistic links between species and its surrounding environment (Kearney and Porter, 2009). This proves to beneficial given the paucity in the amount of data available in some regions (Barbet-Massin et al., 2012). Scientific literature using niche models has had an overwhelming success in the recent past, while debate about usefulness of the approach has also followed (Araújo and Peterson, 2012; Wiens et al., 2009). In general, a 'climatic niche' model rather predicts a suitable habitat of the species, than its actual distribution, which may involve series of evolutionary and ecological processes (Aitken et al., 2008).

The Himalayan forests are undergoing changes in their distribution patterns, and are potentially expected to show shifts in the forest-cover boundaries (Alekhya et al., 2015; Chakraborty et al., 2013; Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Joshi et al., 2012; Manish et al., 2016; Ranjitkar et al., 2014; Telwala et al., 2013). However, more comprehensive detailed assessments of climatic niches of major forest tree species and their potential impacts in the face of climate change are required (Gairola et al., 2013). The need for this information in the Himalayan region is very important since it will allow forest-dependent communities, forest managers and policy makers to assess vulnerability and climate change impact for species adaptation and conservation (Keenan, 2015). Since regional climate models show that temperature and precipitation in the Himalayan region is likely to continue to increase in future (Kulkarni et al., 2013), the knowledge on potential impacts of climate change on forest tree species should be properly established and interpreted. In the light of these considerations, we provide a scientific basis with the application of correlative MaxEnt (or maximum entropy) model to map the current potential distribution of four forest tree species (*Quercus leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *Pinus roxburghii*) and to predict changes in the potential distribution of these species under future climate change scenarios based on representative concentration pathways (RCPs) in the central Himalayan region, for two time periods (2050s and 2070s). We assume that both the extent of suitable climatic habitat and range of the tree species would possibly alter with changes in future climate of the study area.

2. Study area

The study area is located in the Kumaon division in the state of Uttarakhand, falling in the central Himalayan region. It has a total area of approximately 20,397 km^2 and is mostly mountainous consisting of a forest-dominated landscape. The region varies between east longitudes of 80°10′ to 79°27′ and north latitudes of 30°48′ to 28°52′, with an altitude ranging from 157 m at the foot hills to 6980 m at the plateau. This region is bounded on the north by China, on the east by Nepal, on the south by the state of Uttar Pradesh, and on the west by the Garhwal division. Due to the steep altitudinal gradient from south to north, there is significant diversity in the natural vegetation of this region (Singh and Mal, 2014). Depending upon elevation, temperature regime in this area may resemble that of temperate region (above 2000 m elevation) or of tundra region (alpine belt) (Singh and Singh, 1992).

Literature indicates forests in upper areas of western and central Himalayan region being vulnerable to projected impacts of climate change, while forests in eastern Himalayan region are comparatively more resilient (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Joshi et al., 2012; Shrestha et al., 2012). This highlights the sensitivity of different vegetation types in eastern Himalayan region as relatively stable to both temperature and precipitation variables, which is not the case for western and central Himalayan region. The geographically dominant forest types include Upper or Himalayan chir pine forest (9/C1b), Ban oak forest (12/C1a), and moist Siwalik sal forest (3C/C2a). *Quercus* spp. is a large genus with many species, wherein the Himalayan region itself is represented by 35 species. The spatial distribution of *Quercus* spp. is mostly between 1000 m and 3600 m, above mean sea level. In the central Himalayan region, which includes the Kumaon division in the state of Uttarakhand, only five species of oak can be found (Singh et al., 2012). However, given the geographical dominance along with ecological and economic importance, we chose four major tree species, *Q. leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *P. roxburghii* for our study. Locally known as banj or ban oak, *Q. leucotrichophora*, is a valuable keystone species with great societal relevance in the central Himalayan region. It is among the main forest-forming species in the densely populated mid-altitudinal zones and provides a variety of ecosystem services (Singh et al., 2014). *Q. floribunda* (locally known as moru oak) is another dominant oak species found between 1700 m and 2600 m elevation range forming the evergreen climax forests (Negi et al., 1996). The other important oak species, *Q. semecarpifolia* (locally known as kharsu oak), occupies area less than approximately 350 km^2, and has an elevation range higher than all the other evergreen oak forests in Himalaya. Nonetheless, its canopy is often severely disturbed by cutting and lopping (Singh et al., 1997; Vetaas, 2000). On the other hand, *P. roxburghii* occurs extensively in the low-to-mid montane belt of central and western Himalayan region. Locally known as chir pine (or simply, pine), it is a gregarious, fire-resistant, indigenous tree species, often forms pure forest stands. Its capacity to rapidly colonize degraded habitats and high volume returns make this species a precious resource in the region (Chaturvedi and Singh, 1987).