Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal

**Robert J. Zomer · Antonio Trabucco · Marc J. Metzger ·
Mingcheng Wang · Krishna P. Oli · Jianchu Xu**

Abstract Rapidly accelerating climate change in the Himalaya is projected to have major implications for montane species, ecosystems, and mountain farming and pastoral systems. A geospatial modeling approach based on a global environmental stratification is used to explore potential impacts of projected climate change on the spatial distribution of bioclimatic strata and ecoregions within the transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal. Twenty-eight strata, comprising seven bioclimatic zones, were aggregated to develop an ecoregional classification of 12 ecoregions (generally defined by their potential dominant vegetation type), based upon vegetation and landcover characteristics. Projected climate change impacts were modeled by reconstructing the stratification based upon an ensemble

R. J. Zomer (✉) · M. Wang · J. Xu
Key Laboratory for Plant Diversity and Biogeography of East Asia (KLPB), Kunming Institute of Botany, Chinese Academy of Science, Kunming 650201 Yunnan, China
e-mail: r.zomer@cgiar.org

R. J. Zomer · J. Xu
Centre for Mountain Ecosystem Studies, World Agroforestry Center (ICRAF), East and Central Asia Region, Kunming 650201, China

A. Trabucco
IAFENT Division, Euro-Mediterranean Center on Climate Change, Sassari, Italy
e-mail: antonio.trabucco@cmcc.it

A. Trabucco
Department of Science for Nature and Environmental Resources (DIPNET), University of Sassari, Via De Nicola 9, 07100 Sassari, Italy

M. J. Metzger
School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK
e-mail: marc.metzger@ed.ac.uk

K. P. Oli
International Centre for Integrated Mountain Development (ICIMOD), GPO Box 3226, Kathmandu, Nepal
e-mail: koli@icimod.org

of 19 Earth System Models (CIMP5) across four Representative Concentration Pathways (RCP) emission scenarios (i.e. 63 impact simulations), and identifying the change in spatial distribution of bioclimatic zones and ecoregions. Large and substantial shifts in bioclimatic conditions can be expected throughout the KSL area by the year 2050, within all bioclimatic zones and ecoregions. Over 76 % of the total area may shift to a different stratum, 55 % to a different bioclimatic zone, and 36.6 % to a different ecoregion. Potential impacts include upward shift in mean elevation of bioclimatic zones (357 m) and ecoregions (371 m), decreases in area of the highest elevation zones and ecoregions, large expansion of the lower tropical and sub-tropical zones and ecoregions, and the disappearance of several strata representing unique bioclimatic conditions within the KSL, with potentially high levels of biotic perturbation by 2050, and a high likelihood of major consequences for biodiversity, ecosystems, ecosystem services, conservation efforts and sustainable development policies in the region.

1 Introduction

In spite of the fact that rapidly accelerating climate change across the Himalayan region (Shrestha et al. 2012; Singh et al. 2011) will have major implications for this vast mountainous area (Xu et al. 2009a), regional climate change processes are poorly understood (Xu et al. 2007), sparsely monitored, and generally under-researched (ICIMOD 2009; Schild 2008; Xu et al. 2007). However, climate change impacts are becoming increasingly evident within this highly vulnerable and fragile region (Ramesh and Goswami 2007; Shrestha et al. 2012; Zomer et al. 2014), with potentially profound implications for mountain communities (Ebi et al. 2007), water resources (Immerzeel et al. 2010; Shrestha et al. 2012), agricultural production systems (Maikhuri et al. 2001), biodiversity, ecosystem services (Beniston 2003), and both regional and global climate processes. Regional temperatures are rising at rates substantially higher than the global average, and significantly more so in higher altitude areas (Liu 2000; Liu et al. 2009; Shrestha et al. 2012). Large-scale climatic and phenological changes have been documented across the Himalayan region (Shrestha et al. 2012). Between 1982 and 2006, average annual mean temperature increased 1.5 °C, annual mean precipitation by 163 mm, and the average start of the growing season advanced by 4.7 days. In higher altitude areas, a greater proportion of total annual precipitation is falling as rain, rather than snow (Sharma et al. 2009), resulting in earlier snowmelt and shorter winters. This affects river regimes and impacts on water supply (Immerzeel et al. 2010), agro-ecological adaptations, livelihoods, and causes natural disasters, notably increasing glacial lake outburst flows (ICIMOD 2007; Xu et al. 2009b).

Montane species and ecosystems, because of their geographical isolation, limited range, and highly specific environmental adaptations, are among the most vulnerable to climate change (La Sorte and Jetz 2010). Consequently, changing climate will have major implications for biodiversity conservation efforts (Beniston 2003; La Sorte and Jetz 2010; Myers et al. 2000) and the many protected areas established over the last fifty years within the Himalaya (Chettri et al. 2008; Sharma et al. 2010), as well as on the important agro-biodiversity and crop genetic resources found here. It is anticipated that species ranges will shift along altitudinal gradients (Chen et al. 2009; La Sorte and Jetz 2012; Tingley et al. 2009), as much as they are able to within a challenging and complex matrix of biological and physical constraints (La Sorte and Jetz 2010). The range of some species may shift beyond the boundaries of protected areas established for their conservation. Climate change may exacerbate other ongoing environmental

change processes (Thuiller 2007), for example, expansion of fire-adapted or invasive species.

Due to a scarcity of environmental and historical climate data, absence of systematic monitoring, and political sensitivities within the region (Schild 2008), the knowledge base for developing scientifically-based adaptation strategies to mitigate these potentially severe implications is lacking. In this regard, an ever-improving estimation of the nature and magnitude of regional climatic change is essential to provide for informed decision making, risk and vulnerability mapping, sustainable "climate-proof" development, the delineation and development of climate change adaptation and mitigation strategies, and effective biodiversity and conservation management. A better, deeper understanding of the potential impacts of climate change on food security, livelihoods, and local economies of the region is urgently required to inform regional planning and adaptation strategies. An improved understanding of the impacts of climate change on biodiversity is essential for effective conservation within the context of rapidly changing biophysical conditions. In this study, a geospatial modeling approach based upon a statistically-based bioclimatic stratification is used to explore the impacts of projected climate change on the spatial distribution of bioclimatic zones and ecoregions within the transboundary Kailash Sacred Landscape (KSL) of China, India and Nepal (Zomer and Oli 2011).

2 The Kailash Sacred Landscape

The KSL is a recently designated "transboundary landscape" (ICIMOD 2010a, b) comprised of portions of the southwestern Tibetan Autonomous Republic of China, and adjacent portions of northern India and northwestern Nepal (Fig. 1). At its heart, high upon the Tibetan plateau, lies the holy Mt Kailash (6,638 m asl), considered sacred by at least five major religions and over a billion people, and the source of four major rivers: the Ganges, Bhramaputra, Sutlej, and Indus. Covering over 31,000 km², the landscape is rich in biodiversity (notably including agricultural biodiversity) and culture, but also has high rates of poverty amongst its 1 million inhabitants, and daunting environmental challenges (Zomer and Oli 2011).

The altitudinal zonation of bioclimatic zones in the KSL roughly correlates with the steep elevation gradient up to the crest of the Himalaya, ranging from below 500 m to 7,694 m asl (SM-Figure 1). A pronounced orographic rainshadow effect creates arid conditions upon the high, cold Tibetan Plateau portions of the KSL, and delineates the major bioclimatic distinction between monsoonal and continental influences. Bioclimatic conditions found here include hot and semi-arid regions in the lower hills, lush green and humid valleys in the mid-hills, extensive mountain forests, moist alpine meadows, arid trans-Himalayan valleys, high altitude cold deserts, and permanent snow and ice along the crest of the Himalaya. This ecological heterogeneity supports a rich biological diversity (Myers et al. 2000; Sharma et al. 2010; Zomer and Oli 2011), including many diverse forest types ranging from moist subtropical broadleaf to temperate oak forests, sub-alpine conifers, high altitude birch forests, with alpine meadows and grasslands stretching high above the tree line. These habitats support dwindling numbers of threatened wildlife including musk deer, blue sheep, snow leopard, Tibetan antelopes and many other charismatic, endangered and/or rare species (Zomer and Oli 2011).

Like other mountainous regions across the globe, the KSL is ecologically fragile and highly vulnerable to climate change (La Sorte and Jetz 2010; Xu et al. 2009a). More than one million people live in this region, mostly highly natural resource dependent subsistence farmers and semi-nomadic pastoralists. The traditional mountain farming systems found here, with staple crops ranging from rice and maize to highland barley, buckwheat, amaranth and potatoes, and

Fig. 1 Map of the Kailash Sacred Landscape, a highly diverse and mountainous transboundary region comprised of portions of the remote southwest region of the Tibet Autonomous Region of China, northern India, and northwestern Nepal, and including the sacred Mt. Kailash

tightly integrated with transhumance and other livestock systems, are finely tuned and adapted for subsistence within the steep terrain and highly variable climatic conditions. Widespread collection of non-timber forest products, medicinal and aromatic plants, notably *yartsagumba* (*Cordyceps sinensis*), and their transboundary trade, are important livelihood activities. When bioclimatic conditions change, this impacts upon natural ecosystems, and likewise, upon the managed systems located within those bioclimatic zones and/or associated with, and highly dependent upon, those natural ecosystems.

3 Methods

The KSL Environmental Stratification (KSL-EnS) has been subset from the Global Environmental Stratification (GEnS) produced by Metzger et al. (2013a) which is used as the starting point and overall context for this study. It was developed to support global biodiversity monitoring and ecosystem research within the Group on Earth Observations Biodiversity Observation Network (GEOBON 2010; Scholes et al. 2008, 2012). The GEnS has classified the world's land surface into 125 relatively homogeneous bioclimatic strata, which cluster areas with similar climates together, based upon a statistical analysis of "current" climate data (namely temperature, precipitation and seasonality), i.e. averaged over 1960 to 2000 (Hijmans et al. 2005). Since the GEnS uses a quantitative statistical approach to characterize current conditions, the method can be applied in a similar manner to develop a similar stratification based upon predicted future climate conditions. The change in distribution of bioclimatic strata

is used as a surrogate measure of the potential macro-level impacts on terrestrial ecosystems by the year 2050. When combined with other ecosystem or landcover data, these changes can be interpreted in terms of ecosystems services, landuse types, wildlife habitat, risks to endemic or threatened biodiversity, or the risks and opportunities for agricultural production (Metzger et al. 2008).

The modeling approach develops a detailed bio-climatic and ecoregional stratification of the KSL (based on the GEnS), and then models and identifies projected impacts of climate change on the distribution of these strata. The KSL environmental stratification (KSL-EnS) can provide a framework for the design of regional environmental monitoring and long-term ecological research (van Wart et al. 2013). In this study, the KSL-EnS is used as a baseline for estimating climate change impacts on the spatial distribution of bioclimatic zones and ecoregions.

Projected impacts are modeled by reconstructing the stratification based upon future climate conditions as modeled by an ensemble of 19 Earth System Models (ESM) provided by Phase 5 of the Coupled Model Intercomparison Project (CIMP5; Meehl and Bony 2011). Mora et al. 2013 tested the robustness of the CIMP5 model ensemble based on historical observation data (1985–2005) and found a high correlation when using multi-model averages. All four emission scenarios, or representative concentration pathways (RCP's; Vuuren et al. 2011) are analyzed, using a total of 63 CIMP5 ESM runs downscaled using the Delta method (Ramirez and Jarvis 2010) to 30 arc sec resolution (equivalent to ~1 km^2 at the equator) (Supplementary Material: SM-Table 1). The geospatial analysis was performed in ArcGIS 10.1 (ESRI) using the WorldClim (Hijmans et al. 2005) as baseline, and other, primarily global datasets (SM-Table 2), along with a remote sensing analysis, various national and local secondary datasets describing landcover and forest types, and georeferenced photos collected during field visits, which were used for interpretation of the results and aggregation of the bioclimatic strata into ecoregions (Olson et al. 2001), i.e. regions generally defined by their potential dominant vegetation, such as subalpine mixed forests or upper alpine meadows.

3.1 Environmental stratification

To produce the GEnS, Metzger et al. (2013a, b) identified a subset of 36 biophysically relevant bioclimatic variables based on a statistical screening of 42 variables available from various climate geodatasets. Principal Components Analysis (i.e. as reported in Metzger et al. 2008) revealed that the first three principal components, explaining 99.9 % of the total variation, were determined by only four variables:

- Tmean=Degree Days>0 °C (Hijmans et al. 2005)

    – daily sum of annual degrees of temperature above 0 °C, reflecting latitudinal and altitudinal temperature gradients, and plant growth periods (Hijmans et al. 2005);

- Aridity Index (Zomer et al. 2008)

    – ratio of annual precipitation over annual potential evapotranspiration (PET; calculated globally using the Hargreaves (1994) model)

- Monthly Mean Temperature Seasonality (Hijmans et al. 2005)

    – standard deviation of the monthly mean temperature distribution

- PET Seasonality (Zomer et al. 2008)

    – standard deviation of the monthly mean PET distribution

The iterative self-organizing data analysis technique (ISODATA; Tou and Conzalez 1974) was used to cluster the principal components of these four variables into 125 strata, which were aggregated into 18 zones. Consistent descriptive names were attributed to strata and zones, with first letters (in alphabetical order) and lower numbers characterizing colder zones and strata. A full description of the GEnS methodology, along with a detailed discussion of its conservation and environmental monitoring utility is given in Metzger et al. (2013a; 2013b).

3.2 Ecoregional classification

The interpretation and aggregation of the GEnS zones and strata to develop the KSL-EnS ecoregional classification was based on a land cover analysis using various remote sensing datasets, including high resolution IKONOS imagery, secondary sources, and expert knowledge. A geo-referenced photo-survey carried out during a 1-month field expedition to the study area in 2009 was used for ground-truthing. The zones and strata were associated with broad ecological zones, landcover, and forest types, described in terms of dominant vegetation, and then aggregated into broad ecoregions, as per the nomenclature used by the map of "Terrestrial Ecoregions of the World" (Olson et al. 2001). Omernik (2004), defined ecoregions as "areas within which there is spatial coincidence in characteristics of geographical phenomena associated with differences in the quality, health, and integrity of ecosystems. Olson et al. (2001) provides in-depth overview of the conservation utility of the ecoregional approach.

A comparison of the KSL ecoregional classification with Olson et al. (2001) and TISC/MOFSC (2002) shows a good general correspondence, but with greatly improved resolution. However, the WorldClim v4 data tended to over-estimate precipitation on the Tibetan plateau close to the Himalaya, and in the Trans-Himalayan valleys, which lie in the rain shadow of these high mountains. The stratification did a poor job of discriminating between the wetter high altitude valleys, and the very dry trans-Himalayan valleys, although this constitutes a relatively small, but ecologically significant area. This was taken into account when interpreting and aggregating the strata into the ecoregional classification, so as to correct this as much as possible, using secondary data (Jarvis et al. 2008; Olson et al. 2001; TISC/MOFSC 2002) to delineate the rain shadow boundary along the crest of the Himalaya.

3.3 Modeling of projected future climate conditions

The KSL-EnS, which is based on climate data from 1960 to 2000, was reconstructed as per future conditions in 2050 based upon the four significant climate variables (and the same datasets) used in the GEnS analysis. The Maximum Likelihood Classification algorithm in ArcGIS 10.1 was used to construct the projected future spatial distribution of strata, using the modeled future climate conditions as predicted by each of the CIMP5 ESM and RCP emission scenario combinations ($n=63$) for the year 2050 as input parameters. All models within each RCP were combined into a majority ensemble result, using the class with the majority of occurrence within any particular grid cell as the class for that location. The rate of occurrence of other classes is used as a measure of the uncertainty among models (see SM-Figure 2 and 3).

4 Results

4.1 KSL bioclimatic stratification

The KSL-EnS identified seven bioclimatic zones (Fig. 2) ranging from "Extremely Cold and Wet" to "Extremely Hot and Mesic" at current conditions. The mean elevations of these bioclimatic zones align coherently along the altitudinal gradient (Table 1). There is a similar alignment of zones along average mean annual precipitation and average mean annual temperature gradients, altogether giving an indication of robustness for the stratification as applied within the KSL, keeping in mind the highly diverse and heterogeneous terrain of the KSL, with gradients going along elevation, but also from east to west in the case of precipitation.

   More than 70 % of the area is classified as "Cold" or Extremely Cold". The largest proportion is found within the "Extremely Cold and Mesic" zone, much of it on the Tibetan Plateau, accounting for more than half of the total area (15,922 km^2). "Cool Temperate" regions cover less than 5 % of the total area, with "Warm Temperate", "Hot", and "Extremely Hot" zones on the lower slopes of the Himalaya accounting for more than 23 % (7,302 km^2). The "Warm Temperate and Mesic" zone of the mid-hills accounts for slightly more than 15 % of the area (4,828 km^2), and is coincident with much of the agricultural crop production. The characteristics of these zones and their associated ecoregions are each briefly described in SM-Table 3.
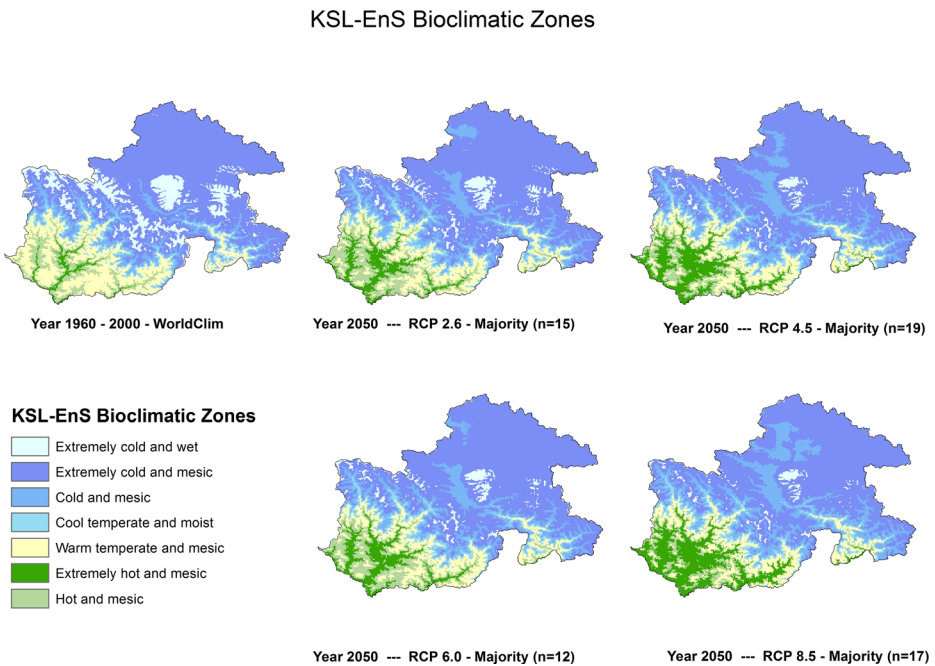

KSL-EnS Bioclimatic Zones

Year 1960 - 2000 - WorldClim

Year 2050 --- RCP 2.6 - Majority (n=15)

Year 2050 --- RCP 4.5 - Majority (n=19)

KSL-EnS Bioclimatic Zones

- Extremely cold and wet
- Extremely cold and mesic
- Cold and mesic
- Cool temperate and moist
- Warm temperate and mesic
- Extremely hot and mesic
- Hot and mesic

Year 2050 --- RCP 6.0 - Majority (n=12)

Year 2050 --- RCP 8.5 - Majority (n=17)

Fig. 2 Distribution of KSL-EnS bioclimatic zones in the year 2000 (using averaged climate data from 1960 to 2000) and as projected for the year 2050 based upon the majority result from a multi-model CIMP5 ESM esemble (total n=63) applied across four representative concentration pathways (RCP), or emission scenarios

Table 1 Characteristics of the KSL-EnS bioclimatic zones and strata, showing the average mean annual temperature, average mean annual precipitation, mean elevation, and the area, based on climate data (Hijmans et al. 2005) from 1960 to 2000 (referred to in the tables and figures as conditions in the year 2000), and the CGIAR-CSI SRTM 90 m digital elevation model (Jarvis et al. 2008)

| KSL-EnS zone	KSL-EnS strata	Mean annual temp (°C)	Mean annual precip (mm)	Mean Elev (m asl)	Area (km^2)
Year		2000	2000	2000	2000
Extremely cold and wet		−4.7	704	5,445	3,469
	D2	−8.1	712	5,982	98
	D3	−4.6	705	5,426	3,364
Extremely cold and mesic		−1.3	695	4,847	15,922
	F4	−4.3	512	5,344	3,344
	F7	−0.5	873	4,704	2,169
	F8	−1.8	702	4,957	4,531
	F13	−0.3	633	4,682	3,600
	F15	2.0	880	4,299	2,278
Cold and mesic		5.5	1,003	3,694	3,044
	67	3.4	861	4,091	176
	68	4.5	1,090	3,805	829
	G11	4.9	877	3,856	952
	G13	7.2	1,069	3,401	1,084
Cool temperate and moist		9.9	1,070	2,952	1,499
	J3	8.5	807	3,259	101
	J4	9.2	1,100	3,052	637
	J5	10.9	1,364	2,757	238
	H5	10.6	944	2,854	514
Warm temperate and mesic		14.9	1,411	2,016	4,828
	K1	12.2	1,177	2,535	976
	K5	13.4	1,018	2,386	291
	K7	14.9	1,486	1,996	1,676
	K10	14.9	1,036	2,132	193
	K13	16.7	1,603	1,652	1,642
	L3	16.1	907	1,931	50
Hot and mesic		18.6	1,749	1,304	2,033
	N1	17.7	1,896	1,468	168
	N2	17.3	1,377	1,545	179
	N3	18.3	1,754	1,363	859
	N5	18.0	1,085	1,563	30
	N8	19.5	1,821	1,144	797
Extremely hot and mesic		21.1	1,866	895	441
	M2	21.0	1,867	904	422
	M8	22.2	1,855	691	19
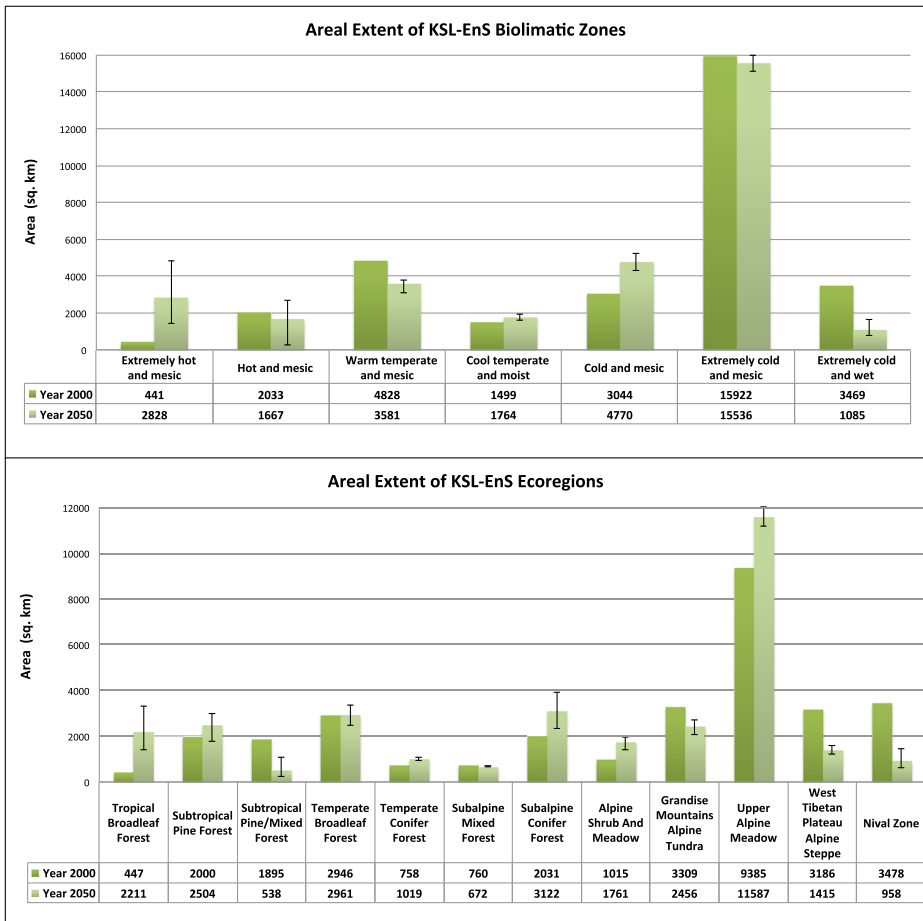
Fig. 3 Areal extent of KSL-EnS bioclimatic zones and ecoregions in the year 2000 (using averaged climate data from 1960 to 2000) and as projected for the year 2050 (showing a average of the four RCPs, with error bars showing the minimum to maximum range of projected areal extent across all four RCPs)

Within these seven zones, 28 strata were identified (Table 1). Like the zones, the strata generally align with the elevation, temperature and precipitation gradients, though less rigorously, reflecting the heterogeneity of the landscape at this scale. Each of the 28 strata were characterized by their dominant (or potential) vegetation types and then aggregated into twelve ecoregions (Fig. 3; SM-Table 3), which were labeled according to Olson et al. (2001). More than half of the KSL is high altitude alpine meadow, tundra or steppe. The area covered by the various ecoregions ranges from less than 450 km^2 of low elevation "Tropical Broadleaved Forest" to over 9,000 km^2 of "Upper Alpine Meadow" mostly found on the Tibetan Plateau. Ecoregions align along the elevation gradient however their ranges overlap substantially, with spreads ranging from just under 1,100 m to over 2,500 m. However, there is a general overall coherence along gradients for the eco-regions, corresponding to the realistic alignment of these identifiable eco-zones in terms of their biophysical parameters, i.e. their average temperature, precipitation and elevation align up correctly, that is to say, areas with pines are drier, broadleaf wetter, subalpine higher than temperate, and so on.

4.2 Projected impacts of climate change on ecosystems by 2050

The results from the multi-model uncertainty analysis (SM-Table 4) show a high correspondence among models within each of the four RCPs. At the (finest) resolution of strata, the majority class accounted for between 59 to 70 % (mean=64 %) of all model results within each RCP, however, confidence levels increased to 71 to 80 % for ecoregions (mean=84 %), and 80 to 89 % for bioclimatic zones (mean=75 %).

Mean annual temperature increases from 2.2 °C (RCP 2.6) to 3.3 °C (RCP 8.5) (SM-Table 5), a slight increase in current measured trends (Shrestha et al. 2012), with the average of 2.6 °C for all RCPs being a slight increase from an earlier analysis based on the CIMP3-SRES A2A scenario (Zomer et al. 2013). Projected mean annual precipitation exhibited a wide spread between the models (SM-Figure 4), reflecting the general uncertainty associated with mountainous terrain in general, and the Himalayas more specifically (Immerzeel, et al. 2013). RCP average predicted increases in precipitation range from 7.1 % (RCP 4.5) to 11.1 % (RCP 2.6) with an average increase of 8.7 % for all RCPs. Although nominally indicating a generally wetter future climate throughout the KSL area, the significance to this change is not known since the variability among models is high, as is local historical variability. The change in temperature, however, shows a high degree of agreement among the models, all indicating a substantial warming throughout the KSL, particularly at lower elevations. The standard deviation of the mean monthly temperature across the year, a measure of seasonality, shows a decrease throughout the area, reflecting warmer winters, and possibly longer rainy seasons and increased cloud cover. Both the distribution and the extent of the bioclimatic zones are substantially shifted by the year 2050 (Fig. 2; SM-Table 6) for all the RCP scenarios, with marked expansion of warmer and more mesic zones (Fig. 3). Based on their average elevation, each of the bioclimatic zones migrate upwards on average from 188 m to 467 m along the elevation gradient, and an overall average upward shift for all zones of 357 m (Fig. 4; SM-Table 7).

Large and substantial changes occur amongst strata within all bioclimatic zones throughout the KSL (SM-Table 8). Several strata disappear altogether under various model runs and within various RCPs. In the case that these strata represent specific conditions or habitat for endemic or threatened species, this change would indicate a major threat to biodiversity and a high risk of extinction for species endemic to these strata, or adapted to its specific conditions. This is similarly true for highly adapted farming and pastoral systems and associated agrobiodiversity. Strata show an average upwards shift in mean elevation of 399 m, with the largest shifts occurring in the lower elevations. There appears a small area of one "new" stratum within the "Extrememly Hot Mesic" zone, representing an expansion along the river valleys of lower slope conditions which are not currently found within the KSL. There is also the appearance of a new stratum within the "Warm Temperate and Mesic".

At the ecoregional level (Fig. 5), changes are large and widespread with a large expansion of the low altitude classes upslope, and decreases in the area of the highest altitude classes (SM-Table 9). From the perspective of ecoregions, used as a surrogate for habitat, biodiversity, or agroecological zones, it is evident that potentially major impacts are likely for endemic flora and fauna, or species and cultivars which are adapted to very specific conditions or small isolated areas. Several ecoregions show large decreases in area. For example, area classified as "Subtropical Pine/Mixed Forest" is reduced by 72 % on average. Likewise, "West Tibetan Plateau Alpine Steppe" is reduced by more than half, going from over 3,100 km^2 to an average of about 1,400 km^2 in 2050, with "Grandise Mountains Alpine Tundra" decreasing by more than 1,000 km^2. The extent of "Upper Alpine Meadow" and "Alpine Shrub and Meadow" increases by more than 3,000 km^2. In contrast, "Tropical Broadleaved Forest" goes from less
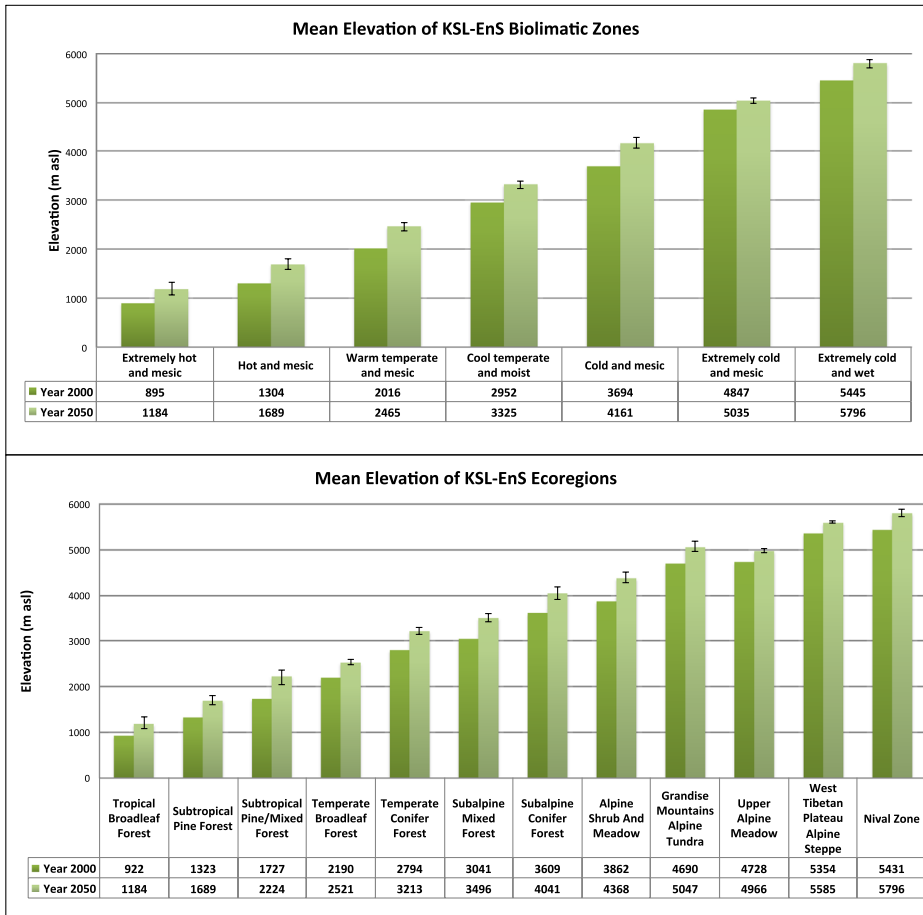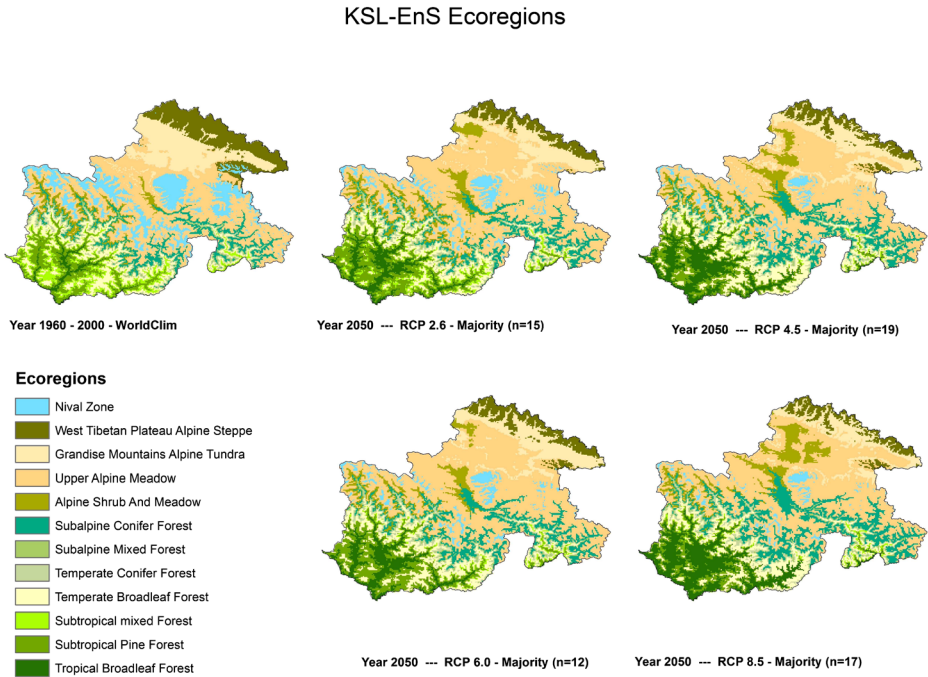
Fig. 4 Mean elevation of KSL-EnS bioclimatic zones and ecoregions in the year 2000 (using averaged climate data from 1960 to 2000) and as projected for the year 2050 (showing a average of the four RCPs, with error bars showing the minimum to maximum range of projected elevation across all four RCPs)

than 450 km^2 to an average of over 2,200 km^2 indicating substantial expansion of the currently lowest elevation and warmest ecoregion. For all ecoregions, the average (across RCPs) upward shift ranges from 231 to 506 m, with an overall average of 371 m (SM-Table 10). As a measure of the magnitude of change occurring within any specific area, 76 % of the total area (23,954 km^2) shifted to another strata, while 55 % (17,914 km^2) shifted to a different bioclimatic zone and 36 % (11,314 km^2) shifted to another ecoregion (SM-Table 11).

4.3 Discussion

Accurate estimates of the effects of climate change in mountain systems are difficult due to uncertainties associated with the various models and climate scenarios, downscaling techniques, and the existence of non-linear feedbacks between impacts (Nogués-Bravo et al. 2007). In the case of the KSL, this is compounded by a sparse regional network of weather stations,

KSL-EnS Ecoregions

Fig. 5 Distribution of KSL-EnS ecoregions in the year 2000 (using averaged climate data from 1960 to 2000) and as projected for the year 2050 based upon the majority result from a multi-model CIMP5 ESM esemble (total *n*=63) applied across four representative concentration pathways (RCP), or emission scenarios

scarce climate and vegetation data, and extreme ruggedness and remoteness resulting in a general lack of research and data available for this region. Nevertheless, given these caveats and the uncertainties associated with the CIMP5 ESM, a majority ensemble result indicates that climate change can be expected to have large and substantial impacts throughout the KSL by the year 2050 within all bioclimatic zones and ecoregions, with consequences for the ecosystems of which they are comprised and the ecosystem services they provide.

The direction and trends predicted for bioclimatic conditions generally correspond with recent findings from the region (Shrestha et al. 2012; Xu et al. 2009a). The rising temperatures, increasing precipitation, and resulting reduction in the volume of glaciers (Xu et al. 2009a) create a host of "cascading effects" and will have major impacts on ecosystems, biodiversity and livelihoods throughout the region (Immerzeel et al. 2013). The impacts on biodiversity are likely to be profound with extraordinary levels of biotic perturbation (La Sorte and Jetz 2010). Overall, the ability of species to respond to climate change will largely depend on their ability to "track" shifting climate through colonizing new territory, or to modify their physiology and seasonal behaviors (such as period of flowering or mating) to adapt to the changed conditions (Thuiller 2007). The efficiency of species' responses under climate change is likely to be highly idiosyncratic and difficult to predict (La Sorte and Jetz 2010). The heterogeneity of the montane terrain of the KSL provides both biological refugia and natural dispersal corridors, but can also present a variety of challenges to the migration of species. Niches for shifting montane species along elevational gradients decrease in size with increasing elevation, or disappear at the mountains' top (Körner 2007). Likewise, rapid changes in seasonal variations, such as the timing and length of the growing season, or warmer winter temperatures, perturb

ecosystem functioning, disrupting finely-tuned pollinator interactions (as when cycles between the insect and the plant it specializes on become unsynchronized), affecting emergence or migration of either predator or prey species, or allowing for the overwintering and survival of pests and pathogens.

Many of these impacts can be expected to manifest relatively soon, i.e. before 2050. These "cascading effects" will also impact agricultural and pastoral systems (Maikhuri et al. 2001). Agricultural systems, mountain communities and mountain livelihoods are susceptible and will be profoundly impacted. Local communities may be able to adapt through expansion of cropping systems into new areas, introduction of new varieties, new technologies, or modification of existing production practices, and by relying on traditional ecological knowledge for coping with variability and maintaining socio-ecological resilience. The highly diverse and environmentally finely-tuned agrobiodiversity of this region may both provide options and be threatened, including the many genetic lines and landraces of various important food crops and livestock breeds found in the KSL. Although conditions may generally improve for production (i.e. warmer and wetter), erratic and highly variable patterns of rainfall, increases in extreme events, occurrence of drought, or changes in the intensity and duration of the monsoon may create major adaptation challenges (Ramesh and Goswami 2007).

The magnitude and speed of these bioclimatic changes are likely to impact upon the conservation effectiveness of protected areas (La Sorte and Jetz 2010), and other conservation efforts within the KSL. Ecological conditions within protected areas may change beyond limits conducive for the species currently found there. As species ranges shift, the ability to survive, adapt or benefit from these changes is species- and site-specific, and depends on factors such as population dynamics, seed dispersal mechanisms, habitat availability and/or fragmentation, and physiological adaptability (Corlett and Westcott 2013). Improving our understanding of these responses by species found in the KSL is imperative if conservation strategies and policies designed to meet these challenges are to be effective. This is equally true for maintaining agricultural production and sustainable development in the KSL, particularly concerning the traditional mountain agricultural systems found in the KSL, which are generally highly adapted to specific climatic niches within the highly heterogeneous mountainous terrain.

5 Conclusion

A multi-model ensemble of modeling results over a range of emission scenarios, with fairly high confidence levels, indicate that potentially high levels of biological perturbation can be expected by the year 2050 within all bioclimatic zones and all ecoregions throughout the KSL, and likely within the Himalayan region more generally. Both natural and managed ecosystems, ecosystem services and livelihoods will potentially be substantially impacted. There will be increased risk for biodiversity, particularly the many endemic and threatened species of fauna and flora already under environmental pressure from landuse change and other regional and global processes. Mountain farmers and pastoralists will need to adapt, plan for, and respond to these changes in bioclimatic conditions, with implications for food security and livelihoods. Conservation and sustainable development will need to be tailored and modified considering the changing climatic conditions and shifting bioclimatic zones, ecoregions and species ranges. Consideration of the likely impacts of climate change must be mainstreamed into the planning and management of conservation and sustainable development efforts in the KSL. The study confirms earlier findings that montane systems are highly vulnerable to climate change

and will experience extraordinary levels of biotic perturbation in the coming years, and highlights the urgency and importance of increased research and monitoring to improve the region's ecological knowledge base, to develop scientifically informed policies and implement effective conservation, adaptation and mitigation strategies.

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