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Environmental Stratification of Kailash Sacred Landscape and Projected Climate Change Impacts on Ecosystems and Productivity

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ICIMOD Working Paper 2013/1

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Kailash Sacred Landscape Conservation and Development Initiative

Environmental Stratification of Kailash Sacred Landscape and Projected Climate Change Impacts on Ecosystems and Productivity

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Acronyms and Abbreviations

CGIAR	Consultative Group for International Agricultural Research
CSI	Consortium for Spatial Information
FAO	Food and Agriculture Organization
GCM	general circulation model
GEnS	Global Environmental Stratification
GEOBON	Group on Earth Observations - Biodiversity Observation Network
GEOSS	Group on Earth Observations Systems of Systems
GPP	gross primary productivity
HKH	Hindu Kush Himalayas
KSL	Kailash Sacred Landscape
KSL-CEMSP	Kailash Sacred Landscape Comprehensive Environmental Monitoring Strategic Plan
KSLCDI	Kailash Sacred Landscape Conservation and Development Initiative
KSLCI LC	Kailash Sacred Landscape Conservation Initiative Land Cover
KSL-CS	Kailash Sacred Landscape Conservation Strategy
KSL-EnS v1	Kailash Sacred Landscape Environmental Stratification (version 1)
masl	metres above sea level
NDVI	normalized difference vegetation index
NPP	net primary productivity
PCA	principal components analysis
PET	potential evapotranspiration
SRTM	Shuttle Radar Topography Mission
WWF	World Wide Fund for Nature

Executive Summary

The Kailash Sacred Landscape (KSL) is a recently designated transboundary conservation landscape comprising remote portions of the southwestern part of the Tibet Autonomous Region of China and adjacent portions of northern India and northwestern Nepal (Figure 1). The landscape covers an area of approximately 31,000 km^2 and contains highly diverse terrain including some of the highest and most remote mountains in the world, most notably the sacred Mount Kailash. It is endowed with a rich array of natural resources and high levels of natural and agricultural biodiversity. Its ecosystems provide important services to the more than one million people living within the KSL and indirectly to the millions more living downstream (Zomer and Oli 2011; Eriksson et al. 2009).

The landscape is part of the Hindu Kush Himalayan (HKH) region, one of the poorest regions in the world. This region and its people are facing enormous challenges from climate and global change including rapid population growth, industrialization, and pollution. The region is further characterized by remoteness, poor infrastructure, illiteracy, and political instability.

Despite the importance of the HKH in terms of biodiversity and the ecosystem services that it provides, climate change across this vast region is poorly understood, sparsely monitored, and generally under-researched. High levels of uncertainty exist regarding the nature and magnitude of projected climate change impacts and drivers, and even as to the direction of change. Meanwhile, change in climate is becoming increasingly evident within these fragile and highly vulnerable mountains, with profound implications for mountain communities, agricultural production systems, biodiversity, and ecosystem services.

This study uses a quantitative spatial analytic approach to environmentally stratify the KSL for use as a baseline for climate change research, for comparative studies, and to model the projected impacts of climate change on the landscape. A modelling approach based on statistical clustering was applied to develop a detailed bioclimatic stratification of the study area. Based on this classification, the impacts of climate change on the distribution of the bioclimatic zones, ecosystems, and vegetation types in the landscape were modelled and identified. The spatial analysis was based on a geodatabase of climate data collected from 1960 to 2000 and statistically downscaled future climate change scenarios with a spatial resolution of 1 km^2. The spatial climate data was combined with other available spatial data and secondary sources and informally 'ground-truthed' using expert knowledge and previous field visits to develop the Kailash Sacred Landscape Environmental Stratification (KSL-EnS v1). The study is intended to support the goals of the Kailash Sacred Landscape Conservation and Development Initiative (KSLCDI). Finished data products resulting from this study are available on the KSLCDI Knowledge Sharing Portal (www.icimod.org/ksl).

The KSL-EnS stratified the KSL into 10 zones and 34 strata; however, nine of these strata cover a very small areal extent (less than 100 km^2). The distribution, extent, and biophysical characteristics of the KSL-EnS bioclimatic zones and strata are presented and described in terms of their elevational range and bioclimatic and ecological characteristics (such as primary land cover, vegetation type, and 'ecosystem' classification). Twelve vegetation types were identified based on their corresponding ecoregion (Olson et al. 2001).

The analysis of the projected impact of climate change, based on the reconstruction of the KSL-EnS strata indicates a significant and substantial change in the distribution, extent, and productivity of ecosystems in the KSL by the year 2050. Mean annual temperature and mean annual precipitation are expected to increase and the distribution and extent of the KSL-EnS zones are expected to shift substantially by the year 2050 (Figure 15).

Based on their average elevation, each of the KSL-EnS zones show an upward shift of from 285 to over 600 m, except for the highest elevation zone 'extremely cold and moist', which remains relatively the same, but shows a decrease in areal extent of nearly two-thirds. Similarly, the high altitude 'extremely cold and mesic to xeric' zone is expected to decrease by more than 1,600 km^2, while the lower 'cold and mesic to xeric' zone is expected to increase by just under 2,300 km^2. The 'warm temperate and mesic zone' is expected to decrease by nearly 1,400 km^2, while the remaining zones show substantial increases in area. A new small area, 'hot and xeric', which is not present under current climate conditions, is projected to appear.

Strata are also expected to shift upward in average elevation of about 400 m, with the largest shifts occurring at lower elevations. Several strata are projected to disappear altogether. Viewed from the perspective of vegetation types and ecosystems, and used as a surrogate for habitat or biodiversity in general, substantial impacts are likely on endemic flora and fauna, particularly species adapted to very specific conditions or small isolated areas.

Total annual net primary productivity (NPP) varies across the KSL from fairly high rates for lower elevation strata (over 900 tonnes per km^2 for tropical broadleaf forest) to areas of very low productivity at higher elevations. NPP rates were found to be highly correlated with elevation. Current annual NPP for the entire KSL area is estimated at nearly 10 million tonnes, with temperate broadleaf forest contributing the highest proportion (20 per cent). Increases in temperature and precipitation are projected to impact on the productivity of all ecosystems in the KSL. Based on the analysis in this study, the productivity of the entire KSL area will increase by nearly 1.9 million tonnes (over 16 per cent) by the year 2050.

Based on the Global Environmental Stratification approach, the stratification provided by this study can be used for global comparative mountain studies. It can also be applied regionally across the HKH to develop a stratified framework for comparative climate change studies and, more generally, for comparative ecosystem studies. Identifying and mapping differences in the distribution of bioclimatic strata provides a baseline for climate change research and allows for the measurement of the projected impacts of climate change on the distribution of land cover types, ecosystems, and habitats. As such, these differences in distribution are useful for looking at impacts on biodiversity. It is assumed that a similar relationship can be inferred between changes in the distribution of bioclimatic strata and agricultural production, transhumance and nomadic pastoralism, and the collection of non-timber forest products and medicinal plants, with implications for the health, livelihoods, and prosperity of mountain communities.

Mountain communities and managed systems will be affected and the impacts on biodiversity, both natural and managed, are likely to be profound. Whereas managed systems and communities may be able to adapt by introducing new varieties and modifying production practices, natural systems may be slower and stochastic in their adaptation to new conditions. In particular, although conditions may generally improve for production as a result of the warmer and wetter climate, erratic and highly variable patterns of rainfall and increases in extreme events or the intensity of the monsoon may create more significant challenges.

In summary, this study concludes that there will be a high impact on biodiversity within all zones and all ecosystems within the KSL and generally within the HKH region. Climate change is likely to increase the risk for many endemic and already threatened species of fauna and flora. The many genetic lines and landraces of important food crops and livestock breeds found in the KSL are at risk. The highly diverse and finely-tuned agrobiodiversity of this region may provide opportunities, while facing risks at the same time under such change. These results should be taken into account when planning for conservation, ecological restoration, and development in the KSL and a high priority should be assigned to adaptation in the area and region.

Introduction

The Kailash Sacred Landscape (KSL) is a recently designated transboundary conservation landscape comprising remote portions of the southwestern part of the Tibet Autonomous Region of China and adjacent portions of northern India and northwestern Nepal (Figure 1). It contains some of the highest and most remote mountains in the world, most notably the sacred Mount Kailash, which is located on the edge of the Tibetan Plateau. This landscape is endowed with a rich array of natural resources and high levels of natural and agricultural biodiversity, providing ecosystem services to the more than one million people living within the KSL and indirectly to the millions living downstream (Zomer and Oli 2011; Eriksson et al. 2009).

The KSL is part of the Hindu Kush Himalayan (HKH) region, one of the poorest regions in the world. This region and its people are facing enormous challenges from climate and global change including rapid population growth, industrialization, and pollution. The region is further characterized by remoteness, poor infrastructure, illiteracy, and political instability.

Despite the importance of the HKH region in terms of biodiversity and the ecosystem services that it provides, climate change across the region, including in the KSL, is poorly understood (Xu et al. 2007), sparsely monitored, and generally under-researched (Bernstein et al. 2008; Eriksson et al. 2009). High levels of uncertainty exist regarding the nature and magnitude of projected climate change impacts and drivers, and even as to the direction of change. Meanwhile, climatic change is becoming increasingly evident within these fragile and highly vulnerable mountains (Ramesh and Goswami 2007), with profound implications for mountain communities, agricultural production systems, biodiversity, and ecosystem services (Beniston 2003) in the region and beyond (Xu et al. 2009).

Studies in Nepal and China have shown that temperatures are rising at higher rates in high altitude areas than in other areas (Shrestha et al. 1999; Liu and Chen 2000). The Tibetan Plateau, in particular, is warming at a rate three times the global average (Liu and Chen 2000; Xu et al. 2009). The observed warming in Nepal is also high at 0.6°C per decade between 1977 and 2000 (Shrestha et al. 1999). Along with changes in temperature, in many

Figure 1: Map of the Kailash Sacred Landscape

Source: Zomer and Oli 2011

high altitude areas a greater proportion of total annual precipitation appears to be falling as rain, rather than snow (Sharma et al. 2009). As a result, snowmelt is beginning earlier and winters are shorter.

These changes in temperature and precipitation patterns affect river regimes and water supply, agroecological adaptations, and livelihoods, and can cause natural disasters. They also have significant implications for biodiversity and conservation efforts (Myers et al. 2000), as species ranges may shift outside historical limits or beyond the boundaries of protected areas established for their conservation. Likewise, climatic change can have significant impacts on the finely-adapted and highly-diversified agricultural and pastoral systems of the region, along with the associated high level of agricultural biodiversity (including livestock adapted to climatic conditions and nomadic herding patterns) upon which subsistence mountain communities depend for their food security (Zomer et al. 2008).

It is important to note that these changes can also provide significant new opportunities, including agricultural opportunities, in addition to the challenges they pose. Changes in seasonality, temperature, rainfall, the onset of monsoon rains, and glacial melt water will all have an effect on mountain farming systems, as well as on forests, wetlands, and other natural ecosystems and the services they provide. Some of these changes may be positive, such as increases in productivity, and some negative, such as the disruption of pollinator cycles and increases in the incidence of pest and disease. In particular, the impact of increases in temperature and changes in the water supply from the HKH on downstream food production is of great concern (Battisti and Naylor 2009).

As a result of the lack of environmental and historical data on climate (Schild 2008) and, to a certain extent, political sensitivities within the region, the magnitude and impact of climate change in the HKH is unclear and occasionally controversial. Systematic monitoring, analysis, and modelling of ongoing change in the region's ecosystems and ecosystem services is weak, preliminary, and fragmented by political boundaries. A better understanding of the impact of climate change in the HKH on food security, livelihoods, and the national economies of the region is urgently required (Schild 2008) to inform decision making and planning in conservation and development, and for the development of climate change adaptation and mitigation strategies.

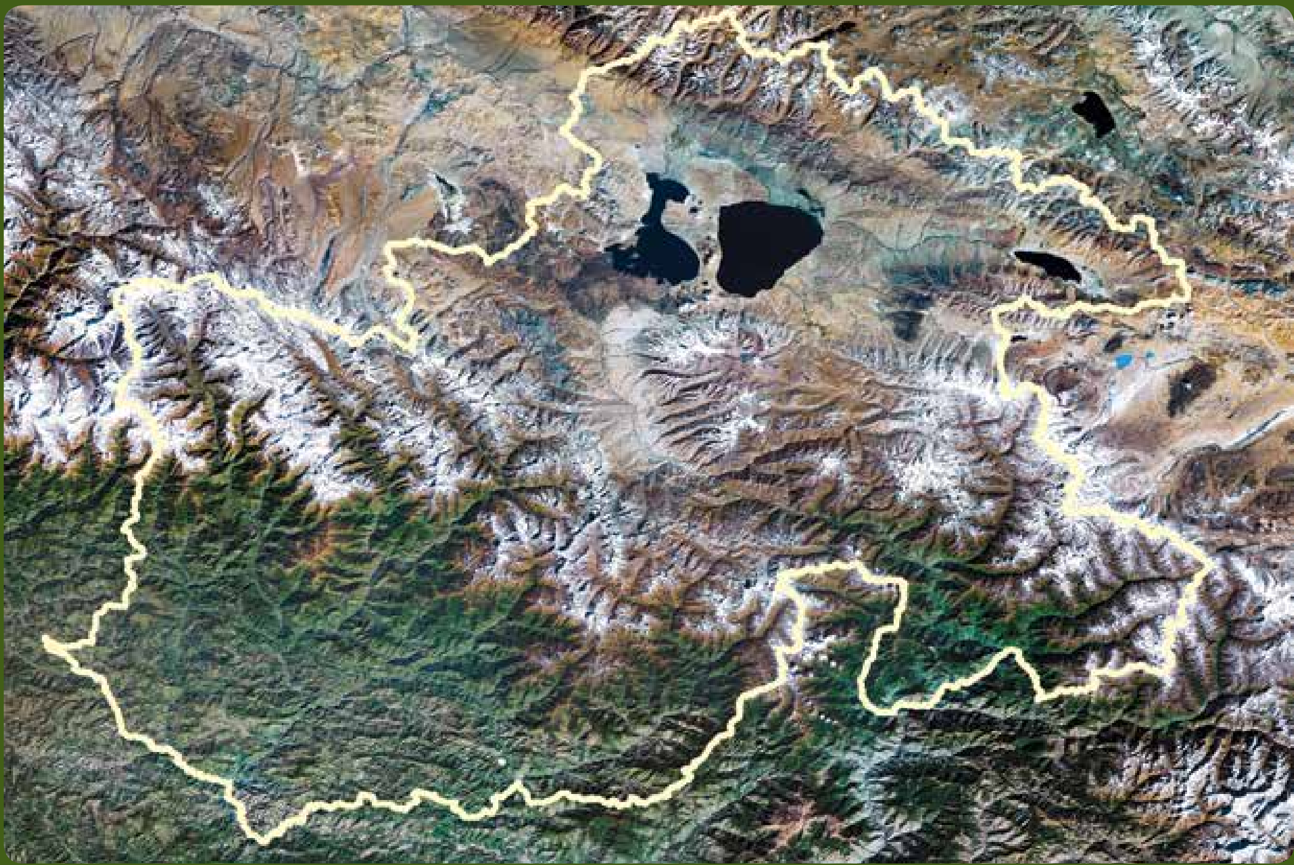
This study uses a quantitative spatial analytic approach to environmentally stratify the KSL for use as a baseline for climate change research and for comparative studies. An environmental stratification based on the statistical clustering of bioclimatic variables was used to develop a detailed classification of the study area. Based on this bioclimatic stratification, the projected impacts on the distribution of bioclimatic zones, ecosystems, and vegetation types in the landscape were then modelled and identified. The spatial analysis is based on a geodatabase of climate data collected from 1960 to 2000, and statistically downscaled future climate change scenarios with a spatial resolution of 1 km^2. The spatial climate data was combined with other available spatial data, available secondary sources, and informally 'ground-truthed' using expert knowledge and previous field visits to develop the Kailash Sacred Landscape Environmental Stratification (KSL-EnS v1).

The study is intended to support the goals of the Kailash Sacred Landscape Conservation and Development Initiative (KSLCDI)., which commissioned and supported this study. The KSLCDI has developed both a Conservation Strategy (KSL-CS) and a Comprehensive Environmental Monitoring Strategic Plan (KSL-CEMSP). Both of these efforts will benefit from the reliable mapping of ecosystems and bioclimatic zones. In particular, an understanding of the nature and magnitude of impacts on ecosystems, habitats, wildlife and other biodiversity, and land cover is required for effective conservation management and planning. This is equally true in the context of the adaptation of managed systems, notably agroecosystems, agrobiodiversity, rangelands and pastoral systems, and other traditional land-use systems found in the KSL. Finished data products resulting from this study are available on the KSL Knowledge Sharing Portal (www.icimod.org/ksl) for unrestricted use by KSLCDI stakeholders, partners, and others.

Kailash Sacred Landscape

The Kailash Sacred Landscape is spread across approximately 31,000 km^2 of highly diverse terrain. This transboundary landscape, although within the boundaries of China, India and Nepal, is historically, ecologically, and culturally interconnected. It is the source of four of Asia's most important rivers, which emanate from near the sacred Mount Kailash, which is revered by millions of people in Asia and throughout the world. The region and its people are highly vulnerable to climate change and environmental degradation, as well as threats associated with globalization and development. The KSLCDI. is the first cooperation of its kind among China, India, and Nepal,

Figure 2: Landsat ETM satellite image of the Kailash Sacred Landscape in 2000



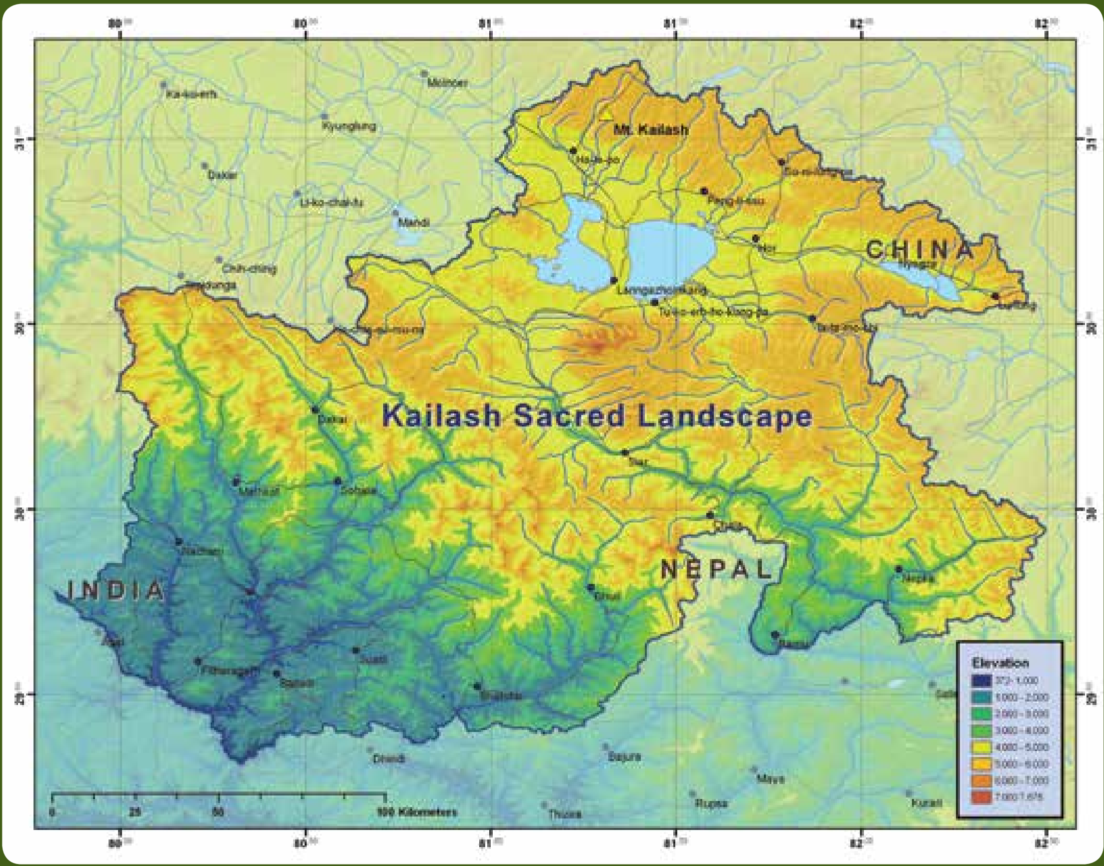
and seeks to conserve this unique landscape through the application of transboundary ecosystem management approaches.

The KSL exhibits great heterogeneity, both geographically (Figure 2) and culturally, covering at least four major geological and physiographic zones. The landscape's bioclimatic zones include, among others, hot and semi-arid regions in the southwest, lush green and humid valleys in the mid-hills, extensive mountain forests, moist alpine meadows, remote and arid trans-Himalayan valleys, and high altitude grasslands and steppes, as well as extensive areas of permanent snow and ice. This geographic heterogeneity has given rise to a high level of biodiversity including an array of forest types (ranging from moist subtropical broadleaf to temperate oak forests, alpine conifers, and high altitude pastures) and wildlife (including musk dear, blue sheep, snow leopard, Tibetan antelopes, and many other rare and endangered species).

Because of its steep altitudinal gradients (ranging from below 400 masl to over 7,600 masl) and extreme variations in topography (Figure 3), the ecosystems of the region vary widely from moist subtropical to temperate, alpine, and cold high altitude desert. Almost 15 per cent of the KSL area is classified as permanent snow or ice (Figure 4), 20 per cent is estimated to be under some form of forest cover, and an additional 18 per cent is bare or uncultivated fallow land (FAO 2010). In the southern part of the landscape, which is dominated by human habitation and use, forest patches are relatively small and more fragmented than in the more northern parts.

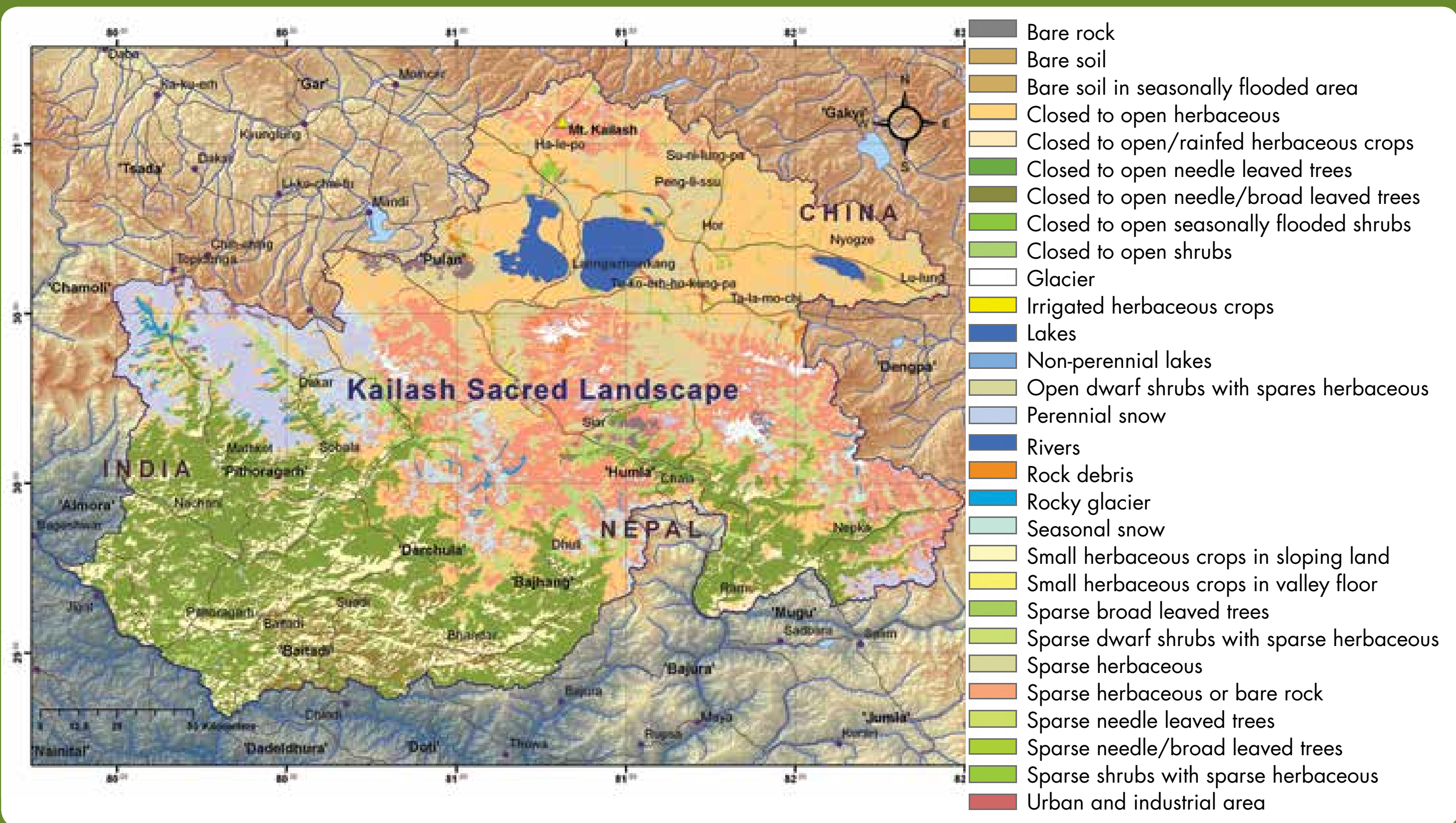
The agricultural land area is low across the whole landscape; it is estimated that less than 10 per cent of land in the KSL is used for growing crops. However, agriculture is a major and important source of livelihood for local mountain communities. Indigenous and local/tribal communities have developed locally-specific patterns of natural resource use in relation to food, medicine, timber, fibre, and trade. The traditional mountain farming systems found in the KSL – in which the cultivation of staple crops (such as rice, maize, highland barley, amaranth, and potatoes) is tightly integrated with transhumance and other livestock systems – are finely tuned and adapted for subsistence within the highly variable and sometimes harsh conditions. Permanent grazing areas and other pasture lands comprise over 27 per cent of the total area. Transhumance, nomadic herding, and on-farm livestock production are important

Figure 3: Elevation map of the Kailash Sacred Landscape



Source: SRTM v4

Figure 4: Land-use map of the Kailash Sacred Landscape



Source: FAO 2010

livelihood activities in much of the region. The collection of non-timber forest products and medicinal plants, particularly yarshagumba (*Cordyceps sinensis*), and transboundary trade are other important sources of income.

Over a million people live within the KSL; most of this population is found in India and Nepal, with very low population densities at the high elevations and on the Tibetan Plateau. The people of this landscape share a cultural heritage and have been linked by historical trade and pilgrimage routes for centuries. These 'heritage routes' and the remnants of this once-flourishing trade add to the beauty and rich cultural history of the region. Today, however, the communities in the KSL are vulnerable – they suffer from the impacts of remoteness, which include limited infrastructure and transport and poor educational and health facilities. The limited livelihood options, together with modern changes in lifestyle as a result of globalization and ongoing climate change (including recent droughts and erratic weather patterns), threaten the sustainability of these mountain communities, the landscape, and its biodiversity. For more detail on the landscape see Zomer and Oli 2011.

Methodology

Methods overview

Spatial analysis was conducted in three steps:

Step 1: Bioclimatic stratification of the KSL (KSL-EnS)

- data preparation
- correction of artifacts (i.e., undesired alterations in data, introduced by a technique or technology)
- identification of KSL-EnS bioclimatic strata based on terrain, land cover, and ecosystem typologies and grouping into bioclimatic zones types to develop a ecosystem-wise spatial clustering
- validation and error checking based on available secondary data
- spatial and tabular analysis/descriptive statistics/mapping

Step 2: Bioclimatic stratification based on projected climate conditions (KSL-EnS 2050)

- multivariate statistical analysis of the significant current climate bioclimatic variables to produce KSL-EnS signature files
- statistical clustering of the projected (i.e., year 2050) bioclimatic variables based on the KSL-EnS signature files
- mapping of KSL-EnS bioclimatic strata depicting projected climate conditions
- correction of artifacts
- spatial and tabular analysis/descriptive statistics/mapping

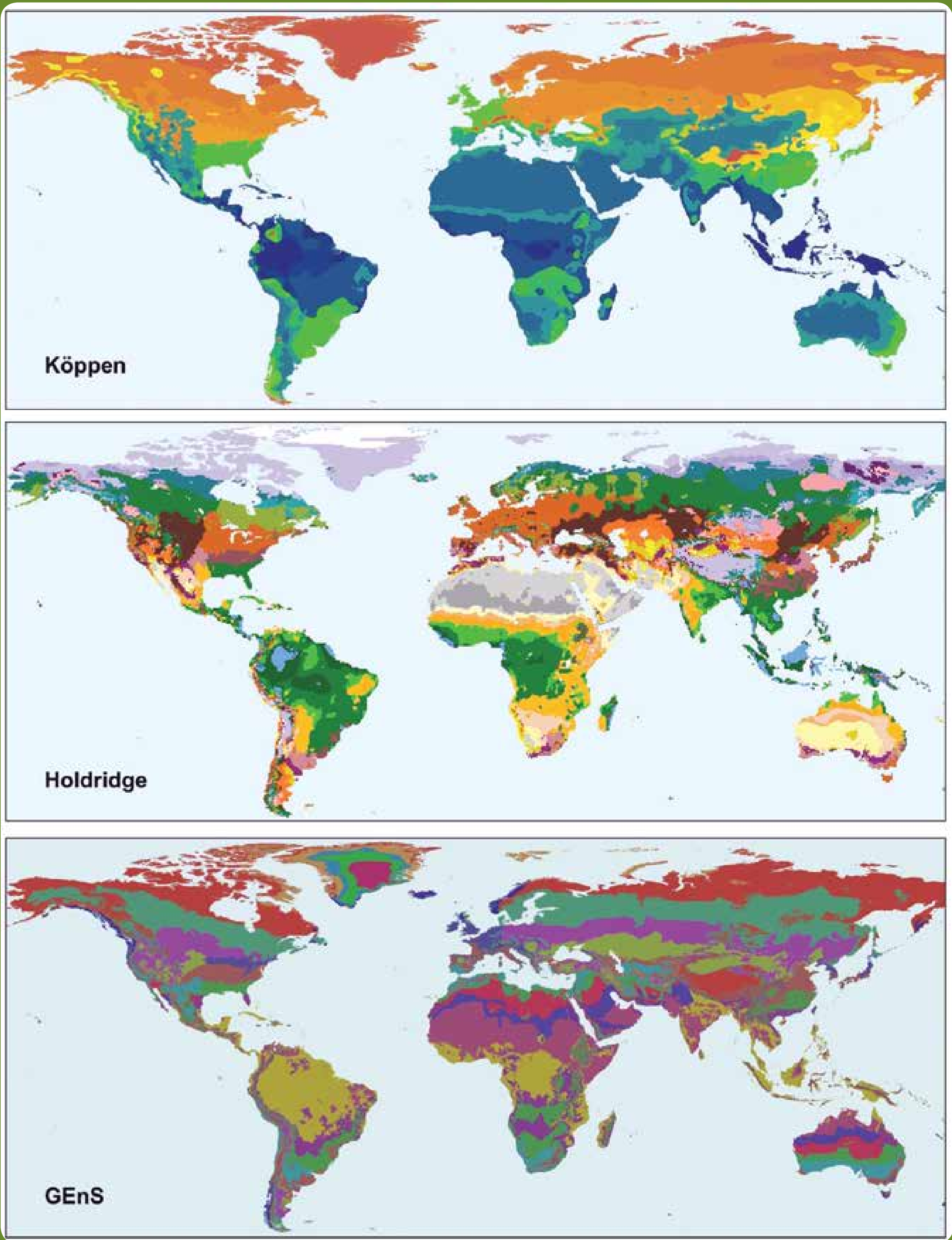
Step 3: Analysis of transformations and migration of bioclimatic strata in the KSL as a result of projected climate change between 2000 and 2050

- delineation of shifts in location and changes in areal extent of KSL-EnS strata and bioclimatic zones and land cover types.
- changes in net primary productivity (NPP) due to shifts in location and areal extent of strata
- descriptive statistical analysis of impacts in terms of land cover types

Modelling approach

This study adopted and modified for the KSL the Global Environmental Stratification (GEnS) developed by Metzger (2012) within the Group on Earth Observations - Biodiversity Observation Network (GEOBON et al. 2008; GEOBON 2010). The GEnS classification model is a statistical stratification of the world's land surface into relatively homogeneous bioclimatic strata, initially intended to provide a global spatial framework for the integration and analysis of ecological and environmental data. The GEnS approach represents a significant advance in methodologies for global environmental stratification, compared to earlier attempts at global bioclimatic or ecosystems mapping such as by Köppen (Peel et al. 2007) and Holdridge (Holdridge 1947; Leemans 1990) (Figure 5).

Figure 5: Comparison of three climate stratification models: Köppen climate classification (Peel et al. 2007); Holdridge Life Zones (Holdridge 1947; Leemans 1990); Global Environmental Stratification (GEnS) (Metzger et al. 2013)



The Köppen system (Peel et al. 2007), which was completed before 1900 and modified in 1918, 1936, and 2007, is still one of the most widely used climate classification systems. It is based on the premise that native vegetation is the best expression of climate. Köppen used observed vegetation patterns to subdivide five global climate zones into 30 classes based on various temperature and precipitation related indicators (primarily average annual monthly temperatures, precipitation, and seasonality of precipitation). Thornthwaite (1948) included measures to represent seasonality and plant available moisture, developing a classification based on humidity and aridity indices (Thornthwaite 1948). Holdridge (1947) developed a 'Life Zone' system of classification based on biotemperature, precipitation, and an aridity index, with 38 classes (for the entire globe) and a spatial resolution of half a degree, which is nevertheless widely used. There have been several more recent classifications using bioclimatic indicators (e.g., Bailey 1998; Sayre et al. 2009).

In contrast, the GEnS approach uses a strictly quantitative method to stratify (classify) bioclimatic zones based on recent climate data and determines future bioclimatic zones based on projected future climate parameters (as provided by the various general circulation models under various scenarios). The change in the distribution of bioclimatic strata can be used as a surrogate for ecosystem data; these macro-level changes can be delineated in terms of their effect on ecosystems services, land cover types, wildlife habitat, and endemic or threatened biodiversity, and the consequent risks and opportunities for farming and pastoral systems (Metzger et al. 2008).

Bioclimatic classification approaches have shown some utility in modelling climate change impacts on vegetation (Cramer et al. 2001; e.g., Sitch et al. 2003; Thuiller et al. 2005), although with only a few biomes recognized globally. The GEnS approach used in this study provides a statistically-based and robust spatial analytical framework for the aggregation of local observations, identification of gaps in current monitoring efforts, and the systematic design of monitoring and research. It also provides a global and overarching context allowing for the comparison and global integration of diverse datasets (Metzger et al. 2012).

Datasets

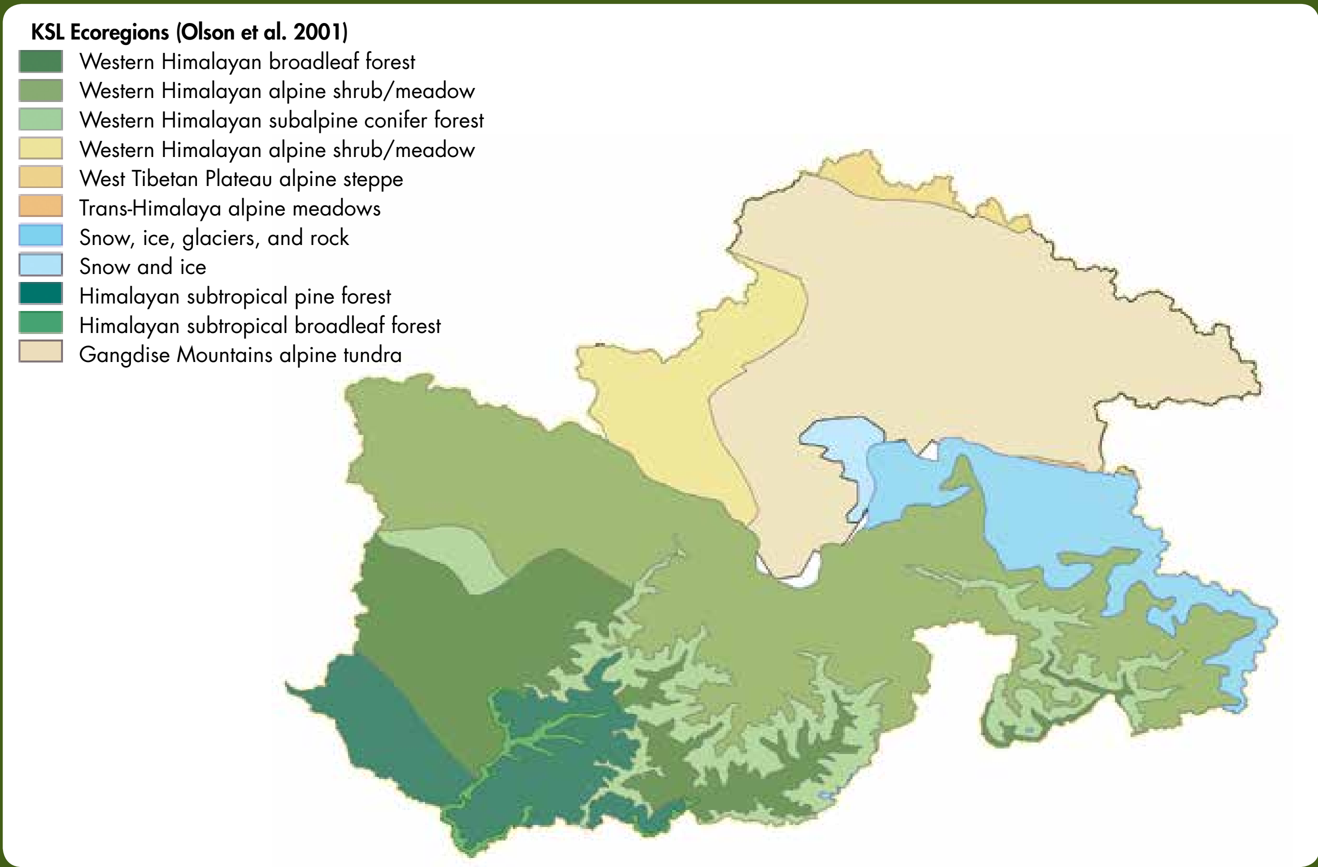
The spatial analysis was performed using the following global, regional, and national datasets:

- WorldClim: Global high-resolution climate surfaces in 1950–2000 (Hijmans et al. 2005)
- FutureClim: Global high-resolution climate surfaces in 2050 (Ramirez and Jarvis 2010)
- CSI-PET: CGIAR-CSI Global Aridity and PET database (Zomer et al. 2008)
- SRTM 4: SRTM Digital Elevation Model Database v4 (Jarvis et al. 2008)
- WWF Ecoregions: Terrestrial ecoregions of the world (Olson et al. 2001)
- Forest and Vegetation Types of Nepal (TISC 2002)
- FAO Land Cover of Himalaya Region in 2000–2005 (FAO 2010)
- MOD17: MODIS Global Terrestrial Net Primary Production 2000–2006 (Running et al. 2004)
- Satellite remote sensing land cover classification of the KSL: Developed as part of KSL baseline study (Zomer and Oli 2011)

The KSL study area, being a transboundary region, presents a serious challenge for consistent spatial environmental studies across the landscape. In particular, national boundaries disrupt the data continuity over the study area for most available spatial datasets. For example, the WWF Ecoregions Dataset (Olson et al. 2001), often used in the region to identify bioclimatic and ecosystems distribution, displays an extreme discontinuity of both scale and resolution, as well as data quality, across national boundaries within the KSL (Figure 6; the KSL-Nepal presents the highest level of detail, spatial accuracy, and stratification richness, whereas the KSL-India and KSL China have insufficient detail to distinguish environmental stratification or more detailed vegetation types). Environmental and ecological studies in these areas (i.e., both in the HKH generally and the KSL more specifically) are scarce. Even when data is available across national boundaries, each of the three countries have applied different methodological approaches with a variety of ecosystem definitions, sampling protocols, accuracies, and, in the case of spatial data, spatial and temporal resolutions.

The use of a more generally applicable approach, such as the global GEnS classification, overcomes these data discontinuity issues to a certain extent. This quantitative classification method stratifies ecosystems purely on a statistical clustering of global geographic and bioclimatic datasets, publically available for the entire globe. This

Figure 6: KSL ecoregions map



Source: Modified from Olson et al. 2001

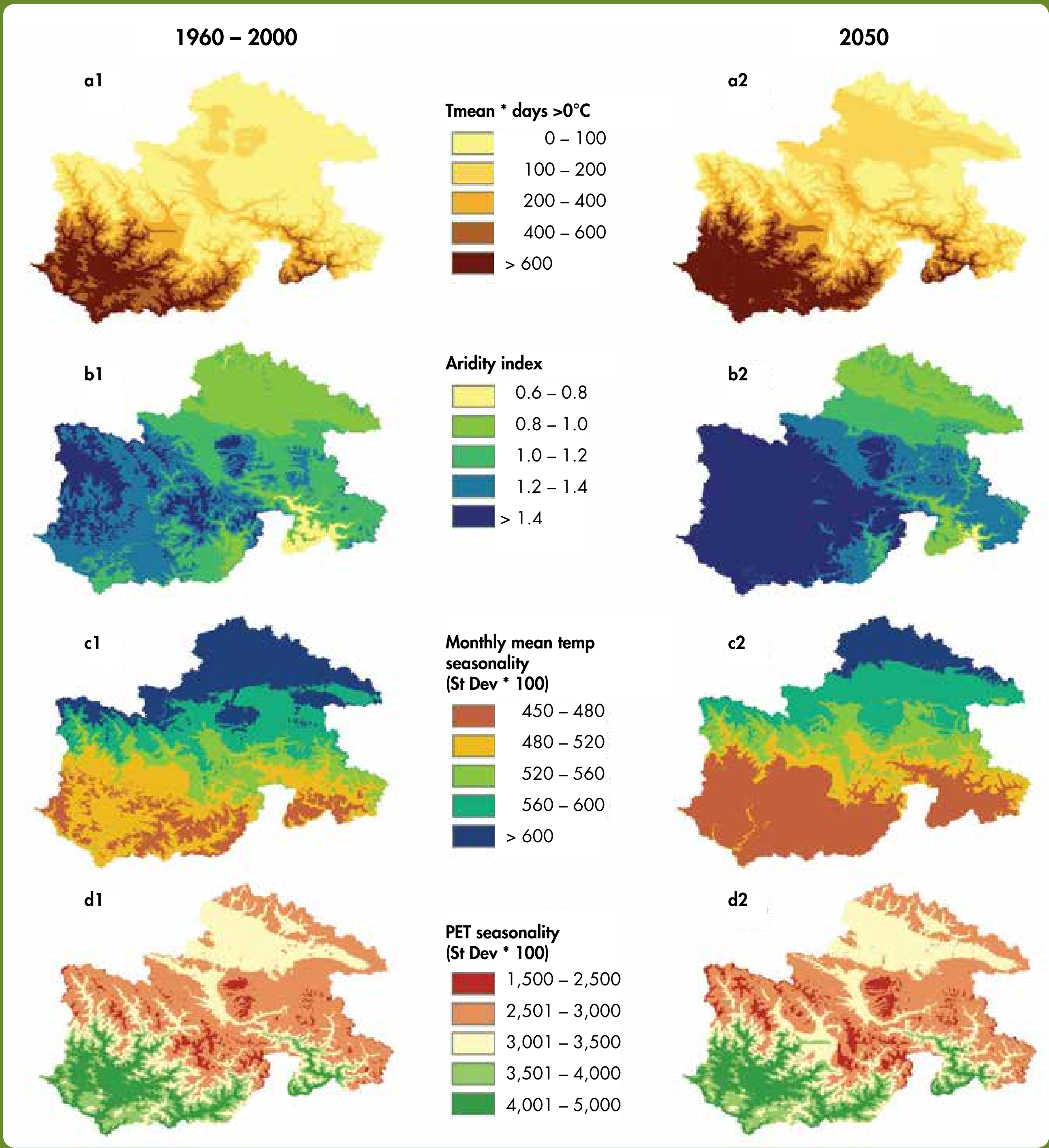
approach, therefore, provides a classification that: a) relates ecosystem spatial distribution solely and quantitatively to an identified set of bioclimatic and geographic parameters, b) creates a continuous and consistent methodology across landscapes and countries that have in the past been mostly studied using different protocols and approaches, and c) creates a tool that can be used to ascertain and project shifts in ecosystems because of climate changes.

GEnS global bioclimatic stratification

This section describes how the global GEnS classification scheme was derived to produce the GEnS global mapping, as described in Metzger et al. (2012). A subset of biophysically relevant bioclimatic variables was first identified based on a statistical screening of the climate data. These statistically significant parameters were then compacted into fewer independent dimensions using a Principal Components Analysis (PCA) of the global datasets. The PCA revealed that the first three components, which explain 99.9 per cent of the total bioclimate variation, were determined by only four variables: the daily sum of annual degrees of temperature above 0°C, reflecting latitudinal and altitudinal temperature gradients, and plant growth periods (Hijmans 2005); the aridity index (Zomer 2008), which is an expression of plant available moisture; monthly mean temperature seasonality (Hijmans 2005); and potential evapotranspiration (PET) seasonality (Zomer 2008).

The first significant variable (Tmean, which represents days greater 0°C, shown as variable 'a' in Figure 7) defines the sum of degrees (mean temperature) of days when Tmean is greater than 0°C. The second variable (variable 'b' in Figure 7) represents the aridity index and is calculated as the ratio of annual precipitation over annual PET (i.e., available water moisture to satisfy vegetation demand). The third and fourth variables (variables 'c' and 'd', respectively, in Figure 7) are the monthly mean temperature seasonality and PET seasonality, calculated as the standard deviation of the monthly mean distribution times 100. These express seasonality and are also a functional measure of continentality.

Figure 7: The four significant climate variables used in the GEnS analysis and to reconstruct the KSL-EnS: a) sum of mean daily temperature degree days above 0°C (Tmean); b) aridity index; c) monthly mean temperature seasonality; and d) monthly PET seasonality



The high-resolution (i.e., downscaled) global geodatasets of these four bioclimate variables were used in the ISODATA clustering routine in ArcGIS 9.3 (ESRI) to classify the principal components into relatively homogenous environmental strata. The global environmental strata were aggregated into environmental zones based on the attribute distances between strata to provide structure and support a consistent nomenclature. The attribute distance defines a dendrogram structure with specific separation of zones and then strata. The ISODATA clustering produces a signature file that can reconstruct a GEnS map (e.g., for future climate conditions) as a function of the four climate variables. The global stratification has a 30 arcsec resolution (equivalent to ~1 km^2 at the equator).

The GEnS classification scheme consists of 125 strata, which have been aggregated into 18 global environmental zones (Figure 8). These zones are ordered based on the mean values of their principal component scores and assigned letters starting with 'A' for the zone with the lowest PCA value. Likewise, within each GEnS zone, strata are numbered by the mean value of their first principal component (PC1) score, assigning '1' to the lowest value. Each stratum has been assigned a unique code based on the combination of the letter (GEnS zone) and number (e.g., A1 or D6). In addition, consistent descriptive names were attributed to zones based on the dominant classification variables. The first principal component is mainly determined (80 per cent of the variation) by the annual temperature sum. Therefore, first letters (in alphabetical order) and lower numbers characterize colder zones and strata.

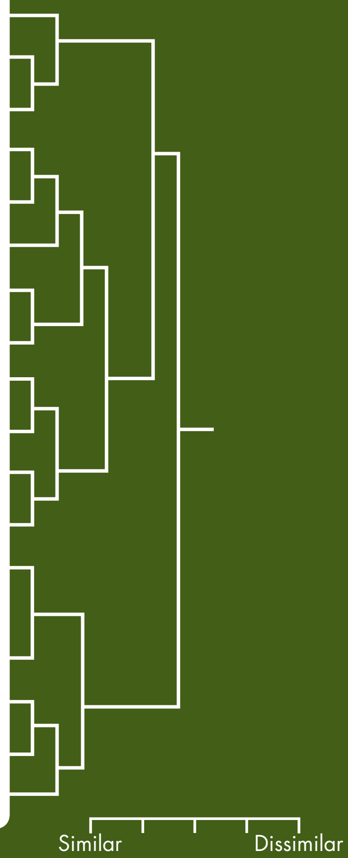
The application of the GEnS methodology within the KSL provides the opportunity to test and apply the GEnS geospatial infrastructure for the first time within the HKH context. The results of this bioclimatic stratification should be comparable with other biodiversity studies conducted within the GEOBON framework and applied elsewhere worldwide and provide a basis for the evaluation of the applicability of this framework to the HKH.

Bioclimatic stratification of KSL and development of KSL-EnS dataset

A major output of this current study is the bioclimatic stratification of the KSL (i.e., the KSL-EnS), interpreted as a biophysically-based ecological mapping of biomes, ecosystems, and functional habitat types that is uniformly applicable across the landscape and can be used for planning and implementing comprehensive environmental and ecological monitoring of the KSL. The KSL-EnS bioclimatic stratification has been correlated with ancillary ecosystem data to improve our understanding of the ecological parameters and used as a surrogate for the mapping of ecosystems and habitat types to label these bioclimate zones and strata according to land-cover and land-use types and dominant vegetation. Further, the classification developed and delineated in this study is used to estimate and predict the impact of climate change on ecosystems, habitat types, biodiversity, and ecosystem services within the KSL by the year 2050.

Figure 8: Global GEnS classification scheme

	Global zones	# Strata
Arctic / Alpine	A. Extremely cold and wet	2
	B. Extremely cold and wet	3
	C. Extremely cold and wet	3
	D. Extremely cold and wet	3
Borea / Alpine	E. Cold and wet	5
	F. Extremely cold and mesic	15
	G. Cold and mesic	14
Cool temperate	H. Cool temperate and dry	9
	I. Cool temperate and xeric	6
	J. Cool temperate and moist	6
Warm termperate	K. Warm temerate and mesic	13
	L. Warm termerate and xeric	6
Sub-tropical	M. Extremely hot and mesic	8
Drylands	N. Hot and dry	11
	O. Extremely hot and arid	3
	P. Extremely hot and arid	2
	Q. Extremely hot and xeric	6
Tropical	R. Extremely hot and moist	10



Source: Metzger et al. 2013

The application, or overlay, of the GEnS to the KSL required detailed screening for artifacts and substantial error correction to produce the KSL-EnS described in this study. Strong local errors and artifacts are visible in the original GEnS stratification (visible in the central portion of the KSL, and steeper elevation bands, see Figure 9) across the extremely rugged, heterogeneous, and steep terrain of the Himalayan range, which the KSL straddles. The artifacts are inherited from inaccuracies in the WorldClim dataset, which in turn were inherited from the SRTM v3 DEM dataset (Jarvis 2008) used in the WorldClim data processing as an explanatory variable to derive the variation of climatic conditions associated with topography and elevation. To fill data voids in the SRTM v3, the WorldClim dataset uses crude interpolation approaches. These incorrect interpolations have been mostly corrected in the more recent SRTM v4 DEM (Jarvis 2008). However, the WorldClim dataset has not yet been updated to integrate this improvement.

There are large areas on the steep slopes and narrow valleys with errors in elevation (difference between CSI SRTM v4 and CSI SRTM v3) suddenly exceeding 1,000 masl and often 3,000 masl (middle map in Figure 9). These errors influence the WorldClim climate classification and create the visible artifacts that we see in the original GEnS classification (GEnS v2, black circles in upper map of Figure 9).

To construct the KSL-EnS, areas with erroneous evaluation were first identified and masked out. A threshold (+/- 200 m) of the difference between SRTM v4 and SRTM v3 (middle map in Figure 9) was used to mask out areas with large elevation errors, which were inherited into the GEnS classification. The masked out areas were then reconstructed based on a multivariate analysis (i.e., a maximum likelihood classification) that uses correct (not masked out) nearby values such as training data and elevation (SRTM v4) and longitudinal gradient (easting) as explanatory variables. The improved interpolation based on the multivariate analysis produced a KSL-EnS classification map without the major discrepancies of the global GEnS classification dataset. This same approach was used again to correct these same artifacts in the future projected KSL-EnS 2050 dataset.

Associating ecosystems and habitat types with bioclimatic strata

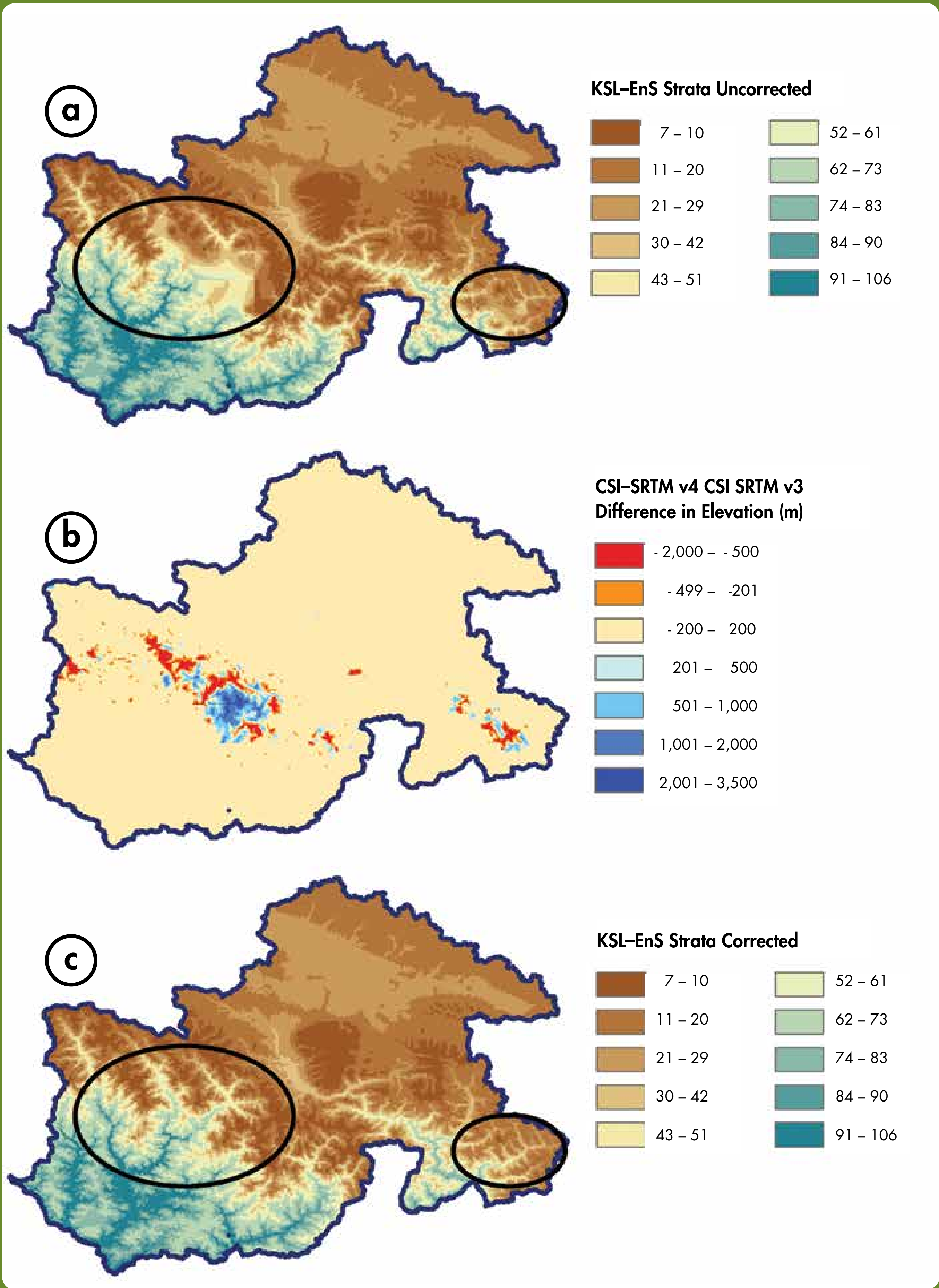
The interpretation of the KSL-EnS bioclimatic zones and strata and their labelling based on existing and projected future vegetation was conducted primarily using expert knowledge and secondary sources, namely the WWF Ecoregions Map (Olson et al. 2001), Potential Vegetation Map of Nepal (TISC 2002), and land use classification based on remote sensing (ICIMOD 2009). A geo-referenced photographic survey of the study area carried out by Zomer (2009) was used for cross reference and spot-checking. Bioclimatic zones and strata were associated with broad ecological zones, land cover, and forest types, and described in terms of predominant vegetation. The KSL-EnS strata were easily identified and associated with vegetation types, however, the resolution of the secondary sources relied upon was significantly higher for Nepal than the other countries covered by the study.

Modelling of projected future climate conditions

The ISODATA clustering used in the creation of the original GEnS classification develops and uses a signature file that classifies GEnS strata as a function of the four significant climate variables (annual temperature sums above 0°C, aridity index, monthly mean temperature, and PET seasonality) identified in the PCA statistical analysis. The signature files have been reconstructed from the KSL-EnS stratification, based upon a multivariate analysis (maximum likelihood classification) of the above significant bioclimatic factors in the KSL. These signature files of the KSL-EnS stratification were then used to project future bioclimatic spatial distribution of the KSL-EnS strata for general circulation model (GCM) future climate conditions, as downscaled in the FutureClim dataset. The FutureClim dataset (Ramirez 2010) provides Hadley GCM scenarios for the entire globe, downscaled to a 1 km^2 spatial resolution using the WorldClim as the base data. The KSL-EnS signature files generated by the multivariate analysis were used to recreate the bioclimatic stratification based upon the future projected values of the set of four significant climate variables and to map ecosystem and bioclimatic zone distribution in 2050.

For the purposes of this study, the Hadley GCM-SERS A2 (Nakicenovic et al. 2000) socioeconomic scenario for the year 2050 was chosen as the basis for the projected climate estimates. The A2 scenario, on the higher end of projected greenhouse gas emissions, envisions a very heterogeneous world with continuously increasing global population and regionally-oriented economic growth. The emissions growth rate since 2000 has been greater

Figure 9: a) Uncorrected KSL-EnS classification with artifacts; b) difference in elevation between SRTM v4 and SRTM v3 DEM datasets; and c) corrected KSL-EnS



than that projected in the most fossil-fuel intensive SRES A1FI emissions scenario (McMullen and Jabbour 2009), meaning that current CO_2 levels are beyond the 'worse case' scenario and implying that the KSL-EnS 2050 projections are conservative.

Modelling changes in productivity

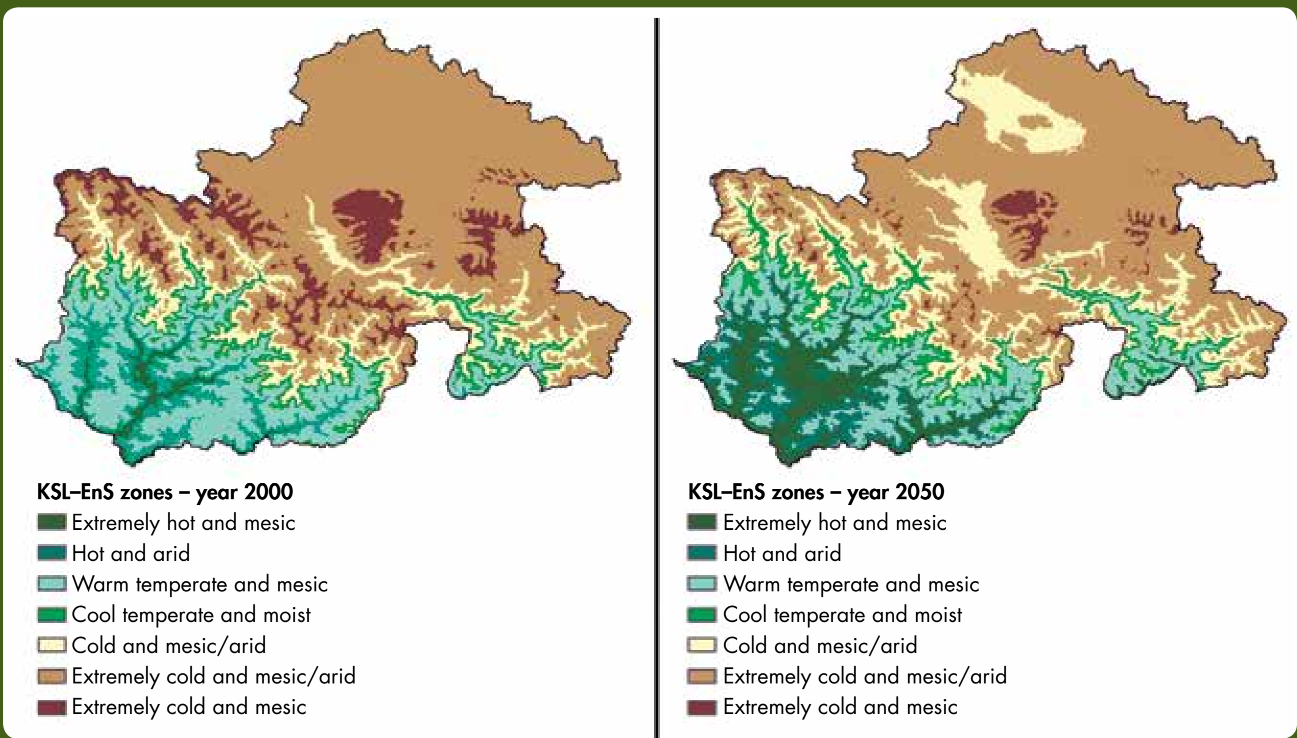
The MODIS/Terra Annual Net Primary Production dataset (MOD17A3; Running et al. 2004) is available from the Numerical Terradynamic Simulation Group (www.ntsg.umt.edu). MOD17A3 Total Gross Primary Productivity is computed using the amount of photosynthetically active radiation (PAR) measured by the MODIS instrument as the driving factor. Land-use specific radiation use efficiency (RUE) defines the values at which different ecosystems efficiently use radiation to produce energy. Maintenance respiration is then computed and used to derive net primary productivity (NPP) from gross primary productivity (GPP). The simulations to produce MOD17A3 are carried out using the BIOME-BGC model. Heinsch et al. (2005) found good correlation ($r^2 = 0.859 \pm 0.173$) between NPP estimated by MOD17A3 and 38 site years of NPP measurements. Several other studies have shown no consistent under or overestimation across different biomes compared to field observed NPP (Zhao et al. 2005; Turner et al. 2003).

The MOD17A3 annual NPP spatial datasets for 2000 to 2006 were aggregated into a single average NPP dataset and used in this study to associate vegetation productivity to each ecosystem defined by the KSL-EnS classification. The average NPP value per square kilometre was then calculated for each KSL-EnS based ecosystem. This average NPP value for the ecosystem was then multiplied by the areal extent of that ecosystem for both current and future climate conditions. Changes in the areal extent of these ecosystems following climate change were used to provide estimates of the potential associated changes in productivity.

Bioclimatic Stratification

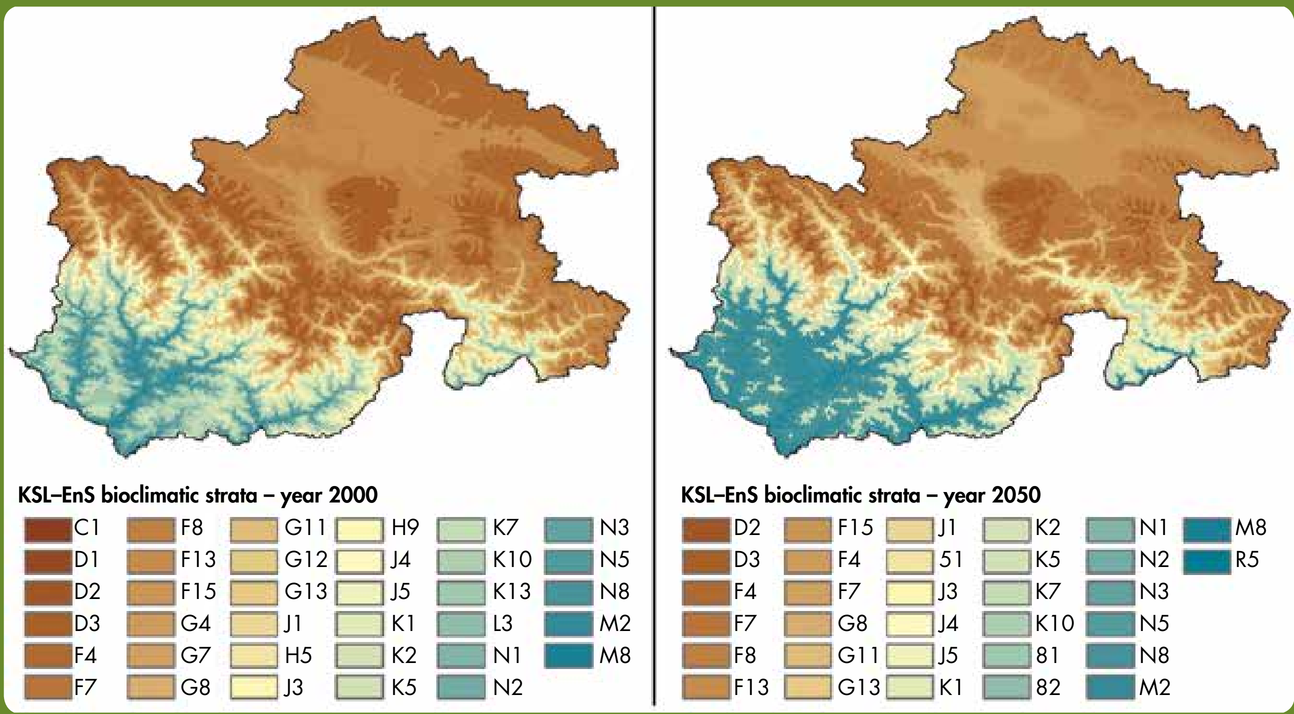
The KSL-EnS stratified the KSL into 10 zones (Figure 10) and 34 strata (Figure 11). However, nine of these strata cover a very small area (less than 100 km^2, and, in several cases, as little as 1 km^2, for example, one grid cell found only on the top of Mount Gurla Mandata). For completeness, we have included all of the strata in the results.

Figure 10: Distribution of KSL-EnS bioclimatic zones (in the year 2000 and projected for 2050)



Source: SRTM v4

Figure 11. Distribution of KSL-EnS bioclimatic strata (in the year 2000 and projected for 2050)



Source: FAO 2010

In general, it was observed that the WorldClim data overestimated precipitation on the Tibetan Plateau and in the trans-Himalayan valleys that lie in the rain shadow of the high mountains. WorldClim uses a set of single location-based climate stations (i.e., points) to develop a spatial grid through algorithms that essentially interpolate between those points to estimate the various parameters at a 1 km^2 spatial resolution; hence, the data does not account for the sharp discontinuity in precipitation level and the rain shadow effect created by the high ridges of the Himalayas. Because of sparse precipitation data and few climate stations at high elevations in the Himalayas or on the Tibetan Plateau, the WorldClim databases have interpolated the precipitation gradient for the KSL from a relatively large region, leading to a misclassification of the leeward side of the Himalayan range as much more humid than it actually is (it is actually xeric with very little rainfall). This implies that increased precipitation as a result of orographic effects on the monsoonal side of the ridges has also perhaps been underestimated. Hence, the stratification did a poor job of discriminating between the wetter high altitude valleys on one side of the mountains and the very dry trans-Himalayan high altitude valleys found on the other side. As the Himalayan ridge roughly follows the border between China and India and Nepal, the location of the Chinese border was used to aid interpretation and zonal aggregation.

The distribution, extent, and averages of the various parameters and biophysical characteristics of the KSL-EnS bioclimatic zones and strata are presented in Tables 1 and 2. Bioclimatic strata are also aggregated (Table 3) and described in terms of primary land cover and vegetation type or 'ecosystem' (Table 4) using the Terrestrial Ecosystem classes ascribed to them by Olson et al. (2001). Each of the bioclimatic zones is described below.

Extremely cold and moist (Zones C and D)

The extremely cold zones (Zones C and D) are found at the highest elevations and cross the Himalayan ridge onto the arid Tibetan Plateau, which is sheltered from the South Asian monsoon by the Himalayan range. Extremely cold and moist climate zones (Zones C and D) and strata (Strata C2, D1, D2, and D3) coincide with what is generally referred to as 'nival zones', mostly above 5,500 masl, with an average elevation of over 6,500 masl. These strata are typically covered by permanent glaciers and snow on the Himalayan ridges and mountain tops and are

Table 1: KSL-EnS zones and their attiributes

KSL-EnS zone	Mean annual temp (°C)	Mean annual precipitation (mm)	Mean PET Std	Tmean_ dd > 0	Mean Tmean Std	Mean aridity index	Elev- ation (m)	Elev- ation (m)	Area (km²)	Area (km²)
Year	**2000**	**2000**	**2000**	**2000**	**2000**	**2000**	**2000**	**2050**	**2000**	**2050**
Extremely cold and moist	-11.1	641	1,995	156	6,042	2.7	6,541	5,773	3,469	1,332
Extremely cold and mesic to xeric	-1.0	717	2,893	870	5,807	1.1	4,802	5,201	15,922	14,319
Cold and mesic to xeric	4.9	960	3,159	2,046	5,216	1.2	3,817	4,297	3,044	5,340
Cool temperate and moist	9.3	1,118	3,372	3,374	4,878	1.2	3,028	3,413	1,499	2,122
Warm temperate and mesic	14.8	1,197	3,965	5,394	4,815	1.0	2,085	2,685	4,828	3,486
Hot and mesic to dry	18.5	1,618	4,374	6,765	4,919	1.2	1,371	1,987	2,033	2,518
Extremely hot and mesic	22.2	1,885	4,865	8,245	5,139	1.2	732	1,016	441	2,032
Extremely hot and xeric	–	–	–	–	–	–	–	–	–	87
								Total	**31,236**	**31,236**

Notes: Mean PET Std = Standard deviation of the mean monthly potential evapotranspiration; Tmean DD > 0 = Mean of the sum of the number of days * degrees, where temperature > 0°C

generally barren land with seasonal snow on the northern side of the Himalaya. On the Tibetan Plateau these strata are generally barren land, with seasonal snow and glaciers on the mountain tops.

The average mean annual temperature for the extremely cold zones (C and D) is -11.0°C. Low estimated PET rates at these extreme altitudes means that the aridity index is high and these areas are considered moist, despite relatively low precipitation. However, this does not take into account the high solar radiation effects, sublimation (as opposed to evaporation) of moisture, and the very heterogeneous and diverse climatic conditions at these extremely high elevations. More than 3,400 km² of the KSL area falls within this zone.

Extremely cold and mesic to xeric (Zone F)

The extremely cold and mesic to xeric zone (Zone F) can be characterized as 'alpine', although on the Tibetan Plateau most of this zone is high altitude cold desert. This zone comprises five strata, covering most ecosystems in the KSL-China below 6,000 masl, but including high Himalayan and trans-Himalayan valleys within Nepal and India.

Strata F4 covers most of the northernmost part of KSL-China, referred to as West Tibetan Plateau alpine steppe. This area should be considered xeric rather than mesic, even though the analysis shows an average aridity index that would imply a more mesic climate, which is the result of an overestimation of precipitation on the Tibetan Plateau. A small portion of the F4 strata is found in India and Nepal and can be integrated with the F7 and F8 strata, together representing Upper trans-Himalayan alpine meadows. Likewise, the F13 strata can be subdivided with a portion in China, identified as the Gangdise Mountains alpine tundra, while the portion in India and Nepal (together with F15) can be aggregated as the Upper trans-Himalayan alpine meadows. Gangdise Mountains alpine tundra is differentiated from West Tibetan Plateau alpine steppe, having a larger portion of open shrubland (35 per cent, compared to 15 per cent) and a smaller portion of barren land (45 per cent, compared to 60 per cent). Upper trans-Himalayan alpine meadows contain limited glaciers, a significant area of permanent and seasonal snow, and support primarily shrub and grassland vegetation types. This zone covers almost 16,000 km² of the KSL, with an average mean annual temperature of -1.0°C and an average elevation of 4,800m.

Cold and mesic to xeric (Zone G)

This zone, comprised of six strata, is generally defined as a cold and mesic climate type. However, significant portions of strata G7 and G11 are found in the upper portion of the Karnali River within China (also known as the Peacock River in China) and are xeric. The ecosystems in this climate zone (exclusive of the xeric areas on

Table 2: KSL-EnS strata and their attributes

KSL-EnS zone	KSL-EnS strata	Mean annual temperature (°C)	Mean annual precipitation (mm)	Elevation (m)		Area (km²)	
Year		2000	2000	2000	2050	2000	2050
Extremely cold and moist	C2	-16.6	584	7,464	NA	1	NA
	D1	-13.6	592	7,127	NA	6	NA
	D2	-9.2	693	6,106	5,840	98	437
	D3	-4.9	695	5,466	5,706	3,364	895
Extremely cold and mesic to xeric	F4	-4.4	508	5,356	5,701	3,344	166
	F7	-0.6	867	4,718	5,112	2,169	5,714
	F8	-1.9	697	4,972	5,443	4,531	2,611
	F13	-0.3	631	4,675	5,047	3,600	1,256
	F15	2.0	883	4,288	4,701	2,278	4,572
Cold and mesic to xeric	G4	4.0	975	4,027	4,532	1	1
	G7	3.6	866	4,055	4,618	176	1,045
	G8	4.2	1,083	3,831	4,246	829	2,794
	G11	5.0	890	3,837	4,261	952	590
	G12	5.9	880	3,743	-	2	NA
	G13	7.0	1,068	3,407	3,829	1,084	910
Cool temperate and moist	J1	8.7	1,434	3,132	3,643	9	458
	J3	8.9	1,088	3,070	3,525	637	345
	J4	10.5	1,352	2,763	3,178	238	1,015
	J5	10.3	919	2,894	3,307	514	304
	H5	8.2	799	3,283	NA	101	NA
Warm temperate and mesic	K1	12.1	1,155	2,542	2,932	976	473
	K2	-			2,775	-	452
	K5	13.5	1,012	2,352	2,809	291	1
	K7	14.7	1,451	2,021	2,259	1,676	2,528
	K10	15.1	1,043	2,088	2,652	193	32
	K13	16.6	1,596	1,648	NA	1,642	NA
	L3	16.5	926	1,856	NA	50	NA
Hot and mesic to dry	N1	17.7	1,951	1,441	1,972	168	3
	N2	17.6	1,394	1,517	2,489	179	1
	N3	18.3	1,803	1,344	1,906	859	105
	N5	18.9	1,096	1,432	1,931	30	5
	N8	19.7	1,845	1,121	1,639	797	2,404
Extremely hot and mesic	M2	21.6	1,872	844	1,208	422	1,910
	M8	22.8	1,898	620	824	19	122
Extremely hot and xeric	R3	-			824		87
						Total area	31,236

Note: NA indicates that this stratum was either not present in 2000, or will no longer be present within the KSL by 2050.

the Tibetan Plateau) are subalpine ecosystems with meadows and shrub vegetation types above the treeline and scattered trees below the treeline, which gradually form closed forest patches at the zone's lower elevational extent.

The three colder climate strata (G4, G7, and G8) in this zone typically support vegetation corresponding to the Western Himalayan alpine shrub and meadow ecoregion, while the three warmer climate strata (G11, G12, and G13) typically support vegetation corresponding to the Western Himalayan subalpine conifer forest ecoregion. This zone has an average elevation of 3,800m, a mean annual temperature of 4.9°C, and covers just over 3,000 km².

Table 3: KSL-EnS strata aggregated by ecoregions according to vegetation type

Biome	Ecoregion (Olsen et al. 2001)	KSL-EnS stratum
Nival	Nival zone	C2 D1 D2 D3
Alpine	West Tibetan Plateau alpine steppe	F4-KSL-China
Alpine	Gangdise Mountains alpine tundra	F13-KSL-China
Alpine	Upper alpine meadow	F4_KSL India / Nepal, F7 F8 F13_KSL India / Nepal, F15
Subalpine	Alpine shrub and meadow	G4 G7 G8
Subalpine	Subalpine conifer forest	G11 G12 G13
Subalpine	Subalpine mixed forest	J1 J3 H5 H9
Temperate	Temperate conifer forest	J4 J5
Temperate	Temperate broadleaf forest	K1 K2 K5 K7
Subtropical	Subtropical mixed forest	K10 K13 L3
Subtropical	Subtropical pine forest	N1 N2 N3 N5 N8
Tropical	Tropical broadleaf forest	M2 M8 R3

Table 4: KSL-EnS aggregated by ecoregions and their attributes

Ecoregion	Mean elevation (m) 2000	(Range)	Mean elevation (m) 2050	(Range)	Area (km^2) 2000	Area (km^2) 2050
Nival zone	5,431	(3,184)	5,653	(2,819)	3,478	1,355
West Tibetan Plateau alpine steppe	5,354	(1,277)	5,652	(527)	3,186	163
Gangdise Mountains alpine tundra	4,690	(1,095)	5,043	(1,064)	3,309	1,250
Upper alpine meadow	4,728	(2,540)	5,007	(2,748)	9,385	12,878
Alpine shrub and meadow	3,862	(1,932)	4,342	(2,359)	1,015	3,843
Subalpine conifer forest	3,609	(2,518)	4,014	(2,368)	2,031	1,467
Subalpine mixed forest	3,041	(1,945)	3,573	(1,881)	760	794
Temperate conifer forest	2,794	(1,876)	3,160	(2,146)	758	1,341
Temperate broadleaf forest	2,190	(2,369)	2,376	(2,574)	2,946	3,481
Subtropical pine/mixed forest	1,727	(2,141)	2,761	(844)	1,895	34
Subtropical pine forest	1,323	(1,774)	1,640	(1,878)	2,000	2,526
Tropical broadleaf forest	922	(1,304)	1,225	(2,317)	447	2,078

Note: Parenthesis denote negative values.

Cool temperate and moist (Zones H and J)

This cool temperate and moist to mesic climatic zone, also referred to commonly as 'upper temperate', is only found in the KSL in Nepal and India. It comprises five strata and lies on the transition between subalpine and temperate zones. The colder strata (J1, H5, and J3) lie in the subalpine zone with typical vegetation of subalpine mixed forest. The two warmer and lower in average elevation strata (J4 and J5) are within the temperate zone, with typical vegetation corresponding to the temperate Western Himalayan conifer forest ecoregion. This zone covers 1,500 km^2, with an average mean annual temperature of 9.3°C and an average elevation of 3,028 masl. Drier areas (H5) exist, but cover just over 100 km^2 and are not represented under future climate conditions. Precipitation in this zone averages approximately 1,100 mm per year, most of it during the summer monsoon. Some patches of scattered 'cloud forest' are found, which are the result of orographic effects.

Warm temperate and mesic (Zone K)

This warm temperate and mesic climatic zone contains elements of both the lower temperate and subtropical zones and, in the KSL, is found only in Nepal and India. It comprises seven strata. The colder strata (K1, K2, K5 and K7) correspond to the Western Himalayan temperate broadleaf forest ecoregion, while the warmer strata (K10, K13 and L3) are Himalayan subtropical mixed forest. The stratum K2 is only present under future conditions (i.e., not under current conditions). This zone covers more than 4,800 km^2, with an average mean annual temperature of 14.8°C and an average elevation of 2,084 masl. Precipitation in this zone averages approximately 1,200 mm per year.

Hot and mesic to dry (Zone N)

This hot and dry climatic zone comprises five strata (N1, N2, N3, N5, and N8) and is commonly referred to as the subtropical zone. It is associated with the presence of Himalayan subtropical pine forest dominated by Pinus roxburghii (chir pine). In the KSL, it is only present within Nepal and India. This zone covers 2,033 km^2, with an average mean annual temperature of 18.5°C, average mean annual precipitation of 1,600 mm per year, and an average elevation of 1,371 masl.

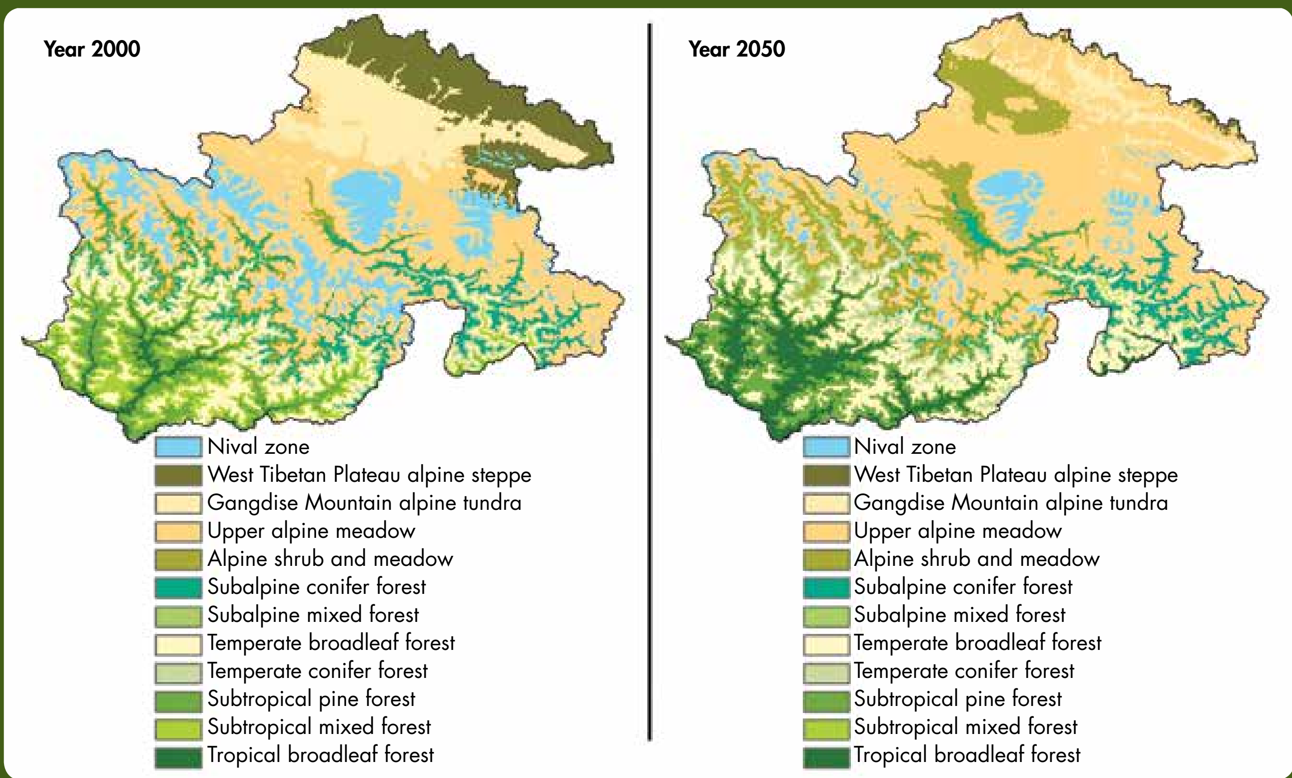
Extremely hot and mesic (Zone M)

This extremely hot and mesic 'tropical' zone comprises two strata (M2 and M8) and currently has only a limited presence in the KSL. These strata are associated with the Himalayan tropical broadleaf forest ecoregion (i.e., hill sal forest dominated by *Shorea robusta*) and are found in the lower elevations of the KSL in India and Nepal. This zone covers 440 km^2, has an average mean annual temperature of 22°C, average mean annual precipitation of 1,885 mm, and average elevation of 737 masl.

Ecoregional Classification According to Vegetation Type

KSL-EnS strata have been aggregated into zones characterized by their dominant ecosystems and vegetation types (Figure 12). This classification, based on aggregating the strata according to their predominant (or most likely)

Figure 12: KSL-EnS bioclimatic agregated and classified by ecoregion according to vegetation type (in the year 2000 and projected for 2050)



vegetation types based on field data and secondary data, does not correspond entirely to the Metzger et al. (2012) GEnS zones. In addition, the GEnS zonal classification does not have an 'extremely cold and dry' class and so needs modification to apply to the HKH, particularly to the Tibetan Plateau. Two strata (F4 and F13) were split in order to assign areas to the correct bioclimatic classification (Table 3).

Twelve vegetation types were distinguished and named based on the corresponding ecoregion (Olson et al. 2001) (Table 4). The area covered by these vegetation zones ranges from less than 450 km^2 for tropical broadleaf forest (hill sal forest dominated by *Shorea robusta*), to over 9,000 km^2 of upper alpine meadow, mostly found on the Tibetan Plateau (Figure 8). As can be seen from the average elevation, these zones align rather neatly along the elevation gradient; however, their ranges overlap, with spreads ranging from just under 1,100 masl to over 2,500 masl. The nival zone has an average elevation of 5,431 masl and a range exceeding 3,100 masl, reflecting the extreme height of the terrain and the mountains found within this zone.

Projected Impacts on Ecosystems

The analysis of the projected impact of climate change, based on the reconstruction of the KSL-EnS strata and their various aggregation into classes, indicates a significant and substantial change in the distribution, extent, and productivity of ecosystems in the KSL by the year 2050. Both mean annual temperature and mean annual precipitation increase substantially (Figure 13). All four of the significant variables used in the bioclimatic analysis show substantial change (Figure 14). Precipitation and, consequently, aridity generally increase (with a few very small scattered areas of decrease), indicating a generally wetter climate throughout the KSL. The change in temperature in terms of number of degree days (greater than zero) shows larger increases in the lower elevations, but significant warming throughout the KSL. The standard deviation of the mean monthly temperature across the year, a measure of seasonality, shows a decrease throughout the landscape. PET both increases and decreases at different localities across the KSL. The FutureClim data appears to suggest that the greatest changes in these variables generally occur in the lower elevations (this is counter to what was expected). Figure 14 shows that the

Figure 13: Average annual temperature (degrees °C) and annual precipitation (mm) (in the year 2000 and projected for 2050)

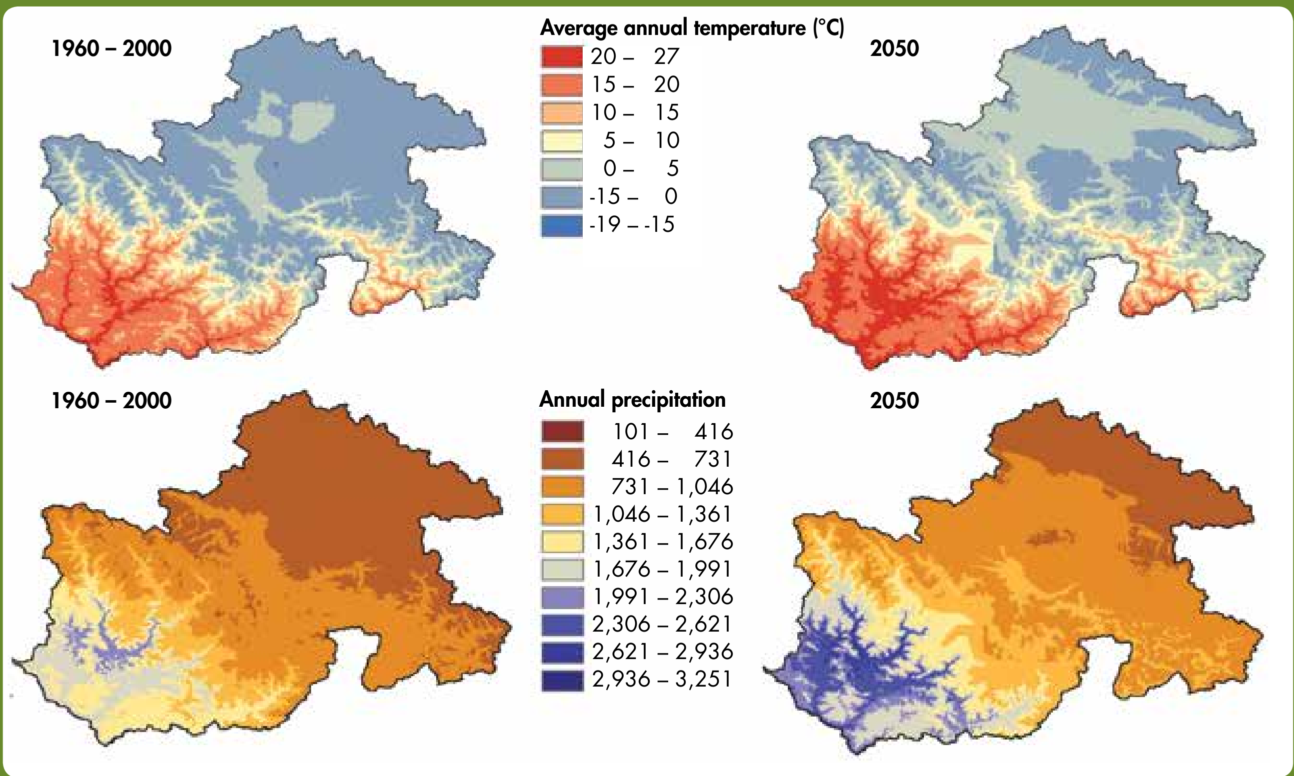
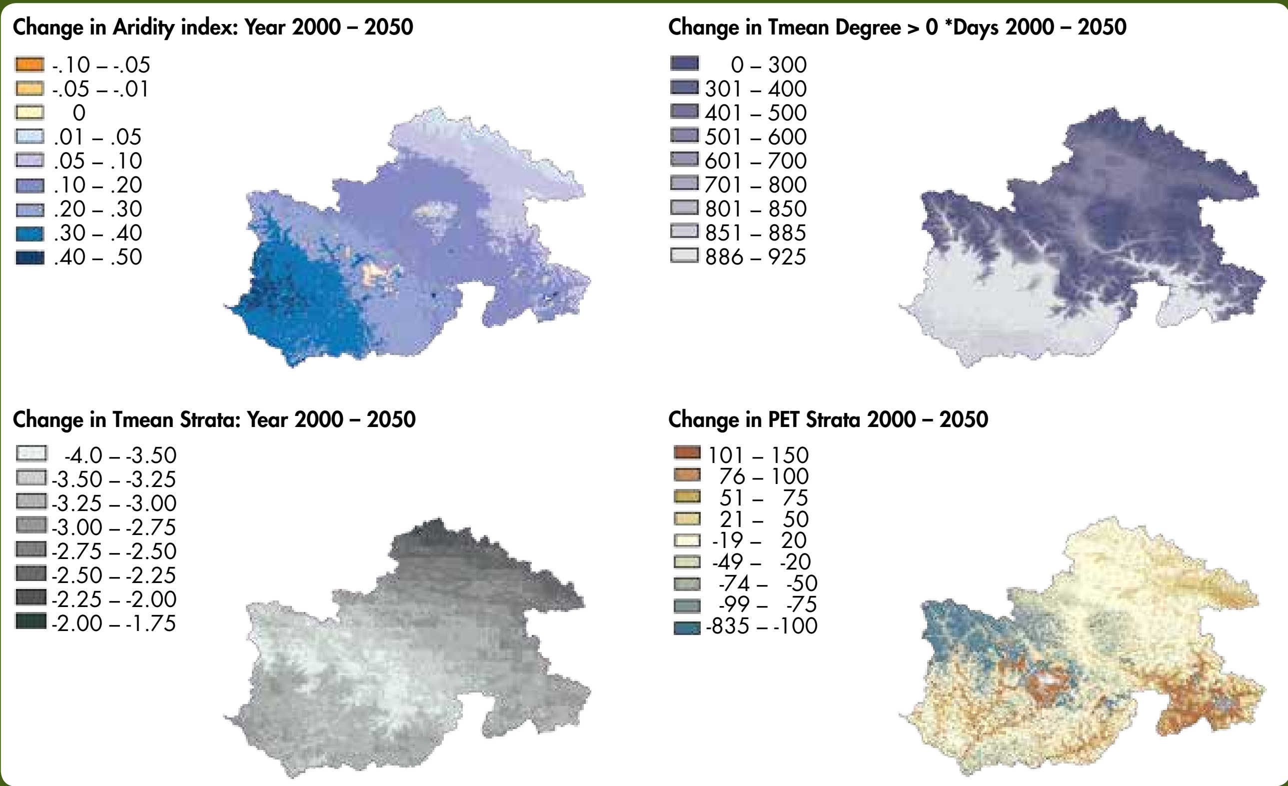


Figure 14: Changes in the four bioclimatic variables used in the KSL-EnS analysis (for the year 2000 and projected for 2050): a) aridity index (with higher positive values indicating moister conditions); b) annual number of degrees greater than zero °C; c) standard deviation of averaged monthly mean temperatures; and d) standard deviation of averaged month PET



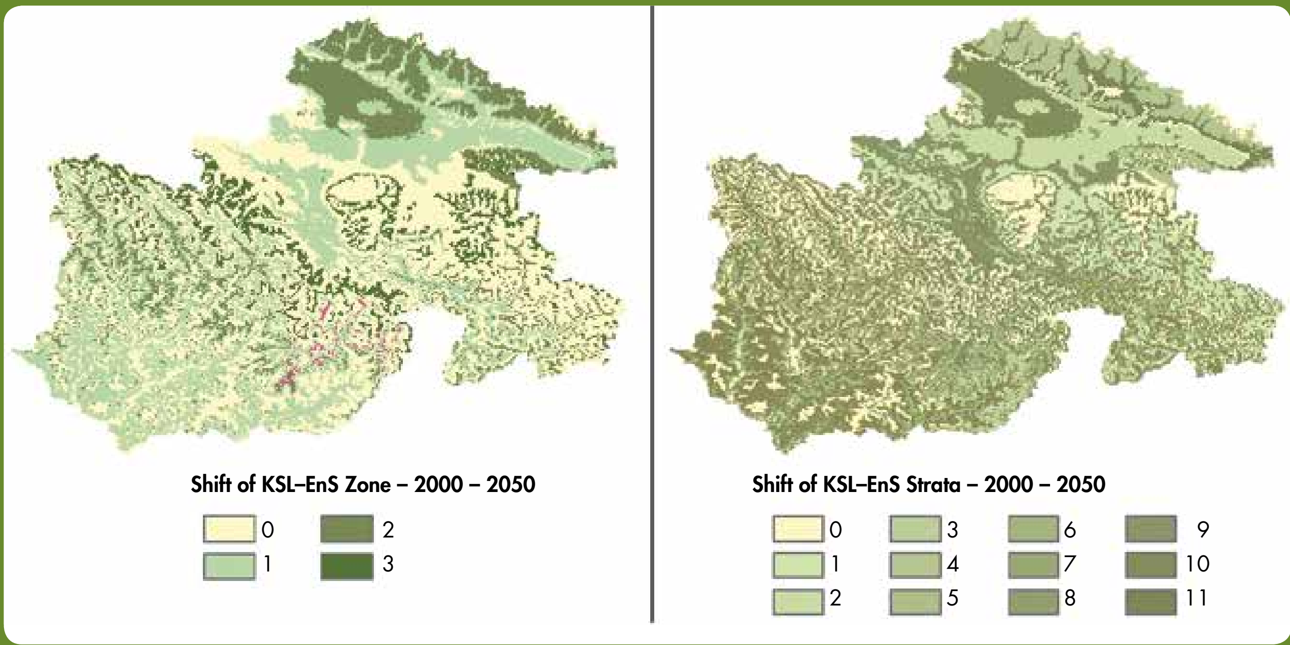
strongest change in temperature in terms of number of degree days and aridity index occurs across an elevational range (change decreases with elevation). However, the change in PET and Tmean seasonality is mostly observed across a longitudinal gradient, with change decreasing from west to east.

Both the distribution and the extent of the KSL-EnS zones are projected to shift substantially by the year 2050 (Figure 15). Based on their average elevation, each of the KSL-EnS zones are expected to migrate upward from 285 m to over 600 m (Table 1), except for the highest elevation zone of 'extremely cold and moist', which remains relatively the same, but shows a substantial decrease in areal extent of by nearly two-thirds. Similarly, the high altitude 'extremely cold and mesic to xeric' zone is expected to decrease by more than 1,600 km^2, while the lower 'cold and mesic to xeric' zone is expected to increase by just under 2,300 km^2. The 'warm temperate and mesic zone' is projected to decrease by nearly 1,400 km^2, while the remaining zones will substantially increase in area. A small area of 'hot and xeric', which is not present under current climate conditions, is projected to arise.

An overview of the changes to strata (Table 2) gives insight into the dynamics of this change. It is evident that there are large and significant changes within all strata (Figure 11). Several strata disappear altogether under future conditions, including strata K13, which currently covers over 1,600 km^2. In the case that these strata represent specific conditions or enabling habitat for endemic or threatened species, this change would pose a significant threat to biodiversity and a high risk of extinction to species endemic to these strata or adapted to their specific conditions. With the exception of those strata that disappear and the strata D2 (which is the highest elevation strata), all strata show an upwards shift in average elevation, averaging about 400 m, with the largest shifts occurring at the lower elevations. For example, strata N8 within the hot and mesic zone will increase in area from 797 km^2 to 2,404 km^2 and in average elevation by more than 500 masl.

As a measure of the extent or magnitude of change in any specific area, the shift between strata was mapped (Figure 15) by calculating the number of strata, or distance along a gradient (corresponding to average elevation) of numerically ordered strata, that each area will transform – in other words, the number of strata they have shifted.

Figure 15: Shift in KSL-EnS zones and strata (in the year 2000 and projected for 2050)



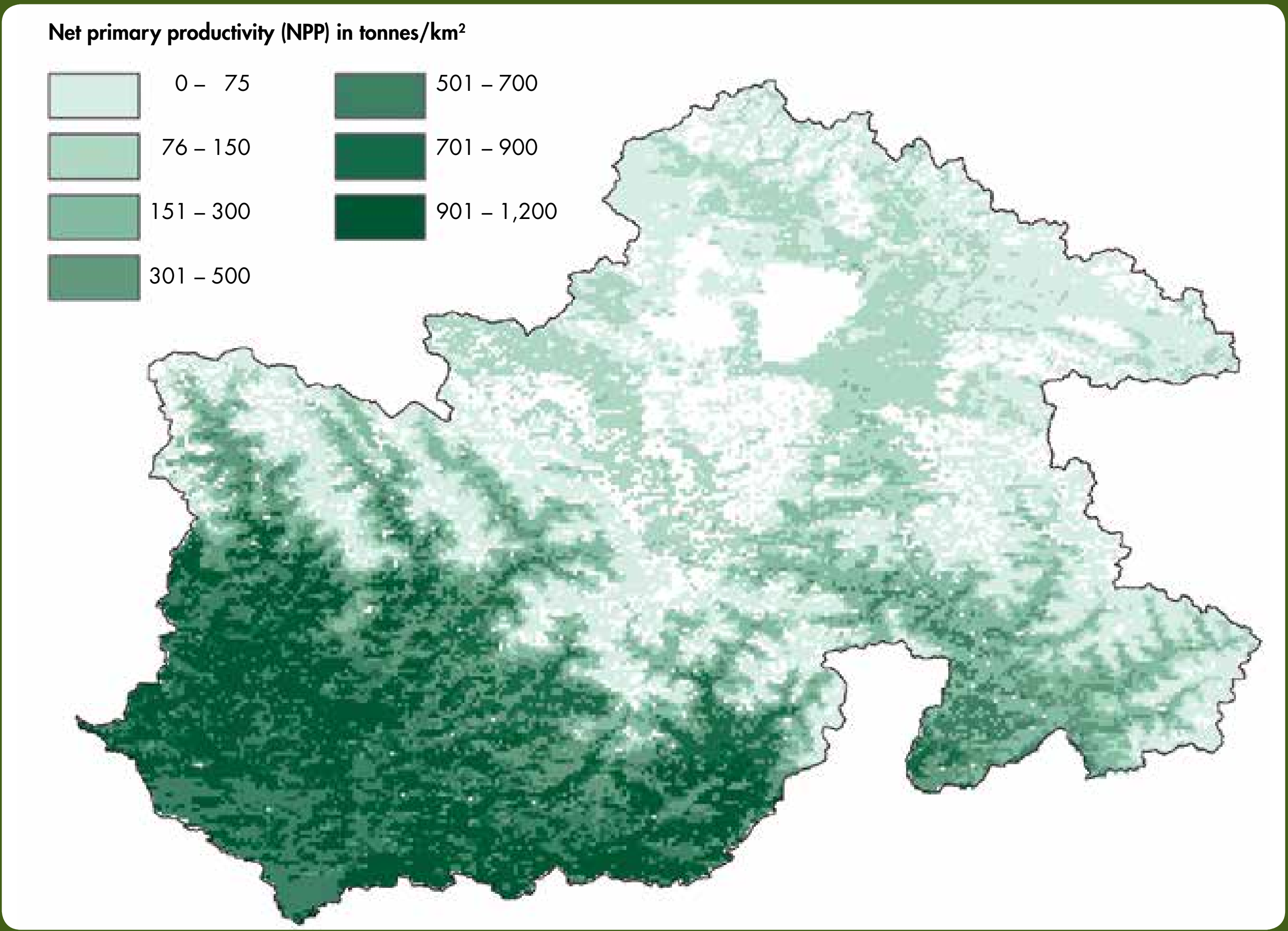
An average shift of six strata is projected for all grid cells, with 60 per cent of the total KSL area experiencing a shift greater than five strata. Likewise, a significant area is likely to experience a shift from one KSL-EnS zone to another, with limited areas shifting two zones.

When these shifts are viewed from the perspective of vegetation types (Table 4) or ecosystems, and used as a surrogate for habitat or biodiversity in general, it is evident that significant impacts are likely, especially for endemic flora and fauna and species adapted to very specific conditions or small isolated areas. For all vegetation type zones, the upward shift averages almost 400 m. Several zones will disappear almost completely. For example, barely 2 per cent of the area currently classified as subtropical pine/mixed forest class remains in this classification in 2050. Likewise, the West Tibetan Plateau alpine steppe goes from over 3,100 km^2 to a mere 163 km^2 in 2050. There are significant increases in the extent of upper alpine meadow and for alpine shrub and meadow classes. Tropical broadleaf forest is projected to increase from less than 450 km^2 to over 2,000 km^2, indicating significant expansion of the extent of the lowest elevation and warmest class.

Changes in Productivity

The total annual NPP varies generally across the KSL (Figure 16) from fairly high rates for lower elevation strata (over 900 tonnes per km^2 for tropical broadleaf forest) to areas of very low productivity at the higher elevations (Table 5). NPP rates were found to be highly correlated with elevation. For the entire KSL area, annual NPP is nearly 10 million tonnes per year, with temperate broadleaf forest contributing the highest proportion at more than 20 per cent of the total. Increases in both temperature and precipitation are projected to affect the productivity of all of the various ecosystems within the KSL, and the KSL as a whole, by increasing the productivity within ecosystems and through the expanding and shifting of higher productivity strata into currently lower productivity areas. Our analysis only looks at the impact of the latter, that is the shifting and expansion of higher productivity vegetation types replacing lower productivity types, in any particular area.

Figure 16: Annual net primary productivity (NPP) averaged from 2000 to 2006 (based on MODIS Global Terrestrial Net Primary Production [MOD17] estimates derived from satellite remote sensing data at a resolution of 250 m²)



Source: MOD17 - MODIS Global Terrestrial Net Primary Production

As almost all areas within the KSL are projected to shift at least one strata, it is assumed that using the average NPP per km² of each strata (as measured by the MODIS instrument) and applying that to the projected area of that strata under future condition is a sufficiently robust method to give an indication of the direction of change and, to some extent, the magnitude of that change. Overall, the productivity of the entire KSL is projected to increase by nearly 1.9 million tonnes by 2050, an increase of over 16 per cent. The contribution of tropical broadleaf forest increases substantially as this type expands, as does alpine shrub and meadow, and upper meadow.

As it is also likely that the productivity of these system may increase (for example, through higher CO_2 levels in the atmosphere), these estimates may be considered conservative. In addition to natural ecosystems, managed systems in the KSL, including both agroecosystems and pastoral and transhumance systems, may experience significant increases in productivity and perhaps expansion, as well as decreases, in their areal extent. However, these potential increases in productivity are far from certain and depend on a multitude of ancillary factors including, for example, impacts on pollinator cycles, pest pressure, invasive species, seasonality and timing of precipitation and glacial melt, and the impact of the disruption of finely-tuned systems as a result of increases in variability and erratic climate conditions (such as increases in dry season droughts or torrential rainfall during the monsoon).

Agronomic factors must also be taken into account in predicting farmers' ability to adapt to new circumstances including, for example, the availability of genetic material. Likewise, for example, recent research has shown that decreased rice yields are correlated with increases in night-time temperatures (Peng et al. 2004). The use of expanded and higher productivity high altitude pastures in the high mountains and grasslands in Tibet may increase carrying capacity and improve the provision of resources required for transhumance and nomadic livestock production within the KSL area.

Conclusions

The approach adopted by this study has provided a quantitative and useful environmental stratification, as well as a novel method for modelling projected change. Adopting the GEnS approach allows this stratification to be used as the basis for global comparative mountain studies. This model can also be applied regionally across the HKH to develop a stratified framework for comparative climate change studies and, more generally, for comparative ecosystems studies throughout the HKH. Mapping the difference in the distribution of bioclimatic zones provides a baseline for, and a measure of, the projected impacts of climate change on the distribution of land-cover types, ecosystems, and habitats and, as such, is a surrogate measure for the impact on biodiversity more generally. It is assumed that a similar relationship can be inferred for agricultural production and other mountain subsistence activities, including transhumance and nomadic pastoralism and the collection of non-timber forest products and medicinal plants, as well as for the health, prosperity, and livelihoods of mountain communities.

The results of this study indicate that large and significant impacts can be expected throughout the KSL area within all ecosystems and with profound consequences for the ecosystem services that they provide within the landscape and downstream. Mean annual temperature and mean annual precipitation are expected to increase and the distribution and extent of the KSL-EnS zones are expected to shift by the year 2050. Strata are also expected to shift upward in average elevation about 400 m, with the largest shifts occurring at lower elevations. Several strata are projected to disappear. The impact on biodiversity will be high in all zones and ecosystems. It is likely there will be increased risk to many endemic and already threatened species of fauna and flora as a result of climate change. Mountain communities and managed systems will also be impacted. The highly diverse and finely-tuned agrobiodiversity of this region may be threatened, including the many genetic lines and landraces of various important food crops and livestock breeds found in the KSL. However, the changes may also provide opportunities for agriculture through generally warmer and wetter weather. A significant and substantial change in the distribution, extent, and productivity of ecosystems in the KSL is expected by the year 2050. Based upon the analysis in this study, the productivity of the entire KSL area will increase by nearly 1.9 million tonnes (over 16 per cent) by the year 2050.

These results should be taken into account when planning for conservation and sustainable development in the KSL. In particular, a consideration of the likely impacts of climate change should be integrated into the planning and management of conservation efforts and schemes for protecting wildlife and biodiversity within the transboundary KSL region. A high priority should also be assigned to adaptation. Managed systems and mountain communities may be able to adapt by introducing new varieties and modifying production practices. Natural systems may be slower and stochastic in their adaptation to new conditions. In particular, although conditions may generally improve for production (e.g., it may be warmer and wetter), erratic or highly variable patterns of rainfall and increases in extreme events or the intensity of the monsoon may create more significant challenges. Improving our understanding of these mountain ecosystems, and the potential ecophysical responses of mountain species to climate change, is urgently required for effective conservation planning, sustainable development, and the development of appropriate adaption strategies conserving both managed and natural systems.

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