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Environmental stratification to model climate change impacts on biodiversity and rubber production in Xishuangbanna, Yunnan, China

Robert J. Zomer [a,b,*], Antonio Trabucco [c,g], Mingcheng Wang [a,b], Rong Lang [a,b], Huafang Chen [a,b], Marc J. Metzger [d], Alex Smajgl [e], Philip Beckschäfer [f], Jianchu Xu [a,b]

[a] Key Laboratory for Plant Biodiversity and Biogeography of East Asia (KLPB), Kunming Institute of Botany, Chinese Academy of Science, Kunming 650201, Yunnan, China
[b] Centre for Mountain Ecosystem Studies, World Agroforestry Center, East Asia, Kunming 650201, China
[c] Euro-Mediterranean Center on Climate Change, IAFENT Division, Sassari, Italy
[d] School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK
[e] CSIRO Ecosystem Sciences, Townsville, Qld 4814, Australia
[f] Chair of Forest Inventory and Remote Sensing, Georg-August-Universität Göttingen, Göttingen, Germany
[g] KULeuven, Division Forest, Nature and Landscape, Celestijnenlaan 200E, 3001 Leuven, Belgium

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ABSTRACT

An analysis and multi-model approach, based on a statistically derived Global Environmental Stratification (GEnS) and using a downscaled ensemble ($n = 63$) of CIMP5 Earth System Models applied across four representative concentration pathways (RCP), has been used to project the impact of climate change on spatial distribution of bioclimatic zones and ecosystems within the biodiverse rich Xishuangbanna Prefecture, Yunnan Province, by the year 2050. Four bioclimatic zones and 9 strata were identified, overlaid with protected areas, and associated with on-going landuse change, i.e. a rapid increase in rubber plantation from 8% to 22% of total area between 2002 and 2010. Significant changes in the areal extent and distribution of all zones and strata are projected, with an averaged mean annual temperature increase ranging from 1.6 °C to 2.4 °C. By 2050, there are significant geographical shifts in all identified strata, with an average upward shift of 309 m of elevation for all strata. On average, more than 75% of Xishuangbanna is predicted to shift to a different zone, with 96% shifting to a different stratum. The area conducive to rubber plantations, currently limited by climatic conditions, expands to nearly 75% of the total area. Climatic change potentially removes the bioclimatic barriers to further expansion of rubber plantations within the area and increases pressure on remaining biodiversity both within and outside of protected areas. The analysis provides the basis for understanding potential impacts of changing bioclimatic conditions on managed and unmanaged ecosystems and landuse change trends, within the context of ongoing rapid change and agricultural expansion in the area. Current efforts to conserve forests, biodiversity and traditional landuse systems require an improved understanding of both the projected climatic changes and the responses of biodiversity and traditional agricultural systems to changing conditions.

1. Introduction

1.1. Overview

Improved understanding of the impact of climate change on landuse change processes in Xishuangbanna, Yunnan, China is required for effective conservation planning within the context of a rapidly changing environment. Habitat loss through landuse and landcover change is a major driving factor accelerating biodiversity loss across the globe, as it is within Xishuangbanna (Xu et al., 2012), an area recognized as China's "Treasure House" of biological diversity, and one of the richest in number of flowering species in the world. At the same time, it is generally agreed that climate change will have major impacts on ecosystems throughout this mountainous region (Xu et al., 2009, 2012). Although more than 12% of Xishuangbanna's land area is designated as various types of protected areas (Guo et al., 2002), the impacts of climate change could undermine current and future conservation efforts if changing conditions, such as shifts in species ranges (Körner, 2007; La Sorte and Jetz, 2010, 2012) are not considered in planning and implementation of conservation policies and initiatives. Likewise, understanding the impact climate might have on agricultural suitability and landcover change, particularly the expansion of agricultural land area, is required if sustainable

* Corresponding author at: Center for Mountain Ecosystem Studies, Kunming Institute of Botany, Heilongtan, Kunming 650201, China. Tel.: +86 871 5223014.
E-mail addresses: r.zomer@cgiar.org (R.J. Zomer), Antonio.Trabucco@cmcc.it (A. Trabucco), marc.metzger@ed.ac.uk (M. Wang).

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development and climate adaptation policies are to be effectively "biodiversity friendly" upon implementation.

Integration and coordination of environmental and biodiversity data, in conjunction with an understanding of landuse change trends, have been highlighted as being essential to respond to the major challenges of climate change and biodiversity decline (Beier and Brost, 2010). The Global Environmental Stratification (GEnS) (Metzger et al., 2013) is a globally consistent classification of land into relatively homogenous units, based upon a statistical clustering of climate variables (Metzger et al., 2013). It was developed in support of the Global Earth Observation – Biodiversity Observation Network (GEO-BoN) (GEOBON, 2010; Scholes et al., 2008, 2012) to provide a framework for comparison and analysis of ecological and environmental data across large heterogeneous areas, and to facilitate the integration of global biodiversity data collection and monitoring efforts. In this paper, a geospatial modeling approach (Zomer et al., 2013) based upon the GEnS is used to analyze projected climate changes and their impact on bioclimatic conditions within Xishuangbanna by the year 2050. The geographic shift of bioclimatic strata as a result of changed climatic conditions can be used as a surrogate measure for inferring potential impacts on the spatial distribution of biomes, ecoregions, ecosystems, vegetation communities or wildlife habitat. An analysis of remote sensing data from 2002 to 2010 is used to assess the direction and magnitude of the landuse and landcover changes in Xishuangbanna. The potential impact of projected climate change on landuse, particularly expansion of rubber plantation area, as well as on efforts to conserve forests, biodiversity, and traditional landuse systems, is examined and compared with current and historic landuse change. The analysis provides a geospatially articulated basis for discerning potential impacts of medium-term climate change (i.e. by 2050) on terrestrial ecosystems, rubber production, and biodiversity conservation efforts in Xishuangbanna.

1.2. Xishuangbanna Autonomous Dai Prefecture

Xishuangbanna Prefecture is located on the southern margins of China's Yunnan Province, bordering Laos and Myanmar (Fig. 1a). Xishuangbanna lies in a transition zone from sub-tropical to tropical climates, and like the whole of Yunnan, it is within the transition zone from the Eastern Himalaya flora and fauna to the biota of mainland Southeast Asia. The region is dominated by mountains, with an elevation range from 542 to 2415 m asl (Fig. 1b), has a generally warm and moist climate, and harbors exceptionally high levels of biodiversity. There are over 5000 flowering plant and fern species, accounting for approx. 35% of all of Yunnan's higher plants, including 153 endemic species and 56 rare and endangered species (Zhang and Cao, 1995). The region contains China's largest area of diverse types of mature tropical forest, which mainly lie within the Xishuangbanna Biosphere Reserve. This reserve features eight vegetation types and twelve sub-types, including tropical rain forest, tropical monsoon forest, and sub-tropical monsoon evergreen broadleaf forest. It is home to the northernmost tropical rainforest in the world. Various measures have been adopted by the government to preserve biodiversity in the area, e.g. the expansion of formally protected areas. Nevertheless, forest area has been decreasing and forest patches have become increasingly fragmented, with the populations of many species reduced (Zhang and Cao, 1995; Pu et al., 2007; Li et al., 2008). There have been dramatic changes in landuse and landcover since the 1950s, with many forests in this area heavily impacted and converted to rubber plantations and other cash crops (Xu et al., 2012).

In conjunction with these landuse changes, Xishuangbanna, being one of the poorest regions in China, is also experiencing a rapid socioeconomic transformation. However, much of the population is still living in relatively poor conditions. Deforestation, fragmentation of forests, and landuse changes, particularly the expansion of agricultural and industrial crops such as rubber, occurring over the last sixty years, led to severe negative impacts on biodiversity and ecosystem services throughout Yunnan, including Xishuangbanna (Chapman, 1991; Fox and Vogler, 2005; Li and Fox, 2012). Rubber (*Hevea brasiliensis*) is the main crop replacing traditional agriculture and forest vegetation in Xishuangbanna (Fox and Vogler, 2005; Xu et al., 2005; Li et al., 2006), and is among the major drivers of deforestation and biodiversity loss throughout Southeast Asia (Li et al., 2006; Hu et al., 2007). The impacts of this landuse change, beyond decreasing biodiversity (Li et al., 2006; Hu et al., 2007), include deterioration of watershed services (Guardiola-Claramonte et al., 2008), and a decline in livelihood options (Xu et al., 2005). Rubber production in Xishuangbanna has increased dramatically in the last decades, and is continuing to increase, heavily impacting natural ecosystems (Li et al., 2008). Climate change has the potential to substantially exacerbate the impacts of these processes, undermining current landuse planning and conservation efforts (Dale, 1997; Hannah, 2010). The average temperature over Yunnan Province has been increasing since the late 1980s and it has become markedly warmer since the 1990s (Cheng and Xie, 2008). The trend of temperature increase in Yunnan is parallel to the trends for the global, northern hemisphere, and China as a whole, with temperatures in

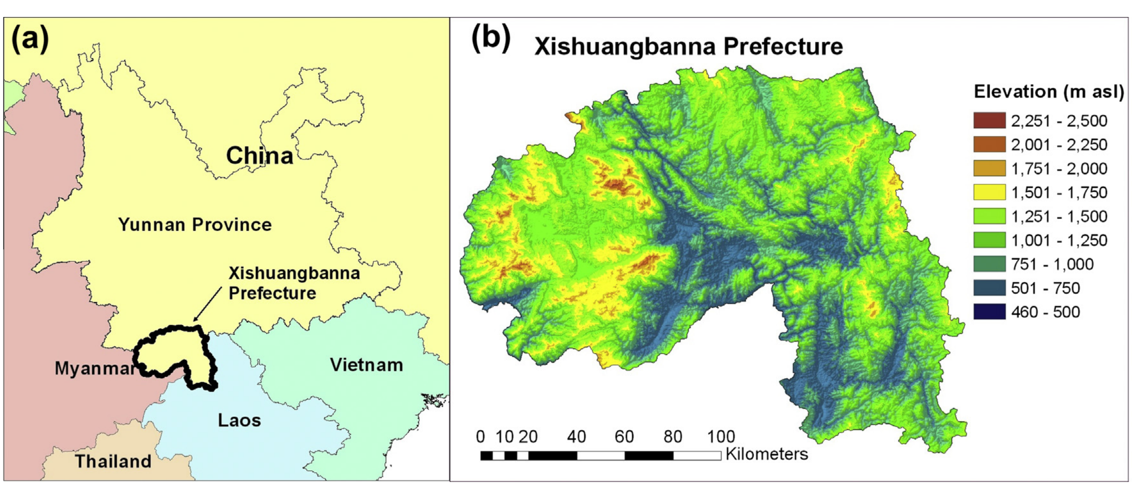

Fig. 1. Location of Xishuangbanna in Southern Yunnan, bordering Myanmar and Laos (panel a). Elevation map of Xishuangbanna (panel b).

Yunnan changing slightly more than the global average and a little less than the averages for the northern hemisphere and China (Lin et al., 2007). As a result of this warming trend, the elevational distribution of bioclimatic zones in this mountainous region is likely to shift markedly (Xu et al., 2009).

Traditionally managed agro-ecosystems, supporting high levels of biodiversity, are found throughout Xishuangbanna, primarily swidden-fallow systems, but also agroforestry systems such as the Dai home gardens, traditional firewood management systems based on *Cassia siamea*, sacred forests, and forest-based tea production (Yu et al., 1985; Guo, 1993; Long, 1993; Cui et al., 2000; Zeng et al., 2001). The area is considered a center of diversity for rice, with over 400 varieties of upland rice found (Dai, 1998). The areal extent of traditional swidden-fallow systems decreased considerably over the past decades due to changes in economic policies, demographic processes, and conservation actions (Ye and Dai, 2000). In recent years, there has been a very large increase in the land devoted to rubber production (Guo et al., 2002; Xu et al., 2012). Rubber planting began in the late 1950s, and by 2010 rubber plantations occupied over 424,000 ha in Xishuangbanna (Xu et al., 2012). Before the 1980s, rubber was grown almost exclusively on state farms. Under new economic and land polices beginning in 1980s local smallholder farmers started to cultivate rubber. While in 1965 only 42 ha were managed as smallholder plantations (0.5% of total rubber plantation area), by 1998 this area had already increased to over 41,000 ha (45% of total rubber plantation). Much of these plantations were established on lands designated as collective forest or swidden-fallow successional forest. In turn, these subsistence activities have been displaced to higher elevations less suitable for growing rubber. Recently, the transition to a market–driven economy has encouraged a transition from swidden-fallow, upland rice, and other subsistence crops to industrial and market oriented crops such as tea, and in particular, rubber.

2. Methods

2.1. Global Environmental Stratification (GEnS)

The GEnS global classification (Metzger et al., 2013) is a statisitical stratification of the world's land surface into homogeneous bioclimatic strata facilitated by high resolution global climate datasets, representing a considerable advance (Metzger et al., 2013, 2012) over earlier global attempts at bioclimatic or ecosystems mapping (Holdridge, 1947; Thornthwaite, 1948; Peel et al., 2007). Based on a statistical clustering of significant climate variables, the GEnS provides a global stratification that can: a) quantitatively relate the spatial distribution of ecosystems to an identified set of bioclimatic parameters, b) provide a consistent methodology across landscapes and countries that have so far mostly been studied using different protocols, approaches and taxonomies, and c) allow for a statistical modeling of bioclimatic zonal shifts that can be used to estimate the direction and magnitude of impacts on ecosystems due to climatic changes.

The GEnS, based on high resolution geospatial monthly climate datasets averaged from 1960 to 2000 (Hijmans et al., 2005), characterizes recent conditions to stratify the globe into 125 strata, aggregated into 18 zones. This quantitative approach allows for the use of the identified set of statistically significant parameters and the statistical profiles of the various strata to reconstruct the stratification based on projected future conditions (i.e. using the parameter values derived from modeled climate scenarios). The strata continue to represent bioclimatic conditions similar to the original strata (i.e. recent climatic conditions), but may shift in areal extent or location. The change in distribution of the bioclimatic strata is analyzed and used as a surrogate measure to describe the potential projected macro-level impacts of climate change on terrestrial ecosystems (Metzger et al., 2008; Zomer et al., 2013). When combined with other ecosystem, vegetation, or landuse data, these shifts in spatial distribution can be interpreted in terms of projected impacts on ecosystems services, landuse, wildlife habitats, risks to endemic or threatened species, or the risks and opportunities associated with future agricultural production. For this study, the zonal nomenclature has been slightly modified to account for conditions as they occur in Xishuangbanna. However, as both strata and zones are labeled by unique alpha-numeric identifiers, the ability to use these for comparative purposes remains.

The geospatial analysis was performed in ArcGIS 10.1 (ESRI 2012) using the global datasets listed below, along with various national and local secondary datasets and information collected on landuse and biodiversity, and a remote sensing based landuse change analysis described below, to corroborate and interpret results:

- GEnS: Global Environmental Stratification v. 1 (Metzger et al., 2013).
- WorldClim v. 1.4: Global high-resolution climate surfaces in 1960–2000(Hijmans et al., 2005).
- CIMP-5: Ensemble of downscaled CIMP5 ESM models (Taylor et al., 2012)
- CGIAR-CSI PET: CGIAR-CSI Global Aridity and PET database (Zomer et al., 2008).
- SRTM: CGIAR-CSI SRTM Digital Elevation Model Database v. 4.1 (Jarvis et al., 2008).

2.2. Landcover change analysis

Landcover change in Xishuangbanna was analyzed based on a comparison of two sets of interpreted remote sensing imagery. A Landsat Enhanced Thematic Mapper image (30 m resolution) classified by object-oriented methods using ENVI EX (ITT Visual Information Solutions, U.S) provided a baseline map depicting landcover in March 2002. A Support Vector Machine and a Fuzzy Logic Model were employed for grouping pixels into landuse classes. Supplementary data such as a vegetation index (NDVI) and a SRTM digital elevation model were applied for land use identification. Ground truthing points, collected using a GPS during fieldwork in 2003, were used for accuracy assessment.

RapidEye satellite images (5 m resolution) captured between January to June 2010 were classified using object-oriented methods, with eCognition 8.0 (Definiens, Germany). All classified images were mosaicked to a regional map of Xishuangbanna. Sample points located within all land use types, randomly generated from high resolution images on Google Earth (Digital Globe, U.S; Google Inc., U.S), were used to assess classification accuracy along with GPS points collected on the ground. The land use categories found in Xishuangbanna are agricultural land, tree plantation, forest land, grassland, water, wetland, built-up land, and bare land.

2.3. Modeling of projected future climate conditions

Metzger et al. (2013) identified a set of significant bioclimatic parameters, based on a statistical screening of the various global climate datasets. Principal Component Analysis (PCA) of the global dataset revealed that 99.9% of the total variation was determined by four variables:

- $T_{\text{mean DD>0}}$ is defined as the annual sum of daily mean temperature degrees of days with a mean temperature above 0 °C, reflecting latitudinal and altitudinal temperature gradients, and plant growth periods (Hijmans et al., 2005);

- Aridity Index (AI), is defined as the ratio of annual precipitation over annual potential evapotranspiration (PET) and forms an expression of plant available moisture (Zomer et al., 2008);
- Monthly Mean Temperature Seasonality is defined as the standard deviation of the monthly temperature means, and is a measure of temperature seasonality (Hijmans et al., 2005);
- PET Seasonality is defined as the standard deviation of the monthly PET means, and is a measure of seasonality of plant available moisture (Zomer et al., 2008).

These four bioclimatic variables were used as the input to the ISODATA clustering routine in ArcGIS to classify the GEnS environmental strata (Metzger et al., 2013). 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 the Coupled Model Intercomparison Project – Phase 5 (CIMP5; (Taylor et al., 2012)), using the same set of significant bioclimatic variables. The statisitical signature profiles of the strata have been reconstructed for Xishuangbanna, based upon a multivariate analysis (maximum likelihood classication) of these four bioclimatic variables. These signature profiles were then used to project the future spatial distribution of the GEnS strata based upon the CIMP5 modeled future climate conditions in 2050.

Four emission scenarios, or representative concentration pathways (RCP; Vuuren et al., 2011) were analyzed using the CIMP5 model predictions for the year 2050 (average of 2040–2060), ranging from RCP 2.6 (aggressive mitigation/lowest emissions) to RCP 8.5 (highest emission scenario). CIMP5 model results were downscaled using the Delta method (Ramirez and Jarvis, 2010) to 30 arcsec resolution (equivalent to $\sim$1 km^2 at the equator). The Maximum Likelihood Classification algorithm in ArcGIS 10.1 was used to construct the projected future spatial distribution of strata and zones, using the modeled future climate conditions as predicted by each of the emission scenario combinations ($n = 63$) as input parameters (Table 1). 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. 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. Other sources of uncertainty in our analysis include the difficulties associated with model predictions in highly heterogeneous terrain and landscape, such as the mountains of SW Yunnan.

3. Results and discussion

3.1. Environmental stratification of Xishuangbanna

Four bioclimatic zones were identified as currently found within Xishuangbanna (Fig. 2), ranging from Extremely Hot/Moist at low elevations, to Warm Temperate/Mesic at high elevations (Table 2). Mean annual temperatures for these zones are correlated with their average elevation, and range from 16.5 °C for the coolest zone at an average elevation of 1756 asl, to 23.4 °C for the warmest zone at an average elevation of 574 m asl. Both the average annual temperature and the average elevation of each of these zones demonstrate an ordered and coherent placement along their respective gradients, indicating the robustness of the GEnS stratification when applied in Xishuangbanna. Annual precipitation increases with elevation in a similarly ordered fashion. By far the largest zone is the Hot/Mesic, comprising 11,737 km^2 at an average middle zone elevation of 1209 m asl. Southern river valleys and lower elevations are mostly Extremely Hot/Mesic with a small area of Extremely Hot/Moist, moist being less humid than mesic in this classification. This is evidenced by the ordered range of the Aridity Index (AI) with decreasing elevation from the wetter Warm Temperate/Mesic (1.22) to the drier Extremely Hot/ Moist zone (0.75). There is a relatively small area (913 km^2) of Warm Temperate/Mesic at the higher elevations.

A similar ordered and environmentally consistent result is evident amongst the 9 strata (Fig. 3), along all these climate gradients (Table 2). Average annual temperature ranges from 14.9 °C for the highest elevation stratum (avg. elev. 2,049 m asl) to 23.4 °C for the lowest stratum (avg. elev. 574 m asl). Annual mean precipitation ranges from 1,624 mm for the highest elevation strata to 1,222 mm in the lowest elevation strata. AI indicates moisture and plant growth conditions conducive for vegetation growth (e.g., AI > .65), with many higher elevation areas exhibiting a surplus of moisture at or above full PET (AI > 1.0). AI values range from fairly moist (0.75) in the Extremely Hot/Mesic zone (1222 mm annual precipitation with high evapotranspiration) to very mesic (1.29) in the highest elevation strata in the Warm Temperate/Mesic zone.

3.2. Projected climate change in Xishuangbanna

Results of the CIMP5 multimodel ensemble of RCP scenarios for Xishuangbanna are in general agreement with projections cited by the China National Assessment Report on Climate Change (He et al., 2006; Lin et al., 2006, 2007), and correspond with observed recent climate trends for the Himalaya region (Shrestha et al., 2012). An overview of the projected future mean annual temperature and precipitation as predicted by each of the CIMP5 models for Xishuangbanna in 2050 (Fig. 4), shows that the climate is likely to accelerate current warming trends, on average becoming generally hotter within all RCP emission scenarios (Table 3). Mean annual temperature averaged across Xishuangbanna is predicted to increase from 1.6° to 2.4 °C, by 2050, or 1.9° on average for all RCP. These result corresponds closely, but are slightly lower than Lin et al. (2007), who reviewed over 40 combinations of various models for China as a whole under various emission scenarios, and found the country-averaged annual mean temperature for China is projected to increase by 2.3–3.3 °C by 2050, and 3.9–6.0 °C by 2100, as compared to the 30-year average of 1961–1990. Weng and Zhou (2006) using a regional climate model (RCM) and weather station data for China from 1951 to 1980, estimated air temperature would increase by 2 °C under the SERS-A2 scenario, with an increase in precipitation of 11–17%.

On average (across the RCP) precipitation is projected to increase very slightly (23 mm or 1.5%), however RCP 6.0 predicts a very slight decrease. Variability among the models is high with a wide spread (Fig. 4) so that confidence in the projections for precipitation appears to be less than the general consensus on an increase in temperature. Recent models (CIMP-4) have generally predicted substantial increases in rainfall for this area, whereas recent years have not substantiated this trend (Peng et al., 2009). However, when temperature and precipitation trends are integrated as AI, it becomes evident that changes associated with PET could be substantial, trending toward increasingly humid tropical growing conditions. Generally, for all of Xishuangbanna, an average AI of 1.03 over the period 1960–2000 indicates already relatively mesic conditions for plant growth, however expansion of the Extremely Hot/ Moist indicates somewhat drier conditions in lower elevations.

There are substantial changes in both the areal extent (Fig. 2) and the average elevation of the bioclimatic zones, as predicted for 2050 (Table 4). Even when averaged for all RCP's, there is a large expansion in the extent of the Extremely Hot/Moist zone (from 35 to 6750 km^2) and to a lesser extent, the Extremely Hot/Mesic zone

Table 1
List of CIMP5 ESM used within each of the RCP analyses.

Center	Country	CIMP5 – ESM	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology	Australia	ACCESS1-0		×		×
Beijing Climate Center, China Meteorological Administration	China	BCC-CSM1-1	×	×	×	×
National Center for Atmospheric Research	United States	CCSM4	×	×	×	×
National Science Foundation	United States	CESM1-CAM5-1-FV2		×		
Centre National de Recherches Meteorlogiques/Centre Europeen de Recherche et Formation Avancee en Calcul Scientifique	France	CNRM-CM5	×	×		×
NOAA Geophysical Fluid Dynamics Laboratory	United States	GFDL-CM3	×	×		×
NOAA Geophysical Fluid Dynamics Laboratory	United States	GFDL-ESM2G	×	×	×	
NASA Goddard Institute for Space Studies	United States	GISS-E2-R	×	×	×	×
Met Office Hadley Centre	UK	HadGEM2-AO	×	×	×	×
Met Office Hadley Centre	UK	HadGEM2-CC		×		×
Met Office Hadley Centre	UK	HadGEM2-ES	×	×	×	×
Institute for Numerical Mathematics	Russia	INMCM4		×		×
Institut Pierre-Simon Laplace	France	IPSL-CM5A-LR	×	×	×	×
Ocean Research Institute and National Institute for Environmental Studies	Japan	MIROC-ESM-CHEM	×	×	×	×
Japan Agency for Marine-Earth Science and Technology	Japan	MIROC-ESM	×	×	×	×
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	MIROC5	×	×	×	×
Ma× Planck Institut für Meteorologic	Germany	MPI-ESM-LR	×	×		×
Meteorological Research Institute	Japan	MRI-CGCM3	×	×	×	×
Norwegian Climate Centre	Norway	NorESM1-M	×	×	×	×

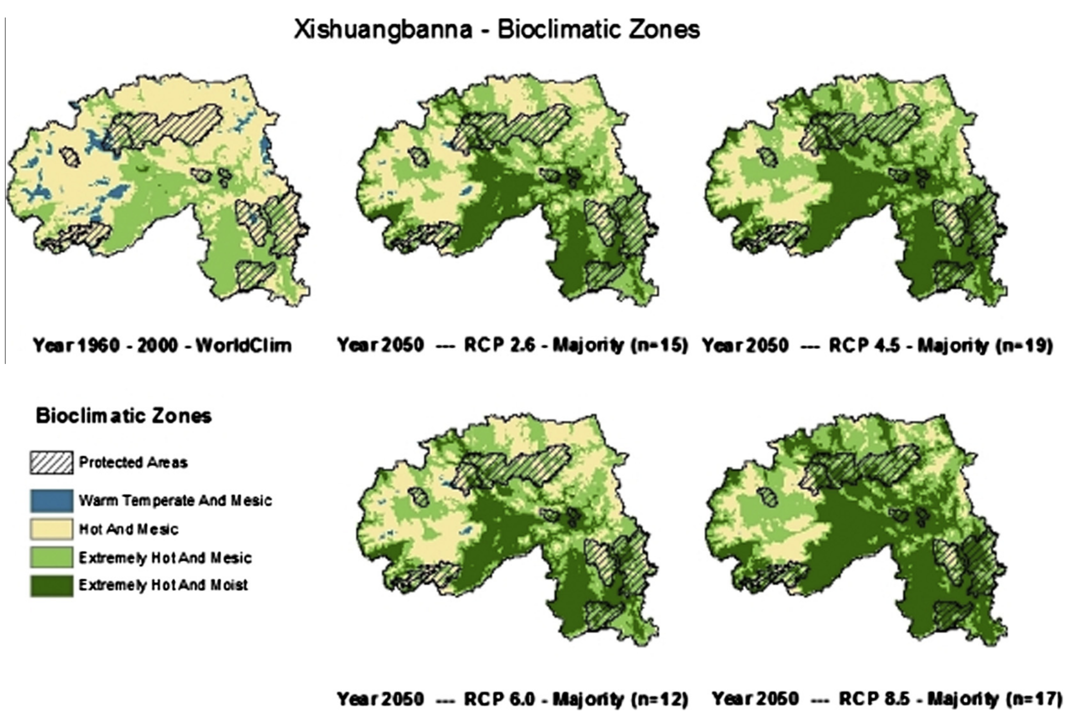

Fig. 2. Predicted impact of climate change on bioclimatic zones in Xishuangbanna Prefecture in southern Yunnan Province. By 2050 almost 75% of the region will be within the Extremely Hot And Moist or Extremely Hot And Mesic zone, providing optimal climatic conditions for rubber production.

(from 6370 to 7492 km^2). There is a drastic a decrease in the Warm Temperate/Mesic zone (from 913 km^2 to 67 km^2), signaling a potential threat for species, and ecosystems, adapted to these mid-elevation zones. All zones exhibit an upward shift in average elevation (280 m average for all zones), ranging from 224 m for the low elevation Extremely Hot/Moist, to 322 m for the next higher elevation Extremely Hot/Mesic zone, while the average elevation of the Warm Temperate/Mesic zone increases 309 m, but its areal extent is reduced by 93%.

Likewise, the finer resolution GEnS strata (Fig. 3) shift significantly (Table 4). One small strata (K7) is no longer present in the region by 2050. Generally, all the higher elevation strata are drastically reduced in area as warmer conditions move upslope. All the strata shift substantially upwards in their average elevation (309 m average for all zones), ranging from a upward shift of 224–370 m.

On average across all emission scenarios, more than 75% of Xishuangbanna is predicted to shift to a different zone, with 96% shifting to a different stratum. However, at the higher emission

Table 2
Characteristics of the bioclimatic stratification of Xishuaungbanna Prefecture, Yunnan Province, based on climate data from 1960 to 2000, showing the area, average elevation, mean average annual temperature, mean annual precipitation, and mean average annual Aridity Index (AI) of the delineated GEnS zones and strata.

Zone	GEnS Strata	Area (km^2)	Avg Elev (m asl)	Mean temp (°C)	Mean precip (mm/yr)	Mean AI
Warm temperate and mesic		913	1756	16.5	1625	1.22
	K7	53	2,049	14.94	1624	1.29
	K13	860	1,738	16.62	1626	1.22
Hot and mesic		11737	1209	19.4	1550	1.07
	N3	3525	1,419	18.25	1592	1.14
	N8	7234	1,138	19.87	1538	1.04
	N11	978	978	20.93	1418	0.93
Extremely hot and mesic		6370	796	21.8	1469	0.94
	M2	1619	893	21.05	1575	1.04
	M4	3912	792	22.09	1419	0.90
	M7	839	626	22.95	1395	0.87
Extremely hot and moist		35	574	23.4	1222	0.75
	R1	35	574	23.4	1222	0.75
Xishuangbanna (all)		19,104	1098	20.1	1525	1.03

scenarios (RCP 4.5 and 8.5) nearly all strata shift to a different stratum, and, more than 80% to a different zone., Overall, these results show a quick and drastic change in the spatial distribution of bioclimatic conditions indicating significant biological perturbance by 2050, with implications for protected areas, threatened biodiversity, and narrow niche endemic species, which may not have to velocity to keep up with the rapid pace of change (Pu et al., 2007; Corlett and Westcott, 2013).

3.3. Landcover change in Xishuangbanna Prefecture

From our results it is evident that landcover patterns in Xishuangbanna (Fig. 5) changed rapidly between 2002 and 2010 (Xu et al., 2012). Change detection analysis for the landcover data from 2002 and 2010 (Table 5) shows a 29% increase in forest area, likely a result of the on-going reforestation efforts, and the conservation and sloping land conversion policies instituted before and during this period (Xu et al., 2005; Willson, 2006). Although the accuracy assessment of the landcover classification indicated a reasonable level of accuracy (Kappa Index = 0.77 for 2002; 0.83 for 2010, with an overall accuracy of 88% for all classes), it is likely that some farmland areas having high tree cover may be misclassified as forest. However, this would most likely constitute a relatively small area composed of home gardens and intercropped tree crops. At the same time, there is a 38% decrease in farmland area. Likewise, the area classified as grassland decreases substantially (79% decrease). Within the relatively short eight-year span investigated here, the area devoted to rubber production increased by 2706 km^2 (176%), to cover 4242 km^2 (22%) of Xishuangbanna.

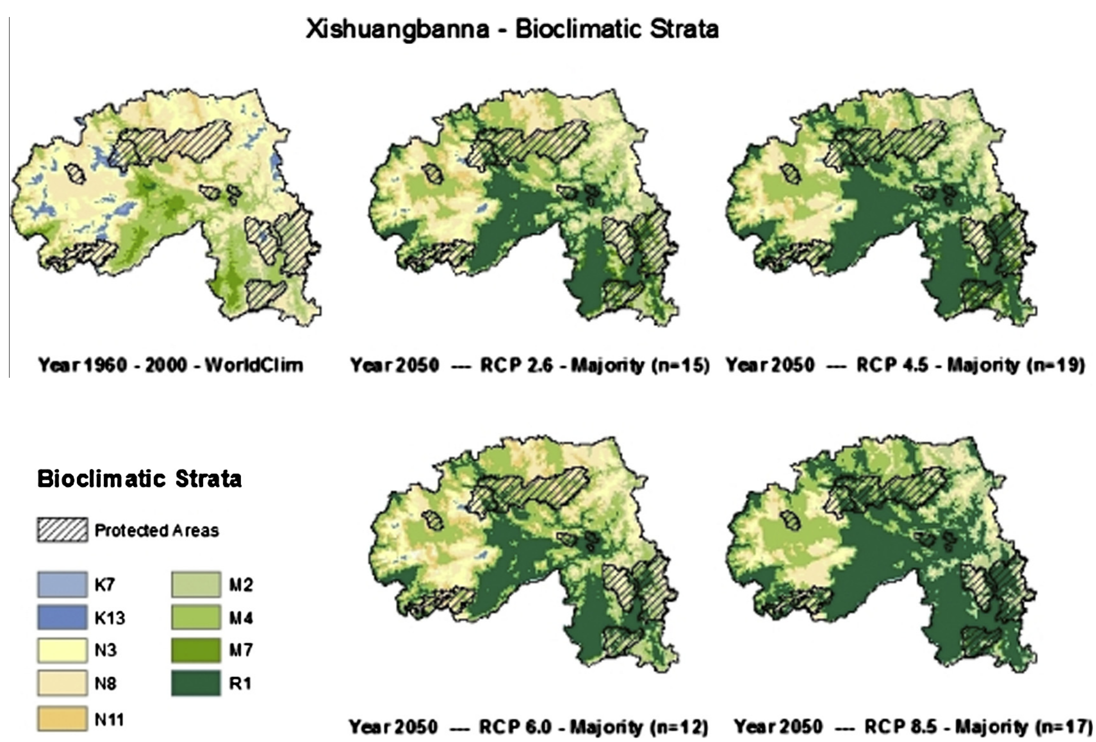

Fig. 3. Predicted impact of climate change on bioclimatic strata in Xishuangbanna Prefecture in southern Yunnan Province, showing location of current biodiversity conservation areas. Substantial shifts by 2050 are indicated, with most biodiversity conservation areas being substantially affected by changes in growing conditions.

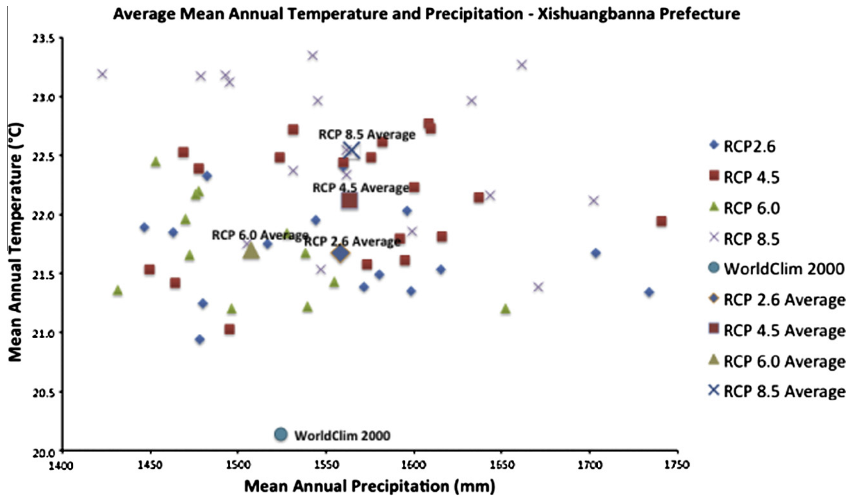

Fig. 4. Average mean annual temperature and mean annual precipitation for Xishuangbanna in the recent past (WorldClim 2000: 1960–2000), and as projected for the year 2050 by four representative conservation pathways (RCP). WorldClim 2000 shows the average for the observed climate data (1960–2000). Each CIMP5-Earth System Model within each RCP is shown, along with the average for each RCP (bigger size marker).

3.4. Impact of climate change on biodiversity and rubber production

There is a distinct correspondence between the rubber growing areas in the 2010 landuse classification and the Extremely Hot/Mesic zone, as well as including the small area of Extremely Hot/Moist zone. Almost all of the rubber plantations are found in these zones, mostly in the M4 and M7 strata. Optimal conditions for rubber within Xishuangbanna are found at elevations below 800 to 900 m asl (Jiang, 1988; Wu et al., 2001), i.e., generally corresponding to the Extremely Hot/Mesic zone. Above this altitude, rubber in Xishuangbanna experiences lower yields due to lower than optimal temperatures and a high incidence of cold weather losses

Table 3
Average mean annual temperature and mean annual precipitation for Xishuangbanna Prefecture under current and future climate conditions. Current conditions (WorldClim 2000) show the average from 1960 to 2000. Projected climate conditions for the year 2050 is shown by averaged results from all CIMP5 – Earth System Models within each of four representative conservation pathways (RCP) representing a range of emission scenarios from RCP 2.6 (aggressive mitigation – lowering of emissons) to RCP 8.5 (continuing growth in emissions at currently high rate), and the overall average for all RCP (RCP Average).

	Mean annual temperature		Mean annual precipitation		
		Increase		Increase	
RCP	°C	°C	mm/yr	mm/yr	%
WorldClim 2000	20.1		1525		
RCP 2.6	21.7	1.6	1558	33	2.1
RCP 4.5	22.1	2.0	1563	38	2.4
RCP 6.0	21.7	1.6	1507	−18	−1.2
RCP 8.5	22.5	2.4	1564	39	2.5
RCP Average	22.0	1.9	1548	23	1.5

Table 4
Bioclimatic stratification of Xishuangbanna Prefecture, showing the area, areal change, average elevation, and average elevational change of GEnS zones and strata, from current conditions (1960–2000 averaged data) to 2050.

Bioclimatic zone	GEnS Strata	Area (km^2)		Area change (%)	Avg Elev. (m asl)		Elev shift (m)
		2000	2050	2000–2050	2000	2050	2000–2050
Warm Temperate/Mesic		913	67	−93	1756	2065	309
	K7	53	0	−100	2049	–	–
	K13	860	66	−92	1738	2065	327
Hot/Mesic		11,737	4847	−59	1209	1472	263
	N3	3525	869	-75	1419	1739	320
	N8	7234	3034	-58	1138	1437	299
	N11	978	913	−7	978	1334	356
Extremely Hot/Mesic		6370	7492	18	796	1118	322
	M2	1619	2322	43	893	1145	252
	M4	3912	4903	25	792	1113	321
	M7	839	267	−68	626	996	370
Extremely Hot/Moist		35	6750	19,186	574	798	224
	R1	35	6750	19,186	574	798	224
				Average Upward Shift – Zones			280
				Average Upward Shift – Strata			309

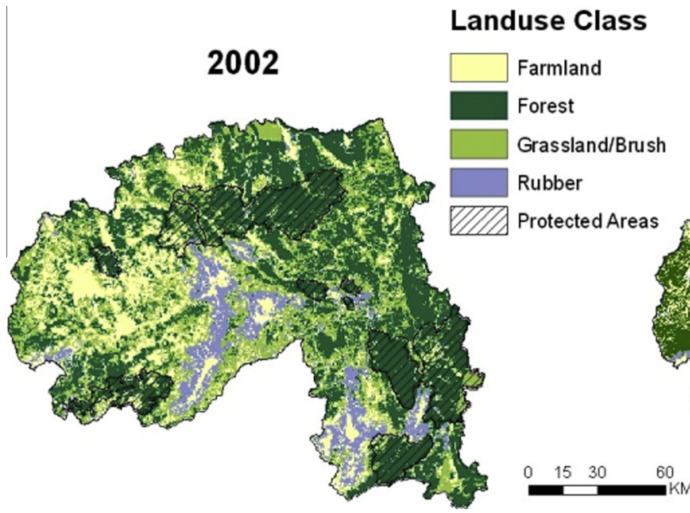

Fig. 5. Landuse in Xishuangbanna Prefecture in 2002 and 2010, showing an expansion of forest, an expansion of rubber plantation, a loss of grassland, and loss of farmland.

Table 5
Landuse Change in Xishuangbanna Prefecture from 2002 to 2010 based on an analysis of remote sensing data.

Land use category	Area (km^2) *Percentage of total area (%)*		Change in area (km^2) *Change in area (%)*
Year:	2002	2010	2002–2010
Forest	8233	10,658	2425
	43	*55*	*29*
Rubber	1536	4242	2706
	8	*22*	*176*
Farmland	3536	2194	−1342
	18	*11*	*−38*
Grass/Bush	5229	1122	−4107
	27	*6*	*−79*

Note: Calculation of changed percentage: change% = ((area of 2010) − (area of 2002))/(area of 2002) * 100.

during winter (Chapman, 1991). Currently, much of the land suitable for rubber cultivation within the Extremely Hot/Mesic zone has already been converted into rubber plantations, and there is also evidence of farmers converting more marginal upslope areas with a lower production potential into rubber plantations (Hu et al., 2007; Li and Fox, 2012; Wu et al., 2001). However, by 2050, the Extremely Hot/Moist and Extremely Hot/Mesic zones are predicted to together expand to cover approximately 75% of Xishuangbanna, indicating that much of the prefecture will have climate conditions conducive to rubber production, i.e. removing current biophysical (i.e. bioclimatic) barriers to expanded cultivation, allowing for further expansion of rubber plantations into higher elevations.

The expansion of rubber production impacts directly on biodiversity through habitat loss, and through the displacement of existing agricultural activities, such as swidden-fallow, to higher elevations, in some cases by encroaching into protected areas (Fox and Vogler, 2005; Li and Fox, 2012). Likewise, it is evident that biodiversity reserves and the large areas mandated as protected areas within the region will experience changes in biophysical and climatic conditions (Figs. 2 and 3), which will impact on their conservation effectiveness, especially for endemic or highly site-specific species (La Sorte and Jetz, 2010, 2012), for example, within the strata that disappear or are substantially reduced. In many cases, bioclimatic conditions within the entire protected area will change substantially.

4. Conclusion

Large scale vegetation distribution patterns are mainly controlled by climate (Barbour et al., 1987; Woodward and Williams, 1987). Thus, the magnitude of predicted change indicated by our analysis points to profound impacts on terrestrial ecosystems, biodiversity, and ecosystem services across Xishuangbanna by 2050 as a result of warming and changing climatic conditions. This change will impact upon the conservation effectiveness of many protected areas and biodiversity reserves within Xishuangbanna (Pu et al., 2007; La Sorte and Jetz, 2010), as ecological conditions within these protected areas change beyond limits conducive for species currently found there. In particular, warm temperate and tropical rainforests, along with high levels of biodiversity found in secondary forest, appear to be at high risk (Li and Fox, 2012), as several strata associated with these ecotypes diminish substantially and become optimal zones with potential for expansion of rubber production. However, impacts on specific vegetation types, particular species, or wildlife, are more difficult to predict, as the spatial distribution of life forms cannot be defined in purely ecophysiological terms (Barbour et al., 1987), and are likewise subject to other secondary change processes, for example changes in seasonality or disruption of pest or pollinator cycles. In general, however, it is possible to define the climatic envelopes of most types of vegetation, and to a large extent associated fauna, on the basis of correlations between their distribution, annual temperature, and precipitation (Holdridge, 1947, 1967; Whittaker, 1970; Leith, 1974; Box, 1981; Woodward, 1991). It is likely that the responses to changed conditions will be closely correlated with those more critical limiting factors (Woodward and Williams, 1987). Although species ranges will 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 fragmentation, and physiological adaptability (Corlett and Westcott, 2013). Improving our understanding of these responses is imperative if conservation strategies and policies designed to meet these challenges are to be effective. This is also true for agricultural production, particularly traditional mountain agricultural systems which may be adapted to highly specific climatic niches (Li and Fox, 2012).

As predicted for Xishuangbanna, climate change will potentially interact with on-going landuse change processes to exacerbate the impacts on biodiversity. This confluence of landuse change processes and projected climate change is likely to impact conservation efforts and ecosystem services, and more generally, terrestrial ecosystems, biodiversity, and agricultural production across Xishuangbanna over the next twenty to fifty years (Yu et al., 2006). Opportunities to anticipate, and to some extent mitigate these impacts may exist if the nature and magnitude of these impacts can be better understood. Biodiversity conservation efforts and landuse polices need to consider the implications of environmental change as they relate to specific conservation or production goals (Xu et al., 2012).

Traditional agricultural systems, which have been shown to conserve agricultural biodiversity and maintain high levels of biodiversity, will also likely be impacted. Global and regional processes, notably the commercialization and globalization of agriculture, have already undermined the viability of these systems. The decline of diverse and cyclic land use systems will affect biodiversity at genetic, species, landscape, and cultural levels (Guo et al., 2002). The warming of Xishuangbanna, while likely to improve the productivity of rubber plantations (Jiang, 1988), may promote their expansion and exacerbate the conversion of agricultural land and forest to rubber plantations, with serious implications for biodiversity and conservation efforts, as well as for local communities dependent upon that diversity. Driven by a predicted increase in demand for rubber (Li et al., 2006), the increase in available areas conducive to rubber production has the potential to encourage large scale conversion of agricultural, grassland, and forest areas across Xishuangbanna, to the point of affecting such large scale ecosystem services as watershed protection and carbon sequestration. If conservation of biodiversity in Xishuangbanna is to be effective in the future, it is important that policies, strategies, and conservation programs consider the challenges and implications of climate change on the environment and landuse change processes. Improved understanding of the ecophysiological adaptation responses of threatened species to changing conditions and the socio-economic context of landuse change is needed to create and provide the knowledge base required to meet these challenges.

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