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Vegetation distribution on Tibetan Plateau under climate change scenario

Dongsheng Zhao · Shaohong Wu · Yunhe Yin · Zhi-Yong Yin

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Abstract The impact of climate change on distribution of vegetation is an important aspect in studies on the responses of ecosystems to the climate change. Particularly in the sensitive environments of the Tibetan Plateau, vegetation distribution may be significantly affected by climate change. In this research, the coupled biogeography and biogeochemistry model, BIOME4, was modified according to the features of vegetation distribution on the Plateau, and the Kappa statistic was used to evaluate the modeling results by comparing the simulated vegetation distribution with the existing 1:1,000,000 vegetation map of China. The comparison showed that modified model was appropriate for simulating the overall vegetation distribution on the Plateau. With the improved BIOME4 model, possible changes in the vegetation distribution were simulated under climate change scenarios. The simulated results suggest that alpine meadows, steppes, and alpine sparse/cushion vegetation and deserts would shrink, while shrubs, broad-leaved forests, coniferous-broad-leaved mixed forests, and coniferous forests would expand. Among these types, shrubs, alpine meadows, and steppes would change the most. The shrubs vegetation would expand toward the northwest, replacing most alpine meadows and part of steppes, and thus causing their shrinkages. Yet broad-leaved forests and coniferous-broad-leaved mixed forests demonstrated smaller changes in their distributions. For all the forest types, the area of coniferous forests would increase the most by spreading to the interior of the Plateau.

Keywords Vegetation distribution · BIOME4 model · Tibetan Plateau · Responses of vegetation to climate change · Vegetation distribution

D. Zhao · S. Wu (✉) · Y. Yin
Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, No. 11 A, Datun Road, Anwai, 100101 Beijing, China
e-mail: wush@igsnrr.ac.cn

S. Wu
Institute of Tibetan Plateau Research, Chinese Academy of Sciences, No. 18, Shuangqing Road, 100085 Beijing, China

Z.-Y. Yin
Marine Science and Environmental Studies, University of San Diego, 5998 Alcala Park, San Diego, CA 92110, USA

Introduction

Observations have proven that significance changes in climate have occurred due to increasing atmospheric greenhouse gases, and the effects of climate change on the ecosystems have already been noticed in many regions (IPCC 2007). Since the tolerance of the environment is not unlimited, the changes to the ecosystems could be large and irreversible. Therefore, an important aspect of the global change research is to investigate the interrelationship between climate change and ecosystems at different scales, and reveal the responses and adaptability of ecosystems to climate change (Hitz and Smith 2004; Woodward 1987; Woodward and Lomas 2004; Wilson et al. 2005). In particular, the relations between vegetation distribution and climate play an indispensable role in understanding the vulnerability and adaptability of the ecosystems against the climate change (Bugmann and Pfister 2000; IPCC 2001, 2007; Yu et al. 2006; Ni 2011). Previous studies have indicated that global warming will drive the vegetation to higher latitude and altitude. In the temperate zone, the distributions of many plants will move at least by 300 km into the higher latitudes with a 3°C rise in temperature (Peters and Parling 1985). On plateaus and highlands, air temperature drops on average by 6°C for every 1,000-m increase in altitude, which is equivalent to a 600-km move to the higher latitudes horizontally. The alpine ecosystems have been ranked as the most sensitive vegetation types corresponding to climate change (Taskforce on China's National Assessment Report on Climate Change 2007; IPCC 2007). However, because of the varied responses of plants to climate change, the speeds and directions of their migration will be different. As a result, the vegetation distribution pattern will alter in the migration process.

The Tibetan Plateau fundamentally affects the distribution pattern, the terrestrial ecosystems in China, owing to its unique location, special climatic system, and high altitude of the plateau surface at approximately 4,000 m above mean sea level (a.m.s.l.) on average. The Plateau is at the continental edge, where the flora relies heavily on the specific climatic conditions, thus being sensitive and vulnerable to climate change (Zhang et al. 1996). There exist not only the coniferous and broad-leaved forests but also various alpine vegetation types including meadows, steppes, and deserts (Editorial Committee for Vegetation of China, 1980). Yet in several previous studies based on various models (Prentice et al. 1992; Haxeltine and Prentice 1996; Neilson 1995; Zhao et al. 2002), the Plateau was presented as being entirely covered by tundra and snow and ice. Such a misunderstanding or overgeneralization led to the incorrect data input of the underlying surface conditions in many models of land surface processes and general circulation models (GCMs), resulting in uncertainties in climate scenarios and underestimation of the Plateau's role in climate change.

The changes in climate should cause disturbances and alter the distribution pattern of vegetation communities, especially in the sensitive ecosystems on the Tibetan Plateau. Therefore, the relationships between the climate and the vegetation on the Plateau have attracted the attention of many researchers (Zhang et al. 1996; Zheng 1996; Ni 2000). Zhang et al. (1996) used the Holdridge scheme to estimate changes in the vegetation distribution on the Plateau under climate change, with an increase of 4°C in temperature and 10% in precipitation however, the Holdridge scheme as a statistical approach has not been approved on large scale studies (VEMAP Members 1995; IPCC 2001, 2007). Ni (2000) simulated the response of vegetation distribution to climate change on the Plateau using the BIOME3 model, but the spatial distributions of certain vegetation types, such as alpine steppe, alpine meadow/shrub, and desert, were incorrect owing to insufficient model parameterization. Additionally, the simulation was based on the climate scenario generated by GCMs with a resolution of 200–300 km, which is too coarse for regional studies.

It can be seen that improvements in study methods and data quality are necessary to achieve a more accurate evaluation of the climatic influences on ecosystems to assess the impact of climate change on the plateau vegetation, which is critical to better support investigations on the impact of climate change and carbon cycle and to provide the basis for local and regional land-use planning and environmental policy making. In this study, according to the distribution and eco-physiological features of the vegetation types on the Tibetan Plateau, we employed BIOME4 (Kaplan et al. 2003), the latest version of the BIOME model recommended by VEMAP Members (1995), for modeling vegetation dynamics. We modified the model parameters and calibrated the model for the study region to simulate the vegetation distribution on the Plateau. Furthermore, the model was used to make predictions on the future impacts of climate change on vegetation distribution based on a regional climate change scenario.

Methods and materials

Study area

The study area is the Chinese part of the Tibetan Plateau covering approximately 2,300,000 km^2 with an average altitude of over 4,000 m a.m.s.l. (Fig. 1). It includes the Tibetan Autonomous Region, Qinghai Province, the southern Xinjiang Uygur Autonomous Region, the western Sichuan Province, and the northwestern part of Yunnan Province. The Tibetan Plateau (73°25′–104°20′E, 27°–40°N) is surrounded by the Qaidam Basin and Tarim Basin to the north, the Himalayas to the south, the Karakoram Range and the Pamirs to the west, and the Hengduan Mountains (a system of mountain ranges running roughly north to south) to the east. The spatial differentiation of its natural environment is determined by the geographic location, terrain conditions, and the atmospheric circulation. From the southeast to the northwest, the climatic conditions of the Plateau change from warm and humid to cold and dry (Zheng 1996). The spatial differentiation of temperature and moisture conditions on the Plateau is mirrored in the variation pattern of vegetation, with successions from forests to shrubs, meadows, steppe, and deserts from southeast to northwest.

The modified BIOME4

Compared with its predecessor (BIOME3, Haxeltine and Prentice 1996), BIOME4 is a more complete and balanced terrestrial biosphere model. It differs from the previous

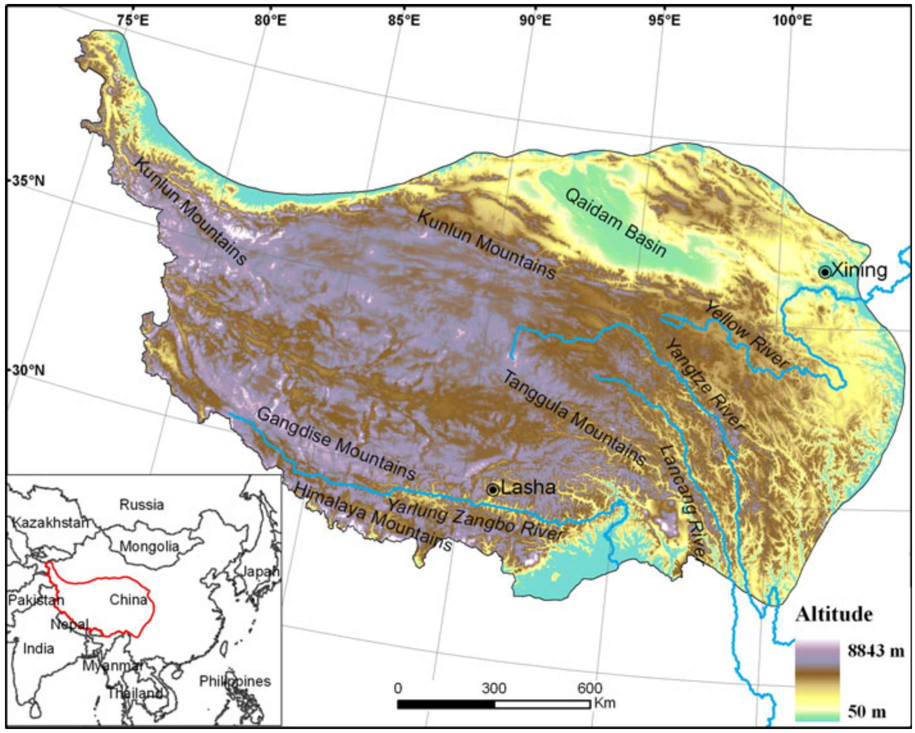

Fig. 1 Location of the study area

versions by additions of more plant functional types (PFTs), integration of the isotopic fractionation in photosynthesis, and reparameterization of the PFTs. Through coupling the carbon and water fluxes, BIOME4 simulates the distribution and structure of global vegetation as well as its biogeochemical processes. The model functions on the basis of 12 PFTs, representing all the major types on Earth ranging from the arctic tundra vegetation to the tropical rainforest. The PFTs are differentiated from one another by the physiological functions. Each of them has its own absolute limiting factors of bio-climate, which determine whether the computation of net primary production (NPP) should proceed in a given grid. The annual computational core of the model is a coupled carbon and water flux scheme, which determines the leaf area index (LAI) that maximizes NPP for any given PFT based on a daily time-step simulation of soil water balance, canopy conductance, photosynthesis, and respiration. The data input of the model includes the monthly averaged temperature, precipitation, and cloud amount, as well as the texture and depth of the soil. The output data from BIOME4 are the biomes, LAI, and NPP based on the presence of primary and secondary PFTs.

As a global-scale ecosystem model, BIOME4 needs parameter modification for regional applications. In the case of the special environment on the Tibetan Plateau featuring high altitude and low temperature, the original model may not produce accurate estimates for the potential vegetation distribution under the current climatic conditions. For example, at the global-scale BIOME4 tends to overestimate the forest distribution on the Plateau. Contrary to the model prediction, observations indicate large areas of forests do not exist on the western part of the Plateau. Instead, the dominant vegetation type should be the alpine meadow (ISEQXP CAS 1988), which almost does not exist in the stimulated results by the unmodified BIOME4. To apply it properly for a high-altitude region, we modified BIOME4 according to the following scheme based on the 1:1,000,000 vegetation map of China (The China Vegetation Atlas Editorial Committee and Chinese Academy of Sciences 2001): (1) the two functional types of boreal evergreen coniferous forest and boreal deciduous coniferous forest were replaced by the type of mountainous evergreen coniferous forest, and types of alpine shrub and alpine grass were added into the model. The newly added types' parameters were set according to previous studies by Ben et al. (1998), Zhou (2001), and Luo et al. (2005a, b); (2) ten PFTs were selected based on the relationship between climate and vegetation distribution on the Plateau (Tables 1, 2), and the bio-climate limiting factors were updated for the PFTs (ISEQXP CAS 1985, 1988); and (3) based on the bio-physiological characteristics of the plateau vegetation, the competing pattern in the model was also readjusted (Wu et al. 2005; Zhang and Yang 1993; Zheng 1996). The steppe and alpine meadow are the two l processes (Table 2), and they are differentiated spatially in the competing module with the wetness index that measures moisture of the upper 30 cm soil layer in the model

(Haxeltine and Prentice 1996; Kaplan et al. 2003). Since the living environment for alpine meadow is wetter than that for steppe, according to Zhou (2001), the cold grass PFT was defined as alpine meadow in the simulated results if wetness index is higher than 40; otherwise it was defined as steppe. This method was adopted after comparisons with several alternatives of more complex methods, which did not further improve the accuracy of results significantly.

Climatic data

The observed climatic data

The climatic data play an important role in initiating BIOME4. To obtain high-resolution results, the model needs high-quality input data with proper spatial resolutions. In accordance with the meteorological records from 2,450 stations in China and its neighboring countries from 1961 to 1990, Daly et al. (2000) generated a spatial dataset of mean temperature and precipitation in China with a resolution of 0.05° × 0.05° latitude and longitude using the PRISM model (Daly et al. 1994). This dataset was found to be accurate when compared with the observational data from the Chinese Ecosystem Research Network (CERN), independent from the national meteorological stations network of the China Meteorological Administration (Zhu et al. 2003). Mean temperature and precipitation data across the Tibetan Plateau (73–105°E, 27–40°N) were extracted from the PRISM dataset. The absolute minimal temperature and the percentage of sunshine were excluded PRISM dataset. We obtained the sunshine percentage and minimum temperature data for 90 stations across the Plateau and its neighboring areas from 1961 to 1990 from the National Climate Center of the China Meteorological Administration. Using the Thin Plate Spline (TPS) method (Hutchinson 1998), the station point data were interpolated to continuous surfaces with a resolution of 0.05° × 0.05° latitude and longitude, so as to match the spatial resolution of the PRISM data. The observed climatic data from 1961 to 1990 were treated as the baseline condition for initial model calibration.

The climate scenarios

The data of future climate scenarios in this study came from the research group of climate change in the Chinese Academy of Agricultural Sciences. On the basis of the Special Report on Emissions Scenarios (SRES) issued by the IPCC in 2000, this research group employed the PRECIS (Providing Regional Climates for Impacts

Table 1 Bio-climate limiting factors for each functional type

PFTs	T_c min (°C)	T_c max (°C)	T_{min} min (°C)	T_{min} max (°C)	GDD_5 min	GDD_0 min	T_{wm} min (°C)	T_{wm} max (°C)	Snow min (cm)
Tropical evergreen broad-leaved forest			0				18		
Temperate evergreen broad-leaved forest			−8	5	1,200		12		
Temperate summer-green broad-leaved forest	3			−8	1,200				
Temperate evergreen coniferous forest	−2				900		10		
Mountainous evergreen coniferous forest	−10	−2						21	
Temperate grass				0		1,500			
Desert shrub			−45		500		10		
Alpine shrub						350		15	15
Cold grass						0		12	
Forbs								10	

Tc the mean temperature of the coldest month, *Tmin* the absolute minimal temperature, *GDD5* the growing degree days of over 5°C, *GDD0* the growing degree days of over 0°C, *Twm* the mean temperature of the warmest month, *Snow* the number of days with snow coverage

Table 2 The newly added PFTs and their several physiological parameters in BIOME4

PFT	*P*	G_{min} (mms^{-1})	E_{max} (mmd^{-1})	R_{30} (%)	L_m (month)	*K*	T_0 (°)	Rs
Mountainous evergreen coniferous forest	1	0.5	4.5	75	24	0.6	2	Yes
Alpine shrub	1	0.8	1	90	12	0.45	−7	Yes
Cold grass	2	0.8	1	96	9	0.3	−5	No

P physiological types (1, evergreen; 2, summer-green), G_{min} the minimal canopy conductance, *Emax* the maximal daily exhalation rate; R_{30} the percentage of roots in the upper soil of 30 mm in depth; L_m relative leaf live span, *K* the extinction coefficient, T_0 the minimal monthly mean temperature for photosynthesis; *Rs* the respiration of the sapwood

Studies) system (Jones et al. 2004), a regional system model recommended by the Hadley Climate Research Center in UK (Met Office 2002), to simulate the twenty-first-century climate change in China and produced the output with a spatial resolution of 0.5° × 0.5° (Xu 2004). In this study, we selected the averaged climatic data for the B2 emission scenario (IPCC 2007) for the four periods of the baseline term (1961–1990), near term (1991–2020), middle term (2021–2050), and long term (2051–2080) according to the IPCC definitions, in order to evaluate the sensitivity of the Plateau vegetation to climate change. Among all the IPCC proposed scenarios, the B2 scenario is one with moderate emissions of the greenhouse gases. It represents a world with a continued but moderate increase in population and moderate economic growth with emphasis of local solutions to economic, social, and environmental sustainability (IPCC 2007). This projection is very close to China's national mid- to long-term development plans (Lin et al. 2007). Moreover, anomalies were calculated from the difference between the observed data and the PRECIS-generated data for the baseline term and then interpolated to the 0.05° × 0.05° resolution using the TPS method. The anomalies were then added to the near-term, middle-term, and long-term climatic data to get the climate scenarios with high resolution to drive the BIOME4 model.

Vegetation data

Through manual digitalization of the 1:1,000,000 vegetation map of China (The China Vegetation Atlas Editorial Committee and Chinese Academy of Sciences 2001), we produced the digital boundaries of vegetation types on the Tibetan Plateau in a geographic information system (GIS) environment. Then, the vector data layer was transformed into a raster dataset in the format of ArcInfo Grid with the spatial resolution of 0.05° × 0.05° using ArcGIS 9.3 (ESRI, Redlands, California, USA). Then, BIOME4 was modified using the scheme described earlier, in accordance with the classification system of the vegetation map of China for the purpose of comparison.

Soil data

This research adopted soil texture data from the map of soil texture types (1:14,000,000) (Zhang et al. 2004), which contains the information of the proportions of mineral grains of different sizes in the top soil and the geographical distribution of different soil texture types in a given region. To meet the data input requirements of BIOME4, the soil textures were reclassified as clay, silt sand, silty sand, sandy clay, silty clay, and clay with silt and sand according to the FAO classification standard for soil texture (Ni et al. 2001). The soil data were then transformed into the ArcInfo grid format and resampled to the spatial resolution of 0.05° × 0.05° latitude and longitude.

Results

Comparison of simulated results

Driven by an integrated dataset produced by Kaplan et al. (2003), the original BIOME4 simulated the potential vegetation distribution on the Tibetan Plateau at the 0.5 × 0.5 resolutions. Errors were found in the distribution of certain vegetation types compared with the actual vegetation distribution (Fig. 2). For instance, the large forests simulated around the western Qaidam Basin could not have existed in reality, because this area was too dry for the forests to grow. Instead, the area is covered mostly by desert vegetation. In the dry area on the northern side of the Kunlun Mountains, there were mainly deserts and steppes but not forests. Additionally, in the Himalayan region, the dominate vegetation types were also meadows and steppes rather than the alpine vegetation, which only grew on the high-altitude mountain tops. Meanwhile, as the same climatic data prepared for this research at the 0.05 × 0.05 resolutions were also input into the original BIOME4, the similar problems occurred even though the spatial resolution has been improved. This may be attributed to the large spatial scale under which the model was developed, and the selection of parameters in this model, as well as the unique environment of the Plateau.

Validation

The Kappa statistic has been widely used in comparisons between two maps with categorical data, especially vegetation maps (VEMAP Members 1995). As proposed by Monserud and Leemans (1992), a Kappa value of 0.8 or higher indicates the highest similarity between the two maps, 0.6–0.8 as very high, 0.4–0.6 as high, 0.2–0.4 as medium, and 0.0–0.2 as low. Due to limited human interference on the Plateau, most of the vegetation communities maintain their natural status. Thus, we can compare the simulated results of the potential vegetation distribution (Fig. 3) with the existing vegetation map of the Tibetan Plateau (1: 1,000,000) (Fig. 2).

The comparison shows that the simulated results agree well with the actual distribution (Table 3) with an overall Kappa value of 0.47. All the Kappa values for the individual vegetation types are also listed in Table 3, indicating good simulation results for the broad-leaved forest, mixed broad-leaved and coniferous forest, alpine meadow,

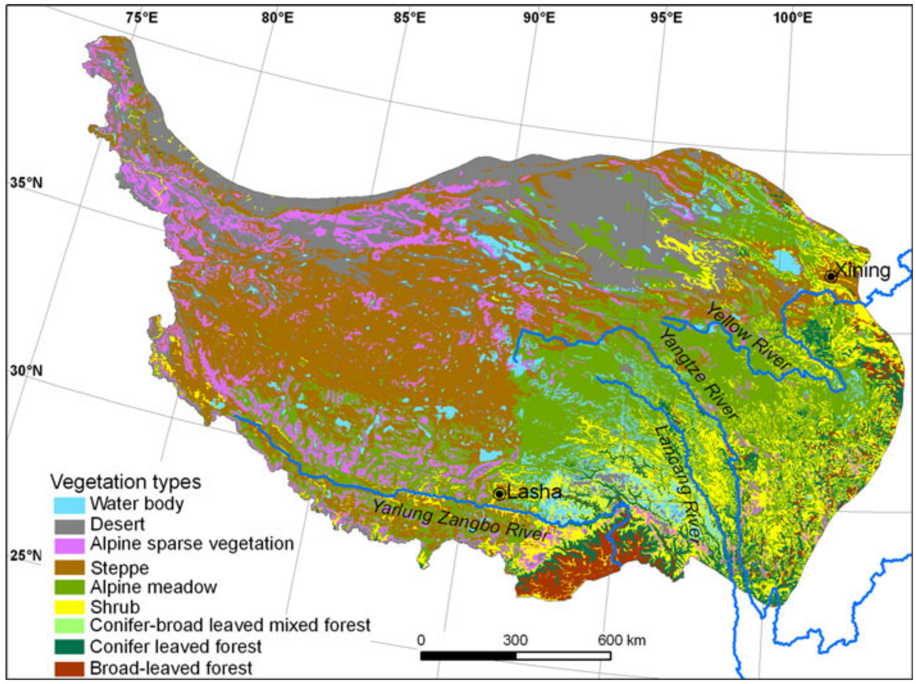

Fig. 2 Actual vegetation distribution on the Tibetan Plateau

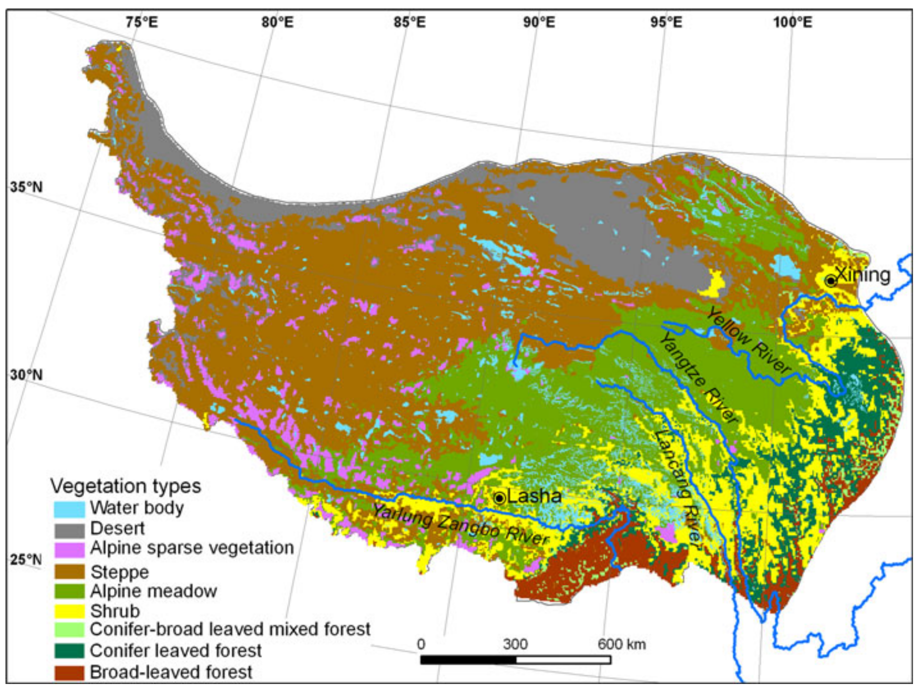

Fig. 3 Simulated vegetation distribution (1961–1990) on the Tibetan Plateau in the modified BIOME4

steppe and desert, fair results for the coniferous forest, and shrub, but poor results for the alpine sparse/cushion vegetation.

The vegetation distribution (1961–1990) on the Tibetan Plateau simulated by the modified BIOME4 is illustrated in Fig. 3. In general, the simulation matches well with the reality, with the vegetation types changing from forests in the southeast, to meadows, steppes, and deserts to the northwest. In the simulated vegetation map, the coniferous forests mainly cover the southeastern mountainous area on the Plateau; and the shrubs are mixed with other types rather than occupying clearly defined areas. The improved BIOME4 performed relatively well in generating the distributions of these two types. However, due to their mixed distribution with other types are not very accurate.

A higher-resolution input could be the key for further improvement. The broad-leaved forests concentrate on the south of the Himalaya Mountains, and the deserts are mostly

Table 3 Kappa values in the comparison between the simulated results and the vegetation map

Vegetation type	Kappa value
Broad-leaved forest	0.59
Mixed broad-leaved and coniferous forest	0.46
Coniferous forest	0.39
Shrub	0.31
Alpine meadow	0.48
Steppe	0.52
Alpine sparse/cushion vegetation	0.20
Desert	0.55

found in the Qaidam Basin and the northern side of the Kunlun Mountains. These two types can be better identified by the model than the others on the Plateau due to the highest net primary productivity (NPP) of broad-leaved forests and lowest NPP of desert. Furthermore, the alpine meadows are the major type that grows in the cold and humid areas, while the steppes occupy the cold and dry areas of the northwest. As shown in Fig. 3 and Table 3, these two typical vegetation types are very well simulated in general. Yet, their patch borders are not accurately predicted in the modified BIOME4, probably because the fine-scale complex terrain along borders has affected the accuracy of the input data, and thus the consequent simulated results.

The alpine sparse/cushion vegetation usually grows on the mountain tops or in extremely cold areas. Its distribution is mainly determined by the terrain. Hence, the simulation of this type performs well in the southwest, but not so on the Kunlun Mountains in the northwest of the Plateau. This may be caused by the overestimated temperature due to the PRISM interpolation (Zhu et al. 2003), which affects the accuracy on the whole.

Possible impacts of climate change on the vegetation distribution

The vegetation distribution on the Tibetan Plateau will change over time in the future climate change scenario. In comparison with the baseline term (1961–1990) (Fig. 3), the overall vegetation distribution does not change significantly in the near-term stage (Fig. 4a). In some regions, however, shrubs begin to invade into the interior of the Plateau, particularly to the north of the Himalaya Mountains where the shrubs replace steppes, and the area of the alpine sparse/cushion vegetation shrinks. In the east of the Plateau, the coniferous forests expand, changing from the existing mixed distribution with other types to a more contiguous coverage. Meanwhile, the broad-leaved forests spread slightly to the interior in the eastern mountainous areas. According to the areal distributions summarized in Table 4, except for the expansions of the shrubs and steppe, the areas of the other types do not alter considerably in the near-term stage. As a result, the overall vegetation distribution pattern under the moderate emissions scenario remains similar to that in the baseline term.

In the middle-term stage (Fig. 4b), the shrubs and meadows appear in the west of the Plateau. The area of shrubs increases more than that in the near-term simulation, while the area of alpine meadows declines by 29% from that in the baseline term, mostly replaced by the expanding shrubs. Even in the northwest where the steppe prevails, small areas of shrubs appear. In the Sanjiangyuan region (the source region of the Yangtze, Yellow, and Lancang/Mekong Rivers), the alpine meadows begin to shrink, but large areas of steppe appear. Hence, under the middle-term climatic scenario, the total area of steppe remains almost the same as under the near-term scenario. Moreover, the coniferous forests spread to the interior of the Plateau along the river valleys, and partly replace the original shrubs. In the eastern mountainous area, the coniferous-broad-leaved mixed forests expand to cover an area 2.4 times larger than that of the reference period but still only occupy approximately 1.42% of the total Plateau area. Additionally, the broad-leaved forests expand northward in southern Tibet from the "elbow" of the Yarlung Zangbo (Brahmaputra) River.

For the long-term stage (Fig. 4c), namely under the warmest climate, the shrubs are projected to expand to cover the northern Plateau entirely, replacing the steppes and alpine meadows. The shrub area is over 2.7 times of that under the baseline term climate, and 29.5% of the plateau area. Meanwhile, the steppe shrinks and retreats to the northwest, partly replacing the deserts. The distribution of the alpine meadows is reduced to 41% of its area under the baseline term climate, mainly in the Sanjiangyuan region and the valley of the Yarlung Zangbo River. The steppes in the northwest, as in the baseline term, are mixed with the shrubs.

Furthermore, the areas of forests continue to enlarge. Particularly, the broad-leaved forests expand in the eastern mountainous area by around 1.8 times compared with their area under the baseline term climate and interweave with the coniferous forests. The coniferous forests move further to the interior of the Plateau and replace more shrubs. At the same time, areas of the mixed broad-leaved and coniferous forests also increase mainly in the eastern mountainous area and southern Tibet. Yet, due to the small percentage (1.77%) of the area occupied by these forests occupy, their expansions are not very obvious.

The alpine sparse/cushion vegetation shrinks the most among all the vegetation types. In the long-term stage, their area reduces to 19% of that under the baseline term climate and occupies only 0.85% of the total plateau area. Their

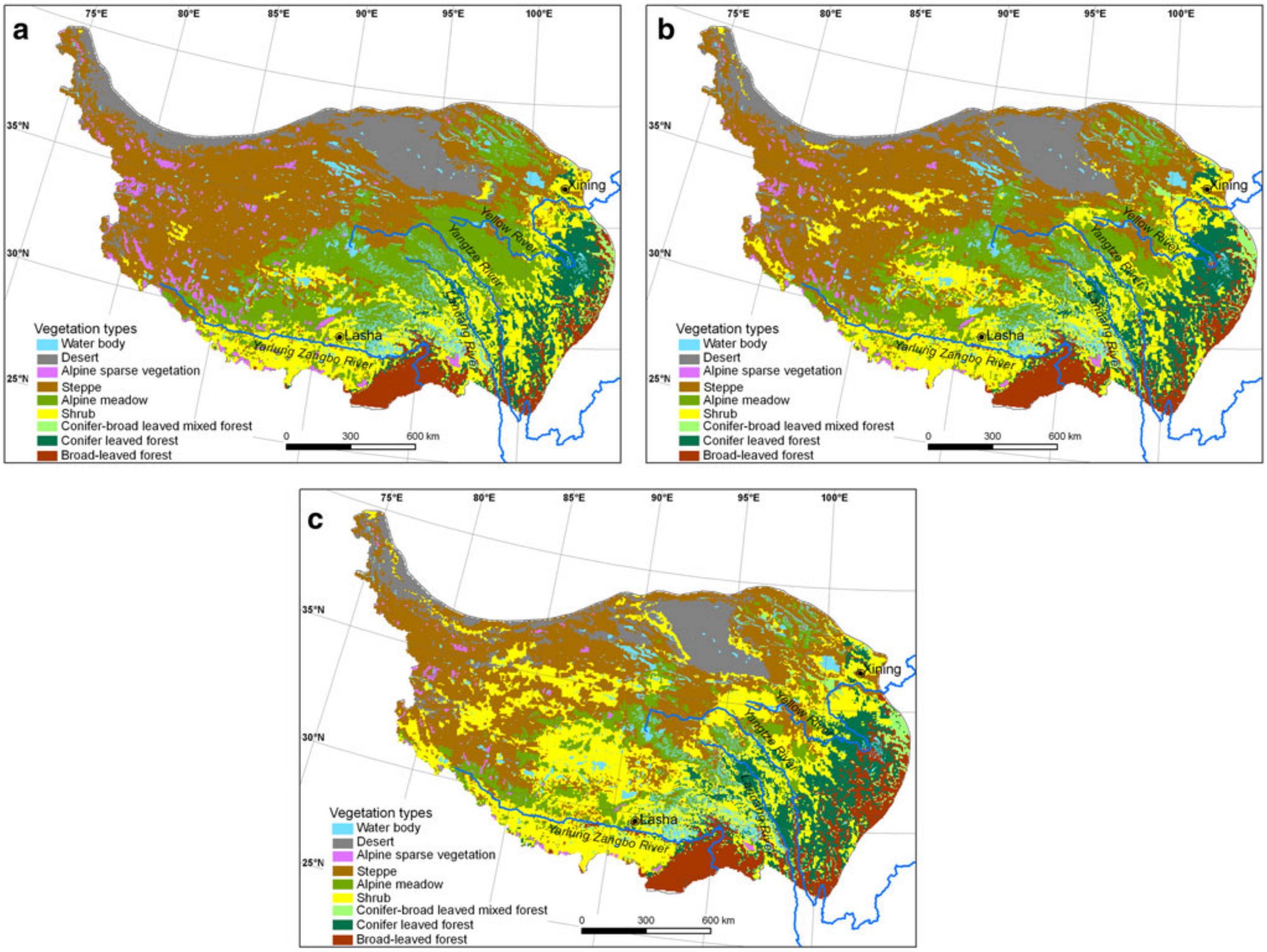

Fig. 4 Vegetation distribution on the Tibetan Plateau at the three climate change stages (**a** 1991–2020, **b** 2021–2050, **c** 2051–2080)

Table 4 Areal distributions of vegetation types on the Tibetan Plateau at the baseline and three climate change stages (%)

Vegetation type	Baseline term (1961–1990)	Near term (1991–2020)	Middle term (2021–2050)	Long term (2051–2080)
Broad-leaved forest	3.91	4.72	5.54	6.95
Conifer-broad-leaved mixed forest	0.60	0.99	1.42	1.77
Conifer forest	5.36	6.61	8.02	9.16
Shrub	11.00	16.11	20.18	29.15
Alpine meadow	23.06	20.90	16.33	9.53
Steppe	40.46	37.12	36.57	33.14
Alpine sparse/cushion vegetation	4.40	2.89	1.73	0.85
Desert	11.19	10.66	10.22	9.45

influence on the changes of vegetation distribution pattern may be minor.

Discussion

According to our simulated results, the projected climate change characterized by rising temperature and increasing precipitation may cause shifts in the vegetation distribution on the Tibetan Plateau. In the B2 scenario, precipitation increases in the desert region. As a result, the deserts may be replaced gradually by other vegetation types that require increased precipitation. In addition, the alpine sparse/cushion vegetation, distributed mainly on the upper parts of the mountains, may be outcompeted by other plants which can now grow at higher altitudes in the warmer climate. Due to their slow responses to climate change (Zhou 2001) and limited distribution on the Plateau, the broad-leaved forests and coniferous-broad-leaved mixed forests may expand at relatively low rates and their areas may remain small. Coniferous forests are the major forest type on the Plateau at present, and they are projected to have the largest increase in area among all the forest types. Most of the new conifer forests may take the place of the original shrubs.

Results from this study are in general consistent with previous studies, but discrepancies do exist. Our simulation suggests that the overall vegetation pattern is likely to shift northward due to future climate change, which is quite similar to those modeled by Zhang et al. (1996) using the Holdridge method and Ni (2000) with BIOME3. Areas of broad-leaved forests and coniferous-broad-leaved mixed forests may be enlarged, and the area of desert may be decreased, again similar to those of Zhang et al. (1996) and Ni (2000). Coniferous forests may significantly increase in the future according to Ni (2000), which is consistent with our study. In this study, we examine the vegetation distributions in three projected periods of near term (1991–2020), middle term (2021–2050), and long term (2051–2080), which improves the understanding of the impacts of different warming levels, whereas vegetation changes were studied under only one period (1970–2099) in Ni (2000) and for an assumption of increased temperature and precipitation in Zhang et al. (1996). Our results indicates that alpine meadow may be the vegetation type that decreases the most under the climate change scenarios, which differed from Ni (2000) using BIOME3. Alpine meadow is not only the most important ecosystem in the Tibetan Plateau (Zhou 2001), but also a key resource for supporting local people's subsistence. Its decline may severely affect the livelihoods of local herdsmen. It should be mentioned that the changing trends in vegetation distribution areas are similar among the different studies mentioned earlier, but the specific locations and spatial range of each vegetation type are different, which is partly attributed to the applications of the climatic scenarios and different ecosystem models. The problems on northward moving steppe and concentrated forest types and alpine meadow, emerged in modeling result of Ni (2000), were solved in our study by adding three new PFTs and detailed model parameterization. The increased spatial resolution of output results from the modified BIOME4, compared with earlier efforts, improved the accuracy of the BIOME4 simulation at the regional scale.

On the basis of the relationship between vegetation and climate, this study investigated the responses of the vegetation to the climate change on the Tibetan Plateau and analyzed the possible variations of the vegetation distribution. However, there are some uncertainties pertaining to the climate change and the vegetation responses. In varied climatic scenarios, the trends of climate change on the Tibetan Plateau may be different. Yet this research only probed the possibilities for the IPCC B2 scenario. Since the climate system is complicated and nonlinear and the topographic factors are very complex on the Plateau, the GCMs are often unable to depict the accurate spatial patterns of the climatic factors used in vegetation modeling with sufficient resolution. Although the output of PRECIS (Jones et al. 2004) has been improved by enhancing the spatial resolution in this study, such problems still cannot be entirely eradicated to rule out the uncertainties. Moreover, the ecosystem models were usually built upon certain assumptions, i.e., simplified ways to describe the ecological mechanisms. Similarly, some lagging responses and self-adaptive mechanisms of the vegetation to climate change were omitted in the BIOME4, which have attracted attentions of ecologists in the world, but there are not enough studying results to support quantifying these processes in the model. These omissions can also lead to the uncertainties in the simulation results to some degree.

BIOME4 predicts distribution of vegetation types according to bioclimatic factors. In other words, the simulated results are potential vegetation distributions free from the influence of human activities. The great expansion in human activity can certainly have major influences on vegetation dynamics, especially in the eastern portion of the Plateau with relatively high population density. For example, Wang et al. (2008) reported that the cropland increased by 20.96% between 1990 and 2000 in Dulan County of the northeastern Tibetan Plateau due to grassland reclamation of mankind. Liu et al. (2008) found that human activities were the most important factor controlling grassland degradation in the Sanjiangyuan region. Therefore, this study could be further improved by integrating human disturbances in the simulations.

Conclusions

In this study, we used a modified version of BIOME4, a coupled biogeography and biogeochemistry model, to simulate the responses of vegetation distribution on the Tibetan Plateau to future climate change. By comparing the simulated results based on climatic data during 1961–1990 with the existing vegetation map of China, it was concluded that the modified model can generate realistic predictions of vegetation distribution patterns for the study region. Three stages of warming were considered in this study in comparison with the baseline term of 1961–1990: 1991–2020 (near term), 2021–2050 (middle term), and 2051–2080 (long term), to determine the sensitivities of major vegetation types on the Tibetan Plateau to global warming.

Our simulations indicate increases in the areas occupied by the broad-leaved forests, conifer-broad-leaved mixed forests, conifer forests and shrubs over the Tibetan Plateau under the warming conditions of the IPCC B2 emission scenario. Decreases are found in the areas of the alpine meadows, steppe, alpine sparse/cushion vegetation, and deserts. Among these types, the shrubs, alpine meadows, and alpine steppe are most sensitive to the projected climate change. The shrubs expand most noticeably and tend to migrate toward the northwest, reducing the areas of the cold-resistant alpine steppe. Although the steppe may shrink by a relatively small percentage, they exert a great influence on the vegetation distribution on the Plateau due to their initial dominant coverage. The projected climate change may also cause the reduction of the deserts by 1.74%. Overall, the total forest and shrub area may increase by 19.12% in 2051–2080 when compared with the reference period of 1961–1990, while the total area of alpine meadow and steppe may decrease by 20.85%. It is conceivable that major changes in the dynamics of the ecosystems may occur accompanying these changes on the Plateau, in combination with increased human population and enhanced human activities in the decades to come.

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