Article

Shifts of the Mean Centers of Potential Vegetation Ecosystems under Future Climate Change in Eurasia

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Abstract: Climate change dominantly controls the spatial distributions of potential vegetation ecosystems; the shift trends in the mean centers of potential vegetation ecosystems could be used to explain their responses to climate change. In terms of the climate observation data of Eurasia for the period from 1981 to 2010 and the climate scenario data for the period from 2011 to 2100 under the three Representative Concentration Pathways (RCPs) scenarios of RCP2.6, RCP4.5 and, RCP8.5, which were released by the Coupled Model Intercomparison Project Phase 5 (CMIP5), the Holdridge Life Zone (HLZ) ecosystem model was improved to quantitatively classify the potential vegetation types, and the shift model of mean center was adopted to compute the trends in the spatiotemporal shifts of potential vegetation types in Eurasia. The results showed that the mean centers of the major potential vegetation ecosystems would be distributed in the central and southern parts of Eurasia. Under the RCP2.6, RCP4.5, and RCP8.5 scenarios, the potential shift distances of the mean centers of the vegetation types under the RCP8.5 scenario would be the largest, and those of the polar/nival area, subpolar/alpine moist tundra, warm temperate dry forest, subtropical moist forest, cool temperate moist forest, cool temperate wet forest, subtropical wet forest, subtropical thorn woodland, warm temperate moist forest and subtropical dry forest would be larger than those in the other potential vegetation types in Eurasia. Moreover, the shift directions of the mean centers of the major potential vegetation types would generally shift northward, and subtropical dry forest, warm temperate moist forest and subpolar/alpine moist tundra would be the most sensitive to change among all vegetation types under the three scenarios for the period from 2011 to 2100.

Keywords: potential vegetation ecosystem; mean center; shift scenarios; climate change; Eurasia

1. Introduction

Changes in vegetation ecosystems, which are major indicators of global change on the Earth's surface, play a crucial role in maintaining the human living environment and its sustainable development [1,2]. Climate change, as an important aspect of global change, has caused a series of changes in the spatiotemporal distribution of vegetation ecosystems [3–5]. The interactions between climate and vegetation ecosystems have always been a hot topic in global change research [6]. A long-term investigation of the correlation between climate change and vegetation ecosystem change [7] showed that there was a strong correlation between climate change and vegetation distributions [8], and that the climate exerts the dominant control on the distributions of the major vegetation types on a large scale [9]. The key climate parameters of biotemperature, precipitation and evaporation directly determine the changes in the spatial distribution of terrestrial ecosystems [10–15]. A series of

models have been developed to simulate the spatial distributions of vegetation ecosystems [16], in which the dominant models include the Holdridge Life Zone (HLZ) ecosystem model [9], the model of predicting physiognomic vegetation types with climate variables developed by Box E.O. (BOX) [17], Dynamic Global Phytogeography Model (DOLY) [8], Mapped Atmosphere-Plant Soil System (MAPSS) model [18] and Integrated Biosphere Simulator (IBIS) [19]. In particular, the HLZ ecosystem model has been widely used and is considered an effective method for simulating the potential distributions of vegetation ecosystems [20–24] because the model parameters only involve the three key climatic factors: Mean annual biotemperature (MAB), average total annual precipitation (TAP) and potential evapotranspiration ratio (PER) [25–27].

Since the early 2000s, a continuous effort has been made to understand the relationship between vegetation distributions and climate change [28–30], especially to reveal the response of vegetation to climate change [31,32]. For instance, an analysis of the historical vegetation and climate data showed that the forest distribution had shifted to the polar region [33]; grass distribution was more sensitive to change than any other vegetation ecosystems in Central Asia [34]; the mean centers of the different terrestrial ecosystems in China showed different shift trends from 1960 to 2002 [35]; the mean center shift of vegetation ecosystem would influence the ecosystem service value [36]; and the mean centers of vegetation ecosystems would show a different shift trend under different climate change scenarios [37]. However, current research mainly focuses on the responses of the shift in the mean center of vegetation ecosystems to historical climate change [38], and is rarely involved in analyzing the response relations between the different shift trends of vegetation ecosystems and climate change in the future.

To explicitly analyze the responses of the different shift trends in vegetation ecosystem types to the different climate change scenarios in Eurasia, the Holdridge Life Zone (HLZ) ecosystem model has been improved to quantitatively classify the potential vegetation types, and the shift model of mean center has been adopted to compute the spatiotemporal shift trends of potential vegetation types. The shift trends of the mean centers in different potential vegetation ecosystems from 2010 to 2100 were obtained from the climate observation data from 1981 to 2100 in Eurasia and the climate scenarios data released by CMIP5 from 2011 to 2100. The different shift distances and directions of the mean center in the different vegetation ecosystem types were compared under the three scenarios of RCP2.6, RCP4.5, and RCP8.5, and we discuss which vegetation ecosystem types will be more sensitive to climate change in Eurasia in the future.

2. Materials and Methods

2.1. Data Sources

The basic climate datasets include the observation data and the scenario data. The observational monthly climate data from 1981 to 2010 were collected from 1360 weather stations in Eurasia as seen in Figure 1. The climate scenario data for the CMIP5 RCP2.6, RCP4.5, and RCP8.5 scenarios from 2011 to 2100 were obtained from the IPCC website. The three climate scenarios of RCP2.6, RCP4.5 and RCP8.5 represent scenarios of low, middle and high emissions of greenhouse gases, respectively (<http://www.ipcc-data.org>) [39]. The Digital Elevation Model (DEM) data seen in Figure 1 was derived from the Shuttle Radar Topography Mission (SRTM) data (<http://srtm.csi.cgiar.org>) with a spatial resolution of 1 km × 1 km resampled to a resolution of 0.125° × 0.125°.

Figure 1. Digital Elevation Model (DEM) data and 1360 weather stations in Eurasia.

The accuracy of spatial distribution data of the climate variables obtained from the observational scatter data and low resolution scenario data is important to the HLZ ecosystem model and the shift model of mean center, which directly affects the quality of the results of the simulation of the shift trends of the mean centers of potential vegetation ecosystems under climate change [11].

The main interpolation and downscaling methods included the inverse distance weighted (IDW) model, kriging (Kriging) model, spline interpolation (Spline) model, triangulated irregular network (TIN) model and high accuracy surface modeling (HASM) method. The IDW model uses an inverse distance weighting function to determine the interpolation value while ignoring the information beyond the neighborhood. Although the Kriging model attempts to have an error equal to zero, this goal is nearly unattainable. The Spline model applies univariate cubic basis-splines to simulate surfaces, but few types of surfaces fit the splines. The TIN model uses a linear function to calculate the value of each point but ignores nonlinear information. HASM is a new method based on the differential geometry theory that could overcome the drawbacks of the IDW, Kriging, Spline and TIN methods [40], and the accuracy of the interpolated and downscaled climate data could be generally increased by 5% compared with that of the other three methods [41,42]. Thus, the HASM method was selected to obtain the spatial grid data of MAB, TAP and PER with a spatial resolution of $0.125^\circ \times 0.125^\circ$ by combining the longitude, latitude and elevation data during the periods from 1981 to 2010 (T0), 2011 to 2040 (T1), 2041 to 2070 (T2) and 2071 to 2100 (T3); the specific methods are described in the references [40–42].

2.2. Methods

2.2.1. The HLZ Ecosystem Classification

The HLZ ecosystem model is a classification system for different HLZ ecosystem types in terms of the three bioclimatic factors: Mean annual biotemperature (MAB), average total annual precipitation (TAP) and potential evapotranspiration ratio (PER) [9,11,23,37]. The HLZ ecosystem model was improved to simulate the potential vegetation ecosystems throughout Eurasia and can be expressed as

$$MAB(x, y, t) = \frac{1}{365} \sum_{j=1}^{365} TEM(j, x, y, t) \quad (1)$$

$$TAP(x, y, t) = \sum_{j=1}^{365} P(j, x, y, t) \quad (2)$$

$$PER(x, y, t) = \frac{58.93MAB(x, y, t)}{TAP(x, y, t)} \quad (3)$$

$$HLZ_i(x, y, t) = \sqrt{(M(x, y, t) - M_{i0})^2 + (T(x, y, t) - T_{i0})^2 + (P(x, y, t) - P_{i0})^2} \quad (4)$$

where $MAB(x, y, t)$, $TAP(x, y, t)$ and $PER(x, y, t)$ are the MAB (°C), TAP (mm) and PER, respectively, at grid (x, y) in period t ; $TEM(j, x, y, t)$ and $P(j, x, y, t)$ are respectively the accumulated temperature above 0 °C and below 30 °C and the total precipitation on the j th day; M_{i0} , T_{i0} and P_{i0} are respectively the values of the MAB logarithm, TAP logarithm and PER logarithm at the central point of the i th potential vegetation type in the HLZ ecosystem criterion; $M(x, y, t) = \ln MAB(x, y, t)$, $T(x, y, t) = \ln TAP(x, y, t)$, and $P(x, y, t) = \ln PER(x, y, t)$; and $HLZ_i(x, y, t)$ is the i th potential vegetation type.

2.2.2. Shift Model of Mean Center in Potential Vegetation Ecosystems

The original mean center model was developed to calculate the mean centers of the population distributions in the USA population census in 1870 [43] and has been mainly used in economic geography [44–46]. Since the 2000s, the mean center model has been improved gradually to compute the shift trends of the mean centers of terrestrial ecosystems [11,35,37] and land cover types [47]. In this study, the mean center model was improved to compute the spatial distribution of the mean centers of different potential vegetation ecosystem types in Eurasia during the periods from T0 to T3, which can be formulated as

$$x_j(t) = \sum_{i=1}^{I_j(t)} \frac{s_{ij}(t) \cdot X_{ij}(t)}{S_j(t)} \quad (5)$$

$$y_j(t) = \sum_{i=1}^{I_j(t)} \frac{s_{ij}(t) \cdot Y_{ij}(t)}{S_j(t)} \quad (6)$$

where t represents time; $I_j(t)$ is the number of patches of the j th potential vegetation type; $s_{ij}(t)$ is the area of the i th patch in the j th potential vegetation type; $S_j(t)$ is the total area of the j th potential vegetation type; $(X_{ij}(t), Y_{ij}(t))$ are the longitude and latitude coordinates of the geometric center of the i th patch in the j th potential vegetation type; and $(x_j(t), y_j(t))$ is the mean center coordinate of the j th potential vegetation type.

To simulate the shift distance and direction of the mean center of different potential vegetation types, a shift trend model of mean center has been developed by extending the mean center model [11,48], which can be expressed as

$$d_j = \sqrt{(x_j(t+1) - x_j(t))^2 + (y_j(t+1) - y_j(t))^2} \quad (7)$$

$$\theta_j = \arctg\left(\frac{y_j(t+1) - y_j(t)}{x_j(t+1) - x_j(t)}\right) \quad (8)$$

where $(x_j(t), y_j(t))$ and $(x_j(t+1), y_j(t+1))$ are the coordinates of the mean center of the j th potential vegetation type in years t and $t+1$, respectively; d_j is the shift distance of the mean center of the j th potential vegetation type during the period from t to $t+1$; and θ_j is the value of the angle of the shift of the mean center in the j th potential vegetation type during the period from t to $t+1$. The shift directions were classified into 8 types: due east is 0°, due north is 90°, due west is 180° and due south is 270°. The shift directions are classified into these 8 types, as seen in Table 1, based on the range of θ_j values.

Table 1. The definition of the shift direction of the mean center in the potential vegetation ecosystem.

Sketch Map of the Shift Directions	θ_j Value	Shift Direction
	345° ~ 15°	East
	15° ~ 75°	Northeast
	75° ~ 105°	North
	105° ~ 165°	Northwest
	165° ~ 195°	West
	195° ~ 255°	Southwest
	255° ~ 285°	South
	285° ~ 345°	Southeast

3. Results

3.1. Distribution of the Mean Centers of Potential Vegetation Ecosystems

The potential vegetation ecosystems simulation results showed that there were 32 vegetation ecosystem types in Eurasia from 1981 to 2010, as seen in Figure 2. Cold temperate wet forest, cool temperate moist forest and desert were the main vegetation ecosystem types, which covered 14.49%, 11.61% and 10.61% of the total area of Eurasia, respectively. The cold temperate wet forest was mainly distributed in the Central Siberian Plateau, the central part of the West Siberian Plain, and the northern part of the Eastern European Plain; the mean center of all patches of this ecosystem was located in the southeastern part of the West Siberian Plain. The cool temperate moist forest was mainly distributed in the Loess Plateau and Northeast China Plain, the Korean Peninsula, and the southern and western parts of the European Plain; the mean center of all patches of this ecosystem was located in the Turan Plain of Russia. The desert was mainly distributed in the western part of the Mongolian Plateau, the Turan Plain, the Arabian Peninsula and the eastern part of the Iranian Plateau, which include the Gobi Desert, Taklimakan Desert, Karakum Desert, Kyzylkum Desert, Arabian Desert and Thar Desert; the mean center of all patches of this ecosystem was located in the eastern part of the Iranian Plateau. The results indicate that the simulations of the spatial distributions of the potential vegetation types and their mean centers could be effectively used to understand the response of the potential vegetation types to climate change in Eurasia.

Figure 2. Distribution of the mean centers of potential vegetation ecosystems in Eurasia in the T0 period.

3.2. Shift Trends of the Mean Center of Potential Vegetation Types

The simulation results of the mean centers of potential vegetation types show that the mean centers of the subtropical dry forest, warm temperate moist forest, tropical thorn woodland and subtropical wet forest ecosystems would exhibit the largest shift distances of more than 150 km per decade during the period from T0 to T3 under the RCP2.6 scenario, as seen in Table 2, Figure 3. The mean centers of the cool temperate rain forest, tropical very dry forest, tropical thorn woodland, desert, and tropical moist forest ecosystems would shift less than 25 km per decade during these periods under the same scenario. The subtropical thorn woodland, cold temperate moist forest, subpolar/alpine dry tundra, and tropical very dry forest ecosystems would shift 1548 km northwest, 1199 km northeast, 286 km southwest, and 121 km northwest, respectively, during the period from T0 to T3.

Table 2. Shift distances (km) and directions of the mean center of each potential vegetation type under the RCP2.6 scenario in Eurasia.

Type	T0-T1		T1-T2		T2-T3	
	Shift Distance	Shift Direction	Shift Distance	Shift Direction	Shift Distance	Shift Direction
Polar/Nival area	198	West	239	West	261	East
Subpolar/Alpine dry tundra	41	Southwest	185	Southwest	60	Southwest
Subpolar/Alpine moist tundra	80	South	218	Southwest	454	Southwest
Subpolar/Alpine wet tundra	425	East	95	Northwest	156	West
Subpolar/Alpine rain tundra	158	East	201	East	193	Southwest
Cold temperate dry scrub	115	Southwest	27	Southwest	100	Northwest
Cold temperate moist forest	511	Northeast	272	Northeast	416	Northeast
Cold temperate wet forest	265	Northeast	234	East	161	Northeast
Cold temperate rain forest	212	East	204	East	99	Southeast
Cool temperate desert scrub	114	Northeast	91	East	77	Northeast
Cool temperate steppe	155	Northeast	176	Northeast	162	Northeast
Cool temperate moist forest	515	East	298	Northeast	292	Northeast
Cool temperate wet forest	239	East	286	East	389	East
Cool temperate rain forest	6	Southwest	8	Northeast	17	Northwest
Warm temperate desert scrub	195	Northeast	172	Northeast	155	Northeast
Warm temperate thorn steppe	276	Northeast	175	Northeast	154	Northeast
Warm temperate dry forest	309	Northwest	198	Northwest	250	East
Warm temperate moist forest	451	Northwest	647	West	934	West
Warm temperate wet forest	177	Northwest	107	Northwest	185	West
Subtropical desert scrub	282	Northwest	218	North	166	North
Subtropical thorn woodland	843	Northwest	496	Northwest	209	Northwest
Subtropical dry forest	755	Northwest	639	Northwest	847	West
Subtropical moist forest	597	Northwest	271	North	165	Northeast
Subtropical wet forest	524	Northeast	475	Northwest	548	Northwest
Subtropical rain forest	116	Northeast	127	East	0	East
Tropical desert scrub	63	North	55	North	109	West
Tropical thorn woodland	52	Northwest	40	Southwest	78	West
Tropical very dry forest	35	Northwest	46	Northwest	40	Northwest
Tropical dry forest	239	East	58	North	32	Northwest
Tropical moist forest	62	East	25	Northeast	130	Northwest
Tropical wet forest	93	Northeast	71	East	78	East
Desert	64	West	118	Southwest	32	West

Under the RCP4.5 scenario seen in Table 3, Figure 4, the results show that the shift distances of the mean centers of the subpolar/alpine moist tundra, subtropical dry forest, warm temperate moist forest, cool temperate wet forest, subtropical thorn woodland, cool temperate moist forest, subtropical wet forest, and cold temperate moist forest would be larger than those in other potential vegetation types and would shift more than 200 km per decade on average, while those of the cool temperate rain forest, tropical very dry forest, desert, and tropical thorn woodland would shift less than 29 km per decade during the period from T0 to T3. The cool temperate wet forest, subtropical thorn woodland, cold temperate moist forest, and tropical wet forest ecosystems would continue to shift 1982 km east, 1741 km northwest, 1278 km northeast, and 264 km east, respectively, during the period from T0 to T3.

Figure 3. Shift trends of the mean centers of each potential vegetation type under the RCP2.6 scenario in Eurasia.

Table 3. Shift distances (km) and directions of the mean centers of each potential vegetation type under the RCP4.5 scenario in Eurasia.

Type	T0–T1		T1–T2		T2–T3	
	Shift Distance	Shift Direction	Shift Distance	Shift Direction	Shift Distance	Shift Direction
Polar/Nival area	178	West	283	West	720	Northeast
Subpolar/Alpine dry tundra	142	Southwest	92	Southwest	74	West
Subpolar/Alpine moist tundra	94	Southeast	270	Southwest	2031	Southwest
Subpolar/Alpine wet tundra	388	East	53	Southeast	394	West
Subpolar/Alpine rain tundra	255	East	166	Southeast	119	Southwest
Cold temperate dry scrub	147	Southwest	30	West	167	West
Cold temperate moist forest	549	Northeast	358	Northeast	370	Northeast
Cold temperate wet forest	217	Northeast	340	East	322	East
Cold temperate rain forest	190	East	301	East	209	Northeast
Cool temperate desert scrub	191	East	101	Northeast	172	East
Cool temperate steppe	186	Northeast	231	Northeast	567	East
Cool temperate moist forest	328	Northeast	469	East	574	Northeast
Cool temperate wet forest	215	East	717	East	1050	East
Cool temperate rain forest	17	Southwest	4	North	70	North
Warm temperate desert scrub	285	Northeast	211	Northeast	330	East
Warm temperate thorn steppe	295	Northeast	235	Northeast	229	Northeast
Warm temperate dry forest	141	Northwest	375	West	363	Northwest
Warm temperate moist forest	307	Northwest	912	West	789	Northwest
Warm temperate wet forest	47	Northwest	244	Northwest	147	North
Subtropical desert scrub	243	Northwest	327	North	270	Northwest
Subtropical thorn woodland	595	Northwest	654	Northwest	492	Northwest
Subtropical dry forest	423	Northwest	840	Northwest	921	West
Subtropical moist forest	488	Northwest	336	Northeast	274	Northeast
Subtropical wet forest	235	Northeast	765	North	368	Northwest

Table 3. Cont.

Type	T0–T1		T1–T2		T2–T3	
	Shift Distance	Shift Direction	Shift Distance	Shift Direction	Shift Distance	Shift Direction
Subtropical rain forest	190	Northeast	52	Southeast	21	Southeast
Tropical desert scrub	105	Northwest	63	West	102	Northwest
Tropical thorn woodland	85	Northwest	38	Southwest	129	West
Tropical very dry forest	40	Northwest	57	North	52	Northwest
Tropical dry forest	108	East	162	East	185	Northwest
Tropical moist forest	95	Southeast	83	Northwest	238	Northwest
Tropical wet forest	167	East	34	East	63	East
Desert	114	Southwest	56	West	61	Northwest

Figure 4. Shift trends of the mean centers of each potential vegetation type under the RCP4.5 scenario in Eurasia.

Under the RCP8.5 scenario seen in Table 4, Figure 5, the results showed that the shift distances of the mean centers of the subpolar/alpine moist tundra, subtropical dry forest, warm temperate moist forest, cool temperate wet forest, subtropical wet forest, subtropical thorn woodland, cool temperate moist forest, cold temperate moist forest, polar/nival area, and subtropical moist forest would be larger than those of other potential vegetation types with a shift distance of more than 200 km per decade on average, while those of the cool temperate rain forest, tropical very dry forest, desert, and cold temperate dry scrub would shift less than 45 km per decade during the period from T0 to T3. The subpolar/alpine moist tundra, cool temperate wet forest, cool temperate moist forest, cold temperate moist forest, and cool temperate desert scrub would continue to shift 3864 km southwest, 2188 km east, 1726 km northeast, 1506 km northeast, and 649 km east, respectively, during the period from T0 to T3.

Table 4. Shift distances (km) and directions of the mean centers of each potential vegetation type under the RCP8.5 scenario in Eurasia.

Type	T0–T1		T1–T2		T2–T3	
	Shift Distance	Shift Direction	Shift Distance	Shift Direction	Shift Distance	Shift Direction
Polar/Nival area	162	West	236	Northwest	908	Northeast
Subpolar/Alpine dry tundra	61	South	298	West	72	West
Subpolar/Alpine moist tundra	165	Southwest	627	Southwest	3072	Southwest
Subpolar/Alpine wet tundra	339	East	59	East	140	West
Subpolar/Alpine rain tundra	285	East	195	Southeast	343	West
Cold temperate dry scrub	118	Southwest	99	West	183	West
Cold temperate moist forest	509	Northeast	668	Northeast	329	Northeast
Cold temperate wet forest	219	Northeast	319	East	490	East
Cold temperate rain forest	248	East	236	East	328	East
Cool temperate desert scrub	181	East	202	East	265	East
Cool temperate steppe	149	Northeast	366	Northeast	498	Northeast
Cool temperate moist forest	378	Northeast	635	Northeast	713	Northeast
Cool temperate wet forest	404	East	879	East	905	East
Cool temperate rain forest	12	Southwest	15	North	168	Northwest
Warm temperate desert scrub	284	Northeast	286	East	508	East
Warm temperate thorn steppe	310	Northeast	274	Northeast	419	Northeast
Warm temperate dry forest	112	Northwest	642	Northwest	387	North
Warm temperate moist forest	377	West	1263	West	648	Northwest
Warm temperate wet forest	77	Northwest	170	Northwest	360	West
Subtropical desert scrub	304	Northwest	416	North	313	North
Subtropical thorn woodland	834	West	634	Northwest	392	Northwest
Subtropical dry forest	327	Northwest	1137	West	1250	Northwest
Subtropical moist forest	446	Northwest	468	North	305	Northeast
Subtropical wet forest	473	Northeast	940	North	593	Northwest
Subtropical rain forest	274	Southeast	242	East	198	East
Tropical desert scrub	33	Northeast	275	West	137	Northwest
Tropical thorn woodland	122	Southeast	327	Northwest	201	West
Tropical very dry forest	9	Northwest	161	Northwest	29	West
Tropical dry forest	242	East	195	Northwest	95	Northwest
Tropical moist forest	86	East	183	Northwest	285	Northwest
Tropical wet forest	95	Northeast	87	Northeast	258	East
Desert	137	Southwest	96	Northwest	72	Northwest

In general, during the periods from T0 to T3, the mean centers of the subtropical dry forest and warm temperate moist forest ecosystems would show the largest shift distances; the subtropical dry forest would shift 249 km, 243 km, and 302 km per decade on average towards the northwest under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, and the warm temperate moist forest would generally shift 226 km, 223 km, and 254 km per decade towards the northwest under the three scenarios, respectively. These results indicate that the distributions of subtropical dry forest and warm temperate moist forest would be increased in southwest Europe, and decreased in the Indian Peninsula and China. The mean centers of both cool temperate rain forest and tropical very dry forest would generally shift less than 23 km north, which means that their distributions will move north under future climate change.

Figure 5. Shift trends of the mean centers of each potential vegetation type under the RCP8.5 scenario in Eurasia.

4. Discussion

The HASM method [11,41,42] was utilized to obtain high-resolution and high-accuracy climate data by interpolating the station observational climate data and downscaling the climate scenario data. The HLZ ecosystem model [9], as a bioclimatic classification scheme [48], has been widely used to simulate the distributions of terrestrial ecosystems [35,36,49], predict land cover change [47], and support land use planning [20–25]. In this paper, the HLZ ecosystem model was improved to simulate the distribution of the potential vegetation type. The shift model of mean center [11,37,47] was improved to quantitatively compute the shift distance and direction of the mean center of each potential vegetation type in Eurasia during the period from 1981 to 2100. The mean center of a given potential vegetation type represented the distribution center weighed by the area of that vegetation ecosystem type. Therefore, the shift distance and direction of the mean center of a vegetation ecosystem type could be used to explain the response of the potential vegetation distributions to climate change [37]. Moreover, related studies show that the existing biogeographical model of potential vegetation ecosystems could be used to predict the impacts of future climate change on different vegetation types [50]. A carbon storage/sequestration model of potential vegetation ecosystems could be used to estimate the changes in carbon storage and sequestration potential in response to climate change [51], and a shift model of mean center could be used to predict the shift intensity of the mean centers of different potential vegetation types [52–54].

Under future climate change, the subtropical dry forest, warm temperate moist forest and subpolar/alpine moist tundra would be more sensitive to climate change than the other vegetation ecosystem types, which can be identified from existing reports [37,55–57]. The amount of polar/nival area will be reduced and replaced by subpolar/alpine tundra between their transition zones [30,55]. Subpolar/alpine moist tundra may be reduced by more than 90% from T0 to T3 [56], which is consistent with the fact that the shift distance of the mean center of subpolar/alpine moist tundra will generally be larger than that of other potential vegetation types. Subpolar/alpine moist tundra would be the most sensitive vegetation type because its area would have the most rapid rate of decrease [56], and its

mean center would shift the largest distance towards the southwest, which means that subpolar/alpine moist tundra could be selected as an indicator of climatic change [11,57]. The shift distances of the mean centers of subtropical dry forest and warm temperate moist forest would be the largest of all potential vegetation types and would generally shift to the northwest from T0 to T3, which means that their distributions would increase in Europe under climate change [58].

The distributions of potential vegetation are significantly controlled by changes in climate [59,60], especially changes in temperature [61]. In the three climate change scenarios, RCP8.5 is the scenario with the highest predicted change, RCP4.5 is the intermediate scenario, and RCP2.6 is the scenario with the lowest predicted change [23,39,62]. The results of the simulated shift trends of the mean centers of potential vegetation types were all similar in that the intensity of climate change directly affects the shift distances of the mean centers of the potential vegetation ecosystems. The mean centers of the potential vegetation types under the RCP8.5 scenario would have the largest shift distances and those under the RCP2.6 scenario would have the smallest shift distances. Under the three climate scenarios, the mean centers of the polar/nival area, subpolar/alpine moist tundra, warm temperate dry forest, subtropical moist forest, cool temperate moist forest, cool temperate wet forest, subtropical wet forest, subtropical thorn woodland, warm temperate moist forest, and subtropical dry forest would have larger shifts than those of other potential vegetation types in Eurasia, which means that these potential vegetation types would be more sensitive to climate change than the others. In contrast, the mean centers of the cool temperate rain forest, tropical very dry forest, desert, cold temperate dry scrub, subpolar/alpine dry tundra, tropical wet forest, tropical desert scrub, tropical dry forest, and tropical moist forest would shift less than those of other potential vegetation types in Eurasia, which means that these potential vegetation types would be the least vulnerable to climate change.

With increasing temperature and precipitation, the potential vegetation ecosystem types would generally show conversion from cool-dry to warm-wet and from cool to warm in Eurasia [56]; the distributions showed trends of shifting to higher latitudes and elevations [62,63], especially in the Northern Hemisphere between the latitudes of 35° and 75° [64]. The simulation results of the shift trends of the mean center of the potential vegetation types showed a similar response, in which the polar/nival area would decrease in the southeast part of the north polar area [56], leading to a mean center shift towards the west. The change in the desert distribution would mainly occur around the existing desert areas [56], and its mean center would generally shift less than 35 km per decade to the west. Moreover, the mean centers of the cold temperate moist forest and warm temperate thorn steppe would continuously shift towards the northeast, and the mean center of the cool temperate wet forest would continuously shift towards the east during the period from T0 to T3 under the three scenarios.

In summary, the simulation results of the shift in the mean center of the different potential vegetation ecosystem types could be used to explicitly analyze the responses of different shift trends in vegetation ecosystem types under different climate change scenarios in Eurasia.

5. Conclusions

The simulation results indicated that the distributions of potential vegetation types would shift northward under the three climate change scenarios of RCP2.6, RCP4.5, and RCP8.5 during the periods from 1981 to 2100. Based on the results of the shift trends of the mean center of the potential vegetation types, we recommend that the subpolar/alpine moist tundra, subtropical dry forest, and warm temperate moist forest be selected as indicators of the response of vegetation to climate change because their shift distances are generally larger than other vegetation types. Moreover, understanding the shift trends of the mean center of potential vegetation would be beneficial for researching the future carbon balance of vegetation ecosystems, which could be approved by the data support for planning the sustainable development of the countries in Belt and Road Initiative (BRI) regions.

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