Changes in global potential vegetation distributions from 1911 to 2000 as simulated by the Comprehensive Sequential Classification System approach

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Vegetation classification models play an important role in studying the response of the terrestrial ecosystem to global climate change. In this paper, we study changes in global Potential Natural Vegetation (PNV) distributions using the Comprehensive Sequential Classification System (CSCS) approach, a technique that combines geographic information systems. Results indicate that on a global scale there are good agreements among maps produced by the CSCS method and the globally well-accepted Holdridge Life Zone (HLZ) and BIOME4 PNV models. The potential vegetation simulated by the CSCS approach has 6 major latitudinal zones in the northern hemisphere and 2 in the southern hemisphere. In mountainous areas it has obvious altitudinal distribution characteristics due to topographic effects. The distribution extent for different PNV classes at various periods has different characteristics. It had a decreasing trend for the tundra and alpine steppe, desert, sub-tropical forest and tropical forest categories, and an increasing trend for the temperate forest and grassland vegetation categories. The simulation of global CSCS-based PNV classes helps to understand climate-vegetation relationships and reveals the dynamics of potential vegetation distributions induced by global changes. Compared with existing statistical and equilibrium models, the CSCS approach provides similar mapping results for global PNV and has the advantage of improved simulation of grassland classes.

potential natural vegetation, spatial distribution, biogeography model, CSCS approach

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Global climate and environmental changes brought about by anthropogenic means and their potentially serious impact on global and local ecosystems are receiving enormous attention from scientists, governments and society in general [1]. The study of Potential Natural Vegetation (PNV) has been proposed as a way to examine the impact of climate changes on vegetation distributions [2,3]. To understand the spatial

distribution patterns of PNV and their spatial and temporal repeatability is therefore a starting point for studying climate-vegetation relationships.

The separation of anthropogenic and non-anthropogenic influences on climate-vegetation relationships is complicated. Climate-vegetation classification or relationship studies, based on existing patterns of vegetation, can potentially enable the evaluation of societal impacts on relationships between climate and vegetation. Potential vegetation

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refers to the most stable and mature climax vegetation possible without human interference, and shows the overall trend in regional vegetation development over a certain period. The study of potential vegetation can therefore reflect the influence of climatic conditions on vegetation change [4,5]. For this reason, potential natural vegetation has received much attention in the fields of geography, botany, climatology, and ecology [1], since the concept was proposed in 1956 [2].

In general, potential vegetation research can be divided into two stages: the first stage is a traditional qualitative investigation that is primarily based on experienced observations, and the second stage is a quantitative examination based on PNV forecast models. Quantitative methods utilizing GIS and RS techniques have generally superseded qualitative approaches for potential vegetation mapping, thereby overcoming the obstacles of subjectivity, repeatability, low efficiency, high cost and consumption of time. The simulation procedures and resulting outputs of such quantitative methods depend strongly on digitization and visualization techniques. Simulations result in two types of vegetation classification models: one consists of statistical models based on biogeographical and plant physiology parameters [6,7] and the other is process-based [8–11]. The latter has particularly improved our ability to understand the response of terrestrial vegetation to past and future environmental variations at global-to-regional scales [1]. However, a process-based model tends to require the integration of more parameters and a great deal of data to adequately consider biogeographical and biogeochemical processes and fully simulate the dynamics of the terrestrial ecosystem (often a shortcoming for the models). There has been little investigation into the level of complexity that is required to capture primary climate-vegetation feedbacks, despite the fact that increasing complexity is raising the computational costs of vegetation classification simulations [12,13]. Additionally, process-based models can have difficulty simulating climate-vegetation relationships from the more distant past, because of the limited availability of historical observations in many parts of the world. This increases the likelihood of errors in plant-types prediction for past time periods [13]. In comparison with process-based models, biogeographic models, which depend on climatic observation data collected over a broad geographical extent and a long time span, are characterized by simple input parameters [11]. In a related field, plant ecologists have been interested in understanding the geographic distribution of vegetation and the consequences of climate change to vegetation dynamics. This aspect has made the biogeographic approach, in which the distribution of vegetation types is predicted from climate variables, more popular [2]. Thus, biogeographic models have an irreplaceable role in the study of the dynamics of potential vegetation distribution on a global scale.

In order to explore the global terrestrial vegetation classes and their areal extent, a natural vegetation classification

approach, the Comprehensive Sequential Classification System (CSCS) [14], is used in this study. The CSCS approach is a biogeographic simulation method that was used originally to classify grasslands in China [15]. Using this approach, global potential vegetation is divided into 42 classes based on a biogeographic model; additional detailed grassland vegetation types can be added, which makes this approach significantly different from most other potential vegetation classification methods. This paper documents the first application of the CSCS approach on a global scale, and provides a scientific basis for the temporal and spatial distribution of potential terrestrial vegetation, with a focus on grassland vegetation. The purposes of this study are (1) to validate the CSCS-derived model at a global scale by comparing it with the Holdridge Life Zone (HLZ) and BIOME4 PNV classification models; (2) to examine the spatial distribution characteristics of global potential vegetation in 2000 as generated by the CSCS method; and (3) to analyze the changes in the global potential vegetation distribution over a 30-year temporal scale during the 90 years from 1911 to 2000, based on the CSCS method applied to broad vegetation categories.

1 Materials and methods

1.1 The CSCS approach for mapping potential natural vegetation

The CSCS approach is formulated through the grouping or clustering of units with similar moisture and temperature properties [14]. CSCS consists of a 3-class level: Class, Subclass and Type. At the first level, vegetation is grouped into classes according to an index of moisture and temperature. At the second level, vegetation subclasses are differentiated by edaphic conditions. At the third level, vegetation types within a subclass are distinguished by vegetation characteristics.

The class level is the basic unit, and it is identified according to zonal characteristics of biological climate. In practice, the class is determined by combining the quantitative biological climate indices of average annual cumulative temperature above 0°C ($\Sigma\theta$) (i.e., Growing Degree-Days on 0°C base, GDD0) and humidity (K), as calculated by [16].

$$K = \text{MAP} / (0.1 \times \Sigma\theta) = \text{MAP} / (0.1 \times \text{GDD0}), \quad (1)$$

where MAP is the annual mean precipitation (mm); and 0.1 is a justified coefficient of the model.

Based on decades of studies [14–19], 7 thermal zones and 6 humidity zones (Figure 1) have been identified and used to differentiate vegetation classes. The CSCS recognizes 42 vegetation classes (Table 1), of which all but the tropical desert class (class code 7 of Table 1) are present in China [14]. To more explicitly reflect the spatial distribution of potential vegetation at a large scale, classes are merged into 10 broad vegetation categories (Table 2).

Table 1 The PNV classes recognized by the CSCS approach

Class-ID	Code	Thermal grade	Humidity	Class name
IA1	1	frigid	extrarid	frigid desert, alpine desert
IIA2	2	cold temperate	extrarid	montane desert
IIIA3	3	cool temperate	extrarid	temperate desert
IVA4	4	warm temperate	extrarid	warm temperate desert
VA5	5	warm	extrarid	subtropical desert i
VIA6	6	subtropical	extrarid	subtropical desert ii
VIIA7	7	tropical	extrarid	tropical desert
IB8	8	frigid	arid	frigid semidesert, alpine semidesert
IIB9	9	cold temperate	arid	montane semidesert
IIIB10	10	cool temperate	arid	temperate semidesert
IVB11	11	warm temperate	arid	warm temperate semidesert
VB12	12	warm	arid	subtropical semidesert
VIB13	13	subtropical	arid	subtropical desert brush
VIIB14	14	tropical	arid	tropical desert brush
IC15	15	frigid	semiarid	dry tundra, alpine steppe
IIC16	16	cold temperate	semiarid	montane steppe
IIIC17	17	cool temperate	semiarid	temperate typical steppe
IVC18	18	warm temperate	semiarid	warm temperate typical steppe
VC19	19	warm	semiarid	subtropical grasses-fruticous steppe
VIC20	20	subtropical	semiarid	subtropical brush steppe
VIIC21	21	tropical	semiarid	savanna
ID22	22	frigid	subhumid	moist tundra, alpine meadow steppe
IID23	23	cold temperate	subhumid	montane meadow steppe
IID24	24	cool temperate	subhumid	meadow steppe
IVD25	25	warm temperate	subhumid	forest steppe
VD26	26	warm	subhumid	deciduous broad leaved forest i
VID27	27	subtropical	subhumid	sclerophyllous forest
VIID28	28	tropical	subhumid	xerophytic forest
IE29	29	frigid	humid	tundra, alpine meadow
IIE30	30	cold temperate	humid	montane meadow
IIIE31	31	cool temperate	humid	forest steppe, deciduous broad leaved forest
IVE32	32	warm temperate	humid	deciduous broad leaved forest ii
VE33	33	warm	humid	evergreen deciduous broad leaved forest
VIE34	34	subtropical	humid	evergreen broad leaved forest i
VIIE35	35	tropical	humid	seasonal rain forest
IF36	36	frigid	perhumid	rain tundra, alpine meadow
IIF37	37	cold temperate	perhumid	perhumid taiga forest
IIIF38	38	cool temperate	perhumid	mixed coniferous broad leaved forest
IVF39	39	warm temperate	perhumid	deciduous broad leaved forest iii
VF40	40	warm	perhumid	deciduous-evergreen broad leaved forest
VIF41	41	subtropical	perhumid	evergreen broad leaved forest ii
VIIF42	42	tropical	perhumid	rain forest

Table 2 Relationships between broad vegetation categories and classes according to CSCS

Code	> 0 Annual cumulative temperature (GDD0)	Humidity (K)	Broad vegetation name	Corresponding class code
1	0–1300	>0	tundra and alpine steppe	1, 8, 15, 22, 29, 36
2	1300–5300	0–0.3	frigid desert	2, 3, 4
3	1300–6200	0.3–0.9	semi-desert	9, 10, 11, 12
4	1300–6200	0.9–1.2	steppe	16, 17, 18, 19
5	1300–3700	1.2–2.0	temperate humid grassland	23, 24, 30
6	1300–5300	>1.2	temperate forest	25, 31, 32, 37, 38, 39
7	5300–8000	>1.2	sub-tropical forest	26, 27, 33, 34, 40, 41
8	>8000	>1.5	tropical forest	28, 35, 42
9	>5300	0–0.3	warm desert	5, 6, 7
10	>6200	0.3–1.5	savanna	13, 14, 20, 21

Figure 1 Index chart for potential vegetation class (refer to Table 1) in the CSCS-derived model [14].

1.2 Global climatic data

Two sources of monthly precipitation and mean temperature data with different spatial resolutions for global land areas (excluding Antarctica) were used in this study to produce CSCS-based global potential vegetation distribution maps. The first was the global monthly precipitation and mean temperature dataset gridded at a 30 arc-second (i.e., about 1 km) spatial resolution over the 50 years from 1950 to 2000. This was generated using the thin-plate smoothing spline algorithm implemented in the ANUSPLIN software package [20] using weather stations from a large number of global, regional, national, and local sources [21]. We chose this dataset because the method that created it has been used in other global studies [22,23] and performed well in comparative tests of multiple interpolation techniques [21,24]. The other source of data was the Climate Research Unit (CRU) global climate dataset of CRU_TS 2.1 [25]. It consists of multi-variate mean monthly climatology records at 0.5° resolution for global land areas (excluding Antarctica) for the period 1901–2000. In this study, the monthly precipitation and mean temperature datasets for each decade were used. To compare the agreement between the CSCS and HLZ PNV maps and simulate the change of global potential vegetation distribution using the CSCS approach, the average annual GDD0 and precipitation grid data for different periods using the two datasets were generated using ArcGIS software.

1.3 Global DEM and continent boundary data

The global digital elevation model at a 30 arc-second spatial resolution [21], based on the Shuttle Radar Topography Mission (STRM) dataset, was downloaded from <http://srtm.csi.cgiar.org>. To analyze the areas of different vegetation types, the boundary databases of Europe, Asia, Africa, the

Americas and Oceania were downloaded from <http://www.diva-bgis.org/Data>, and utilized in this study. Using ArcGIS software, all of the related databases are transformed to the Mollweide projection with the WGS_1984 spheroid to calculate the area of each vegetation class.

1.4 Comparative maps of global potential vegetation

HLZ is a model that formulates the distribution of potential terrestrial ecosystems in terms of biotemperature, precipitation and potential evapotranspiration [26]. It relates the distribution of major ecosystems (termed “life zones”) to the bioclimatic variables. The HLZ classification divides the world into over 38 life zones (Table 3) on the basis of mean annual biotemperature (in °C), average total annual precipitation (in mm) and potential evapotranspiration ratio (PER) logarithmically [6,26,27]. BIOME4 is a process-based equilibrium, biogeographically- and biogeochemically-coupled vegetation model, modified from Biome3 [28], which simulates global vegetation in the form of 13 plant functional types (PFTs) that are combined to form 28 biomes (Table 3) [29–31]. BIOME4 has been employed in a number of studies of past, present and potential future vegetation patterns [1,32–34].

To study changes in the potential vegetation distribution and make direct comparisons between the CSCS-derived and other well-known global PNV maps (e.g., HLZ, BIOME4), the following PNV maps were used or created by ArcGIS software. First, to demonstrate the accuracy of CSCS PNV map and make appropriate comparisons over the same time period, the CSCS and HLZ PNV maps used in this study were created for 1961–1990 using global mean annual climatology data from the CRU_TS 2.1 dataset, and an existing global BIOME4 PNV map covering the same time period for global mean annual climatology data [29–31]. Consideration of the big differences between the CSCS, HLZ and BIOME4 models in terms of classification indices, threshold values, classification approaches, etc. is required in order to make direct comparisons (i.e., CSCS vs. HLZ, CSCS vs. BIOME4 and HLZ vs. BIOME4) of the three vegetation models; some merging of categories is required. Through repeated tests, a reclassification into five broad categories was proposed; i.e., the 10 categories of CSCS, 38 categories of HLZ, and 28 categories of BIOME4 were divided into the same 5 broad categories, so that systematic comparisons and analyses of the three models would be possible. The five reclassified broad vegetation categories are tundra, desert, boreal and temperate forest, sub-tropical and tropical forest, and grasslands (Table 4). We found that it was not possible to divide the boreal and temperate forest class into boreal forest, temperate forest, sub-tropical forest and tropical forest, since there is also no way to find the same subclasses in the HLZ and MOME4 models. The HLZ model divides forest into boreal forest, cool temperate forest, warm temperate forest, subtropical

Table 3 Global PNV types in the HLZ and BIOME4 models

Classification system	PNV type name and code
HLZ	Polar desert(1), subpolar dry tundra(2), subpolar moist tundra(3), subpolar wet tundra(4), subpolar rain tundra(5), boreal desert(6), boreal dry scrub(7), boreal moist forest(8), boreal wet forest(9), boreal rain forest(10), cool temperate desert(11), cool temperate desert scrub(12), cool temperate steppe(13), cool temperate moist forest(14), cool temperate wet forest(15), cool temperate rain forest(16), warm temperate desert(17), warm temperate desert scrub(18), warm temperate thorn scrub(19), warm temperate dry forest(20), warm temperate moist forest(21), warm temperate wet forest(22), warm temperate rain forest(23), subtropical desert(24), subtropical desert scrub(25), subtropical thorn woodland(26), subtropical dry forest(27), subtropical moist forest(28), subtropical wet forest(29), subtropical rain forest(30), tropical desert(31), tropical desert scrub(32), tropical thorn woodland(33), tropical very dry forest(34), tropical dry forest(35), tropical moist forest(36), tropical wet forest(37), tropical rain forest(38)
BIOME4	Tropical evergreen forest(1), tropical semi-deciduous forest(2), tropical deciduous forest/woodland(3), temperate deciduous forest(4), temperate conifer forest(5), warm mixed forest(6), cool mixed forest(7), cool conifer forest(8), cold mixed forest(9), evergreen taiga/montane forest(10), deciduous taiga/montane forest(11), tropical savanna(12), tropical xerophytic shrubland(13), temperate xerophytic shrubland(14), temperate sclerophyll woodland(15), temperate broadleaved savanna(16), open conifer woodland(17), boreal parkland(18), tropical grassland(19), temperate grassland(20), desert(21), steppe tundra(22), shrub tundra(23), dwarf shrub tundra(24), prostrate shrub tundra(25), cushion-forb, lichen and moss(26), barren(27), land ice(28)

Table 4 Broad vegetation categories reclassified by the CSCS, HLZ and BIOME4 PNV types

Category name	Broad vegetation code ^{a)} in the CSCS	Vegetation type code ^{b)} in the HLZ	Vegetation type code ^{b)} in the BIOME4
Tundra	1	1, 2, 3, 4, 5	22, 23, 24, 25, 26, 28
Desert	2, 3, 9	6, 7, 11, 12, 17, 18, 19, 24, 25, 31, 32	21, 27
Boreal and temperate forest	6	8, 9, 10, 14, 15, 16	4, 5, 7, 8, 9, 10, 11, 15, 17
Sub-tropical and tropical forest	7, 8	20, 21, 22, 23, 26, 27, 28, 29, 30, 33, 34, 35, 36, 37, 38	1, 2, 3, 6
Grassland	4, 5, 10	13	12, 13, 14, 16, 18, 19, 20

a) Broad vegetation name in the CSCS model refers to Table 2. b) The vegetation type name refers to Table 3.

forest and tropical forest, whereas BIOME4 divides it into only two subclasses of temperate forest and tropical forest. Second, to study the changes of global potential vegetation distribution in space at a 0.5° resolution in latitude and longitude, as well as in time for 30-year periods from 1911 to 2000, three CSCS PNV maps for the periods 1911–1940 (T1), 1941–1970 (T2) and 1971–2000 (T3) were created from the global CRU_TS 2.1 datasets. Third, to reflect the detailed spatial distribution characteristics at the most recent time (i.e., year 2000), a global CSCS PNV map was created using the 30 arc-second high spatial resolution datasets from 1950 to 2000 [20,21]. To calculate the area of each PNV class in the global CSCS PNV map, water, and permanent snow and ice cover were excluded using the MODIS IGBP land cover classification dataset from 2001, sourced from <http://wist.echo.nasa.gov>.

1.5 The KAPPA statistic for PNV map comparisons

The Kappa statistic is widely used in assessing model-simulated vegetation distributions. The advantage of the Kappa statistic is that it takes chance agreement into account, regardless of the number of categories being compared in the maps [1,8]. In this study, the Kappa statistic was used to evaluate the similarities between the two kinds of PNV maps. For each category, i is the constructed error matrix for two compared PNV maps, the Kappa statistic is

calculated by the following equation:

$$K_i = \frac{(p_{ii} - p_{i,\text{row}} p_{\text{col},j})}{((p_{i,\text{row}} + p_{\text{col},j}) / 2 - p_{i,\text{row}} p_{\text{col},j})}, \quad (2)$$

where $p_{i,\text{row}}$ is the row total for each category i ; $p_{\text{col},j}$ is the column total for each category j ; and p_{ii} is the individual entry for the row and column on the main diagonal of constructed error matrix. The overall agreement between two compared maps is estimated by the formula:

$$K = (p_0 - p_e) / (1 - p_e), \quad (3)$$

where $p_0 = \sum_{i=1}^c p_{ij}$; $p_e = \sum_{i=1}^c p_{i,\text{row}} p_{\text{col},j}$; and c is the number of categories in each data set.

In general, Kappa statistics greater than 0.85 are considered excellent, values 0.7–0.85 are very good, values 0.55–0.7 are good, values 0.4–0.55 are fair, and values below 0.4 are considered poor or very poor [28].

2 Results

2.1 Agreement in CSCS, HLZ and BIOME4 PNV maps

From Table 5, it can be seen that the CSCS and HLZ PNV maps are more in agreement than comparisons of maps

Table 5 The Kappa statistics for the 5 broad PNV categories identified by CSCS, HLZ and BIOME4 maps for the period 1961–1990 at a global scale

Category name	Broad vegetation category					
	Tundra	Desert	Boreal & temperate forest	Sub-tropical & tropical forest	Grassland	Overall
CSCS vs. HLZ	0.90	0.92	0.78	0.64	0.26	0.74
CSCS vs. BIOME4	0.76	0.67	0.62	0.68	0.42	0.63
HLZ vs. BIOME4	0.84	0.68	0.72	0.60	0.14	0.62

from CSCS and BIOME4 or HLZ and BIOME4. The agreement between the CSCS and BIOME4 PNV maps (overall Kappa statistics of 0.63) is similar to that of the HLZ and BIOME4 PNV maps (overall Kappa statistics of 0.62), both notably less than the very good agreement between CSCS and HLZ PNV maps (overall Kappa statistics of 0.74). Good agreement also occurs for CSCS vs. BIOME4 and HLZ vs. BIOME4 PNV maps with a 0.5° block size simulated by CSCS, HLZ and BIOME4 models using global climatology datasets collected over the same time period (e.g., the 30 years from 1961 to 1990).

In the 5 broad vegetation categories, the tundra has an excellent agreement (0.90) between CSCS vs. HLZ maps, and very good agreements (0.76 and 0.84) between CSCS vs. BIOME4 and HLZ vs. BIOME4 maps. A similar result is found for the desert, where the Kappa statistics vary from 0.67 to 0.92. The predicted extents of the boreal and temperate forest show very good agreements (0.78 and 0.72) under CSCS vs. HLZ and HLZ vs. BIOME4 comparisons and good agreement (0.62) for the CSCS vs. BIOME4 comparison. For sub-tropical and tropical forests, there are good agreements among the three PNV maps, with the Kappa statistics varying from 0.60 to 0.68. The grassland category has only fair agreement (0.42) for the CSCS vs.

BIOME4 comparison, and very poor agreements (0.26 and 0.14) for CSCS vs. HLZ and HLZ vs. BIOME4 comparisons.

2.2 Spatial distribution characteristics of PNV in year 2000

From Figure 3, 10 broad vegetation categories and 42 classes of the potential vegetation can be identified for the world excluding Antarctica. Statistical analysis indicates that the area of global potential vegetation, excluding regions of permanent snow and ice cover, is 1.289335×10^8 km², which covers 96.07% of the total land area of Earth (Table 6).

The spatial distributions of classes of potential vegetation are significantly different from region to region. In Asia, the potential vegetation area is about 4.29036×10^7 km², which is the most extensive of the 5 continental regions and covers 33.28% of the total area of global potential vegetation excluding Antarctica (Table 6). Because of its extent and complicated ecological environment, Asia has the greatest number of vegetation categories in comparison to the other continental regions. Based on the CSCS classification approach (Table 1), there are 42 potential vegetation

Table 6 Statistical result of global CSCS PNV broad categories

Extent	Indicator	Broad vegetation category code ^{a)}									
		1	2	3	4	5	6	7	8	9	10
Globe	Area (10 ⁴ km ²)	1398.83	207.52	773.78	378.10	710.41	2407.96	989.25	1809.23	1893.66	2324.61
	Globe (%) ^{b)}	10.85	1.61	6.00	2.93	5.51	18.68	7.67	14.03	14.69	18.03
Asia	Area (10 ⁴ km ²)	825.38	185.76	404.61	154.75	325.02	825.25	294.97	430.66	520.78	323.18
	Globe (%) ^{c)}	59.00	89.51	52.29	40.93	45.75	34.27	29.82	23.80	27.50	13.90
Europe	Area (10 ⁴ km ²)	67.04	0.02	38.28	70.19	174.99	658.45	13.97	1.52	0.30	10.66
	Globe (%) ^{c)}	4.79	0.01	4.95	18.56	24.63	27.34	1.41	0.08	0.02	0.46
Africa	Area (10 ⁴ km ²)	0.02	0.77	57.80	18.89	0.92	21.53	252.08	438.52	1118.29	1061.26
	Globe (%) ^{c)}	0.00	0.37	7.47	5.00	0.13	0.89	25.48	24.24	59.05	45.65
America	Area (10 ⁴ km ²)	506.13	20.97	224.51	121.66	208.39	846.83	402.23	923.83	60.61	481.70
	Globe (%) ^{c)}	36.18	10.10	29.02	32.18	29.33	35.17	40.66	51.06	3.20	20.72
Oceania	Area (10 ⁴ km ²)	0.27	0.00	48.59	12.60	1.09	55.90	25.99	14.71	193.68	447.81
	Globe (%) ^{c)}	0.02	0.00	6.28	3.33	0.15	2.32	2.63	0.81	10.23	19.26

a) The numbers from 1 to 10 correspond to the broad vegetation categories: 1, tundra and alpine steppe; 2, frigid desert; 3, semi-desert; 4, steppe; 5, temperate humid grassland; 6, temperate forest; 7, sub-tropical forest; 8, tropical forest; 9, warm desert; 10, savanna. b) The percentage of the Earth's land surface covered by the vegetation category. c) The percentage of the global distribution of the vegetation category found in the continent or region.

Figure 2 The CSCS (a), HLZ (b) and BIOME4 (c) PNV maps simulated by 30-year (1961–1990) global climatology grid data at 0.5° spatial resolution.

classes in Asia. Of these, 16 account for over 50% of each corresponding global area. The top 6 classes found in Asia account for over 80% of their corresponding global extent. They are temperate desert (3), warm temperate desert (4), frigid semidesert and alpine semidesert (8), dry tundra and alpine steppe (15), moist tundra and alpine meadow steppe (22), and montane meadow steppe (23).

The Americas form the second largest region and they contain 42 potential vegetation classes. The potential vegetation area is 3.79686×10^7 km², which covers 29.45% of the total area of the global potential vegetation. The dominant vegetation classes are deciduous broad leaved forest iii (39) and rain forest (42), with their individual areas accounting

for over 50% of each corresponding global area.

Africa and Oceania have potential vegetation areas of 2.97008×10^7 and 8.0064×10^6 km², or 23.04% and 6.21% of the total global potential vegetation area, respectively. The dominant vegetation classes include tropical desert (7), tropical desert brush (14), seasonal rain forest (35) on the African continent, and rain tundra and alpine meadow (36), perhumid taiga forest (37), and rain forest (42) in Oceania.

Europe has a potential vegetation area of 1.03542×10^7 km², including 24 potential vegetation classes, and covers 8.03% of the total global potential vegetation. The dominant vegetation classes are forest steppe (25), deciduous broad leaved forest (31), perhumid taiga forest (37) and mixed

Figure 3 The spatial distribution of the 10 broad vegetation categories (a) and 42 vegetation classes (refer to Table 1) (b) in the global CSCS PNV maps in year 2000.

coniferous broad leaved forest (38).

The potential vegetation is characterized by a significant distribution pattern in latitudinal and altitudinal directions (Figure 3). From the Equator to the North Pole, there are 6 major latitudinal zones, which in sequence are: (1) tropical forest, dominated by rain forest (code 42), mainly distributed in the north of South America, Middle Africa and south-eastern Asia; (2) Savanna, dominated by tropical desert brush (14) and sub-tropical desert brush (13), mainly distributed in eastern and central Africa, Central America, and the south of southern Asia; (3) warm desert and sub-tropical forest, principally including tropical desert (7), evergreen broad leaved forest ii (41), and mainly distributed in North

Africa, North America and a large part of Asia; (4) semi-desert and frigid desert, mixed with steppe in central Eurasia and southwestern North America, as well as tundra and alpine steppe in the Tibetan Plateau, dominated by the classes of temperate semi-desert (10), warm temperate semi-desert (11), warm temperate desert (4), and rain tundra and alpine meadow (36); (5) mixture of temperate humid grassland and temperate forest, mainly including the classes of perhumid taiga forest (37), mixed coniferous broad leaved forest (38) and meadow steppe (24), and distributed over all of Eurasia, extending from the east of North America to the east coast of the Pacific Ocean; and (6) tundra and alpine steppe, dominated by the classes of rain tundra and

alpine meadow (36) and tundra and alpine meadow (29), mainly distributed in northern North America, Greenland and most northern Eurasia.

In the southern hemisphere, from the Equator to the most southern edge of Oceania, there are just two major latitudinal zones: (1) The first is dominated by tropical forest, sub-tropical forest and savanna vegetation categories, mixed with a little bit of steppe, and warm desert. Major classes found in this zone include rain forest (42), seasonal rain forest (35), tropic desert brush (14), sub-tropic desert brush (13) and tropical desert (17). This region is mainly distributed in southern and central Africa, northern and central South America, the south of southeastern Asia, and northern Oceania. (2) The second region is dominated by temperate forest and semi-desert, mainly including the classes of perhumid taiga forest (37) and sub-tropical desert brush (13), and mainly is distributed in southern-most America, Africa and Oceania. As a result of interactions among topography, climate and vegetation, there are probably more vegetation categories distributed in eastern South America.

In mountainous areas, spatial vegetation distribution is more complicated and has obvious vertical distribution characteristics because of topographic effects. For example, in the Himalaya mountains and Tibetan plateau in southwestern China and adjacent areas (Figure 4), there is a great deal of tundra and alpine steppe (purple color) scattered with ice and snow (white color) mixed with temperate humid grassland (yellow color) and temperate forest (dark

blue color) (Figure 4(a) and (b)). From the top area of Mt. Everest to the southwest through Nepal and India (Figure 4(c)), the elevation decreases from > 8200 m to about 50 m (Figure 4(d)). The potential vegetation categories change stepwise from tundra and alpine steppe, to temperate forest, to sub-tropical forest (bright green) to tropical forest (red color) in the southern Nepal, and to savanna (dark green) in the north of India.

2.3 Change in global PNV distribution from 1911 to 2000

From Table 7, clear decreasing trends can be seen for the area of tundra and alpine steppe and desert vegetation categories. This has amounted to 6.06% and 5.90%, respectively, over the 90 years from 1911 to 2000. Over the same period, the area of forest and grassland vegetation categories has increased by 2.23% and 4.39%, respectively.

In the 3 forest vegetation categories, the total area increased by 3.06% over the period from 1940 (Figure 5(a)) to 1970 (Figure 5(b)), then slightly decreased by 0.80% over the period from 1970 to 2000 (Figure 5(c)). The area of temperate forest increased significantly from 1940 to 1970, but no obvious trend emerged from 1970 to 2000. The area of sub-tropical forest changed slightly in the 90 years. It had a small increase from 1940 to 1970, which was followed by a slight decreasing trend after 1970. This is the same as what was observed for variation in tropical forest cover. In

Figure 4 The spatial distribution of the CSCS PNV on vertical level in the Himalaya mountains. (a) and (b) depict the PNV map and digital elevation model in the Himalaya area; (c) and (d) are PNV map and digital elevation model in the area surrounding Everest.

Table 7 Area variation for the 10 broad vegetation categories in the periods 1911–1940 (T1), 1941–1970 (T2) and 1971–2000 (T3)

Broad vegetation category	Area (10^4 km^2) in different periods			Variation rate (%)		
	T1	T2	T3	T1 vs. T2	T2 vs. T3	T1 vs. T3
Tundra and alpine steppe	1400.95	1363.57	1316.04	−2.67	−3.49	−6.06
Frigid desert	204.25	207.59	165.97	1.64	−20.05	−18.74
Semi-desert	783.88	754.44	771.85	−3.76	2.31	−1.54
Steppe	437.79	395.19	398.12	−9.73	0.74	−9.06
Temperate humid grassland	489.38	431.56	444.87	−11.82	3.08	−9.10
Temperate forest	2557.1	2691.17	2699	5.24	0.29	5.55
Sub-tropical forest	911.22	919.65	903.58	0.93	−1.75	−0.84
Tropical forest	2329.52	2364.2	2324.4	1.49	−1.68	−0.22
Warm desert	1863.03	1831.54	1745.2	−1.69	−4.71	−6.32
Savanna	1896.96	1915.18	2105.06	0.96	9.91	10.97

Figure 5 The geographic distribution of broad vegetation categories in the three CSCS PNV maps simulated by the CRU TS 2.1 climatic data in the periods from 1911 to 1940 (T1), 1941 to 1970 (T2) and 1971 to 2000 (T3).

the three desert vegetation categories, the overall area had a decreasing trend, falling by 2.02% and 3.96% for the periods from 1940 to 1970 and 1970 to 2000, respectively. The semi-desert vegetation category also had an obvious decreasing trend in the period from 1940 to 1970, but then a slight increasing trend from 1970 to 2000, but overall the trend decreased for the entire study period. For frigid desert, there was no obvious variation in the period from 1940 to 1970, whereas a significant decrease, 20.05%, occurred during the period from 1970 to 2000, the greatest change rate of the ten broad vegetation categories. The warm desert showed a decreasing trend of 6.32% for the entire period. In the three grassland vegetation categories, the area variation rate decreased by 2.91% in the period from 1940 to 1970, then increased by 7.52% from 1970 to 2000. As a whole, the area increased significantly for the savanna, but decreased for the steppe and temperate humid grassland vegetation categories.

3 Discussion

Overall, good agreement was found among the CSCS, HLZ and BIOME4 PNV maps in their evaluations of the extent of tundra, forests and desert, and poor agreement was found for grassland vegetation coverage. However, it is not an easy task to explain why. A first point to consider is that discrepancies exist in the level of detail under which grassland vegetation is classified in the three PNV models. Grassland vegetation accounts for 25% of global land coverage, but it is simplistically represented in the HLZ and BIOME4 models. In the HLZ model, 38 PNV types are recognized, but only one type of grassland (i.e., cool temperate steppe) is specified and no type of savanna [35]. The BIOME4 model focuses more on forest vegetation, including 13 types that are based on thermal grades, and evergreen, deciduous, needleleaf and mixed types from vegetation characteristics (Table 3). However, the BIOME4 model does improve over HLZ in its examination of grasslands. Of the 28 PNV types identified by BIOME4, 5 are grasslands (i.e., tropical grassland, temperate grassland, tropical savanna, cold parkland and temperate deciduous broadleaf savanna). That is, the CSCS PNV approach is even more suitable for classifying grasslands — which it was originally devised to do. Not only does it provide a detailed classification of grassland vegetation, but also produces a detailed classification of the other vegetation types. The CSCS can distinguish 42 classes of vegetation, consisting of 11 classes of grassland, 15 classes of forest, 6 classes of tundra, and 10 classes of desert (Table 1). This means that the CSCS model can produce a more balanced classification of the terrestrial ecosystem than the HLZ and BIOME4 models do. Therefore, the poorer agreements for grassland coverage as assessed by CSCS vs. HLZ and BIOME4 vs. HLZ comparisons could be primarily due to the simplification of grass-

land types in the HLZ and BIOME4 models.

A second point to consider is that there are significant differences in the constraints applied in constructing the CSCS, HLZ and BIOME4 models. Both HLZ and CSCS are statistical and equilibrium models based on biologically determined climatic constraints, which consider biotemperature and precipitation (MAP) as important classification constraints. However, the model definitions are quite different. In the CSCS model, the biotemperature is defined as growing degree-days on a 0°C base (GDD0), and precipitation is used in the index K ($K = \text{MAP}/0.1 \times \text{GDD0}$) [14]. However, a mean annual biotemperature is defined (i.e., the average value of mean daily temperature over 0°C and below 30°C, BT), and precipitation is not only directly used as a constraint, but generally used to simulate the potential evapotranspiration ratio (PER) (e.g., $\text{PER} = 58.9 \times \text{BT}/\text{P}$) as well in the HLZ system [6,26,27]. In comparison, BIOME4 is a coupled biogeographic and biogeochemical model that simulates the equilibrium distribution of major PNV types (biomes). Compared to the CSCS-derived model, the BIOME4 model employs not only more bioclimatic constraints (e.g., GDD0, GDD5, temperature of coldest month, mean monthly precipitation, temperature, and percent sunshine) but also other constraints (e.g., PFT, LAI, soil moisture) [29–31]. The above discrepancies among the CSCS, HLZ and BIOME4 models ordinarily lead to different definitions for the same vegetation type. Consequently, there are still some deviations in the definition of broad vegetation categories, even after aggregation with the original types. By repeating tests, we found that separation of the current five big categories into finer categories (e.g., the division of the forest class into boreal forest, temperate forest, sub-tropical forest and tropical forest) is difficult. This is because there are big differences in the three sets of classification indices, threshold values and classification approaches.

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [36,37] indicated that during the 20th century, precipitation in much of the Northern Hemisphere land areas increased by 0.2% to 1% per decade, and that no comparable systematic changes were detected in broad latitudinal averages over the Southern Hemisphere. The increase in temperature during the 20th century was the largest of any century during the past 1000 years. As a whole, global temperature had an increasing trend over the 20th century, but most of the warming occurred in the two periods from 1910 to 1945 and 1976 to 2000. Our study shows that over the entire study period, the extent of desert vegetation decreased by 5.90%, and the area of grassland vegetation increased by 4.39%; decreasing trends were found for the extent of sub-tropical and tropical forests, and an increasing trend for temperate forest; the tundra and alpine steppe had a decreasing trend, but more sharply decreased since the late stage of 1970s (T3). Similar results were also found at regional and global scales [1,38–42].

This suggests that the late 1970s may be a critical period or key starting point when the spatial distribution of potential natural vegetation started to change significantly because of obvious changes related to global climatic warming [36,37].

This study demonstrates the significant role that the CSCS approach can play in the simulation of potential vegetation distributions in relation to climate change at a global scale. This suggests that the CSCS-based models not only have the ability to investigate the effects of climate change on vegetation type and distribution, but also can contribute to balanced predictions of various vegetations, especially detailed classes of grassland vegetation. This is an obvious advantage of the CSCS-based model and a necessary supplement to the other well-known global PNV models.

4 Conclusions

On a global scale, there is good agreement among the CSCS, HLZ and BIOME4 PNV maps. The CSCS-derived model has the ability to successfully predict the distribution of tundra, desert and forests, and has better abilities than the HLZ classification system for the simulation of grassland. Compared to globally well-accepted PNV models like HLZ and BIOME4, the CSCS model has advantages in the simple input parameters and low computational costs. It can not only systematically classify the extent of known and unknown global terrestrial vegetation, but can recognize more detailed grassland vegetation classes as well. Additionally, a CSCS-derived model can be used to predict potential vegetation classes and their spatial distribution, which is a critical part of research regarding the effects of climate change on vegetation successions, and plays an important role in the management and planning of anthropogenic controls on terrestrial vegetation, especially in grasslands.

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