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China Vegetation Classification: concept, approach and applications

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Abstract

Classification of vegetation is an essential tool to systematically describe and understand the characteristics of vegetation. China is one of the vegetation type-richest countries in the world. However, the methodologies and achievements of vegetation research in China, especially its vegetation classification system, are little known to the world. Here we briefly review the developmental history of the China vegetation classification system (China-VCS), and present its key concepts, main features and detailed protocols, as well as the applications. Professor Hou first presented the vegetation classification principles and a five-level system for the vegetation of the entire country in 1960. The system was modified to eight levels and more than 500 formations were defined in 1980. The system was revised in the book "Flora and Vegetation Geography of China" in 2014. The China-VCS separates cultural vegetation from natural/semi-natural vegetation; for natural/semi-natural vegetation, it uses an integrated physiognomic-ecological-floristic-dynamic classification approach. It has eight hierarchical levels, i.e., *Vegetation-type-group*, *Vegetation-type*, and *Vegetation-subtype*; *Formation-group*, *Formation* and *Subformation*; as well as *Association-group* and *Association*. Each vegetation-type-group is considered as a consistent classification section (CCS). Seven vegetation-type-groups, 40 vegetation-types and 93 vegetation-subtypes have been described in this system. About 1519 formations belonging to 711 formation-groups have been primarily vetted and listed, while the systematic census data on subformations, association-groups and associations are still not available due to the lack of a national plot database. Cultural vegetation is classified according to plant growth form, community structure, habitat factors, cultivation regimes and economic significance. The classification system for cultural vegetation includes five hierarchical levels, i.e., *Category*, *Type*, *Subtype*, *Cultivation-group* and *Cultivation*. The China vegetation classification system has been widely used not only for vegetation description and mapping but also for biodiversity conservation and ecosystem management. Areas of the system that need further improvement include increasing its compatibility with other major vegetation classification systems in the world, using more quantitative indicators, using other indicators if no dominant species can be identified and developing a more appropriate system for cultural vegetation classification.

Keywords: China-VCS (China Vegetation Classification System); vegetation-type; formation; association.

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Introduction

China's territory spans several climate zones, from tropical to cold temperate, and has large relief variations from coastal to the Himalayan Mountains. The territory is rich in vegetation types. However, the methodologies and achievements in vegetation research in China, especially the vegetation classification system used by Chinese scientists, are little known to the world. In addition to the obvious reason that all major achievements in vegetation research in China were published in Chinese, two other reasons may explain the lack of sharing classification knowledge. First, modern vegetation research in China started relatively late and the early vegetation scientists adopted different approaches from different schools of vegetation science in their work (ECVC 1980; Song 2001); thus, China lacked a unified standard and method. Second, China is a country with a vast territory, complex

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natural conditions and diverse vegetation types. Most Chinese vegetation scientists focused their research on specific vegetation types in local regions and failed to acquire comprehensive knowledge on vegetation characteristics at the national scale.

Vegetation classification is an essential tool to systematically describe vegetation characteristics and prepare vegetation maps, as well as to understand, manage and protect biodiversity and ecosystem function, especially for a large region or nation (De Cáceres et al. 2015). There are various vegetation classification approaches and systems in the world, even in China, which seriously hinders integration, sharing and application of vegetation information and data (UNESCO 1973; Song 2004, 2011, 2013; ECVMC-CAS 2007; Chen et al. 2014). Recently, we have launched a large project to systematically synthesize and summarize available information on Chinese vegetation types to compile the "Vegetation Monographs of China". One of the challenges in this project is to propose a proper vegetation classification system; i.e., deciding to continue to use the current China vegetation classification system (ECVC 1980, ECVMC-CAS 2007, Chen et al. 2014), or to improve it so that the classification system can be more easily compatible with major international classification systems (Song 2011).

To enhance the communication with international vegetation scientists who do not understand Chinese and improve their understanding of vegetation classification in China, here we introduce: (1) the history of vegetation study leading to the vegetation classification in China; (2) the China Vegetation Classification System (China-VCS); and (3) the application of China-VCS in vegetation mapping and ecosystem management. Finally, advantages and limitations of this approach and system are discussed.

History of vegetation study leading to the vegetation classification in China

Pioneer studies characterized by local investigation and simple descriptions of plant communities without systematic vegetation classification

The rise and development of phytocoenology and vegetation ecology in the world, especially in Europe, was mainly during the 100 years before 1950, whereas the vegetation survey and research in China started much later, in the 1920s, and used the various methods from different schools of vegetation science in America and Europe (Song 2001). In 1922, plant ecology or phytocoenology was first introduced in the text book "High Botany". Sung-Shu Chien started to teach plant ecology and research in 1925 in Tsinghua University. He published "Preliminary Notes on the Vegetation and Flora of Huang Shan" in 1927 and "Vegetation of the Rocky Ridge of Chung-shan, Nanking" in 1932 (ECVC 1980, Qian 2004). These papers are considered the earliest classification works in China. After Sung-Shu Chien, Ji-Tung Li continued to teach in Tsinghua and mainly focused on forest investigation. His students and other researchers published a series of vegetation investigations and studies at regional scales or on special habitats. However, these studies mainly described the characteristics of plant communities, such as the dominant species and ecological distribution patterns, without a systematic vegetation classification.

Extensive vegetation surveys and effective organization led to systematic vegetation classification from 1950's to 1980's

After the civil war in the mainland of China, in order to exploit natural resources effectively, a large number of extensive vegetation survey programs were successively conducted from the 1950's to the 1980's at the provincial scale and in many key regions with ecological and/or economic significance. At the same time, many departments and local governments also organized local vegetation surveys for special purposes. Overall, these surveys covered most of the country.

A large number of plots were acquired from these projects, but these surveys were conducted by different experts with various methods, such as the geobotanical approach learned from Russia (Lavrenko & Korcagin 1959) and the phytosociological approach learned from Europe (Braun-Blanquet 1964). Most of the plot data were kept by the investigators themselves or the survey organizers, and a large number of plant communities were defined in various publications. Characteristics of associations or plant communities were described based on these plots, but there was not a consistent national vegetation classification system.

Xue-Yi Hou played the most important role in unifying vegetation research methods including vegetation classification in China. He published the first version of "Vegetation of China" (Hou 1960), in which the overall characteristics of Chinese vegetation were described and a "phytocoenological-ecological principle" for vegetation classification was proposed and used. This principle integrated both plant community physiognomy and ecological attributes in vegetation classification. He proposed a draft China vegetation classification system with five levels: *vegetation-type*, *formation-group*, *formation*, *association-group* and *association*; 27 vegetation-types were defined for natural/semi-natural vegetation. He also suggested that the addition of a level below *vegetation-type* might be necessary and some types might be redefined as research progressed.

In 1976, the Chinese Academy of Sciences organized the Editorial Committee of Vegetation of China (ECVC)

to systematically summarize the achievements of vegetation surveys and research in China and to compile the book "Vegetation of China". Experts from throughout the country pooled their plot data together and conducted an intensive discussion on vegetation classification. Based on Hou's phytocoenological-ecological principle and their plot data, they reached a broad consensus on the vegetation classification system with three classes including eight levels and set up the primary criteria for each level. The criteria included vegetation physiognomy, dominant species, floristic composition, and environmental attributes; thus, it is an integrated physiognomic-ecological-floristic-dynamic classification approach. Finally, 29 *vegetation-types* and 561 *formations* for natural/semi-natural vegetation were defined in this book based on plot data and associations previously published (ECVC, 1980). However, some of the criteria were equivocal and were not strictly enforced. Further, the nomenclature of classification units was not unified.

Cultural vegetation was also classified. Criteria included plant growth form, community structure and habitat factors, as well as management patterns and economic significance (see below).

Completion of China-VCS; The classification approach

During the next 30 years, more and more plot data were acquired from continuous vegetation surveys. Dozens of vegetation books, thousands of papers and theses were published and many new plant community types were described. In these publications, the phytocoenological-ecological principle and the framework of vegetation classification were modified in general, but some criteria were revised and classification levels were renamed. For example, in "Vegetation Map of the People's Republic of China (1:1.000.000)" complied during the 1980's and 1990's (ECVMC-CAS 2007), the consistent classification sections (CCSs; a subset of a classification system where vegetation types are defined using the same criteria and procedures; De Cáceres et al. 2015) and the protocols of vegetation classification were modified, and the number of *vegetation-types* was changed to 46 for natural/semi-natural vegetation and seven for cultural vegetation.

Based on synthesizing the latest vegetation research, China-VCS was revised in the book "Flora and Vegetation Geography of China" (Chen et al. 2014). All classification levels were revised, and most of the consistent classification sections (CCSs) were re-defined with more exact criteria. A unified nomenclature was established. In total, 40 vegetation-types of seven vegetation-type-groups were defined in the latest China-VCS. More details are described below.

China Vegetation Classification System (China-VCS)

Overall structure and main features of the classification approach

Natural/semi-natural vegetation classification

The classification system for natural/semi-natural vegetation has three main levels: upper level *vegetation-type*, middle level *formation*, and lower level or basic level *association*. Above each of the three main levels, an auxiliary level is additionally used, i.e., group of the level. Under the *vegetation-type* and *formation* levels, there is also an auxiliary sublevel. So, there are eight levels in total (Table 1). Each of the seven vegetation-type-groups is considered as a CCS. Within each vegetation-type-group, some vegetation-types that have only one vegetation-subtype are directly classified into formation-groups. For example, there is not a subtype under the 'Sclerophyllous evergreen broad-leaved forest vegetation-type' that only includes one formation-group and 13 forma-

Table 1. Hierarchy of China Vegetation Classification System.

Levels	Units	Examples
Upper	Vegetation-type-group	Forest
	Vegetation-type	Deciduous needle leaved forest
	Vegetation-subtype	Cold temperate deciduous needle leaved forest
Middle	Formation-group	Larch forest (*Larix* forest)
	Formation	*Larix gmelinii* forest
	Subformation	–
Lower (basic)	Association-group	*Larix gmelinii-Ledum palustre* forest
	Association	*Larix gmelinii-Ledum palustre-Vaccinium vitis-idaea-Sphagnum squarrosum* forest

tions dominated by 13 evergreen oaks mainly occurring in areas of southwestern China, where the climate is characterized by a hot and dry period during the spring and early summer. As finer resolution levels are always nested within a coarser resolution level, a new plot can be assigned by comparing the attributes of the sampled community with the criteria of CCSs in the top-down direction. Here we briefly describe the concept of each level:

Vegetation-type-group is the uppermost unit and is defined based on the comprehensive ecological conditions and the physiognomy of vegetation. The unit generally reflects the main continental biomes (zonal vegetation) and the main azonal vegetation. Seven vegetation-type-groups are defined as forest, scrubland, desert, steppe, meadow and herbaceous thicket, alpine vegetation, and swamp and aquatic vegetation (Chen et al. 2014).

Vegetation-type is the main upper class unit in the same vegetation-type-group, which is the assemblage of the plant communities with the dominant species in the dominant stratum sharing same or very similar life form (or growth form; Supplement S1). Communities with the same physiognomy and similar ecological processes were classified into a vegetation-type. For example, deciduous needle-leaved forests and evergreen needle-leaved forests are defined as different vegetation-types. Forty vegetation-types are defined in the current China-VCS.

Vegetation-subtype is classified mainly based on the differences in ecological conditions of the same vegetation-type. The determining factors are different among CCSs. For example, temperature may be one of the main factors in some vegetation-types but not in others; 93 vegetation-subtypes are defined.

Formation-group is the assemblage of the formations, of which the dominants have very similar growth form and ecological habits (Supplement S2) and belong to the same taxonomic genus. About 711 formation-groups have been defined, including those only containing one formation.

Formation is the main middle class unit under one vegetation-type or vegetation-subtype, and is the assemblage of the plant communities with the same dominant species in the dominant stratum. About 1519 formations are defined, but some of them need to be reviewed.

Subformation is an auxiliary class unit below formation. Some species with wide ecological amplitudes may dominate in plant communities occurring in obviously different ecological habitats, but the difference is not large enough to assign the communities into different vegetation-types or vegetation-subtypes. These communities can be classified as different subformations. For example, the desert communities dominated by *Haloxylon ammodendron* can be assigned to four subformations, i.e., *H. ammodendron* sandy desert, *H. ammodendron* gravelly desert, *H. ammodendron* loamy desert and *H. ammodendron* halophytic desert. It is not necessary for most formations to be classified into subformations.

Association-group is the assemblage of communities with the same dominant species in the dominant stratum and in a second stratum which share similar structure and ecological conditions, such as temperature, moisture, soil pH and texture, landform, etc. There is not a systematic census of association groups in China's classification system.

Association is the basic class unit, which is the assemblage of the communities with same or very close properties, such as the same dominants in all strata or *synusiae*, very similar overall species composition and structure, and very similar ecological conditions. Currently, there is not a systematic census of associations for the entire country, but some have been identified and described in publications (Song 2013; Wang et al. 2014; Yang et al. 2014).

Cultural vegetation classification

Cultural vegetation is classified according to plant growth form, community structure, habitat factors, management patterns and economic significance. The hierarchy of the cultural vegetation classification system is defined separately from that of natural vegetation; it has five levels: *category*, *type*, *subtype*, *cultivation group*, *cultivation* (Supplement S3). There are three categories, i.e. herbaceous, woody, herbaceous and woody, defined by plant life form. Type is defined by the physiognomy and structure of the community and the economic products. Field crop type is classified into dry-land crop and paddy-land crop subtypes, while both economic forest types and orchard types are classified as deciduous subtype and evergreen subtype. Cultivation group is recognized by the cultivation regime; for example, number of crops per year, including crop rotations and multicrop systems. Cultivation is recognized by the cultivated plant species.

Classification protocols for natural/semi-natural vegetation

The protocols for assigning a plot to a classification unit are listed in Table 2 and Supplement S4; separate protocols are given for each of the CCSs (each hierarchical level for each vegetation-type-group). For vegetation-type-groups, criteria focus on climate and dominant physiognomic cover. Classification protocols for the middle levels of the hierarchy (formation-group, formation, and subformation) are mainly based on the floristic dominants in the dominant strata, and the subformations usually reflect the differences of community habitats. Classification protocols for the lower levels of the hierarchy (association-group and association) are the floristic

Table 2. The criteria to define the seven vegetation-type-groups.

Vegetation-type-groups	Criteria of plant communities	Additional ecological and physiognomic features
Forest	Dominated by trees, and coverage of tree layers ≥ 30%	Humid and semi-humid climate, or the tree roots can reach underground water; Normally, tree layer is higher than 5 m with exceptions in mangrove forest, coral island forest and dwarf forest near tree line up to alpine in mountains.
Scrub	Dominated by mesophytic scrub layers and coverage of the scrub layers ≥ 30%	Humid, semi-humid and semi-arid climate, or the scrub roots can reach underground water; Saplings with scrub height may be included in scrub layer. Height is normally < 5 m.
Desert	Dominated by shrubby and/or semi-shrubby super-xerophytes; plants usually are sparse; the coverage of plant community is usually < 30%	Arid climate; Usually bare land is more than 50%. Plants of *Haloxylon* genus grow sometimes as small trees and more than half of the twigs are withered and die in winter. They had been recognized as dwarf semi-arbor and the communities dominated by them recognized as desert.
Steppe	Dominated by xerophytic herbs or semi-shrubs.	Semi-arid climate mainly; Most of aboveground parts of the semi-shrubs wither and die during winter, and only the basal part of the individual may produce new shoots.
Meadow and herbaceous thicket	Dominated by herbaceous mesophytes.	Temperate to cool-temperate and semi-humid to humid climate; or with shallow groundwater; or a relatively stable succession state in herbaceous phase of forest or scrub under frequent human interference.
Alpine vegetation	Dominated by mesophytic herb	Above the forest-line or shrubland in altitudinal belt.
Swamp and aquatic vegetation	Dominated by hygrophyte hydrophyte, but not include the mangrove communities.	Extremely wet soil and water on ground surface, and even in water body. Mangrove is defined as one vegetation-type belonging to forest.

dominance in multiple strata or *synusiae*. The criteria below represent the intensive class definitions of the types.

In the forest vegetation-type-group and the scrub vegetation-type-group, the protocols and criteria to distinguish vegetation-types are mainly life form of the dominants and community physiognomy, and sometimes particular ecological habitats (Supplement S4.1-4.2). For example, forest vegetation-type-group is divided into 12 forest vegetation-types having the same or similar dominant growth forms: deciduous needle-leaved forest, evergreen needle-leaved forest, mixed needle and broad-leaved forest, deciduous broad-leaved forest, mixed deciduous and evergreen broad-leaved forest, evergreen broad-leaved forest, etc. For classifying vegetation-subtypes, the criteria are based mainly on the ecological conditions, such as temperature, moisture availability and soil properties, and occasionally on particular community structures (ECVC 1980, Chen et al. 2014). For example, evergreen needle-leaved forest includes four vegetation-subtypes adapting to regional temperature: cold temperate evergreen needle-leaved forest, temperate evergreen needle-leaved forest, warm evergreen needle-leaved forest, and hot evergreen needle-leaved forest. At the formation-group level, cold temperate evergreen needle-leaved forest can be divided into four formation-groups dominated by different taxonomic genera: cold temperate *Abies* forest, *Picea* forest, *Pinus* forest and *Sabina* forest. At the formation level, the cold temperate *Abies* forest can be classified into different formations dominated by different *Abies* species; e.g., *Abies fargesii* forest, *Abies chensiensis* forest, *Abies georgei*, etc. Finally, *Abies fargesii* forest can be classified into different associations showing the same dominant species in all strata, very similar species composition and structure and similar ecological conditions.

In the desert vegetation-type-group, the protocols and criteria to distinguish vegetation-types especially focus on leaf morphology of the dominants (Supplement S4.3). Two vegetation-subtypes (i.e., succulent leaved semi-shrub desert vegetation-subtype and succulent leaved halophytic semi-shrub desert vegetation-subtype) are defined within the succulent leaved semi-shrub desert vegetation-type, while the other seven vegetation-types have no subtypes classified. In the steppe vegetation-type-group and the meadow and herbaceous thicket vegetation-type-group, the protocols and criteria to define vegetation-types are the dominant life form (growth form) and community physiognomy (Supplement S4.4-4.5). For vegetation-subtypes, criteria are the habitat properties and the ecological types of the dominant (component) species. Moisture availability is especially important for defining steppe vegetation-subtypes. In the alpine vegeta-

tion-type-group and the swamp and aquatic vegetation-type-group, the classification protocols to define vegetation-types and vegetation-subtypes are community physiognomy and habitat features (Supplement S4.6-4.7). The dominant life form is important for defining vegetation-subtypes of alpine tundra and the features of water habitats for classifying swamp and aquatic vegetation.

Applications of China Vegetation Classification System

Spatial and temporal scope

The classification is based on expert knowledge from studies completed from 1950 to present and encompassing all known plant communities throughout China, albeit plot data are limited in some areas.

Degree of completeness

Generally, the concept and definition of formations are relatively clear and widely accepted by most of Chinese ecologists, although sometimes it is difficult to determine the dominant species of complex communities in subtropical and tropical areas. Most books currently describe the characteristics of vegetation at the formation level. As noted above, about 1519 formations have been vetted after systematically summarizing the published data. Assemblage of these formations above Formation levels is confirmed as well. As few books describe the vegetation at the association level (Song, 2013; Wang et. al. 2014), the quantities of associations and association groups in the classification are still not clear.

Applications

Since the publication of "Vegetation of China" in 1980, the vegetation classification approach has been applied by most Chinese scientists in their research and practices, such as vegetation surveys, biodiversity monitoring and nature conservation, ecosystem classification (Sun 2005) and regional development planning. Most books describing vegetation in a province or region adopted this system. In some applications, the systems were more or less modified, for example on classification levels and CCSs as well as protocols and nomination standards, to cope with particular vegetation features in a province or region (Huang et al. 1988; IBCAS 1988), or due to authors' preference or traditional habits (Wang et al. 2014). The classification system and map were also widely used in the study of global change effects, such as in the estimates of ecosystem carbon fluxes, biodiversity and ecosystem dynamics.

Mapping

China-VCS was widely applied in different versions of national vegetation maps (scale 1:4 000 000, scale 1:1 000 000) and in vegetation maps of different provinces and regions with various scales. Formation is the most common vegetation mapping unit. Lower levels, however, are also mapped according to the variable distribution patterns of particular formations. For example, *Larix gmelinii* forest is the most common formation in the Daxinganling Mt. Its extent on a vegetation map (scale 1:1 000 000) would be very large compared to most other types. Therefore, some subformation units for this formation may be applied so that more detailed information about the distribution pattern of this formation can be realized for research and land stewardship.

Supportive infrastructure

Currently, there is not a national vegetation database and most plot data are kept by vegetation scientists personally or ecology-related departments, such as the Institute of Botany, Chinese Academy of Sciences, and Peking University. We are trying to construct a national vegetation information database to manage comprehensive vegetation data and information of China, including plot data and habitat features, pictures of communities and component species, pertinent literature, vegetation maps, descriptions of the vegetation classification system and community types, etc.

Advantages and limitations of the approach

China-VCS is a fundamental achievement and a useful tool for ecological research in China. The classification approach is highly adaptive and can be easily implemented in practice to define new community types and describe their characteristics. Based on the top-down hierarchical levels of the classification system, it is easy to assign a new vegetation plot into the current vegetation classification system or define a new classification unit if the plot does not match any given unit. Based on the classification system, most vegetation types in China have been described at different detailed levels during the past 40 years. It is an introduction and short way to comprehensively understand and sustainably manage the vegetation of China.

The classification system still has many limitations, although it has been modified by many experts personally or collaboratively in various research and applications. Four areas are in need a consideration for classification improvement. The first area is compatibility with other vegetation classification systems. The current classification levels and unit names are not consistent with other

major vegetation classification systems in the world; even in China, there are many personally modified versions (e.g., Song 2004, 2011; ECVMC-CAS 2007; Chen et al. 2014; Wang et al. 2014). This inhibits academic communication. For example, "formation" in this system refers to the communities with the same dominant species in the dominant stratum, whereas in other systems, these same criteria may define as a "group" or "alliance" (e.g., US National Vegetation Classification or Braun-Blaunquet approach). The second involves the accuracy of the description of plant communities using quantitative, instead of qualitative, descriptors. For instance, plant growth of the same species may vary among habitats. Life form of *Haloxylon* is considered a tree, but they often grow in shrub form. Assigning a plot or community dominated by these shrub-like plants is still difficult and seems arbitrary. The third area for improvement may be on subtropical and tropical forests, which often consist of diverse species in the canopy tree layer that have nearly equal dominance. Thus, defining such a plant community using its dominant species is arbitrary. The fourth area for improvement is within cultural vegetation, which is very complex and may vary due to many external drivers, including economic conditions and societal development. Current classification approaches do not cope with all of the complex cultural vegetation types.

Author contributions

K.G. conceived this paper and led the writing, K.G. and C.C.L. wrote the first manuscript, and Z.Q.X., F.Y.L., S.B.F., Z.J.L. and K.P.M. revised the manuscript.

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Supplement S1: Plant Life form system.
Supplement S2: Plant ecological types (Plant ecological habits).
Supplement S3: Hierarchy for cultural vegetation.
Supplement S4: Classficiation protocols and criteria to define vegetation-types and vegetation-subtypes in the seven vegetation-type-groups.

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