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Cross-reference for relating Genetic Soil Classification of China with WRB at different scales

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ABSTRACT

Soil classification systems are not consistent between countries or organizations thereby hindering the communication and organizational functions they are intended to promote. World Reference Base for soil resources (WRB) was endorsed and adopted by the International Union of Soil Sciences (IUSS) as the standard for soil correlation and international communication. As a widely used classification system in China, Genetic Soil Classification of China (GSCC) differs from WRB in its underlying understanding about the genetic process. The differences limit communication between Chinese and international soil scientists because there is no standard cross-reference between GSCC and WRB. This paper describes a cross-reference of GSCC to WRB at different scales. The basic soil data set used in the study includes 7292 soil profile data (representative of soil series) collected throughout China. First, a brief history of soil classification in China is provided to familiarize readers with GSCC and its origins. Second, cross-reference at the pedon scale is addressed based on data compiled from 51 monoliths acquired in China by the International Soil Reference and Information Centre (ISRIC) in the 1980s and 1990s. Each of GSCC's 7292 soil series is classified into their equivalent reference soil groups according to the WRB soil reference key. Pedon scale cross referencing is discussed using the database from the Second National Soil Survey of China. Third, the concept and calculation of referencibility is introduced and the process for cross-referencing soil classification systems at national scale is addressed. GIS based analysis generates 60 reference results between GSCC soil great groups and WRB reference group. Results demonstrate that there is great variability in the maximum referencibility between soil great groups of GSCC and WRB soil groups, which ranged from 29.4% to 100%. In terms of the maximum referencibility, it can be divided into three categories: high (80%–100%), intermediate (50%–80%), and low (<50%). Among the 60 soil great groups of GSCC, 12 could be labeled as high maximum referencibility, 27 categorized as medium maximum referencibility and the remaining 21 are associated with low maximum referencibility. Finally, the main cause of low maximum referencibility is explored and the potential solution to improve cross reference accuracy was proposed.

1. Introduction

Classification is a fundamental part of rational study and management of soil resources, serving as an organizational framework and descriptor of soil properties (Smith, 1963; Isbell, 1996; Droogers and Bouma, 1997; Shi et al., 2006a; Simas et al., 2008). Systematic soil classification is also a vehicle for communicating research results and extending the benefits of new knowledge to other locations. Classification in conjunction with soil mapping provides a method for planning agricultural output, allows the application of new management techniques, and supports the use of environmentally sound land use practices.

The first official version of the World Reference Base for Soil Resources (WRB) was released at the 16th World Congress of Soil Science at Montpellier of France in 1998 (FAO/ISRIC/ISSS, 1998). It was endorsed and adopted as the International Union of Soil Sciences (IUSS)'s standard for soil correlation and international communication. After eight years of intensive worldwide testing and data collection, the second version of WRB was published in 2006 (IUSS Working Group WRB, 2006). The system has contributed to the understanding of soil science in the public debate and in the scientific community, and has been used extensively. Soil scientists all over the world have been devoting untiring efforts to establish a globally applicable soil reference system. Notably, the International Soil Reference and Information Centre (ISRIC) conducted an extensive effort to develop a global soil reference collection. To date, 950 monoliths from 74 countries were collected and a pedon scale cross-reference was established (http://www.isric.org, 2005). It improved correlation and communication between China and the international community. "Soil Classification — A Global Desk Reference"

Abbreviations: GIS, geographical information system; GSCC, Genetic Soil Classification of China; CST, Chinese Soil Taxonomy; WRB, World Reference Base for Soil Resources.

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edited by noted soil taxonomists, was published recently to stimulate formation of an international soil classification system (Eswaran et al., 2003).

With the continuous improvement of the WRB system, it is gradually being adopted by many countries in the world. Meanwhile, some tentative efforts have been made in several countries to translate national or local soil classification system into WRB (Kleber et al., 2004; Barreta-Bassols et al., 2006; Reintam and Köster, 2006; Junge and Skowronek, 2007; Dümig et al., 2008; Simas et al., 2008; Dazzi et al., 2009). Soil classification in China also provides an interesting example of how systems can be cross referenced to improve the understanding of soil properties globally.

Soil classification in China has undergone several important transformations, resulting in the creation of two soil classification systems based on different genetic philosophies, namely Genetic Soil Classification of China (GSCC) (Xi et al., 1998) and Chinese Soil Taxonomy (CST) (Gong et al., 2000; Shi et al., 2006b). Nevertheless, large volumes of soil data and information gathered and accumulated since the initiation of modern soil science study in the early 1930s, including soil maps and soil survey reports, have mostly been prepared and sorted on the basis of GSCC. For example, the Second National Soil Survey (1979–1994) was documented using GSCC, as were all the soil maps and soil survey reports at all administrative levels (township, county, city, province and country). Although these GSCC-based data contain useful and detailed descriptions, GSCC differs sharply from WRB, which is a qualitative system and used extensively all over the world. Since non-Chinese scientists and other users of soil data outside of China do not know much about GSCC, it is extremely difficult for Chinese soil scientists to exchange information, cooperate with foreign colleagues and publish papers in international journals. Further, it is difficult for soil scientists from countries outside of China to acquire a working knowledge of GSCC terminology and criteria, because the source materials are published in Chinese, which is not a familiar second language for many soil researchers.

To overcome these barriers, Chinese soil scientists know and are compelled to relate all soil information in terms of WRB. However, such relations are performed in the course of individual investigations without guidance on how to conduct them, which increased the possibility for inconsistencies when relating soils from GSCC to WRB. A simple solution is to establish a cross-reference between GSCC and WRB based on existing soil survey data. To that end, Chinese soil scientists have committed significant and initiatory studies (Gong et al., 1999, 2002; Chen et al., 2004; Gu and Liu, 2007). These studies mainly focus on the reference at single scale (e.g. province) or at higher categorical level (e.g. order).

The aim of our study was to create a cross-reference relating GSCC to WRB at various scales and at multiple categorical levels. To improve the range of soils considered in the reference, "Soil Series of China (six volumes)" and provincial soil series were consulted to identify attributes of each soil series according to both GSCC and WRB. Finally, referencibility was used to help define reference rules for establishing correlation between the two systems based on data describing 7292 soil profiles.

2. History of soil classification in China

Modern soil classification research in China began in the early 1930s, through the introduction of methods from the United States, developed from the work of C.F. Marbut. As a result some 2000 soil series were identified. In 1930, the first paper describing soil survey and classification in China was released, followed in 1934 by the first research report concerning the same topic. In 1936 a book entitled "Soil Geography of China", presented the first general description of soils in China at a national scale (Thorp, 1936). In 1941, the first Chinese soil classification system was drafted and used as a basis for the identification of soils in most of the country.

In 1954, the genetic classification approach was introduced from the former Soviet Union, which was strongly based on the setting of the soil's location (Scalenghe and Ferraris, 2009). From this introduction, a genetic soil classification was proposed for adoption as a national system. Extensive investigations were made for classifying and naming cultivated soils, further modifying the genetic soil classification system according to the formation factors relevant to the country.

In 1978, a standard GSCC — "Provisional Draft of Soil Classification of China" (Gong et al., 1978) was established as a three level hierarchies: soil order, great group and subgroup. The classification criteria were founded on extensive field work and adopted soil names had long been used in the country. The system was soon recognized by the soil science community in China and accepted as the basis for soil classification in the Second National Soil Survey of China. In 1979, the "Soil Working Classification System (Revised draft)" was formulated for the Second National Soil Survey of China. The draft, after several amendments, was developed into the "Genetic Soil Classification System of China" in 1992. Finally in 1998, a six-grade soil classification system was completed, i.e. order, suborder, great group, subgroup, family and series (Xi et al., 1998).

However, GSCC has many qualitative criteria and not employed outside China, making it difficult to be applied for the advancement of soil science on a global basis. To address these problems a 20 year study on CST was begun. In 1991, "Chinese Soil Taxonomy (Primary edition)" was first published. As follow-up efforts, two monographs were then published: "Chinese Soil Taxonomy (Theory, Methodology and Practice)" in 1999 and "Key to the Chinese Soil Taxonomy (English version)" in 2001. The system is now composed of 6 categories and is being adopted more and more extensively in China.

3. Materials and methods

The study procedure is illustrated in Fig. 1 as a series of steps to cross-reference between GSCC and WRB. GIS processing of a single data set was used to efficiently summarize and distribute the soil classification descriptors. The referencibility method is adopted as a means of correlation at a national scale.

The data set used in this cross-reference study was taken from "Soil Series of China" (six volumes) (The Office for the Second National Soil Survey of China, 1993, 1994a, 1994b, 1995a, 1995b, 1996) and provincial soil surveys, which includes information describing 7292 soil profiles collected throughout China (Yu et al., 2007). The soil profile attributes are used as the initial link between GSCC and WRB. It should be noted that these were selected from a set of more than 30,000 profile descriptions collected as part of the second national soil survey of China. Data from the 7292 soil profiles

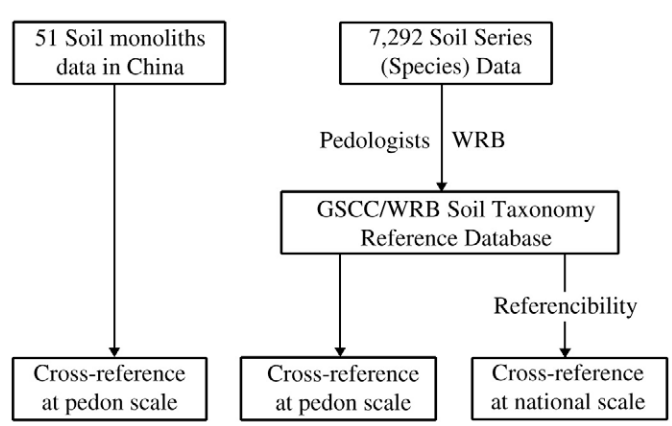

Fig. 1. Flow chart for cross-referencing GSCC to WRB at various scales.

were deemed complete enough to provide sufficient information for determining the classification in both GSCC and WRB.

The basic attributes for each soil profile are composed of descriptive and quantitative data, recorded in thematic sections. One section lists classification (soil order, suborder, great group, subgroup, family and series), geographic distribution, major soil properties, profile characteristics and production capacity. Major soil properties recorded include parent material and soil profile structure and thickness of the soil layer. The data for profile characteristics details location, elevation, parent material, climatic information (such as annual mean temperature), natural vegetation and crops on the profile site. The second section is referred to the field profile record, which describes each soil layer characteristics such as color, texture and structure of the soil layer and plant root system therein. The third and final section lists attributes such as soil physical and, chemical properties and nutrient status.

Based on the data of 7292 soil profiles and the soil series of provinces, a group of experienced pedologists were assembled to review and assign these data into WRB lower-category level soil groups (FAO/ISRIC/ISSS, 1998) according to the WRB key. The process was an iterative one, with classifications proposed and then reviewed, to assure consistency in the assignment process.

In this study, two methods "Conceptual reference method" and "Referencibility characteristic method" must be first introduced to familiarize users with the reference methodology. The former requires a typical soil profile to represent the whole soil type, and then the reference results of this soil profile could be applied to all of this type of soil. But the latter interprets each of the same GSCC type (e.g. red soils) into the high-category from the initial classification system into different kinds of soil nomenclatures in WRB system by using referencibility. Here referencibility refers to the reliability of a soil type in the initial GSCC system to be related to a certain soil type in WRB system. At a national scale, referencibility can be calculated using the profile number of one soil type in GSCC being interpreted into a certain soil type in WRB divided by the total number of profiles of this soil type in GSCC.

Table 1
12 selected from 51 monoliths in China to display soil reference between GSCC with FAO/Unesco.

Monolith no.	Location	Parent material	GSCC type	FAO/Unesco (1988)
CN002	Nanjing, Jiangsu	Xiashu loess	Yellow brown soil	Gleyi-Calcaric Cambisol
CN003	Shanghai	Clayey alluvial deltaic deposit	Paddy soil	Fluvi-Stagnic Luvisol
CN005	Changsha, Hunan	Purple shale	Calcaric purple soil	Siltic-Calcaric Cambisol
CN021	Yujiang, Jiangxi	Quaternary red clay	Red soil	Alumi-Orthic Acrisol
CN022	Yujiang, Jiangxi	Fine sandstone	Red soil	Alumi-Ferric Alisol
CN023	Yujing, Jiangxi	Red sandstone	Red soil	Alumi-Dystric Cambisol
CN025	Jinxian, Jiangxi	Quaternary red clay	Red soil	Niti-Haplic Acrisol
CN028	Yanshan, Jiangxi	Acid igneous rock	Red soil	Alumi-Haplic Alisol
CN029	Wengyuan, Guangdong	Shale	Red soil	Alumi-Ferralic Cambisol
CN030	Wengyuan, Guangdong	Quaternary clay	Red soil	Alumi-Ferralic Cambisol
CN043	Luliang, Yunnan	Quaternary red clay	Red soil	Pachi-Haplic Acrisol
CN045	Yuanjiang, Yunnan	Granite	Red soil	Rupti-Ferralic Cambisol

Source: (ISS-AS& ISRIC, 1994).

4. Results and discussion

The pedon was originally adopted by soil scientists as the basis for cross-reference across scales. A cross-reference between two systems can be created based on soil morphology and descriptive soil profile data, as well as the key to different soil classification systems. In this study we focus on establishing the cross-reference of GSCC to WRB at various scales (e.g. pedon and national).

4.1. Cross-reference at pedon scale based on the data from ISS-AS&ISRIC

Based on the data from ISS-AS&ISRIC, cross-reference at pedon scale can be simply conducted between GSCC and WRB. Among the 950 monoliths, 51 were collected throughout China, which covered 19 of total 61 soil great groups in the GSCC system and were assigned to Latosols, Latosolic red soils, Red soils and Yellow soils. For instance, 9 soil monoliths were assigned into Red soils (Table 1). Table 1 gives an example of the reference results for 12 soil monoliths in China (ISS-AS& ISRIC, 1994).

As can be seen from Table 1, each soil monolith has its own corresponding nomenclature to different soil classification systems. For example, Monolith CN021 was collected under the sparse masson pine forest in the Red Soil Ecological Experiment Station (RSEES), Chinese Academy of Sciences, which is located in Yujiang County, Yingtan City, Jiangxi Province of South China. In GSCC, this soil monolith was named "red soil." According to the soil properties of the Monolith CN021 and the Key to FAO/UNESCO Soil Map of the World (1988), it was determined that it had Ochric A and Argic B horizons. Consequently, it was cross referenced as an Alumi-Orthic Acrisol in the FAO/UNESCO Soil Map of the World (1988) (later developed into the WRB system).

Cross-reference at the pedon scale only defines the relationship between different classification systems for a single soil profile and does not consider the soil spatial distribution. The advantage of this method is that it clearly defines the soil profile, which can be classified into different systems at the appropriate level. But, it is only applicable to field-scale soil cross-referencing for exchanging academic findings. For instance, the aforementioned red soils collected by the RSEES can also be directly referred to as Alumi-Orthic Acrisol or Udic Kandiustult, to promote international understanding.

Although this straightforward method is easily applicable for supporting academic exchange between China and other countries, the application scope is narrow for limited databases. For example, if a GSCC soil type such as Hydromorphic paddy soil from the area proximal to the aforementioned RSEES were studied, it is difficult to know what nomenclature in WRB corresponds to it, because only one type of soil developed from Quaternary red clay under the sparse masson pine forest was collected by ISRIC. Thus, it would be hard to determine a corresponding WRB nomenclature from the ISRIC database. ISRIC database development greatly advanced Chinese soil reference work. However, it was still difficult for Chinese soil scientists to cooperate with foreign colleagues as only 51 soil monoliths were available to support information exchange. This number underrepresents the highly variable soils in China. Obviously, the direct solution is to increase the number of soil profiles.

4.2. Cross-reference at pedon scale based on the data from the Second National Soil Survey of China

As above mentioned, other ways have to be found in order to meet the cross-reference need of Chinese soils due to the limited number of soil pedons. To solve this problem, one method relating GSCC to WRB at pedon scale is to take full advantage of the data from the Second National Soil Survey of China. Among the 7292 soil profiles, 20 of them have been chosen as a reference example, which are shown in Table 2. The summary includes information such as land use, parent material and soil orders, great groups, subgroups, family and series in GSCC as

Table 2
20 selected from 7292 soil profiles to display cross-reference between GSCC with WRB.

Location (county/ province)	Land use	Parent material	GSCC					WRB reference subgroup
			Order	Great group	Subgroup	Family	Series	
Qiongshan/ Hainan	Sugar cane	Basalt	Ferrallisols	Latosols	Latosols	Clayey latosols	Clayey latosols	Acric Ferralsols
Zhuhai/ Guangdong	Litchi and pineapple	Sandy shale		Latosolic red soils	Latosolic red soils	Sandy latosolic red soils	Sandy latosolic red soils	Chromic Alisols
Xinfeng/Jiangxi	Sparse masson pine or oil-tea	Quaternary red clays		Red soils	Red soils	Clayey red soils	Clayey red soils	Plinthic Acrisols
Panxian/Guizhou	Corn and potato	Tuff		Yellow soils	Yellow soils	Clayey yellow soils	Clayey yellow soils	Dystric Luvisols
Nanjing/Jiangsu	tea	Sandstone	Alfisols	Yellow-brown soils	Yellow-brown soils	Sandy yellow-brown soils	Sandy yellow-brown soil	Leptic Cambisols
Qixia/Shandong	Wheat, corn and peanut	Diluvium		Brown soils	Brown soils	Diluvial brown soils	Yellowish brown soils	Haplic Luvisols
Longjing/Jilin	Woodland	Granite		Dark-brown soils	Dark-brown soils	Dark-granitic brown soils	Granitic brown soils	Eutric Cambisols
Antu/Jilin	Corn	Loess		Bleached soils	Bleached soils	Loessial bleached soils	Loessial bleached soils	Albic Luvisols
Yuanmou/Yunnan	Corn, sesame and peanut	Granite	Semi-Alfisols	Torrid red soils	Torrid red soils	Granitic torrid red soils	Granitic torrid red soils	Chromic Luvisols
Pingshan/Hebei	Corn, millet and peanut	Limestone		Cinnamon soils	Cinnamon soils	Grey cinnamon soils	Grey cinnamon soils	Leptic Luvisols
Shuangcheng/ Heilongjiang	Soybean and corn	Loess		Black soils	Meadow black soils	Yellowish black soils	Clayey yellowish black soils	Haplic Phaeozems
Hailaer/Neimeng	Wheat	Loess	Pedocals	Chernozems	Chernozems	Dark chermozems	Thick dark chemozems	Luvic Chernozems
Shangyi/Hebei	Grassland	Shale		Castanozems	Castanozems	Clayey castanozems	Thick clayey castanozems	Calcic Kastanozems
Emin/Xinjiang	Dominant plant: *Artemisia* L	Loess	Aridisols	Brown caliche soils	Brown caliche soils	Brown caliche soils	Brown caliche soils	Luvic Calcisols
Tongxin/Ningxia	Grassland	Diluvium		Sierozems	Sierozems	Skeletal Sierozems	Skeletal Sierozems	Calcaric Cambisols
Zichang/Shangxi	Wheat and millet	Loess	Amorphic soils	Loessial soils	Loessial soils	Loessial soils	Slope loessial soils	Calcaric Regosols
Zunyi/Guizhou	Corn and soybean	Marlite		Limestone soils	Yellow rendzina	Grey yellow rendzina	Grey yellow rendzina	Haplic Luvisols
Nanjiang/Sichuan	Wheat, corn and potato	Purple shale		Purplish soils	Neutral purplish soils	Decalcified purplish soils	Decalcified purplish soils	Leptic Cambisols
Wuxian/Jiangsu	Rice and wheat	Loess	Anthrosols	Paddy soils	Hydromorphic paddy soils	Yellow-brown paddy soils	Yellow-brown paddy soils	Hydragric Anthrosols
Fengqiu/Henan	Wheat and corn	Alluvium	Semi-aqueous soils	Fluvo-aquic soils	Fluvo-aquic soils	Fluvo-aquic loamy soils	Fluvo-aquic loamy soils with bottom clay layer	Calcaric-Fluvisols

well as the corresponding reference soil groups and subgroups in WRB system for each soil profile.

However, there is a large difference in the number of soil profiles attributable to GSCC soil orders (Table 3). Among the 12 soil orders, 2 soil orders: Anthrosols and Semi-Aquatic soils have more than 1000 soil profiles and account for 1654 and 1185 of the 7292 soil profiles, respectively, while 3 soil orders, Alpine, Aqueous and Desert soils, have fewer soil profiles and account for 165, 133 and 82 of the 7292 soil profiles, respectively. In addition, the numbers of GSCC soil great group profiles vary widely. Among 60 soil great groups, 3 soil great groups, Cinnamon soils, Fluvo-aquic soils and Paddy soils are dominant, accounting for 509, 800 and 1490 of the 7292 soil profiles, respectively. Twenty-eight great groups have less than 50 soil profiles, including Podzolic soils and Phospho-calcic soils having only one and two soil profiles, respectively. Additionally, 12 great groups have a range of 50–100 soil profiles and 17 great groups number between 100 and 500 soil profiles each.

With the reference database of 7292 soil profiles and the pedological professional knowledge, cross-referencing at pedon scale can be addressed with more options. For instance, if Hydromorphic paddy soils of GSCC taken from the RSEES could be interpreted into the corresponding reference soil groups or subgroups in WRB, the most direct approach is to search related sampling sites from reference database of 7292 soil profiles. However in this case the information sought would not be available as there are no profiles for that particular soil. As an alternative we have to look for similar soil profiles according to the rule of identity or similarity in soil types and parent materials as well as the nearest distance between reference soil profile and non-reference soil profile.

At first, we would find whether or not there was the soil profile for Hydromorphic paddy soils within the Yujiang County, Jiangxi Province from the 7292 soil profile reference database. Finding none we extend the search area: Yingtan City (including Yujiang and Guixi Counties). It would be found that there exists a soil profile for Hydromorphic paddy soils in Guixi County adjacent to Yujiang County which was called as Hydragric Anthrosols in WRB. Thus, Hydromorphic paddy soils could be referenced to Hydragric Anthrosols in WRB. The soils database permits to change our query by modifying the geographic and/or properties criteria to find a suitable reference soil profile(s).

4.3. Soil cross-reference at national scale

We illustrated above how the expanded data base can solve reference problems for academic exchange at pedon scale. However, it can not meet all the soil reference information needs. For example, when the global soil map was compiled using the FAO WRB system, one part of the work we had to do was to assemble the soil map of China using WRB system by means of reference methods based on a series of soil maps such as 1:10,000,000, 1:4,000,000 or even greater scale soil maps (Shi et al., 2004). The actual difficulty we were facing was to try to address the problem of high level classification being

Table 3
Distribution of 7292 soil profiles by GSCC soil order and great group.

Soil order	Number of soil orders	Soil great group	Number of soil great groups	Soil order	Number of soil orders	Soil great group	Number of soil great groups
Ferrallisols	803	Latosols	92	Amorphic soils	983	Loessial soils	61
		Latosolic red soils	138			Red primitive soils	51
		Red soils	390			Neo-alluvial soils	173
		Yellow soils	183			Takyr	4
Alfisols	747	Yellow-brown soils	241			Aeolian soils	112
		Yellow-cinnamon soils	84			Limestone soils	127
		Brown soils	249			Volcanic soils	25
		Dark-brown soils	118			Purplish soils	257
		Bleached baijiang soils	35			Phospho-calcic soils	2
		Brown coniferous forest soils	19			Skeletal soils	131
		Podzolic soils	1			Lithosols	40
Semi-Alfisols	697	Torrid red soils	29	Semi-aqueous soils	1185	Meadow soils	243
		Cinnamon soils	509			Fluvo-aquic soils	800
		Gray-cinnamon soils	62			Sajiang black soils	69
		Black soils	73			Shruby meadow soils	15
		Gray-forest soils	24			Mountain meadow soils	58
Pedocals	487	Chernozems	146	Aqueous soils	133	Bog soils	107
		Castanozems	210			Peaty bog soils	26
		Castano-cinnamon soils	78	Anthrosols	1654	Paddy soils	1490
		Dark loessial soils	53			Irrigated warped soils	115
Aridisols	118	Brown caliche soils	41			Irrigated desert soils	49
		Sierozems	77	Alpine soils	165	Felty soils	36
Desert soils	82	Gray desert soils	32			Dark felty soils	46
		Gray-brown desert soils	20			Frigid calcic soils	20
		Brown desert soils	30			Cold calcic soils	21
Alkali–saline soils	238	Meadow solonchaks	103			Cold brown calcic soils	23
		Coastal solonchaks	72			Frigid desert soils	12
		Acid sulphate soils	6			Cold desert soils	2
		Dry solonchaks	17			Frigid frozen soils	5
		Frigid plateau solonchaks	4				
		Solonetzes	36				

interpreted into another classification system at national scale. For example, what kind of soil in WRB system could be one certain GSCC soil type (e.g. red soil or yellowish red soil) referenced to at national scale?

Based on the conceptual reference method, the complicated reference described above can be simplified. Taking Chinese red soils as an example, when we would like to know what type of soil in WRB system it will be referenced to at national scale, we could choose monolith CN021 under the sparse masson pine forest in RSEES as a representative soil profile of red soils (Table 1). It might be referenced to Alumi-Orthic Acrisol in WRB system. Consequently, can the conclusion be drawn that all the Chinese red soils will be related to Alumi-Orthic Acrisol in WRB system? We must be concerned then about the consistency of assigning WRB classifications globally to GSCC soils of a single type.

From Table 1, it can be seen that there are 9 monoliths which are called red soils. It is not clear which one should be chosen. If monolith CN021 was chosen, Chinese red soils might be referenced to the aforementioned Alumi-Orthic Acrisol; if monolith CN022 was chosen, Chinese red soils might be referenced to Alumi-Ferric Alisol in WRB system; and if monolith CN029 was chosen then Chinese red soils might be referenced to Alumi-Ferralic Cambisol in WRB system. Thus, the same soil great group in GSCC would be interpreted into different soil groups in WRB system which led to the great uncertainty of reference results at a national scale.

Obviously, it represents the limitations of the conceptual reference method. Consequently, referencibility characteristic method is proposed. It takes full advantage of the information of each profile as much as possible rather than choosing a single typical soil profile to represent this type of soil. Just give an example, Table 1 shows that there are 9 soil profiles which are called red soil in GSCC. Among the 9 soil profiles, the profile numbers of being interpreted into Acrisol, Alisol and Cambisol in WRB system amounts to 4, 2 and 3, and their referencibilities are 44.5%, 22.2% and 33.3%, respectively.

Among the 60 soil great groups, purplish soils accounted for 257 of the 7292 soil profiles. These 257 soil profiles could be interpreted into seven different WRB soil groups: Cambisols, Regosols, Luvisols, Leptosols, Acrisols, Alisols, and Andisols (Table 4), of which Cambisols dominate, accounting for 208 of the 257 soil profiles, while Andisols are linked to only one soil profile. According to the aforementioned concept and calculation of soil referencibility, it was known that the referencibility between purplish soils in GSCC and Cambisols in WRB was 80.9% and that between purplish soils in GSCC and Andisoils in WRB was only 0.4%. Thus, purplish soils in GSCC could be interpreted into Cambisols in WRB. The reference information is critically important in exchanging research findings with colleagues at home or abroad. Also, it could meet a number of users' demand and greatly promote the academic exchange and dissemination of research results.

In the same way, other soil great groups in GSCC could also obtain the reference results like purplish soils. Actually, however, most users prefer to know that one soil great group in GSCC was related to which certain soil group in WRB instead of clearly knowing that this soil great group was related into how many soil groups in WRB. So, the maximum referencibility tends to be more meaningful and applicable,

Table 4
Cross-reference results of purplish soils in GSCC to its counterparts in WRB.

WRB reference soil groups	Cambisols	Regosols	Luvisols	Leptosols	Acrisols	Alisols	Andisols	Total
Number of soil profiles	208	33	7	4	2	2	1	257
Referencibility %	80.9	12.8	2.7	1.6	0.8	0.8	0.4	100

indicating that one soil great group in GSCC has the highest similarity to one certain corresponding WRB soil group. In terms of the preceding example, it is enough for users to know that purplish soils in GSCC could be interpreted into Cambisols with a referencibility of 80.9%.

Table 5 shows the reference results between 60 soil great groups in GSCC and their counterparts in WRB. As can be seen, the maximum referencibilities between soil groups in the two systems vary widely from 29.4% to 100%. Based on the maximum referencibility, soil great groups in GSCC can be divided into three categories: high (80–100%), intermediate (50–80%), and low (<50%). The number of soil great groups with maximum referencibility in the range of 80–100%, 50–80% and <50% amounts to 12, 27 and 21, respectively.

Soil great groups with high maximum referencibility in GSCC include Podzolic soils, Cold desert soils, Phospho-calcic soils, Meadow soils etc. Among the 12 soil great groups in GSCC, Podzolic soils, Cold desert soils and Phospho-calcic soils can completely be sorted into Podzols, Cambisols and Arenosols in WRB by direct reference, meaning the reliability of reference reaches 100%. Among the 21 soil great groups with low maximum referencibility, 4 soil great groups have maximum referencibility values below 40%, especially Latosols. Latosols can be sorted into Acrisols in WRB by reference, with maximum referencibility only being 29.4%.

Soil types in GSCC were identified mainly based on their Zonality. For instance, Latosols, Latosolic red soils and Red soils were developed in the topical, south-subtropical and mid-subtropical zones, respectively. Climate as a classification criteria departs sharply from WRB, which is a system based on diagnostic horizons and characteristics. As the most suitable approach relating GSCC with WRB, referencibility characteristic method underlines its prominent advantage of utilizing every soil profile's information so as to greatly improve the reference reliability between the two systems. Furthermore, it is necessary to further study referencing at lower classification categories or regional subdivision to improve the maximum referencibility. In terms of classification category, it is better to establish the cross-reference between soil subgroups in GSCC and soil groups or subgroups in WRB. In terms of study area, it is proposed to select provinces to provide better coincidence between the two systems.

5. Conclusion

In the last century, soil classification systems had been established by soil scientists in many countries like China based on their own natural environmental characteristics and at various scales. The application of different classification approaches results in limited communication about soil information like the gap between GSCC and WRB. Therefore, it is necessary to establish cross-references between GSCC and WRB. This paper demonstrated that the soil cross-reference approach for the pedon scale adopted by ISRIC was quite applicable to field-scale soil reference issues. Based on the data from the Second National Soil Survey of China and the key to WRB system, the Chinese soil reference database consisting of information for 7292 soil profiles was also an effective way to solve the soil cross-reference problem at pedon scale between GSCC and WRB.

In order to meet soil reference information needs at a large scale it is essential to establish another soil reference methodology. The introduction of referencibility can provide a good solution to this issue. In this paper, the relative relationships between GSCC soil great groups and WRB reference soil groups were identified based on referencibility. To illustrate, the cross-reference results of 60 soil great groups in GSCC were obtained as well based on the maximum referencibility. However, the maximum referencibility between soil great groups of GSCC and reference soil groups in WRB varies widely from 29.4% to 100% due to the difference in theory and standard for

Table 5
Maximum referencibilities of 60 GSCC soil great groups related to WRB soil groups.

GSCC soil order	GSCC soil great group/ number of soil profiles	WRB reference soil group	Maximum referencibility (%)	GSCC soil order	GSCC soil great group/ number of soil profiles	WRB reference soil group	Maximum referencibility (%)
Ferrallisols	Latosols/92	Acrisols	29.4	Amorphic soils	Limestone soils/127	Cambisols	52.8
	Latosolic red soils/138	Acrisols	39.9		Volcanic ash soils/25	Andosols	68.0
	Red soils/390	Cambisols	34.6		Purplish soils/257	Cambisols	80.9
	Yellow soils/183	Cambisols	45.4		Phospho-calcic soils/2	Arenosols	100.0
Alfisols	Yellow-brown soils/241	Cambisols	39.4		Lithosols/40	Leptosols	92.5
	Yellow-cinnamon soils/84	Luvisols	58.3		Skeletal soils/131	Regosols	53.4
	Brown soils/249	Luvisols	51.4	Semi-queous soils	Meadow soils/243	Cambisols	84.8
	Dark-brown soils/118	Cambisols	47.5		Fluvo-aquic soils/800	Cambisols	79.1
	Bleached beijiang soils/35	Luvisols	45.7		Lime concretion black soils/69	Cambisols	87.0
	Brown coniferous forest soils/19	Cambisols	47.4		Shrubby meadow soils/15	Cambisols	60.0
	Podzolic soils/1	Podzols	100.0		Mountain meadow soils/58	Cambisols	55.2
Semi-Alfisols	Torrid red soils /29	Luvisols	48.3	Aqueous soils	Aqueous soils/107	Gleysols	47.7
	Cinnamon soils/509	Cambisols	43.2		Peat soils/26	Histosols	92.3
	Gray-cinnamon soils/62	Cambisols	30.7	Alkali–saline soils	Meadow solonchaks/103	Solonchaks	46.6
	Black soils/73	Phaeozems	76.7		Coastal solonchaks/72	Solonchaks	36.1
	Gray-forest soils/24	Phaeozems	50.0		Acid sulphate soils/6	Solonchaks	50.0
Pedocals	Chernozems/146	Chernozems	61.0		Desert solonchaks/17	Solonchaks	88.2
	Castanozems/210	Kastanozems	39.5		Frigid plateau solonchaks/4	Solonchaks	50.0
	Castano-cinnamon soils/78	Cambisols	59.0		Solonetzes/36	Solonetz	83.3
	Dark loessial soils/53	Cambisols	35.9	Anthrosols	Paddy soils/1490	Anthrosols	70.0
Aridisols	Brown caliche soils/41	Cambisols	63.4		Irrigated warped soils/115	Anthrosols	67.5
	Sierozems/77	Cambisols	44.2		Irrigated desert soils/49	Anthrosols	69.4
Desert soils	Gray desert soils/32	Cambisols	78.1	Alpine soils	Felty soils/36	Cambisols	61.1
	Gray-brown desert soils/20	Cambisols	65.0		Dark felty soils/46	Cambisols	69.6
	Brown desert soils/30	Cambisols	33.3		Frigid calcic soils/20	Calcisols	45.0
Amorphic soils	Loessial soils/61	Cambisols	47.5		Cold calcic soils/21	Cambisols	66.7
	Red primitive soils/51	Regosols	51.0		Cold brown calcic soils/23	Cambisols	87.0
	Neo-alluvial soils/173	Fluvisols	71.7		Frigid desert soils/12	Cryosols	41.7
	Takyr/4	Cambisols	75.0		Cold desert soils/2	Cambisols	100.0
	Aeolian soils/112	Arenosols	79.5		Frigid frozen soils/5	Leptosols	80.0

classification. Based on the maximum referencibility, soil great groups in GSCC can be divided into three categories: high (80%–100%), intermediate (50%–80%) and low (<50%). Among the 60 soil great groups in GSCC, the number of soil great groups with maximum referencibility in the range of 80–100%, 50–80% and <50% amounts to 12, 27 and 21, respectively. This indicates that additional processing is needed to improve accuracy of the reference. It is essential to further study the reference at lower categories or at a provincial level.

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