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CLASSIFICATION OF CRYOSOLS: SIGNIFICANCE, ACHIEVEMENTS AND CHALLENGES

CHEN Jie, GONG Zi-tong, CHEN Zhi-cheng, TAN Man-zhi
(*Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, P. R. China*)

ABSTRACT: International concerns about the effects of global change on permafrost-affected soils and responses of permafrost terrestrial landscapes to such change have been increasing in the last two decades. To achieve a variety of goals including the determining of soil carbon stocks and dynamics in the Northern Hemisphere, the understanding of soil degradation and the best ways to protect the fragile ecosystems in permafrost environment, further study development on Cryosol classification is being in great demand. In this paper the existing Cryosol classifications contained in three representative soil taxonomies are introduced, and the problems in the practical application of the defining criteria used for category differentiation in these taxonomic systems are discussed. Meanwhile, the resumption and reconstruction of Chinese Cryosol classification within a taxonomic frame is proposed. In dealing with Cryosol classification the advantages that Chinese pedologists have and the challenges that they have to face are analyzed. Finally, several suggestions on the study development of the further taxonomic frame of Cryosol classification are put forward.
KEY WORDS: Cryosol; permafrost; soil classification; taxonomy

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1 INTRODUCTION

As a substantial component of the cryosphere, permafrost is defined as ground (soil or rock including ice and organic materials) that remains at or below 0℃ for at least two consecutive years. Permafrost underlies approximately 24% of the exposed land surface. Most permafrost in the Northern Hemisphere is distributed between latitudes of 60° N and 68° N. Around 35° N, however, there also is a significant amount of permafrost occurring in the Qinghai-Xizang (Tibet) Plateau and Rocky Mountains, as well as their neighbouring alpine areas (WILLIAMS and SMITH, 1989; BROWN *et al*., 1998; ZHANG *et al*., 1999). In the Southern Hemisphere permafrost mainly occurs in the Antarctica. An estimated 37% of the world′s permafrost is distributed in the Antarctica, although only about 24% of the Antarctic region contains permafrost (BOCKHEIM, 1995; FRENCH, 1996). In fact, a great portion of the landmass beneath Antarctic ice sheet, despite its temperature below 0°C, is unfrozen due to the low pressure melting point (HERTERICH, 1988; BOCKHEIM and HALL, 2002) (Fig. 1 and 2)

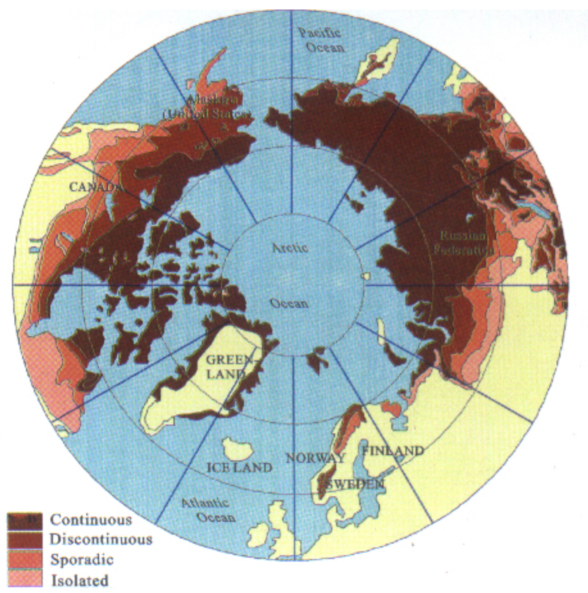

Fig. 1 World map of permafrost distribution based on IPA (International Permafrost Association, 2001)

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Biography: CHEN Jie (1967–), male, a native of Henan Province, professor, Ph. D., specialized in soil geography and resources, pedogeochemistry and environment. E-mail: jchen@issas.ac.cn
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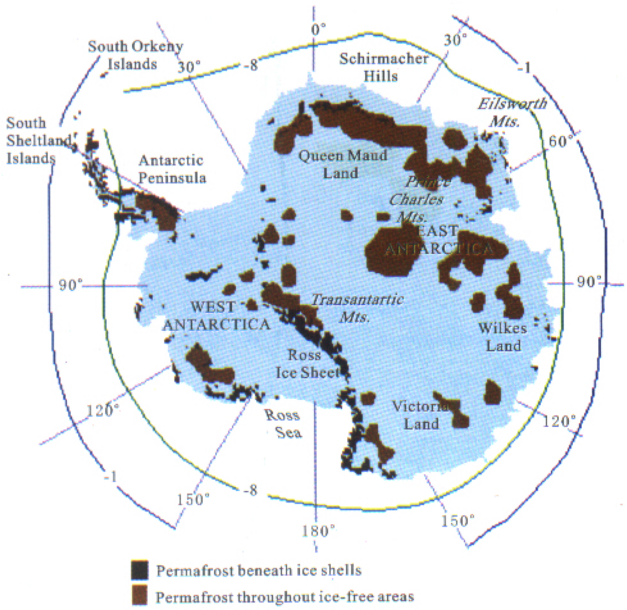

Fig. 2 The map of permafrost distribution in continental Antarctica (after BOCKHEIM and HALL, 2002)

Cryosols, one of soil types formed in permafrost environments, are the dominant soils in the polar region, widespread in circumpolar zones of the Northern Hemisphere and sporadic in more temperate alpine regions, covering approximately $18\times10^6 km^2$ or about 13% of the Earth's land surface (BOCKHEIM *et al*., 1994). Major areas with Cryosols are found in Russia ($10\times10^6 km^2$), Canada ($2.5\times10^6 km^2$), China ($1.9\times10^6 km^2$) and Alaska ($1.1\times10^6 km^2$) and in parts of Mongolia. Smaller occurrences have been reported from permafrost regions in the northern Europe, Greenland and the ice-free areas of Antarctica (DRIESSEN *et al*., 2001) (Fig. 3).

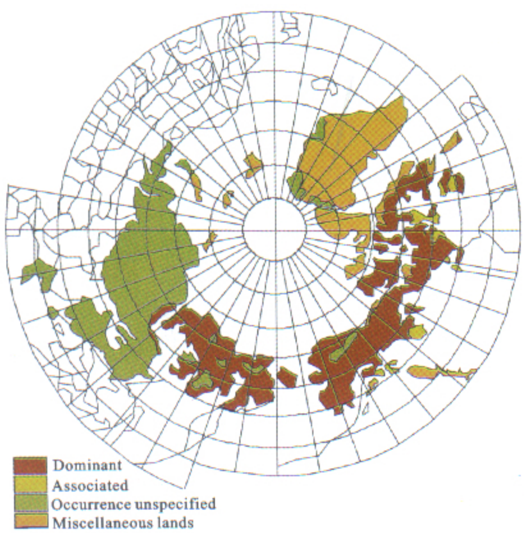

Fig. 3 Distribution of Cryosols based on World Reference Base for Soil Resources and the FAO/UNSCO Soil Map of the World (after FAO-GIS,1997,with different projection)

Together with other permafrost-affected soils, Cryosols are attracting more attentions in agricultural production and civil engineering, because all soils are affected by global change, in which, it is greatest for Cryosols.

2 STUDY DEVELOPMENT OF CRYOSOL CLASSIFICATION IN GREAT DEMAND

Studies on permafrost-affected (or frost-affected) soils were initiated in the Russian Arctic by the pedologists of the former Soviet Union since the middle of the 1920s. The early studies of Cryosols were concentrated on general description of soil characteristics, regional classification and mapping (TARNOCAI, 2000). Since the last decade of the 20th century, there has been increasing interest in the effects of global change on permafrost-affected soils and responses of permafrost terrestrial landscapes to such change. The emphasis has shifted to degradation and shrinking of Cryosols under a changing circumstance and their impacts on cold terrestrial ecosystems (BROLL, 2000; TARNOCAI, 2000).

First of all, Cryosols in the Northern Hemisphere are known to act as a great carbon sink, containing large amounts of organic carbon and locking greenhouse gases like methane away for thousands of years (TARNOCAI, 1998, 2000). Only in the permafrost environment of the Arctic lands, it is estimated that around 14% of the world′s carbon is stored. The increasing temperature of permafrost-affected soils, however, will cause carbon to be released into the atmosphere, making them be a carbon source (TARNOCAI, 1999). Besides, permafrost underlying the Cryosols, despite its name, is actually characterized by its instability (WILLIAMS and SMITH, 1989). As temperature rises, there would be a sharp increase in thaw depth of Cryosols, resulting in a drastic shrinking of these soils. The reduction in the areal coverage of Cryosols has important impacts on the local ecosystems. And, there would be impact on roads, building, pipelines and other infrastructure in the frozen areas as result of the melting of Cryosols.

In order to archive a common circumpolar soil database for determining stocks and dynamics of soil carbon in the Northern Hemisphere, to lucubrate cryopedological processes for a better understanding of soil degradation and the best ways to protect the fragile ecosystems in permafrost environment, and to facilitate a wider international approach to deal with the challenges raising from increasing human activities in per-

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mafrost regions, in-depth studies on cryosol classification should be enhanced and a system with common basis and easy access is strongly needed.

3 STATUS QUO OF CRYOSOLS CLASSIFICATION IN THE WORLD

3.1 Canadian System of Soil Classification

Permafrost-affected soils occupy vast regions of the northern Canada where permafrost exists close to the surface of both mineral and organic deposits. It was in 1978 that the inclusion of an independent order named Cryosolic was made to the Canadian System of Soil Classification when it replaced the former System of Soil Classification for Canada published in the 1950s and revised in 1974 (Agriculture Canada, 1974).

As first modern soil taxonomies with Cryosols in climax units, internationally, Cryosolic soil in the Canadian System is defined as formed in either mineral or organic materials that have permafrost either within 1m of the surface or within 2m if the pedon has been strongly cryoturbated laterally within the active layer, as indicated by disrupted, mixed, or broken horizons. The Cryosolic order is divided into three great groups (the second level): Turbic Cryosol, Static Cryosol, and Organic Cryosol based on the degree of cryoturbation and the nature of soil materials, mineral or organic (Soil Classification Working Group, 1998). The Canadian System of Soil Classification (the third edition) newly published had carried out major revisions to the Cryosolic order, including adding several new subgroups (the third level) in both the Turbic Cryosol and Static Cryosol great groups and revising the description of all subgroups to make them as uniform as possible and to clearly identify those properties diagnostic of the particular subgroup (ACECSS, 1987; Soil Classification Working Group, 1998).

3.2 U. S. A. Soil Taxonomy

The permafrost-affected soils, termed Gelisols (Cryosols) in this context, were differentiated at the highest level in the second edition of Soil Taxonomy published in 1999. As one of the two newly adopted soil orders (another is Andisol) in Soil Taxonomy, Gelisols have the central concept that of soils with gelic materials underlain by permafrost. Concretely, Gelisols have one or both of the following: 1) permafrost within 100cm of the soil surface; 2) Gelic materials within 100cm of the soil profiles and permafrost within 200cm of the soil profiles (Soil Survey Staff, 1999). The characterizing diagnostic horizons in Gelisols may or may not present. Gelic materials are important and essential in diagnostic soil characteristics of the soils underlain permafrost within 200cm of the soils profiles. According to Soil Taxonomy, Gelic materials contained mineral or organic soil materials show evidence of cryoturbation and/or ice segregation in the active layer (seasonal thaw layer) and/or the upper part of the permafrost(FOX, 1994; BOCKHEIM and TARNOCAI, 1998; Soil Survey Staff, 1999).

Three suborders are included in Gelisols, namely Histels, Orthels and Turbels. Histels are the Gelisols with large amounts of organic carbon that commonly accumulates under anaerobic conditions, or the organic matter at least partially fills voids in fragmental, cindery, or pumiceous materials. Orthels are the Gelisols that show little or no evidence of cryoturbation and are the second most abundant suborder of Gelisols. They are generally drier than the other two suborders. Turbels have one or more horizons with evidence of cryoturbation in the form of irregular, broken, or distorted horizon boundaries, involutions, the accumulation of organic matter on top of the permafrost, ice or sand wedges, and oriented rock fragments. As the dominant suborder of Gelisols, Turbels account for about half the Gelisols on a global basis (Soil Survey Staff, 1999).

3.3 WRB: World Reference Base for Soil Resources

After reviewing FAO's Revised Legend, 30 reference soil groups were identified to constitute the World Reference Base for Soil Resources. As one of the three newly introduced reference soil groups (the highest level, the other two are Durisols and Umbrisols), Cryosols are used to identify a group of soils which occur under the unique environmental conditions of alternating thawing and freezing, defined as the soils having one or more cryic horizons within 100cm from the soil surface. Here the cryic horizon is a perennially frozen soil horizon in mineral or organic soil materials (FAO *et al.*, 1998).

In WRB system, the diagnostic criteria to differentiate lower level units, for keeping the system simple and easy to access, are mainly derived from the already established reference group diagnostic horizons, properties and other defined characteristics. Because Cryic horizons may bear characteristics of other horizons such as histic, andic or spodic horizons, and may occur in association with salic, calcic, mollic, umbric or ochric horizons, 19 common soil units (second level)

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have been recognized in the Cryosol reference group, including Histic, Salic, Andic, Umbri, Mollic, Calcic Cryosols etc. (FAO *et al*., 1998; DRIESSEN *et al*., 2001).

4 PROBLEMS IN APPLICATION OF PRESENT CLASSIFICATION SYSTEMS

Doubtless, three soil classification systems as mentioned above play a lot of roles in further studies of the unique soil-forming processes occurring in permafrost environments and the enhancement of the classification of Cryosols, especially in working out conceptual frames in which well-defined and usable internal boundaries try to be set up for differentiating Cryosols from the other soils and separating the lower categories within Cryosols. However, some common shortages still could be found in the above systems and the challenges would be faced in several aspects. Particularly, it seems problem to determine the feasibility of Cryosol classification of the systems in the field.

4.1 Problematic Field-based Maneuverability in Determining Permafrost Depth

The three systems recited above Cryosols are firstly differentiated upon the presence or absence of permafrost at prescriptive depth. As known, permafrost in the taxonomies is defined as a thermal condition in which a material keeps below 0℃ in 2 or more years. Then how can pedologists determine the presence and depth of permafrost in the field? There are three problems significantly to reduce the feasibility of permafrost determination: 1) It is extremely difficult to fix the date of greatest seasonal thaw when the active layer is greatest in the Cryosols. 2) It is not feasible to measure the presence of permafrost and its maximum depth in those alpine soils with a very thin soil and a lithic contact or underlain by a solid terrain. 3) It is not possible to accurately determine permafrost in the regions where distribution of permafrost in discontinuous and sporadic patterns unless long-term soil temperature monitors intensely installed (THORN and DARMODY, 2002).

4.2 Ambiguous Significance of Permafrost in Pedogenetic Processes of Cryosols

The studies showed that it is more obvious that the soils sampled in Canada and Alaska are highly cryoturbated when compared with the ones in Russia①. Since all of the soils used in this comparison are distributed in the area of continuous permafrost, therefore it is in question what soil forming factors are soil development in permafrost environments controlled and what is the role of permafrost in pedogenesis of Crysols? As known, cryoturbation is regarded as the dominant pedogenetic process in the cold regions. However, the contribution of permafrost presence to cryoturbation process is not discernable. In deed it is very difficult to distinct whether the cryogenic features of soils form in the presence of deep seasonal freezing or permafrost. For the shallow soils developed in mountainous areas, absence of permafrost or presence at a much deeper depth than the bottom limit of soil actually means nothing different in shaping the diagnostic characteristics of cryoturbation. In this context, on the three systems of permafrost failed to provide genetic track or provide the descriptive elements for developing genetic track.

4.3 Influences of Topography-climate on Generalization of Ground Temperature

The historical approach to determine the location and extent of permafrost is based on the hypothesis that the ground temperature is corresponded with the overlying air temperature. But, a difference caused by ground and air temperature is usually different from varying amounts (WILLIAMS and SMITH, 1989). Real challenges come from determination of permafrost in the mountainous areas where the dynamics of ground temperature is closely associated with topoclimate. As known, topoclimate is a climatic concept that embraces all of the complexities including the factors such as elevation, aspect, slope angle, vegetation, and material making up the near-surface layer (GEIGER, 1965). Of particular, seasonal snow cover can significantly influence both ground temperatures and ground moisture regimes (GOODRICH, 1982; THORN, 1978), therefore permafrost distribution in the marginal regions, for instance, in the alpine contexts, will demonstrate a sporadic spatial and indeed perhaps ephemeral temporal (FRENCH, 1996). Then the question would be raised as what a field pedologist makes continuous generalization associated with the field mapping of soils (THORN and DARMODY, 2002).

① KIMBLE J M, PING C L, TARNOCAI C *et al*., 1999. Comparison of Permafrost-affected Soil of North Canada, Alaska, and the Lower Kolymar Region of Far Eastern Russia [R]. (an unpublished poster)

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5 CRYOSOL CLASSIFICATION IN CHINA: CHALLENGES AND CHANCES

5.1 Permafrost and Related Soils in China

China is amongst the countries where permafrost is widely spread. Just after Russia and Canada, China is in the third place in distributing areas of permafrost in the world, totally covering $2.15\times10^6 km^2$, or 22.4% of the national terrestrial surface (ZHOU *et al.*, 2000). The permafrost in the northeastern China is mainly distributed in the regions of the Hinggan Mountains and the Sanjiang Plain under normal altitudes below 1000m, and shows the discontinuous and isolated patterns and ranging. The permafrost in the western China is distributed in the alpine areas of Qinghai-Xizang (Tibet) Plateau and its surroundings under the normal altitude beyond 2000m. The alpine permafrost covers an area up to $1.76\times10^6 km^2$, or 82.2% of the permafrost distribution areas of China, and contributing a share of 75.5% to the total alpine permafrost areas in the Northern Hemisphere (ZHAO *et al.*, 1993) (Fig. 4).

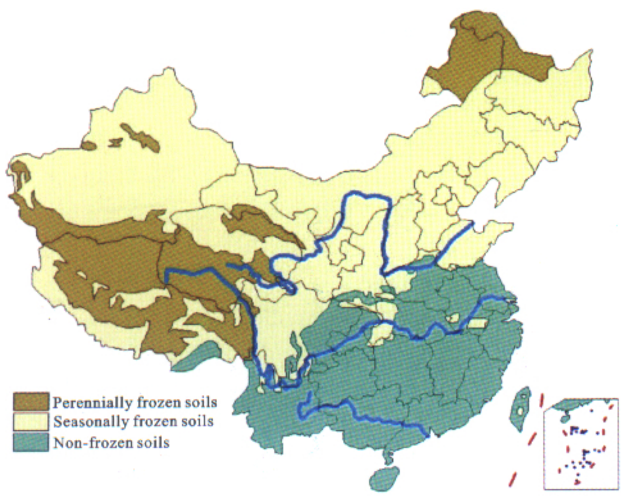

Fig. 4 Sketch map of distribution of frozen soils in China (Source: Science Museums of China)

The permafrost-affected soils in the permafrost environment of the northeastern China mainly include the pergelic subtypes of a variety of latitudinous zonal soils such as phaeozems, chernozems, dark brown soils and other tundra soils. However, a few intrazonal types including peat soil, bog soils and gley soils could also be found and developed in the isolated patterns. Comparatively, the soil types formed in the alpine permafrost environment of the western China are much more than that of the northeastern China, and great complexity is involved in the soil catena analysis due to the highly discontinuous and sporadic distribution of underlying permafrost, of which the presence and occurring depth are not only influenced by the latitudinal setting, but also by the elevation and topoclimate. In general, the alpine soils and cold desert soils are dominant types of the frozen soils developed in the alpine permafrost environment.

5.2 Attempts to Classify Permafrost-affected Soils

The taxonomic theory and method practiced in the United States and the other western countries was introduced into China in 1985. The permafrost-affected soils had not been recognized as independent categories at all of the levels of a variety of the Chinese systems dominated by the genetic soil classification patterns adopted from that of the former Soviet Union. In 1987, Chinese Soil Taxonomy (second draft) was published. In this draft the permafrost-affected soils were differentiated as one of independent soil orders, named Cryosols. It was the first time that this sort of soil had recognized at the top level in the Chinese systems of soil classification. It is more than 10 years earlier than the Cryosols and the Gelisols emerged as the top categories in the WRB and Soil Taxonomy (RGCST, 1987).

In the Chinese Soil Taxonomy (second draft), the Cryosols were simply defined as the soils having the permagelic temperature regime within 100cm of the surface, and occurrence of the morphological features formed by cryoturbation characterized by patterned grounds (or stone circles) in the surface. Here the word permagelic means temperature is perennially at or below 0^oC, implying the presence of permafrost. Obviously, the definition of the Cryosols was almost the same with that employed in the WRB system. However, in comparison with the forenamed soil classification systems, the second draft did not employed soil horizons or characteristics associated with cryoturbation as the diagnostic criteria for differentiating Cryosols.

In the second draft, within Cryosols two suborders were differentiated simply according to the soil moisture regimes, i.e. Perudic Cryosols for the soils with perudic moisture regime and Aridic Cryosols for the soils with aridic moisture regime, and still no diagnostic horizons and soil characteristics showing cryoturbation were involved in the subdivision of the Cryosols. Actually, only a rough frame for Cryosol classification was worked out in the Chinese Soil Taxonomy (second draft), and it would be very difficult for pedoloists to classify soils in the practical application, due to the

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lack of definitive diagnostic criteria (RGCST, 1987).

In the Chinese Soil Taxonomy (first proposal) published in 1992 and the subsequent revised proposal in 1995, for various reasons the permafrost-affected soils were not any longer taken as one of the independent soil orders. However, two diagnostic characteristics, i. e. permafrost layer and frost-thawic features were defined in the first proposal as the criteria to differentiate the soils underlain by permafrost at the second and third levels. It is worth mentioning that temperature requirement of permafrost layer in the Chinese Soil Taxonomy is "below 0℃ perennially", virtually differing from "two or more years in succession" in the systems of the United States, Canada and WRB (CRGCST, 1995; 2001).

5.3 Resumption and Reconstruction of Cryosol Classification

For further studies on Cryosols in China, the resumption and reconstruction of Cryosol classification should be one of the priorities. To do this, Chinese pedologists have the advantages including the followings: 1) long-term monitoring programs and field investigations for a variety of purposes in permafrost environments have been conducted and cryosphere data base concentrated in permafrost dynamics has been constructed in China; 2) studies of the utilization and management of the permafrost-affected soil have achieved plentiful knowledge accumulation on natures and properties of this kind of soils for more than ten years; 3) the first attempt to classify Cryosols in China ten years ago had laid a good foundation for further in-depth studies; 4) theories and methodological approaches of the advanced taxonomic systems has been successfully introduced into the practices of Chinese soil classification; and 5) significant knowledge and experiences of the related setup and definition of diagnostic horizons and soil characteristics can be obtained from the existing taxonomies in which Cryosol classification has been established.

To achieve successful classification of Cryosols, there still are great challenges facing the Chinese pedologists, because the Cryosols distributed in the alpine permafrost environments shares a large proportion of the permafrost-affected soils of China. The challenges originate not only from the difficulties to determine presence or absence of permafrost in the areas spatially fragmented into a multitude of highly diverse micro-environments, but also from ephemeral conditions in which temporal change moves environments across the permafrost boundary. Therefore, to deal with the resumption and reconstruction of Cryosol classification, the following in-depth studies should be emphasized.

(1) It is necessary to carry out comprehensive and systemic soil surveys in permafrost environments and develop the well-populated spatial and pedon databases of Cryosols and lay a good foundation for the representativeness and generalization of the future Cryosol classification.

(2) Further studies are needed to determine the permafrost criteria and develop the corresponding field techniques for the determination of the presence or absence of permafrost at the depth specified in the future classification. Meanwhile, the theories and methods should be developed to deal with analysis and generalization of the soil succession in the landscapes.

(3) In-depth studies on the effect of cryogenic processes on soil morphology and soil chemical and physical properties should be enhanced in order to improve knowledge on the pedogenetic significance of permafrost and its present depth, and determine the cryoturbated horizon or characteristics of Cryosols.

(4) Great efforts would be made in the alpine Cryosol classification. The categorical definition and practical maneuverability must be underpinned by a sound conceptual framework, within which spatial and temporal variability of micro-environmental factors should be seriously considered and a series of defining variables should be employed to address the pedogenetic expressions resulting from the changes of micro-environments.

(5) International exchanges and cooperative research on Cryosols need to be facilitated, in order to share the understanding of the nature of the permafrost-affected soils, and ensure the future system to be developed within internationally common concepts of classification of Cryosols and have a common reference basis with the existing taxonomies.

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