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Review

Controversies on the genesis and classification of permafrost-affected soils

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Abstract

The concept of permafrost-affected soils, described as Cryosols or Gelisols, has initiated a lively debate in the scientific literature that pertains to key issues in pedology, including the concept of soils, soil-forming factors and processes, and regional and global soil taxonomic systems. In this review paper, we offer explanations to justify the introduction of the Cryosol and Gelisol orders, particularly in view of the importance of permafrost in global-change scenarios. Our view is that Cryosols contain a cryic horizon or gelic materials resulting from cryogenic processes that include cryoturbation, ice segregation, or cryodesiccation in the presence of permafrost. These processes are pedogenic (i.e., cryopedogenic) and characteristic of permafrost-affected soils. Cryosols also are influenced by physical weathering, geochemical and biochemical weathering that occur at varying degrees. Cryosols are linked to the landscape by the presence of permafrost and the accompanying cryopedogenic processes, which attain dominance over other soil properties and processes in incorporating these soils into global taxonomic systems. We encourage further debate on the issue.

Keywords: Cryosols; Gelisols; Permafrost; Soil concept; Cryopedogenic processes; Soil classification

Contents

1. Introduction

Permafrost-affected soils occupy 11×10^6 km^2 or 8% of the global land area (Soil Survey Staff, 1999) and are prevalent in the Northern Hemisphere (Fig. 1). These soils are of particular importance (1) because they occur in areas of pronounced climate warming, (2) contain large amounts of organic carbon (268 Gt in the Northern Hemisphere, or 16% of the world soil total; Tarnocai et al., 2003) that upon oxidation and methane formation could result in large amounts of CO_2 and CH_4 being released to the atmosphere, (3) contain large amounts of segregated ice that upon melting may lead to thermokarst, and (4) are subject to disturbance from increased interest in fossil fuel and gas hydride extraction, mining, agriculture and forestry, hydroelectric power generation, and other human activities. In the arctic tundra regions, native peoples are particularly concerned about climate warming effects on aquatic and terrestrial ecosystems from which they subsist (http://www.inuit.org). As

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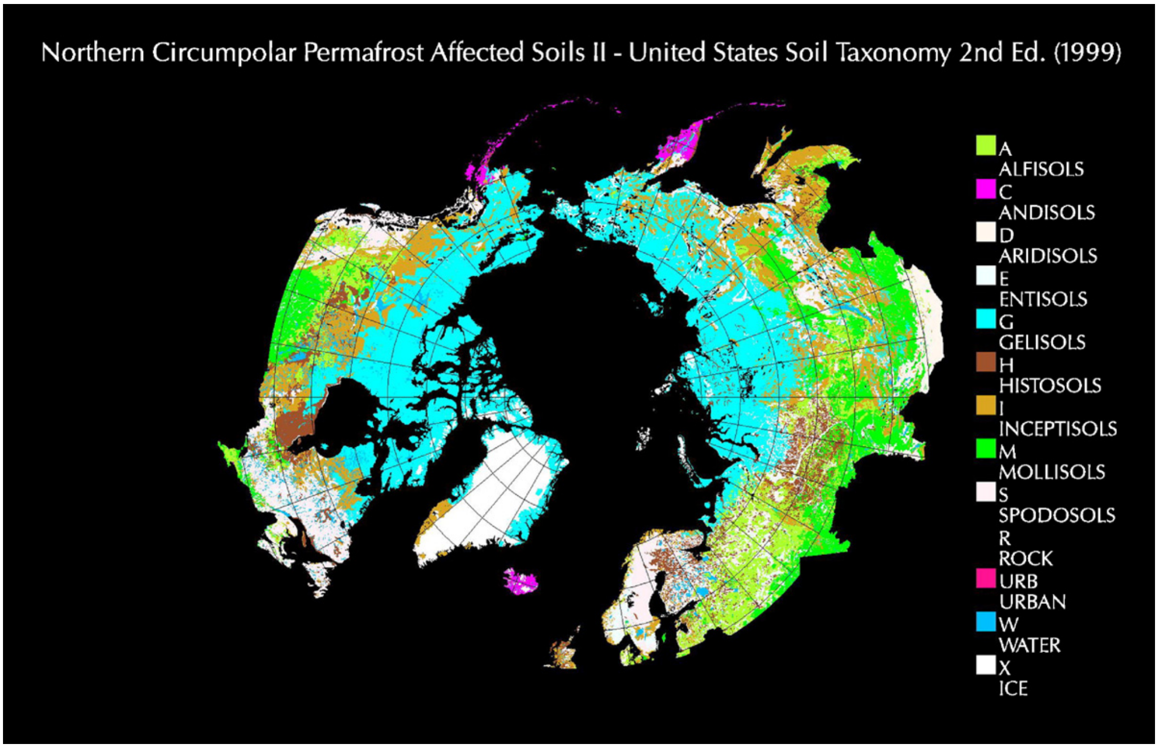

Fig. 1. Distribution of cryosols in the northern circumpolar region (Tarnocai et al., 2003).

with many high-level soil categories, there are debatable theories of permafrost-affected soils that influence our understanding of soil dynamics, use and classification. In the United States, there has been a conceptual evolution in the recognition of permafrost-affected soils beginning with early observations of Kellogg and Nygard (1951). These authors recognized Tundra soils as the normal or zonal soil of the arctic regions, despite that the soils were poorly drained and, therefore, would traditionally have been considered in the Intrazonal (hydromorphic) soil order. Tundra soils were recognized as zonal soils of the arctic because the hydromorphic conditions were due to the presence of impermeable subsurface permafrost, a feature that they associated with climate. Also, the areal extent of the Tundra Biome played a role in this decision. Later, Tedrow and Cantlon (1958) pointed out the inconsistency of naming a poorly drained soil as a climatogenic soil. With the advent of *Soil Taxonomy* (Soil Survey Staff, 1975), the genetic imprint of permafrost-affected soils survived by putting weight on diagnostic horizons as with soils in temperate and other regions. The presence of permafrost was indicated by the subgroup prefix “pergelic.” Following the approach adopted by the Canadians (Soil Classification Working Group, 1998), the second edition of *Soil Taxonomy* (Soil Survey Staff, 1999) recognized permafrost-affected soils at the order level, but as Gelisols rather than Cryosols. Gelisols constitute one of 12 soil orders, which are delineated from other soils by the presence of gelic materials, mineral or organic soil materials that show evidence of cryoturbation and/or ice segregation in the active layer and/or upper part of the permafrost.

In the *World Reference Base for Soil Resources* (FAO, 1994), permafrost-affected soils are identified as Cryosols, one of 30 soil groups, which contain a cryic horizon, a perennially frozen horizon “showing evidence of cryogenic processes and/or characteristic platy, blocky or vesicular macrostructures resulting from vein ice development and banded microstructures originating from sorting of coarse matrix materials” (p. 34). However, many soils containing permafrost are excluded from the Cryosol group if they contain diagnostic horizons other than a calcic, folic, histic, mollic, ochric, salic, umbric, or yermic horizon. In Canada, where permafrost underlies 40% of the land area, permafrost-affected soils likewise are recognized at the highest level and are included in the Cryosol order (Soil Classification Working Group, 1998).

In the first edition of the proposed Russian classification system (Shishov et al., 2001), permafrost-affected soils were limited to the Cryozems. The Cryozem concept was based primarily on the ideas of Sokolov and others (1997) who defined Cryozems as highly cryoturbated soils displaying hydromorphism (soil properties resulting from poor drainage) but without pronounced gleying. Here, we emphasize that permafrost underlies approximately 60% of Russia and yet Cryozems in the first edition of the Russian system occupy less than 1% of the soils of the country (Stolbovoi and McCallum, 2002).

The second edition of the Russian soil classification system (Shishov et al., 2004) contains two high-level Cryosol-related taxa: Cryometamorphic and Cryoturbated soils, the latter containing various Cryozems. Cryometamorphic soils have expressions of cryogenic processes but may not have permafrost in the soil profile. Cryogleyzems are classified at a lower taxonomic level. No taxa are included to indicate the effects of cryogenesis on other soils, e.g., Podzols, Podburs, Podzolic (Luvisolic), Lithosolic, human-affected soils, and other soils. It is impossible to assess the geographic distribution of the two newly introduced taxa because they have not been previously defined or mapped before. The presence of permafrost is recognized at different levels depending on the degree of soil development.

Previous Russian classification systems varied considerably with regard to permafrost-affected soils. Many authors (e.g., Glazovskaya, 1972, 1973; Kovda and Lobova, 1975; Elovskaya et al., 1979; Makeev, 1981) place permafrost and cryogenesis high in classification systems and/or map legends. In the course of transition from a factor-based to a property-based approach, permafrost and many cryopedogenic features disappeared from Russian soil classifications as being "non-soil" properties. In our opinion, radical and frequent changes in both WRB and the Russian systems indicate that the concept of permafrost-affected soils still is not clear.

The purpose of this article is to elucidate the concept of permafrost-affected soils, referred to here as Cryosols, and identify misinterpretations that affect our understanding of them and the role they play in modern soil classification systems. This summarizes activities over the past 15 years of the Cryosol Working Group of the International Permafrost Association (http://igras.geonet.ru/cwg/) and the International Union of Soil Science (IUSS). A clear consensus has not yet been reached, but the need for a strong conceptual model is necessary, particularly in view of rapid global change in the polar regions.

2. Misinterpretations regarding the nature and properties of Cryosols

A key misinterpretation regarding Cryosols is that *cryogenic processes are geologic rather than pedogenic and belong to the realm of geocryology* (Tedrow, 1966; Sokolov et al., 1980). Our view is that cryogenic processes involve inputs, outputs, transfers, and transformations of energy, water, and soil material and, therefore, according to classical definitions of soil-forming processes (Rode, 1955; Simonson, 1959), are pedogenic (i.e., cryopedogenic). Gerasimov (1975) identified deformation, which included cryogenic processes, as key elementary soil processes. Cryopedogenic processes can be observed at the landscape scale by the presence of patterned ground and at the pedon scale by cryoturbation (transfer), cryodesiccation (transfer), and ice segregation (transfer/transformation). These processes are manifested by characteristic platy, blocky, or vesicular macrostructures and banded and orbiculic microstructures (Gerasimova et al., 1992; Fox, 1994; Rusanova, 1996, 1998).

A second common misinterpretation is that *Cryosols are skeletal, poorly developed, and subject primarily to mechanical weathering* (Grigor'ev, 1930; Gorodkov, 1939; in Tedrow, 1974). Our response is that as with soils delineated at the highest level in most soil classification systems, Cryosols vary in their deviation from a centrally defined concept. Although some soils may show less development, others may contain advanced physical, chemical, and/or biological weathering. Based on our collective experience, the proportion of Cryosols containing mollic, umbric, argic (argillic), and podzolic (spodic) horizons is probably <5% of the total area of Cryosols.

The following soil-forming processes have been reported in Cryosols (note: the citations are representative only and not intended to be all-inclusive): (1) brunification (Nogina, 1964; Ugolini et al., 1990), (2) alkalization/salinization (Tedrow, 1966, 1968), (3) podzolization (Kuzmin and Sazonov, 1965; Ugolini et al., 1987; Mazhitova, 1988), (4) calcification (Zolnikov et al., 1962; Tedrow, 1968), (5) decalcification (Mann et al., 1986), (6) pervection (silt migration along a freezing front) (Bockheim, 1979), (7) chemical weathering of phyllosilicate minerals (Hill and Tedrow, 1961), (8) paludification (accumulation of organic materials) (Tarnocai, 1972), (9) retinization of humus (accumulation of organic matter on top of the permafrost table) (Dimo, 1965), (10) gleization (Brown, 1967; Allan et al., 1969), (11) hydromorphism without gleying (Sokolov et al., 1997), and (12) melanization (Rieger, 1966).

Processes such as cryoturbation rejuvenate soil materials (the "cryohomogenization" concept of Sokolov et al., 1980) and increase the soil surface area, which is important in chemical weathering (Tarnocai, 1994). Finally, the permafrost table acts as a barrier to leaching so that weathering products accumulate in the active layer (Munroe and Bockheim, 2001). In some environments, permafrost induces lateral subsurface flow, which is critical for the development of associated hydromorphic soils (Alfimov, 1989).

A third controversial issue is that *permafrost-affected soils featuring podzolization, salinization, gleization, or other elementary soil-forming processes (*Rode and Fridland, 1974; Zonn, 1996*) should be classified as Podzols, Solonchaks, Gleysols, etc. and not Cryosols* (Sokolov et al., 1997). Our view is that although these processes may be operative in Cryosols, they are secondary compared with the stronger cryopedogenic processes (Tarnocai, 1994). For example, Fig. 2 shows a Spodic Haploturbel from the eastern European Russia tundra. Although this soil displays properties that enable it to be classified as a Podzol/Spodosol (Mazhitova and Lapteva, 2004), the soil is strongly cryoturbated and contains gelic materials and permafrost within 100 cm of the surface.

A fourth misinterpretation regarding Cryosols is that *cryogenic processes destroy soil horizons and are inflicted upon "natural" soil-forming processes* (Douglas and Tedrow, 1960; Gerasimov, 1973; Sokolov et al., 1997). In fact, Sokolov and others (1997) claimed that "cryogenic processes … do not result in soil formation" (p. 7) and Cryosols are characterized by the "absence of well developed pedogenic horizons and features" (p. 4). Tedrow (1968) identified two sets of processes acting contemporaneously on polar soils: a pedologic process that gives rise to a "genetic" morphology and a geologic process that tends to disrupt any acquired morphology (Douglas and Tedrow, 1960; Tedrow, 1968). Tedrow (1968) referred to these destructive elements as "cannibalization" and viewed the so-called "natural" soil-forming processes as resulting in soil horizons more or less parallel to the ground surface, and geologic processes as resulting in irregular and broken horizons reflective of a "negative" process contrary to soil formation.

Our view is that cryopedogenic processes are "natural" and characteristic of permafrost-affected soils. An analogous situation is the "vertization" process leading to the development of Vertisols. The irregular and broken horizons that are common to Cryosols are the natural product of cryopedogenic processes,

Fig. 2. Spodic Haploturbel (Gelic Podzol in the WRB), from the eastern European Russia tundra.

such as cryoturbation, freeze–thaw, frost heaving, cryogenic sorting, thermal cracking, and ice segregation (Bockheim and Tarnocai, 1998). These processes are characteristic of permafrost regions and result in soils that have markedly different properties than those not influenced by cryopedogenic processes (Makeev and Kerzhentsev, 1974; Hendershot, 1985; Dobrovol'skiy, 1996). For example, podzolic soils underlain by permafrost are "genetically … the product of the podzolic process in combination with the cryogenic process" (Kuzmin and Sazonov, 1965, p. 1272). Permafrost actually induced podzolization in the Transbaikal region through its control on hydrologic and thermal regimes. In other environments, like those of central and southwestern Yakutia, permafrost, along with low precipitation, suppresses podzolization by limiting leaching of weathering products (Zolnikov et al., 1962). Many aspects of the cryopedogenic process are "positive," including size reduction of particles, arrangement of soil particles, formation of soil aggregates, disintegration of rocks, and ice–salt exclusion (Tedrow, 1968; Makeev, 1981; Marion, 1995).

A fifth misinterpretation of Cryosols is that *soil climate is a soil-forming factor and should not be used in modern soil classification systems based on measurable soil properties*. In the new Russian soil classification system (Shishov et al., 2001, 2004), soil temperature and the occurrence of permafrost are viewed as soil-forming factors and not as diagnostic properties that can be used to classify soils, despite the obvious presence of ice in the soil profile. Moreover, soil temperature and moisture are considered as transitory and not suitable as characteristics from which to classify soils. Sokolov (1993) suggested that it is impossible to combine stable soil properties and transitory soil properties, such as soil temperature and moisture regimes into one soil classification system, despite that these properties are intrinsically linked. The WRB (FAO, 1994) adopted the same view.

We believe that soil temperature and moisture are soil properties that can readily be measured in the field; therefore, they are legitimate soil-forming properties that can be used in soil classification. Soil climate is no more transitory than some chemical properties (pH, base saturation, organic carbon concentration) used to differentiate soils at the higher levels in global soil taxonomic systems. Historically, thermal characteristics of soils have played an important role in Russian soil classification systems (Makeev, 1981). Soil temperature and moisture regimes are important in separating soils at the suborder level in *Soil Taxonomy* (Soil Survey Staff, 1999; ST). Gelisols in ST are not delineated solely on the existence of permafrost but also on the presence of gelic materials. Therefore, it is difficult to envision how a "substantive-genetic" soil classification system such as that proposed for Russia (Shishov et al., 2001, 2004) and the WRB (FAO, 1994) and can ignore a soil property such as soil temperature, which is integral to soil genesis.

A sixth misinterpretation of Cryosols is *that permafrost is a condition of the soil parent material, belongs to the realm of geocryology, and should not be the focus of study by cryopedologists* (Sokolov et al., 1997). Proponents of this notion recognize cryoturbation as being a property of the soil mantle and not of the soil itself. However, we believe that pedologists as well as permafrost scientists need to study cryopedological processes in order to determine the effects of these processes on soil morphology, chemical and physical soil properties, and stability of the soil (Tarnocai, 2005). The Circumpolar Active Layer Monitoring (CALM; http://www.udel/Geography/calm/) project has shown that the thickness of the active layer varies markedly over a decadal scale. The "transition zone," often existing in the upper part of permafrost, displays evidence of soil formation (Bockheim and Hinkel, 2005). Therefore, near-surface permafrost should be described and sampled by cryopedologists as it is in the lower part of the solum.

All of the soil classification systems that we have mentioned declare as one of their aims suitability for practical needs. A farmer, developer, or road engineer in Alaska or the upper Kolyma area of Russia will discredit a soil map that shows various subunits of Podzols/Spodosols but completely ignores the presence of permafrost within one meter of soil surface. This is especially important with regards to the latest Russian soil classification system (Shishov et al., 2004), which does not have a taxon to reflect cryoturbation and permafrost in the soil.

A seventh concern is that some cryopedologists (Sokolov et al., 1997) have suggested that *the definition of Cryosols should be limited to that of Cryozems, which are defined as strongly cryoturbated soils subject to hydromorphism but without gleying*. Sokolov and others (1997) consider Cryosols as including only those soils in which cryogenesis creates completely new soil properties/profile, and the only example they can find are Cryozems with their hydromorphic but non-gleyed conditions. However, they do recognize cryogenic processes as occurring in other permafrost-affected soils but at lower taxonomic levels.

Our view is that the Cryozem (Fig. 3) is not the only soil-map unit unique to permafrost-affected regions. The Cryozem is of minor occurrence in its Russian type locality (<1% of the total area; Stolbovoi and McCallum, 2002) and should not be the sole soil unit defining Cryosols. The concept of gelic materials or cryic horizon links soils of the permafrost-affected regions.

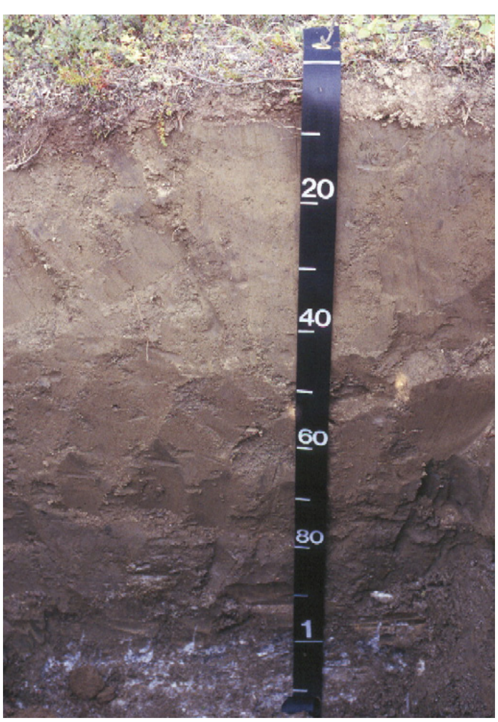

Fig. 3. Cryozem (Typic Haplorthel in ST, Haplic Cryosol in WRB) near Cherskiy, Russian Far East.

An eighth issue regarding Cryosols is that *cryoturbation and gelic materials may occur in areas without permafrost* (e.g., Van Vliet-Lanoë, 2004). Our response is that (1) cryoturbation features may be relict from a previous permafrost environment (Van Vliet-Lanoë, 2004), (2) cryoturbation may occur in alpine and subarctic environments lacking permafrost due to the presence of bedrock or some other confining layer in the upper 200 cm of soil, and most importantly (3) cryoturbation should be recognized as a process that links soils at the highest category in soil classification systems and that intergrades can occur.

Finally, to some scientists, *countries having a large area of Cryosols and/or being located "in the motherland of genetic soil science" have a unique understanding of Cryosols* (Sokolov et al., 1980, 1997). In our view, an understanding of Cryosols and their position in modern soil taxonomic systems is predicated on the state of knowledge of pedology and cryopedology and is not a matter of national identity or historical "ownership."

3. Conclusions

Herein, we identify nine misinterpretations regarding the nature and properties of Cryosols, the processes leading to their development, and the manner in which they are classified in modern global soil taxonomic systems. Our view is that Cryosols (1) are soils underlain by permafrost and are characterized by the presence of a cryic horizon or gelic materials; (2) may feature "mechanical" weathering, but geochemical and biochemical weathering also occur to varying degrees; (3) are subject to cryogenic processes that are pedogenic (i.e., cryopedogenic) and characteristic of the permafrost zone; (4) can be classified on the basis of soil temperature and moisture, which are legitimate soil properties that can be readily measured and on which modern soil classification systems can be built; (5) are linked to the landscape by the presence of permafrost and the accompanying cryopedogenic processes, which are dominant over other soil properties in defining Cryosols in global soil taxonomic systems; and (6) contain permafrost, either in the lower part of the solum or close enough to the solum to exert a major influence on soil formation and should be studied by cryopedologists.

If cryogenic processes are recognized as pedogenic, then most of the soils in the permafrost region can be linked within the range of a single genetic process (cryopedogenesis), and the soil complex can be classed as a unit. "The advantage of this concept, once extended to all of the potential frost-affected soils and including all cryopedogenic features, is that soils could then be considered an integral part of the landscape, and therefore of the geomorphic cycle. This approach appears particularly attractive for the Arctic, where the soils under the impact of short summers, limited rainfall, and frost disturbances are very shallow and apt to reflect the cryopedogenic influences" (Ugolini, 1966, p. 6).

In view of the dramatic climate changes in the polar regions, it is important that global soil taxonomic systems recognize the unique features of Cryosols and that cryopedologists reach some accord in these soils are identified and classified. Finally, we recall the wisdom of Everett and Brown (1982) with regards to classification of permafrost-affected soils: "In the final analysis, the soil classification system that gains the most acceptance in tundra areas is the one that communicates the greatest amount of information at the functional or ecosystem level" (p. 270).

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