Published July 2, 2013

Gelisols: Part II. Classification and Related Issues

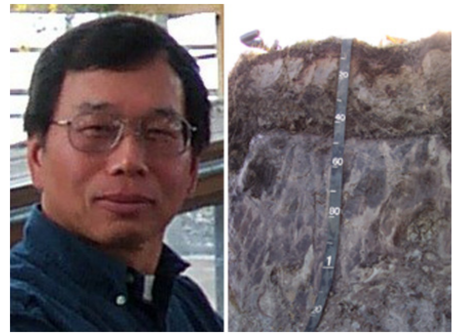
C.L. Ping

Editor's note: This is the second in a two-part series on Gelisols. Part I (https://www.soils.org/publications/sh/articles/54/3/sh2013-54-3-gc) examined the cryogenesis and the state of formation, and part II looks at classification and related issues.

In North America, permafrost-affected soils were first studied by J. Tedrow followed by K. Everett, J. Brown, and J. Drew during their expeditions in the Arctic and Antarctica beginning in the 1950s. W. Pettapiece, C. Tarnocai, S. Zoltai, and their colleagues have been investigating these soils in arctic Canada since the 1970s. They all recognized the cryoturbated soil profiles in association with patterned grounds. The cryogenic nature of these soils was recognized and built into Soil Taxonomy (1975) in which soil climate became an important taxonomic differentia.

Cold soils with mean annual soil temperature (MAST) at 50 cm <8°C were classified at the cryic great group, and soils with MAST <0°C were placed at the pergelic subgroup. When S. Rieger worked on the exploratory soil survey in arctic Alaska in late 1960s, he observed some soils with broken surface organic horizons across the nonsorted circles. Thus, he introduced the taxa of Ruptic-Histic Pergelic Cryaquepts for those cryoturbated soils formed in tussock tundra with permafrost. But soil scientists soon realized that "pergelic" soils cannot be consistently mapped because some soils have MAST <0°C without permafrost. To fill the gaps of knowledge in permafrost-affected soils, Rieger did a thorough literature review on cold soils and summarized the results in his monumental publication *The Genesis and Classification of Cold Soils* by Academy Press (1982). In this book, Rieger summarized the thermal regime, cryogenesis and cryoturbation in cold soil formation, and classification according to Soil Taxonomy (1975). In this book, Rieger also thoroughly reviewed Russian literature on cold soils, which was scarcely known to the Western scientists at that time. For the first time, Rieger delineated the soils affected by permafrost (pergelic subgroups) in the *Exploratory Soil Survey of Alaska* (1975), which served as the basis for the later STATSGO mapping of Alaska.

In the past decades, scientists involved in the National Science Foundation-funded Arctic program have focused on the arctic tundra ecosystem because of its role in the global C cycle. The research programs have further advanced the knowledge on permafrost-affected soils, and the need for a separate order for these soils was brought to the forefront. Then an opportunity presented itself during the National Cooperative Soil Survey (NCSS) conference in Corpus Christi, TX (1988) when I asked Tarnocai about his Cryosol research in Canada, and he agreed to host a collaborative Cryosol study trip transecting from the Yukon to Northwest Territories joined by the USDA-NRCS and University of Alaska–Fairbanks in 1989. This project provided the first sample set of permafrost-affected soils to the USDA National Soil Survey Center and served as the core database for the 1993 International Soils Correlation on Permafrost-affected Soils in which scientists from seven countries participated in a field excursion from Inuvik to Fairbanks to review and discuss the genesis and classification of those cold soils.



Dr. C.L. Ping, Palmer Research Center, Agricultural & Forestry Experiment Station, University of Alaska–Fairbanks. On the right is a highly cryoturbated Gelisol profile, formed in moist nonacid tundra, Arctic Coastal Plain, Alaska.

During the conference, the development of the Gelisol order was discussed among the group, the precursor of the Cryosol Working Group, which continues to be active under the auspices of the International Union of Soil Sciences (IUSS) and the International Permafrost Association (IPA). However, the stage for international cooperation on cold soils research was set even earlier when the pedologists from Alaska-Yukon and northeastern Russia exchanged field visits in the summer of 1992. The joint U.S.–Russia Seminar on Cryopedology and Climate Change in

C. L. Ping, Palmer Research Center, Agricultural & Forestry Experiment Station, University of Alaska–Fairbanks, Palmer, AK; (cping@alaska.edu).

doi:10.2136/sh2013-54-4-gc
Published in *Soil Horizons* (2013).

Pushchino, Russia, was held in the fall of 1992. In this conference, permafrost soil sampling protocols were first discussed.

Thus, the Gelisol proposal was the result of a joint international effort among pedologists and geocryologists. In 1993, the Gelisol order was proposed as the 12th order in Soil Taxonomy. Basically, the proposed taxa followed the Canadian classification for permafrost-affected soils: the Cryosolic soil order. At the suborder level, the mineral soils without cryoturbation were Haplels (later changed to Orthels), mineral soils with cryotubation were Turbels, and the organic soils were Histels.

Gelisols Classification and Related Issues

A few issues are very important in the conceptualization of Gelisols as mapped soils and an environmental component. These issues are centered on definitions, observed natural conditions of Gelisols, and predicted responses to climate change.

Current Status

The technical requirement for classification into the Gelisol order is the presence of permafrost within a specified depth, and for suborder classification, it is soil material (organic vs. mineral) and the presence of gelic materials. In Soil Taxonomy, gelic materials are defined as "mineral or organic soil materials that show evidence of cryoturbation (frost churning) and/or ice segregation in the active layer (seasonal thaw layer) and/or the upper part of the permafrost. Cryoturbation (frost churning) is defined as "the mixing of the soil matrix within the pedon that results in irregular or broken horizons, involutions, accumulation of organic matter on the permafrost table, oriented rock fragments, and silt caps on rock fragments."

In Soil Taxonomy, soil temperature regime (STR) is based on MAST at 50 cm. There are two STRs for cold soils: the cryic STR has a MAST range of 0 to 8°C and the gelic STR has a MAST ≤ 0°C. However, not all soils with MAST ≤ 0°C are Gelisols because depth to permafrost may be greater than that required for classification and the active layers may have mean summer soil temperature (MSST) at 50 cm >0°C. Thus, the thermal status of soils colder than cryic STR is defined within both the STR and soil temperature class:

Gelic – MAST ≤ 0°C for gelic suborder and gelic great group
MAST ≤ 1°C for Gelisols
hypergelic ST class – MAST < -10°C
gelic ST class – MAST -4 to -10°C
subgelic ST class – MAST +1 to -4°C

As noted previously, gelic suborders and great groups are for those soils with MAST ≤ 0°C but MSST > 0°C. These soils commonly occur on alpine or high mountain environments subject to strong summer solar radiation influx but with severe winter freezing and in deltaic environments with deep fluvial deposits in which soil temperature is conditioned by a shallow water table. In order to accommodate gelic taxa without permafrost, gelic suborders have been amended in Andisol, Inceptisol, Mollisol, and Spodosol orders, and gelic great groups are now classified in the Andisol, Entisol, and Inceptisol orders in the 11th edition of *Keys to Soil Taxonomy* (2011)

Definition of Orthels

One may ask why the MAST for Gelisols is set ≤1°C. This is because of the "cyclic" nature of soil temperature fluctuation on an annual or decadal basis, which puts these soils in the subgelic family. Currently, the depth requirement for the presence of permafrost in Orthels is within 1 m of the surface. This causes a problem in soil-mapping efforts because permafrost in equilibrium with its environment fluctuates up and down through the annual cycle. This condition is most notable in the boreal and subarctic regions where the interaction of vegetation, wildfires, and climate variation controls the permafrost depth, such that it fluctuates above and below the required 1-m depth limit. Thus, it is more practical to set the depth of permafrost within 2 m.

Aridic Gelisols or Gelic Aridisols?

Historically, research on permafrost-affected soils has been primarily focused on the Northern Hemisphere, where more than 90% of these soils occur. The emphasis has been on soils with ice-cemented permafrost because of land use interpretations. However, due to our interest in interplanetary exploration and the effects of climate change, there is increased attention in the "soils" of an extreme environment such as those in the Dry Valley area of Antarctica since they may serve as an analog to conditions on planets like Mars. But "dry" permafrost soils exist not only in Antarctica, but also in the extremely dry environment of the western Tibetan Plateau, the high Andes, and other polar regions where the aridity index (AI) often is <0.05 (average annual precipitation divided by average yearly potential evapotranspiration as defined by the United Nations Environmental Programme) and classified as hyperarid. These soils share many genetic traits and properties with Aridisols, and were it not for the cold STR, would be classified as such. Thus, there is a long-standing argument whether these soils classify as Aridic Gelisols or Gelic Aridisols.

In Gelisols containing ice-cemented permafrost, even if they experience net moisture deficiencies, (e.g., soils of the High Arctic), plants still get moisture from the thawing ice within the permafrost. However, those with dry permafrost or those with extremely low precipitation with AI < 0.05 do not support any plants. Currently, these soils are keyed at the "anhydric" great group. Since Aridisols are defined with MAST > 8°C, these soils affected by dry permafrost would be more appropriately classified as Aridic Gelisols, perhaps at the suborder level as "Aridels."

"Biological Zero" in Gelisols

The permafrost environment and Gelisols present a challenge to the definition of "biological zero" of 5°C as defined in wetland delineation protocol. During the growing season in the arctic tundra, when the ericaceous shrubs are flowering and producing fruit, permafrost tables can often be found at 40–60 cm, and the MSST at 50 cm is generally <5°C. In early studies, botanists found that the optimal temperature for cotton grass (*Eriophrum* sp.—a dominant member of the tundra community) root growth is 2°C! Both laboratory and field measurements have verified microbial activity in frozen soils because of the presence of unfrozen water despite the matrix temperature <0°C. This is why the upper permafrost (Cf) often tests positive with α, α - dipyridyl, indicating the presence of ferrous iron, thus reducing conditions promoted by microbial activity.

Gelisols in a Changing Climate

There is genuine concern about a warming climate, which in turn, will induce thawing of permafrost. In areas with thaw-sensitive permafrost, such as the zone of discontinuous, isolated, and sporadic permafrost on the fringes of the arctic regions, the complete thawing of thinner and "warmer" permafrost is expected by the middle of this century. In areas like southwestern Alaska, where both the Pacific Ocean and Bering Sea are very influential in climatic zone dynamics, permafrost may persist for two or more years and disappear for two or more years according to the annual and decadal weather patterns. Hence, what is mapped as a Gelisol in one effort may not be mapped as such in the future. More recently, the major concern is the products and consequences of permafrost thawing. Because of permafrost degradation, more thermokarst ponds are forming across the boreal and arctic regions. This pattern of obvious loss of the frozen soil threatens not only the infrastructure of human communities, but also shifts sequestered C to a labile, dynamic reservoir, as CO_2 and methane are released from the ice and frozen soils, thus accelerating greenhouse-type warming.

In the past decades, there has been a lot of research dedicated to the quality of soil organic carbon (SOC) stored in Gelisols or within the permafrost-affected zone. In most climate-modeling approaches, only the SOC quantity has been used to estimate the greenhouse gas flux and contribution to global warming. Total SOC data does not always lead to accurate modeling of regional or even global C dynamics. It is not just the quantity, but also the quality (i.e., labile condition or susceptibility to decomposition), that controls the SOC dynamics and flux rates. Thus, research in finding robust indicators of SOM quality related to susceptibility to rapid decomposition processes becomes even more important.

Soil Climate Regime

The current STR is based on MAST at 50 cm regardless of the depth of permafrost, and at present, there is no soil moisture regime applied to soils with gelic STR. To geocryologists, the difference between MAST and MAAT and between mean summer and winter temperatures is most critical to cryogenesis. Biologists view the mean July temperature as more critical to the vegetation community. It is also influenced by day length. A challenge to the current climate regime is high altitude areas at relatively low latitudes such as the Qinghai-Tibet Plateau and Andes Mountains where the soils experience diurnal temperature fluctuations and freeze every night and crops cannot grow. Yet, these soils are all mapped the same as those in Alaska, Canada, and Russia where some crops can grow. The relationship between the plant community and soil temperature and/or heat unit deserves re-evaluation.

Permafrost as Soil-Forming Factor

Permafrost plays a controlling role in the genesis of Gelisols. However, the question has always been raised: is permafrost a climate factor or is it parent material or geological formation? Permafrost is cold. However, in many cases, it is a relic of ancient (mostly Pleistocene) climatic conditions and certainly not a true reflection of the current climate conditions except palsas caused by peat buildup and increased insulation. Thus, on top of Jenney's basic state factors of soil formation, permafrost acts as a partially independent factor—partially in the sense that climate and topography strongly affects its dynamics—influencing soil formation in the circumpolar and high-elevation environments.

Conclusions

Soil Taxonomy is designed as the guide for categorizing soils and developing interpretations of soils in soil surveys. Thus, Soil Taxonomy is utility orientated, like many other classification systems. The Gelisol order was created because of the potential hazards and limitations on land use imposed by frost heaving and thawing of ice-rich permafrost and recently the focus of much attention due to the tremendous amount of C stored in frozen soils and the potential feedbacks to climate change with amplified warming in the Arctic. Gelisols, most notably those with ice-cemented permafrost, have unique morphological properties caused by patterned ground formation, cryoturbation, and cryostructures caused by freeze–thaw cycles. Permafrost exerts strong control on the interactions among the five factors of soil formation, which in turn, control the active layer dynamics and the biogeochemical processes in Gelisols. Although Gelisols only account for 9% of the total land surface area on earth, they store up to 40% of the terrestrial C. With rising ambient temperatures and the gradual thawing of permafrost, the considerate C storage and the capacity of Gelisols and the underlying permafrost to release global warming gases, i.e., carbon dioxide and methane, will have a major impact on the global climate. The Gelisol order and gelic STR have certainly addressed the need for categorizing permafrost-affected soils and cold soils without permafrost.

Based on pedon data, soil taxa can be reasonably extrapolated to a geographic base such as the STATSGO map of Alaska done by the USDA-NRCS. Soil great groups were most useful in building the STATSGO map at the current levels of soil inventory. Such a model proves useful in estimating the total C stocks in different physiographic regions of Alaska. However, the current Gelisol classification system is far from perfect and definitely not static. Soil Taxonomy is a comprehensive system designed to accommodate new data for modification, for the system to evolve and remain relevant. Based on observations and published studies, the following modifications should be considered to augment the current taxonomy.

The current list of suborders should be amended to include soils with dry permafrost that share more common properties with Aridisols than the ice-cemented Gelisols. An "Aridels" suborder should be considered. The current limit of permafrost presence within 1 m for Orthels failed to describe the dynamic or annual to decadal cyclic nature of permafrost table depth in the boreal and subarctic regions. The limit to the depth of the top of permafrost should be extended to 2 m. The monitoring of these soils is essential to detect the changes over time and their impact on C dynamics and hydrological cycles in the arctic ecosystem.

There is more information to be added to the great group and subgroup levels to incorporate observed phenomenon. Currently, cryoturbation is not considered in the Histel suborder. However, in the field, cryoturbation features have been observed at the contact between histic epipedons and underlying mineral horizons. Thus a Turbic-Terric subgroup can be used to describe such features.

The hilly terrain in interior Alaska presents a unique land cover locally called "hanging bogs" in which a thick organic layer, mostly consisting of mosses overlying frozen mineral soils on slopes >20% (often up to 60%). In this setting, organic horizons are not saturated long enough during the growing season to be classified as "histic" materials, but rather "folistic." Thus a "Folistic" subgroup should be introduced to Aquiturbels or Aquorthels. On steep slopes where a thick moss layer overlies thin frozen mineral soils over fractured bedrocks, a Folistel suborder should be considered.

Currently, there is no moisture regime assigned to the circumpolar regions, but it is noticeable that the soil temperature regime and class do not apply well to the alpine or high plateau regions. Soil climate of the circumpolar regions needs to be reviewed and reconstructed to reflect the differences between high latitudinal and high altitudinal environments.

Finally, the definitions used in great group differentiation are often difficult to comprehend for non-soils people. A simplification of the differentiae would facilitate the usage of Soil Taxonomy, especially when cross-referenced with other taxonomic systems. This is essential if Soil Taxonomy is to better serve end-users such as climate modelers, land managers, and policy makers.