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The Cold Region Critical Zone in Transition: Responses to Climate Warming and Land Use Change

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Abstract

Global climate warming disproportionately affects high-latitude and mountainous terrestrial ecosystems. Warming is accompanied by permafrost thaw, shorter winters, earlier snowmelt, more intense soil freeze-thaw cycles, drier summers, and longer fire seasons. These environmental changes in turn impact surface water and groundwater flow regimes, water quality, greenhouse gas emissions, soil stability, vegetation cover, and soil (micro)biological communities. Warming also facilitates agricultural expansion, urban growth, and natural resource development, adding growing anthropogenic pressures to cold regions' landscapes, soil health, and biodiversity. Further advances in the predictive understanding of how cold regions' critical zone processes, functions, and ecosystem services will continue to respond to climate warming and land use changes require multiscale monitoring technologies coupled with integrated observational and modeling tools. We highlight some of the major challenges, knowledge gaps, and opportunities in cold region critical zone research, with an emphasis on subsurface processes and responses in both natural and agricultural ecosystems.

Contents

1. INTRODUCTION

Moderate- to high-latitude terrestrial ecosystems and mountainous regions are rapidly changing because of climate change. In Arctic and boreal regions, seasonal mean temperatures are increasing twice as fast as the global averages, with the greatest warming occurring during the winter (1, 2). If global warming continues as projected, the surface air temperature in the Arctic may increase by 5–6°C by the end of the twenty-first century, much higher than the estimated mean global increase (3).

The Earth's cold regions have already undergone significant climate-driven hydro(geo)logical changes. Retreating snowpacks and earlier snowmelt in mountainous watersheds are decreasing mean annual streamflow and causing peak runoff earlier in the year, while permafrost thaw and seasonal freeze-thaw are modifying the relative importance of surface and groundwater flows in northern ecosystems (4–6). These hydrological changes are accompanied by changes in, among others, vegetation cover, thermal regime of soils, fluxes and timing of nutrient export to aquatic ecosystems, emissions of greenhouse gases (GHGs), and the mobilization of organic carbon and geogenic contaminants (7–10). That is, climate warming generates a set of interrelated changes in the critical zone (hydro)geophysical properties, hydro(geo)logical flows, biogeochemical processes, and ecosystem functions in the world's cold regions.

The critical zone comprises the life-sustaining near-surface earth environment that connects the terrestrial biosphere with the atmosphere, hydrosphere, and shallow geosphere (11, 12). Compared with the temperate regions, cold regions are characterized by a shorter growing season, more persistent snow cover, extensive permafrost, and pronounced cycles of freezing and thawing. In addition to accelerating many abiotic and biotic soil processes, rising air and soil temperatures also facilitate the expansion of population and agriculture in cold regions (13). Agricultural intensification (including aquaculture), infrastructure construction (e.g., roads and pipelines), and mining operations are adding further pressures to the ecological health of the cold regions' critical zone (11). In turn, changes in the critical zone may engender feedbacks to the water cycle and climate system that extend the environmental impacts to the regional and even global scale.

Previous reviews of the critical zone in cold regions have primarily focused on the hydrological consequences of permafrost thaw and the northward retreat of permafrost and seasonally frozen soils (4, 6, 8). Here, we provide an admittedly nonexhaustive overview of key aspects of cold region critical zone science, with an emphasis on the climatic, hydro(geo)logical, and agricultural drivers of changes in subsurface biogeochemistry, water quality, and ecology. We pay special attention to knowledge gaps and emerging issues, as well as to opportunities for assessing the local and regional responses of the critical zone to anthropogenic pressures through enhanced monitoring and modeling capabilities coupled with the establishment of cold region critical zone observatories (CZOs).

Permafrost: ground with temperature ≤0°C for at least two consecutive years; also called perennially frozen ground

GHGs: greenhouse gases

CZO: critical zone observatory

2. HYDRO(GEO)LOGICAL PROCESSES UNDER A CHANGING CLIMATE

2.1. Thermal Regimes in the Cold Shallow Subsurface

Active layer thickness: the lesser of the maximum seasonal frost depth and the maximum seasonal thaw depth

Talik: the year-round unfrozen zone within a permafrost area that is either closed (isolated) or open (interconnected)

Rising temperatures in high latitudes and high altitudes are changing the thermal regimes of the near-surface environment (9). For example, over the past 40 years soil temperatures at shallow depths have increased by up to 2°C in northern Europe (14). Ongoing trends in soil temperatures increase the probability for large areas of the cold regions to experience annual duration of soil temperatures remaining above 0°C (15). This, in turn, impacts soil hydro(geo)logical processes, including permafrost degradation, freeze-thaw cycles, and soil hydrophysical properties (**Figure 1**) (16).

Increasing ground temperatures are causing the progressive northward retreat of perennially frozen soils whose areal extent has shrunk by more than 10% within the past four decades (17). In addition, historically continuous permafrost areas are becoming disconnected with sporadic permafrost patches turning into seasonally frozen ground (4). Higher summer air temperatures correlate with increases in the active layer thickness, while higher winter air temperatures are associated with decreases in the annual thickness and duration of seasonally frozen ground in the cold and cold-temperate regions (18, 19). Consequently, the increases in the coverage of taliks

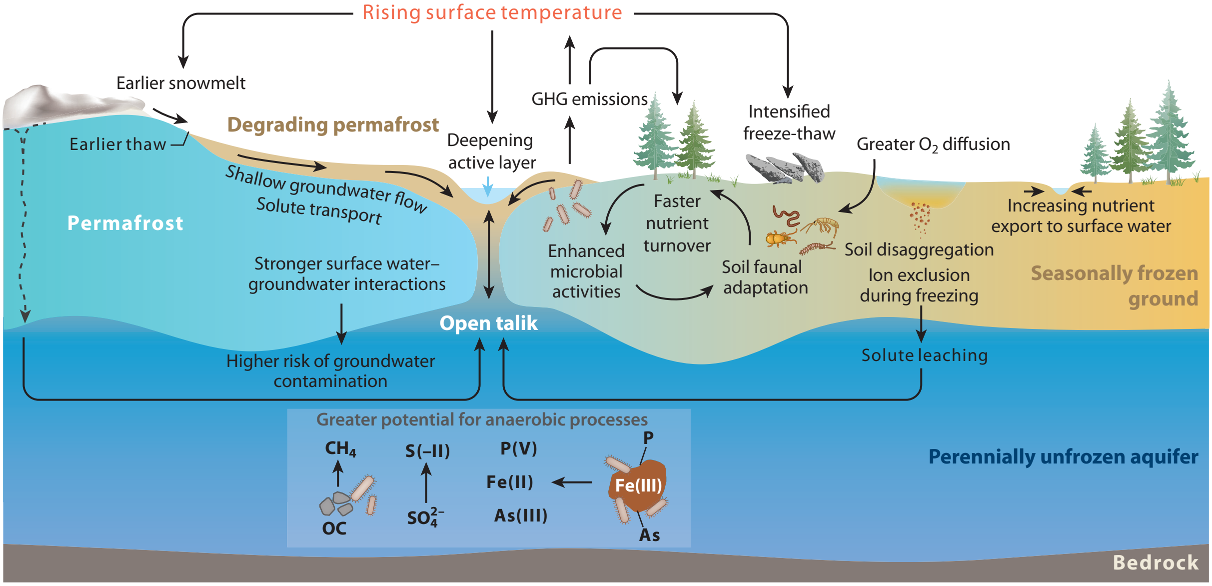

Figure 1

Coupled hydro(geo)logical, (bio)geochemical, and ecological responses of the cold region critical zone to climate warming. The hydrological responses, including earlier snowmelt, earlier spring thaw, deepening of the active layer, and intensified freeze-thaw cycles, are expected to enhance surface water–groundwater interactions, for example, through more intense exchanges along open taliks. The changing hydrological and soil thermal regimes can further amplify biogeochemical cycling in the subsurface, including higher soil carbon turnover, solute leaching, and microbially driven anaerobic processes that, together, may alter the quality of both surface water and groundwater. At the same time, a warming climate causes shifts in the composition and structure of the aboveground vegetation and subsurface macro- and microbiota. Abbreviations: GHG: greenhouse gas; OC, organic carbon; S(–II), sulfide sulfur; Fe(III), ferric iron containing minerals.

and drainage of thermokarst rivers and lakes often cause ambient active layers to fail to refreeze over the winter season (20).

Thermokarst: a land surface configuration resembling karst that results from the thawing of ice-rich permafrost and/or massive ice

Overall, mean annual heat fluxes from the ground surface down into the permafrost or seasonally frozen ground are increasing over the years. These heat fluxes, however, are modulated by interactions among soil properties, including seasonal variations in soil moisture, snow cover and vegetation, as well as the near-surface water redistribution and mid-winter thermal anomalies that positively or negatively affect the ground stability (9). Consequently, the heat fluxes vary spatially and temporally, which complicates the predictive understanding of the evolution of permafrost and the intensities of soil freeze-thaw cycles in seasonally frozen areas.

Physics-based analytical approaches to estimate the changes in soil heat fluxes due to climate warming include the Kudryavtsev and modified Stefan models (4). More advanced numerical models, however, may perform better when addressing more complex freeze-thaw and snow cover conditions, for instance, by explicitly coupling heat transfer calculations and subsurface water dynamics (21). Nonetheless, most models consider only vertical heat transfer and thus cannot account for lateral variations in heat transfer resulting from heterogeneous hydrothermal properties in the subsurface (22).

2.2. Hydrological Responses

Climate-driven degradation of the ice-rich permafrost alters the water balance and hydrological processes as well as their seasonal dynamics within the cold region critical zone (4, 16). Specifically, permafrost thaw can connect previously separated vertical and lateral flow paths, resulting in larger subsurface water fluxes. It also alters the landscape within a short period of time, enhancing surface water routing and runoff (20). It has been postulated that the 7% increase in the base flow of the six largest Eurasian rivers draining into the Arctic Ocean between 1936 and 1999 is due jointly to increased suprapermafrost water flow and enhanced regional groundwater discharges from discontinuous permafrost zones (23). In addition, by removing ice from the soil's large interconnected pore spaces, deepening thaw increases the soil's hydraulic conductivity and modifies the timing and extent of winter and spring runoff (4).

Changes in the depth and duration of seasonally frozen ground control soil hydrological processes such as snowmelt infiltration, runoff, and soil moisture. For instance, the ground snow depth tends to correlate negatively with the freeze depth, but positively with the active layer thaw depth, hence generating strong couplings between variations in surface temperature, snowmelt, and soil moisture (24). Less snow accumulation may result in sufficiently deep frost penetration to impede snowmelt infiltration and enhance overland runoff to the surface water network (16). Therefore, in general, peak winter surface flows are followed by declining spring and early summer runoff. Increased runoff and flooding in the surface and active layer system in turn increases the soil temperature, further deepening the active layer (25). This positive feedback intensifies the water cycle and accelerates the changes in subsurface water and heat flows.

The compounded interactions between the hydrological and thermal regimes render the analysis and prediction of impacts on hydrological processes at different scales fairly challenging (9, 26). This has been shown when assessing the consequences of variable snowpack development on surface water–groundwater exchanges (27). For example, an analysis of a 52-year hillslope runoff record near Swift Current, Canada, indicated decreasing snowmelt runoff and spring soil moisture in response to winter snowfall decline (28). By contrast, a whole-catchment analysis for the same region suggested a multifold increase in snowmelt runoff since 1975, regardless of the decreasing snowfall (29, 30). These results illustrate the need for a careful consideration of both spatial and time scales when interpreting hydrological responses to climate warming in cold regions.

2.3. Surface Water–Groundwater Interactions

Groundwater in cold regions represents a secure, long-term water resource for northern communities. In Canada's New Brunswick, for instance, more than 66% of the population relies on groundwater for their drinking water supply (31). Groundwater also moderates regional variations in the streamflow and enhances ecosystem resilience toward hydroclimatic extremes, regional population growth, and industrial development (32). A warming climate tends to intensify water and heat exchanges between groundwater and surface water bodies, in particular the groundwater recharge and discharge fluxes (19, 33).

In permafrost areas, groundwater resides in the suprapermafrost, intrapermafrost, and subpermafrost aquifers. Increases in surface water infiltration and groundwater discharge to the surface network may occur when the permafrost thaws and enhances subsurface transmissivity (34). The formation of lateral suprapermafrost taliks underlying the active layers can further cause a spatial shift in groundwater discharge from upslope to downslope, as well as a temporal shift with more groundwater discharge in the winter (35). In continuous permafrost, subsurface water exchange through open taliks tends to intensify regional groundwater circulation (36), whereas upwelling of deep groundwater enhances heat transfer, further expanding talik development within the permafrost (37).

The strengthened connectivity between groundwater and surface water compartments raises the possibility of a transition from a surface water–dominated to a groundwater–dominated hydrology across vast areas of the Holarctic region as well as possibly in mountainous regions (34, 38). A diagnostic signature of this shift is the reduced seasonal variability of stream discharge and water temperature as proportionally more water is supplied through the subsurface. In areas of seasonally frozen ground, surface water–groundwater interactions are primarily modulated by the seasonality of groundwater recharge and subsequent discharge into the surface water network (26, 39). For instance, a reduction in seasonal freeze depth, due to the rising winter soil temperature, favors infiltration of melting water that can ultimately reach the underlying aquifer (18, 40). This then increases deep flow as well as early and late season groundwater discharge (26).

The complex spatiotemporal variations in subsurface water pathways and fluxes, together with the lack of baseline information, hinder the detailed and scale-dependent prediction of groundwater dynamics in cold regions. Nonetheless, advances have been made by combining existing observational data with numerical model-based simulations of the hydrogeology in high-elevation, boreal, and Arctic regions (4, 6). The existing thermohydraulic models usually couple a Richards-type equation for subsurface water flow to a Fourier-type equation for heat transfer while accounting for the energy exchanges during phase changes (9). The modeling efforts, including comparing the effects of future climate change to those in temperate regions, are helping to better quantify the responses to climate forcing of subsurface hydrology (e.g., changes in active layer thickness, depth and duration of seasonally frozen ground, and timing and magnitude of groundwater recharge and discharge). Considerable work is, however, required to link these dynamic and evolving hydrogeological processes to their consequences for water chemistry and subsurface biogeochemical processes.

3. HYDROGEOCHEMICAL RESPONSES

3.1. Soil and Groundwater Geochemical Responses

Increased frequency and magnitude of freeze-thaw cycles in (sub)boreal and mountainous regions may intensify the deformation of the soil structure and change aggregate stability (33, 41). When soils freeze, exclusion of dissolved ions from the ice increases their concentrations in the residual water films. This can induce clay particles to flocculate and cementing minerals, e.g., calcite, silica, gypsum, and iron (hydr)oxides, to precipitate at the interfaces between primary particles and smaller aggregates (8, 42). As a consequence of the mechanical fragmentation of the coarser minerals and the aggregation of the fine particles, the particle size distribution of the soils may become increasingly homogeneous over time, leading to the formation of loess-like deposits.

Variations in the cryogenic structure of seasonally frozen soils may also lead to the remobilization and redistribution of ionic and mineralogical components. Increasing soil temperature decreases the solubility of carbonate minerals and that of atmospheric gases but increases the solubility of most other minerals (43). Porewater solutes may move vertically under the control of thermal and concentration gradients that shift across summer and winter seasons. For instance, migration of ions, including Na^+, Mg^{2+}, Ca^{2+}, $SO_4{}^{2-}$, and $HCO_3{}^-$, up to the depth of seasonal temperature alternations was reported for permafrost soils along the Russian Arctic coast over a 12-year period (44, 45).

SOM: soil organic matter

DOC: dissolved organic carbon

Soil respiration: comprises the rapid turnover of root exudates (autotrophic respiration) and the slower degradation of soil organic matter (heterotrophic respiration)

Rising winter soil temperatures and enhanced shallow groundwater flow through organic soils increase the microbially mediated decomposition of soil organic matter (SOM), even at subzero temperatures (46). This, in turn, increases the annual export and seasonal variability of dissolved organic carbon (DOC) delivered to cold region streams, rivers, lakes, and coastal zones (47–49). How future climate warming will continue to affect soil DOC mobilization and subsequent utilization by aquatic microorganisms remains a major source of uncertainty in global carbon cycle projections. Similarly, the mineralization of soil organic nitrogen and subsequent leaching to groundwater and receiving surface waters has important consequences for water quality and GHG emissions (Section 3.2).

In addition to direct temperature effects, the growing hydrogeological connectivity in cold regions affects chemical fluxes by changing the residence time of water in the critical zone, as well as the pathways and magnitude of groundwater flow (7). By acting as the suprapermafrost aquifer, the active layer provides the contact time and environmental conditions for mineral dissolution, organic matter degradation, and nutrient transformations to significantly alter the water chemistry (33, 50). Increasing groundwater contributions to streamflow may then elevate the concentrations of dissolved inorganic solids, carbon, nitrogen, and other nutrients in the receiving surface waters (51, 52). Further characterization of the hydrochemistry, including stable isotope measurements, of the various water compartments will be required to fully understand the solute sources, transformations, and transport pathway in the cold regions (33). This knowledge, in turn, is essential to make informed predictions of how water quality will respond to climate change and other anthropogenic pressures.

3.2. Greenhouse Gas Emissions

Arctic and (sub)boreal ecosystems are not necessarily net sources of CO_2. In fact, boreal forests characterized by dense tree stands may assimilate more CO_2 from the atmosphere than they release, resulting in annual net ecosystem uptake fluxes of up to 270 g C m^{-2} $year^{-1}$ (53). Northern peatlands act as net sinks of atmospheric CO_2 with current accumulation rates of approximately 0.1 Pg C $year^{-1}$ (54). In contrast, the Holarctic region is a major net source of CH_4, in part because historically trapped CH_4 is released upon permafrost thaw (55). Nitrogen limitation inherent to many cold ecosystems usually produces only small N_2O fluxes to the atmosphere (56).

Freeze-thaw cycles of the active layer and seasonally frozen soils affect the emission of GHGs by modulating the spatial and temporal distributions of soil moisture and temperature, that is, two key environmental variables controlling soil respiration and fermentation processes (57). Under frozen conditions, the liquid water available within the soils can still support microbial metabolic processes that mineralize SOM and produce CO_2 (58, 59). Thawing of frozen soils also causes a burst release of gases entrapped over the winter season when exchanges with the atmosphere are limited, because the soil's surface layer is frozen (55). For example, the N_2O emissions in the winter and following spring thawing may account for a considerable fraction of the annual total N_2O emission, up to 50%, in drained agricultural peatlands (56, 60).

In addition to regulating temperature and moisture regimes, soil freeze-thaw cycles can enhance the mineralization of organic carbon and nutrients through the breakdown of soil aggregates and the die-off of fine roots and microorganisms (61). These increase substrate supply to the active microbial community, which in turn favors the production of GHGs even during the non-growing season (62). For example, because of low soil temperatures and reduced root uptake of nutrients in the winter, the end-product of denitrification may increasingly shift toward N_2O, rather than N_2, despite the overall slower denitrification rate (63).

The feedback between GHG emissions and climate warming raises concerns about possible abrupt (nonlinear) effects in cold regions where accelerating hydro(geo)logical and biogeochemical responses may cause significant changes in the magnitude and even the direction of GHG fluxes over relatively short periods of time. Reliable quantification of the major environmental controls on soil GHG emissions over space and time in cold regions is therefore particularly imperative (10). Among these factors, winter soil conditions, the preceding vegetation growth activity, and disturbances such as wildfires appear to play important, albeit incompletely understood, roles in the annual GHG emission budgets (62, 64, 65). Vegetation also plays a role in the transport of GHG to and from the atmosphere, for example, by facilitating CH_4 emissions to the atmosphere along tree stems or via the aerenchyma (66).

3.3. Contaminant Fate and Transport

The environmental assessment of contaminants in cold regions includes the identification of sources, mobilization processes, delivery to the hydrological network, and ecosystem and human health impacts. Contaminants originate either locally from autochthonous sources, e.g., emissions from mine tailings, or remotely from allochthonous sources, which is the case of volatile pollutants transported via the atmosphere (67). The latter may involve transport over very long distances, via so-called long-range atmospheric transport, with sources that are distant from the cold regions where the negative impacts occur. For example, gaseous elemental mercury and methylmercury can travel across continents and oceans before ultimately being deposited in the Arctic (68).

The release of geogenic contaminants, such as arsenic, uranium, and copper, from the dissolution of minerals present in the critical zone depends on the physicochemical conditions in the subsurface (69). The latter are closely associated with the microbially mediated degradation of SOM. For example, mineralization of organic carbon by heterotrophic bacteria produces dissolved (bi)carbonate ions that form strong aqueous complexes with uranium(VI), hence facilitating uranium release to, and transport by, groundwater (70). In a similar vein, DOC leached during SOM degradation may form aqueous complexes with trace metals, whereas microbial respiration may lead to the development of anoxic conditions that favor the mobilization of iron(III) oxide–bound arsenic (71).

From the above, it follows that permafrost degradation can significantly increase the risks of contaminants reaching groundwater and surface water resources in cold regions (72). Warming conditions, by stimulating microbial activities in the shallow subsurface, expanding hydrological connectivity, and increasing surface and subsurface water flows, may therefore increase threats to water quality and related ecosystem functions and services. Snowmelt may result in the rapid runoff to aquatic ecosystems of contaminants deposited from the atmosphere, such as mercury and persistent organic pollutants (POPs) (73). Forest fires are an additional source of contaminants, including polycyclic aromatic hydrocarbons produced during high-temperature biomass combustion (74).

POPs: persistent organic pollutants

SOC: soil organic carbon

The soil freeze-thaw cycles significantly affect the fate and transport of contaminants. Typically, the mobilization of POPs and nutrients is reduced when the ground freezes and enhanced when the ground thaws (67). Thus, thawing alters the timing at which the contaminants enter the hydrosphere. Equally important are the chemical forms under which the contaminants occur, as soluble inorganic ions are likely to be released early on whereas hydrophobic organic compounds may exhibit significant lag times (67). The chemical speciation of contaminants also determines their bioavailability and toxicity and, hence, the resulting ecological and public health risks.

3.4. Hyporheic and Riparian Zones

Cold regions' stream corridors, including their hyporheic and riparian zones, experience preferential thaw. Streams with steeper topographical gradients generally show higher variations in freeze-thaw depths, in comparison with lower gradient streams that usually maintain deeper thaw depths over a longer time (75). Furthermore, differences in stream bed sediments result in longer hyporheic pathways and shorter water residence times in alluvial stream reaches relative to peat-dominated reaches (76).

Similar to temperate and (sub)tropical regions, the hyporheic and riparian zones of streams and rivers in cold regions are biogeochemical hotspots (77). Biogeochemical activities in these transitional environments may vary abruptly with the timing of periods of high activity and chemical exchanges, that is, hot moments, closely tied to stream hydrology and hillslope freeze-thaw processes (76, 78). Interestingly, rates of microbially mediated biogeochemical reactions in the hyporheic zone of some Arctic streams are comparable to those in temperate zones (79), likely reflecting the adaptation of the hyporheic microbial communities to the ambient cold temperatures.

Because surface waters in cold regions are typically nutrient (co)limited, hyporheic exchanges may become an important source of nutrients to the river network and the receiving lakes and coastal areas. Tracer experiments in four Arctic stream reaches did show that the hyporheic zone is a hotspot for organic matter mineralization, ammonification, and nitrification, resulting in the net release of nitrate, ammonium, dissolved phosphate, and CO_2 to the streams (79).

4. SOIL ECOLOGICAL RESPONSES

4.1. Microbial Communities

Microbes play key roles in soil organic carbon (SOC) turnover, nutrient cycling, and pore water quality, all of which influence aboveground plant productivity (80). Soil microbial communities mainly comprise bacteria and fungi, the primary consumers of dead organic matter (decomposers), plus archaea, protists, and viruses. Because of low soil temperatures, together with limited liquid water availability, soil microbial ecosystems in cold regions tend to be relatively simple and functionally limited in nutrient cycling, compared with their temperate counterparts (81, 82).

Soil microbial communities rapidly adjust to new conditions and are therefore vulnerable to disturbances such as those accompanying climate warming (83, 84). In degrading permafrost, for example, specific members of the microbial community respond preferentially to the rising temperature and availability of energy and growth substrates released during thaw (83, 84). In Alpine and Arctic ecosystems, the snowpack insulates soil microbial communities from the harsh winter conditions (85). Increasing or decreasing snowpack depth may therefore strongly affect the soil's geomicrobial functioning. For instance, in Alpine pastures, the activities and abundances of nitrifiers and denitrifiers are significantly enhanced when the winter snowpack is thin or even absent (85).

In addition to conventional biomass determinations and phospholipid fatty acid analyses, recent developments in molecular biology allow for the detailed DNA- and RNA-based assessments of microbial community compositions in cold subsurface sites (86, 87). Whereas bacteria have received comparatively more attention, the responses of soil archaea and protists to climate change impacts have been less well characterized. Soil warming, however, has been shown to change the abundance, species diversity, and assemblage composition of testate amoebae even after one growing season (88). The impacts of warming on the diversity and activity of viruses are poorly understood, despite their relatively high abundance in cold ecosystems and their potentially significant effect on soil microbial community dynamics (89).

The responses of soil microbial communities to climate warming are heavily context dependent with frequently no clear emerging patterns that can easily be generalized. In part, this is attributed to the variable nature of the climate forcings, e.g., long-term (decadal) versus short-term (seasonal) warming, or the gradual increase in average air temperature versus extreme hydroclimatic events (90). Furthermore, microbial responses are highly interactive and heavily influenced by changes in hydrology, soil properties, and other (soil) organisms (91). For example, responses of soil microbes to variations in surface temperature may differ dramatically depending on their position along the soil profile (90).

The characterization of the soil microbial community structure is often accompanied by microbial activity measurements, such as mineralization rates (92), GHG emissions (93), and microbial enzyme activities (94). The responses inferred from these two types of observations, however, are often difficult to reconcile. For example, whereas the experimental warming of a subarctic peatland caused measurable variations in enzyme activities, no changes in the microbial community composition were detected (94). Metatranscriptomics may help unravel the underlying reasons for these apparent inconsistencies (95).

4.2. Faunal Communities

Small soil fauna, in particular nematodes, participate in organic matter turnover by mineralizing nitrogen and carbon and, thus, represent a key component of the soil food web. Macrofauna, such as earthworms, can change the structure of SOM and alter soil porosity when they migrate to deeper soil horizons to avoid the upper frozen layer (96). In turn, this creates vertical flow paths in deeper soil horizons that alter infiltration processes and enable macropore flow.

Under extreme cold climate conditions, macrofauna are largely absent and smaller soil faunal communities, for example, microarthropods (collembola and mites), enchytraeids, and nematodes, tend to dominate the faunal impacts on soil ecological responses. As changes in the faunal community composition may play a disproportionally large role in soil functioning (97), there is a need to understand the effects of global climate warming on the fauna within the critical zone, as well as the consequences for the winter activities of soil biota.

Existing evidence from experimental climate manipulations and long-term field observations indicate that the effects of climate warming on soil faunal communities are mostly modulated through water availability (98). In North American boreal forests, four years of imposed warming had little effect on SOM decomposition by invertebrate detritivores (99). A reduction by 40% of summer precipitation, however, resulted in a reduction in feeding activity by almost 14%. These results imply slower SOM biodegradation than generally expected, and thus a weaker positive feedback to climate warming.

Climate warming alters faunal vertical zonation, which in turn impacts carbon release from different soil layers (100). Additionally, climate warming may change predator–prey interactions with considerable consequences for soil ecosystem functioning in cold regions (101). Notably, most of the existing studies support the assumption that soil microarthropods are bottom-up controlled, and the observed changes are linked more to changes in vegetation and food availability than to direct climatic forcing.

Climate warming in cold regions may not only alter established soil faunal communities but also change the geographic ranges of specific members of the soil fauna. Although soil faunal dispersal is generally slow in cold regions, the combination of human dispersal and climatic change can exponentially accelerate the establishment of new soil ecosystems, including the appearance of invasive organisms (102). The resulting soil biological responses alter the soil food web structure, net soil respiration, and provision of ecosystem services. For example, the establishment of human-dispersed burrowing earthworms in subarctic Sweden, although currently still sparse, is expected to have potentially far-reaching consequences for soil hydrology, nutrient cycling, and carbon emissions if continued (103, 104).

In contrast to the long-term climate warming trend, more sudden extreme events, e.g., repeated freeze-thaw cycles, have been shown to negatively impact species survival and community diversity of soil fauna (105). The question, however, remains as to whether the observed responses of the soil fauna community are a direct consequence of the climate forcing or are mediated via responses of the rest of the soil food web.

5. COLD REGION AGRICULTURE AND AGROECOSYSTEMS

5.1. Agricultural Expansion Into Cold Regions

Faced with an ever-increasing demand to feed the world's growing population, agroecosystems are under pressure to maintain high productivity levels while also ensuring their long-term sustainability (106). In cold regions, the relatively short growing season is determined by the early soil frost in autumn and late soil thaw in spring (107). Increasing winter temperatures are therefore causing a lengthening of the growing season that is accompanied by the expansion of agriculture toward higher latitudes and altitudes (**Figure 2**) (13).

Between 1983 and 2004, the growing period for cotton in northern China increased on average by nine days, owing to a corresponding decrease in the number of frost days (108). Meanwhile, between 1980 and 2007, the geographical reach of rice cultivation in northern China moved northward from approximately 48 to 52 °N. With ongoing climate warming, these trends can be expected to continue across many of the world's cold regions. A plausible scenario is that increasing thawing permafrost areas give way to wetland-rich landscapes, which subsequently would be converted into arable land rich in SOM (109). Without proactive management of the new agroecosystems, this could lead to negative environmental impacts of agriculture similar to those seen in temperate regions but exacerbated by the harsh environmental conditions found in cold regions.

5.2. Soil Degradation

To support agricultural intensification, various agricultural practices are introduced, including more extensive tillage and drainage as well as increased application of chemical fertilizers, manure, pesticides, and herbicides. Although these practices increase crop productivity, they may lead to long-term land degradation and loss of natural soil fertility.

The negative impacts of extensive cultivation on fertile, organic-rich grassland may yield lessons for the management of agroecosystems in cold regions. Of particular concern are the often observed decreases in SOM content. For example, Hou et al. (110) investigated the effect of

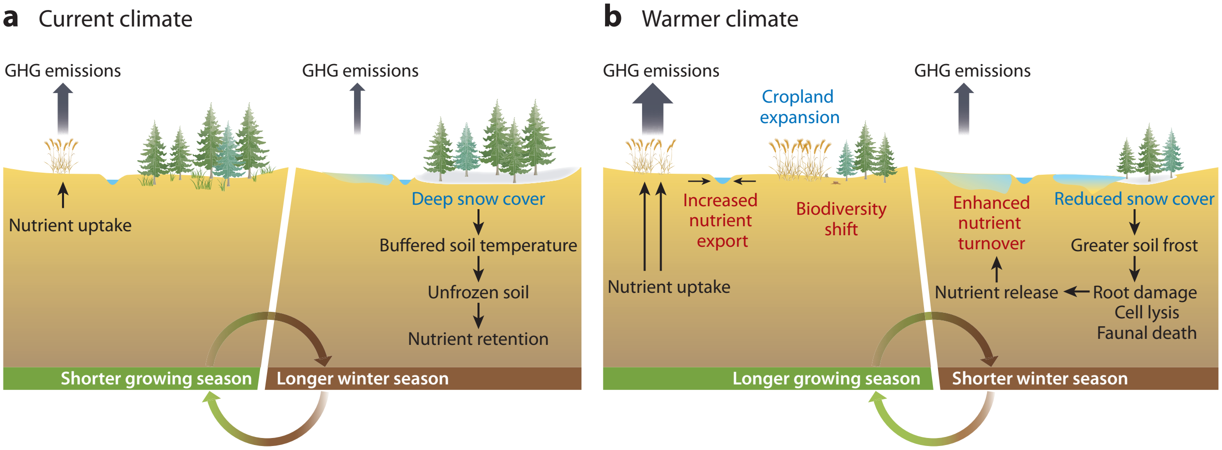

Figure 2

Hypothetical cold region agroecosystem in a future warmer climate (*b*) compared to current conditions (*a*). Panel *b* illustrates the combined responses (*red text*) to changes in conditions (*blue text*) such as shortening of the winter season, expanding cropland, greater fertilizer application, and generally higher air temperature. The shorter winter (i.e., non-growing) season, altered hydrological regime (including reduced snow cover, increased freeze-thaw events, and changing soil moisture status), and agricultural intensification may result in increased nutrient enrichment of surface waters, higher greenhouse gas (GHG) emissions, and changes in biodiversity of the cold region agroecosystem.

land use on the stabilization of SOC in the Mollisols of northern China by comparing grassland, cropland, and bare fallow treatments over a period of 10 years. The SOC content decreased on average by 17% in croplands relative to the grasslands, reaching levels close to that of the bare fallow fields. In the same region, another study found that 50% of SOC was lost after 50 years of cultivation, with the decreasing trend likely to continue into the future (111).

The considerable SOC losses that typically accompany the conversion to agriculture call for a sustainable agricultural intensification that in turn requires the implementation of proactive and adaptive management practices and policies (112). For example, the use of animal manure, no-till farming and optimizing the application rates and timing of industrial fertilizers, as well as the introduction of intercropping systems can reduce erosion and protect local biodiversity (110, 113). Maintaining natural wetland, grassland, and forest areas and creating new buffer zones not only help reduce agricultural land degradation but also contribute to the attenuation of excessive nutrient enrichment and contaminant dispersal (114). Protecting against SOC losses and practicing mixed agriculture-agroforestry additionally reduce GHG emissions to the atmosphere.

5.3. Cold Region Agroecosystems Under Climate Change

As northern agroecosystems expand, they will also respond to ongoing climate change, with significant feedbacks to the soil thermal regime and water balance. Crop cultivation may profoundly alter the soil texture through the destruction of the macropore network of the pristine soils (115). In turn, this reduces the soil structural stability and enhances physical erosion. The resulting drop in soil permeability and decrease in infiltration of spring snowmelt further affect the soil moisture conditions and, thus, crop growth.

As for natural landscapes, agroecosystems respond to changes in the depth of snow cover and the patterns of snow accumulation and melting (**Figure 2**). In particular, decreasing snow depth reduces the insulation capacity of the soil surface and increases the risks of deep soil frost and more intense freeze-thaw cycles in conventionally tilled fields. Knowledge of winter soil

Mollisols: soils characterized by a thick, organic-rich surface horizon typically forming under a grassland cover processes, including those related to snow cover dynamics, can help inform farming practices in cold regions. For example, on commercial potato farms in northern Japan, ground snow cover was mechanically removed to induce deep soil frost, in order to kill the weed seeds before the upcoming crop season (116). The same process may take place naturally in areas where climate change is causing a reduction in snow cover (**Figure 2**). Extreme soil freezing, however, may limit the potential for cultivating winter crops (117).

5.4. Biogeochemical and Ecosystem Responses

Agriculture in cold regions can profoundly modify the soil–atmosphere exchanges of CO_2 and other GHGs. Such changes have been observed, for instance, for the cumulative CO_2 release from agricultural Mollisols in northern China following the amendment of plant and animal waste (118) and the application of different tillage methods (119). These changes have in part been ascribed to reduced snow cover on agricultural fields and the resulting deep soil frost that restricts bacterial activities in the plough layer. Interestingly, it was found in one study that the emissions of N_2O from agricultural fields during the winter season was comparable to those during the growing season, whereas this trend was not observed in a nearby forest site (120).

A major anthropogenic driver of environmental change that accompanies the expansion of agroecosystems in cold regions is the increased inputs of nutrients from fertilizer application and animal husbandry. In addition to higher inputs, the export efficiency of these nutrients, in particular nitrogen and phosphorus, tends to be higher for agricultural than natural land cover. For instance, in cold forest ecosystems tree roots provide a persistent supply of easily degradable substrates to the soil's microbial community that in turn enables the retention of soil nutrients (e.g., nitrate) mobilized by soil freeze-thaw events (121). By contrast, harvested agricultural fields are fully exposed to harsh winter conditions. More intense freeze-thaw cycles over the shoulder seasons then increase the risk of nutrient leaching to the groundwater and surface water compartments. In addition, facilitated soil nitrogen mineralization and transformation has the potential to disproportionately increase the export of nitrogen to aquatic systems relative to that of DOC (122). The resultant uncoupling of carbon and nitrogen cycling may further drive the receiving streams and lentic environments toward a more autotrophic state.

Agricultural intensification in cold regions poses significant, but incompletely known, risks to the biodiversity and ecosystem services of the cold regions' critical zone. In particular, the soil biodiversity of cold (agro)ecosystems is relatively low compared with tropical and temperate soils (82, 83). Hence, the soil microbial and faunal communities in cold regions are likely more vulnerable to climate warming, land use changes, contamination, and diseases, including extreme weather events, invasive species, agricultural chemicals, and insect and airborne diseases (123). These threats may, in turn, negatively impact the critical zone's ecosystem functions and increase the risk of diminishing crop and livestock yields (124, 125). By developing ecological resilience to both climatic and anthropogenic forcings, sustainable intensification of agriculture in the existing and new cold agroecosystems offers the potentially best approach to counter unexpected and unintended long-term environmental problems.

6. COLD REGION CRITICAL ZONE RESEARCH: CHALLENGES AND OPPORTUNITIES

6.1. Some Known Unknowns

A major challenge for critical zone research in general is the complex and sometimes nonintuitive feedbacks between climate forcing, hydro(geo)logical flows, and biogeochemical processes. This may be even more challenging in cold regions where climate warming, changes in land cover and land use, and human settlement are proceeding at unprecedented rates. Cold region critical zone research will have to be greatly stepped up to generate in a timely fashion the essential knowledge that is required to support sustainable and adaptive environmental management strategies.

As discussed above, agricultural conversion brings about major changes in the biogeochemistry and ecology of seasonally frozen belowground terrestrial environments. However, there is a lack of comparative studies between land under cultivation and that minimally affected by human use. Such comparative studies would help delineate what changes are actually resulting from the agricultural activities and what their extent and impacts are. Agricultural land and water management can, for example, greatly benefit from a clearer understanding of how soil freeze-thaw cycles, soil aggregate stability, and SOC evolve after converting a natural grassland or forest into croplands.

Infrastructure, such as roads and pipelines, mining operations, and geological repositories, also change the seasonally frozen ground and permafrost dramatically, with often irreversible consequences for near-field hydrogeology and ecological functions (126). In turn, permafrost degradation and more intensive freeze-thaw cycles may compromise the stability of artificial structures through frost heave processes and thermokarst development (127). The far-field and global-scale environmental impacts of engineering and construction activities in cold regions remain comparatively less known.

Given the substantial amounts of SOC and GHGs stored in permafrost areas, the possibility of accelerating, even abrupt, release of GHGs from cold regions over time scales of years remains controversial (10). There is therefore a need for a deeper understanding of the mechanisms that control the magnitude and timing of net ecosystem GHG emissions to the atmosphere from permafrost-degrading areas and the consequences for global climate change.

Research should also focus on how CO_2 production by soil respiration and fermentation processes is being modified by evolving freeze-thaw cycles in cold regions, including the liquid water–supported organic matter biomineralization in frozen soils (59). Similarly, more work is required to characterize the nature and reactivity of DOC exported from cold regions' soils and its subsequent fate along the river-ocean continuum. At the same time, the effects of snow cover dynamics and freeze-thaw cycles in the nongrowing season on the timing and fluxes of nitrogen and phosphorus released from landscapes to aquatic ecosystems deserve further investigations (128, 129).

Liquid water–ice phase transitions in soils of cold regions make subsurface water flow and heat transfer inherently three-dimensional and more complex in comparison to nonfrozen soils. The predictive understanding of water movement and associated solute fluxes during soil freeze-thaw remains incomplete. This is also true for the relationships between winter activities of soil (micro)organisms and hydrological processes and between winter biogeochemical activity and GHG emissions, nutrient availability, and water quality during the subsequent growing season.

6.2. Cold Region Critical Zone Research: The Path Forward

Research at the frontier of critical zone science is highly interdisciplinary and covers multifaceted processes and their interactions, from local to global scales (8, 12). In cold regions, holistic approaches are required to unravel the complex effects of freeze-thaw cycles on soil stability, microbial diversity, nutrient and contaminant mobilization, GHG emissions, and long-term agricultural productivity. The acquisition and analysis of complementary, multidisciplinary datasets will test the extent to which existing conceptual and quantitative models adequately represent the functioning of the cold region critical zone.

The international CZO network has been highly successful in delivering high-quality time series datasets that enable the integration and upscaling of site-specific knowledge (130). The establishment of additional CZOs in cold regions would strengthen the actionable knowledge that can inform adaptive policies and management strategies to address ongoing and potential future environmental impacts of climate warming and land use change on these rapidly changing regions of the world.

New observatories would help compensate for the scarcity of historical data and contextual information on many cold regions. As such, long-term CZOs could significantly enhance the science-based management of cold regions' natural resources and ecosystems (including agroecosystems) and the services they provide. In many countries, however, the creation and operation of new CZOs may be economically challenging. This emphasizes the need for international collaboration with multi-institutional teams who share expertise, equipment, and personnel; participate in the design and implementation of joint field experiments; and provide access to each other's datasets, facilities, and research networks.

Diffusive gradients in thin films (DGT): a passive sampling method where labile components move through a diffusive layer and accumulate in a binding-gel layer

6.3. Technological Opportunities

Despite the demanding field conditions, there is a need for on-site measurements of master variables in the cold region critical zone. For example, vertical temperature distributions in permafrost are mostly model-derived based on the surface temperature conditions (131). Nevertheless, the variable insulation by snow cover and lateral heat transfer may complicate the relationship between surface and in situ temperatures. Direct, high-resolution measurements of soil temperature distributions together with innovative methods to monitor the range and thickness of snow cover, including, for example, acoustic sounding, remain a priority in cold region research.

Portable instruments and flexible sample collection devices may greatly boost our capacity to decipher the dynamic hydrochemistry and biogeochemistry of soils and aquifers in cold regions. As an example, the diffusive gradients in thin films (DGT) (132) is an effective method to collect, concentrate, and preserve labile solutes in situ. This technique has been used to measure high-resolution (mm-scale) depth profiles (133) and two-dimensional solute distributions in the pore waters of soils and sediments (134) and to generate proxy information on the bioavailability of aqueous components in various environments (135), including in the rhizosphere (136). Although DGT deployments in cold region studies are fairly recent, the method shows promise in helping solve water quality monitoring problems, such as tracing heavy metal contamination linked to anthropogenic activities in Antarctica and Greenland (137, 138).

Other opportunities in cold region subsurface research include the use of geophysical methods, remote sensing, and isotopic tracing. Among the various geophysical methods, those based on variations in the electrical properties of the subsurface are among the most promising for hydrochemical and biogeochemical applications (139). The areal coverage of geophysical methods fills the gap between local site investigations and airborne remote sensing surveys. Geophysical methods have been successful in monitoring the seasonal variations in active layer thickness, acquiring high-resolution profiles of soil moisture, and determining the distribution of open taliks (4).

Remote sensing is bound to play a growing role in complementing in situ measurements and geophysical surveys. High-spatial resolution remote sensing has been used to map near-surface permafrost and estimate the active layer thickness in the Arctic region (140). The combination of multisensor observational data with deep learning methods will further expand the reach of remote sensing and contribute to regional-scale and long-term trend analyses of environmental changes in the cold region critical zone.

Natural radionuclides can help trace the rates and mechanisms of sedimentation (141), the intensity of surface water–groundwater interactions (142), and particle transport and scavenging in cold regions (143). Artificial radionuclides (e.g., isotopes of cesium, iodine, strontium, and plutonium) and other smart tracers add to the toolbox to decipher hydrological pathways and erosional processes across cold regions (144, 145). In addition, techniques based on the fractionation of natural stable isotopes (e.g., ^{13}C, ^{15}N, and ^{34}S) represent a powerful tool to unravel biogeochemical transformations in cold soils and agroecosystems (146).

7. CONCLUSIONS

The cold regions contain vast reserves of freshwater and biodiversity and provide key provisioning and cultural ecosystem services to local communities. They also offer many opportunities for further resource development and the expansion of agriculture. The cold regions are also experiencing rapid environmental change with far-reaching implications for people and ecosystems, regional hydrology and biodiversity, and global climate feedbacks. The changing winter conditions are among the greatest threats to high-altitude watersheds where retreating snowpacks and earlier snowmelt are causing decreases in mean annual streamflow and peak runoff earlier in the year, as well as to the Holarctic areas where the joint effects of rising surface temperature, invigorated water cycling, and enhanced organic matter mobilization likely lead to nonintuitive consequences for the critical zone and the associated agroecosystems. Shifts in these systems in turn exhibit feedbacks to the climate system and thus extend environmental impacts on the regional and global scales. Consequently, the hydrology, ecology, and biogeochemistry of the cold region critical zone present unique features and response dynamics that are not found elsewhere. Therefore, there is ample need to better understand how and why critical zone properties and processes in the cold regions, in particular those occurring in the subsurface compartments, are changing in response to global warming, land use change, and other environmental drivers.

SUMMARY POINTS

1. The pathways and fluxes of water between soil water, groundwater, and surface water compartments play a central role in the soil moisture and temperature distributions, near-surface energy exchanges, and regional water cycles; however, the hydro(geo)logical connections remain to be fully unraveled through both conceptual and quantitative understanding.
2. The knowledge and data on soil porewater and groundwater hydrochemistry and their dynamic responses to climate forcings remain fragmentary at best. This limits our ability to observe and predictively simulate the mobility and chemical speciation of nutrients and contaminants in cold regions.
3. The community structures of cold subsurface microbiota and fauna, as well as the controls on their metabolic activities and ecological interactions, require further explorations.
4. The seasonal effects of winter weather conditions, crop management, and fertilizer applications on soil organic matter mineralization, nutrient dynamics, and soil structure require better characterization and understanding. This will inform agroecosystem adaptation strategies, including the sustainable intensification of agriculture, that help counteract negative impacts of climate change in cold regions.
5. The knowledge gaps identified above, and many other ones, would benefit from the expansion of CZOs linked to each other across the world's cold regions. These observatories should enable the deployment of monitoring methods that can detect dynamic environmental changes at the landscape scale.

FUTURE ISSUES

1. The dynamic hydraulic properties of frozen and partially saturated soils add more complexity to the spatiotemporal heterogeneity of hydrogeological processes but, overall, may lead to a drier land surface.
2. In addition to the GHG emissions, the cold region critical zone may experience accelerated transport of DOC, nutrients, and contaminants from the local to regional scales, and to constrain the associated groundwater quality problems, we need a far deeper mechanistic understanding of the coupled geophysical, hydrological, and biogeochemical processes that regulate the hydrochemistry of water compartments in cold regions.
3. Climate change will continue to enhance changes in soil biological communities that lead to shifts in the higher consumers being supported and the functions and services of the cold ecosystems, including their resilience to invasive species and water plus nutrient stress.
4. The complex impacts of anthropogenic perturbations on soil hydrology and biogeochemical cycling, and their responses to projected climate change, call for more attention to the management of existing and new agroecosystems in cold regions.
5. Systematic monitoring at the cold region CZOs, including during the winter and shoulder seasons, will be crucial to establish baseline information, capture delayed ecosystem responses to altered environmental forcings, and scale process understanding up to whole-watershed impacts on, among others, water quality, stream and groundwater flow, biogeochemical cycles, and the provision of ecosystem services.

DISCLOSURE STATEMENT

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