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RECARBONIZING GLOBAL SOILS

A technical manual of recommended management practices

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HOT SPOTS AND BRIGHT SPOTS OF SOIL ORGANIC CARBON

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Permafrost

9. Permafrost

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1. Definition and description

Permafrost is perennially frozen ground, such as soil, rock, and ice. In permafrost regions, plant and microbial life persists primarily in the near-surface soil that thaws every summer, called the 'active layer' (Figure 20). The cold and wet conditions in many permafrost regions limit decomposition of organic matter. In combination with soil mixing processes caused by repeated freezing and thawing, this has led to the accumulation of large stocks of soil organic carbon in the permafrost zone over multi-millennial timescales. As the climate warms, permafrost carbon could be highly vulnerable to climatic warming.

Permafrost occurs primarily in high latitudes (e.g. Arctic and Antarctic) and at high elevation (e.g. Tibetan Plateau, Figure 21). The thickness of permafrost varies from less than 1 m (in boreal peatlands) to more than 1 500 m (in Yakutia). The coldest permafrost is found in the Transantarctic Mountains in Antarctica (−36 °C) and in northern Canada for the Northern Hemisphere (-15 °C; Obu *et al.*, 2019, 2020). In contrast, some of the warmest permafrost occurs in peatlands in areas with mean air temperatures above 0 °C. Here permafrost exists because thick peat layers insulate the ground during the summer. Most of the permafrost existing today formed during cold glacials (e.g. before 12 000 years ago) and has persisted through warmer interglacials. Some shallow permafrost (max 30–70m depth) formed during the Holocene (past 5000 years) and some even during the Little Ice Age from 400–150 years ago.

There are few extensive regions suitable for row crop agriculture in the permafrost zone. Additionally, in areas where large-scale agriculture has been conducted, ground destabilization has been common. Surface disturbance such as plowing or trampling of vegetation can alter the thermal regime of the soil, potentially triggering surface subsidence or abrupt collapse. This may influence soil hydrology, nutrient cycling, and organic matter storage. These changes often have acute and negative consequences for continued agricultural use of such landscapes. Thus, row-crop agriculture could have a negative impact on permafrost (e.g. Grünzweig *et al.*, 2014). Conversely, animal husbandry is widespread in the permafrost zone, including horses, cattle, and reindeer.

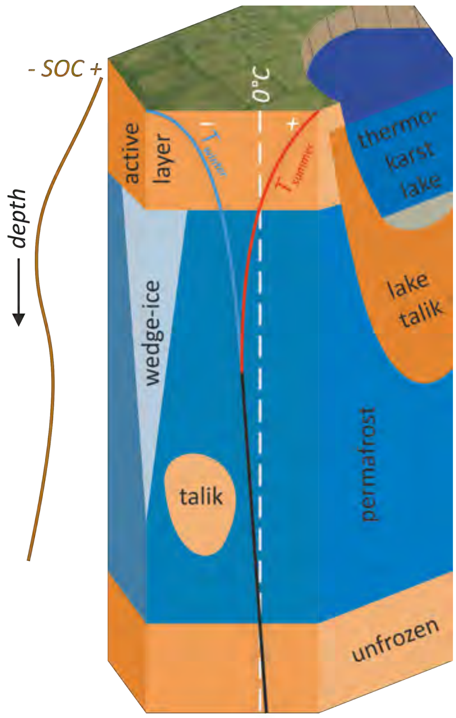


Figure 20. Diagram of the vertical structure of permafrost consisting of the active layer, permafrost including ground ice such as ice wedges, and unfrozen parts called taliks

The red and blue curved lines down the center of the diagram show the typical ground-thermal regime, indicating maximum (T_{summer}) and minimum temperatures (T_{winter}), the point of zero annual amplitude (intersection T_{winter} and T_{summer}), the increase in temperature with depth (geothermal gradient), and the depth of seasonal thaw (the active layer)

Taliks are unfrozen areas within the layer of frozen materia

The density of soil organic carbon (SOC) with depth is shown on the left by the brown line, based on Harden *et al.*, 2012 (top 3 m) and Strauss *et al.*, 2015, 2017 (deeper SOC deposits)

2. Global distribution of hotspot

The global permafrost distribution is controlled by long-term mean air temperature. Locally, the distribution of permafrost is also affected by the properties of the ground surface and various ecosystem factors. Permafrost is more likely to occur in areas of low snow cover, insulative soil (e.g. peat) or vegetation, and absence of surface water. Permafrost regions are commonly subdivided by the proportion of the land area underlain by frozen material (Figure 21): continuous permafrost with >90 percent coverage, discontinuous permafrost with 50–90 percent coverage, sporadic permafrost with 10–50 percent coverage, and isolated permafrost, which has <10 percent coverage (not included in Figure 21).

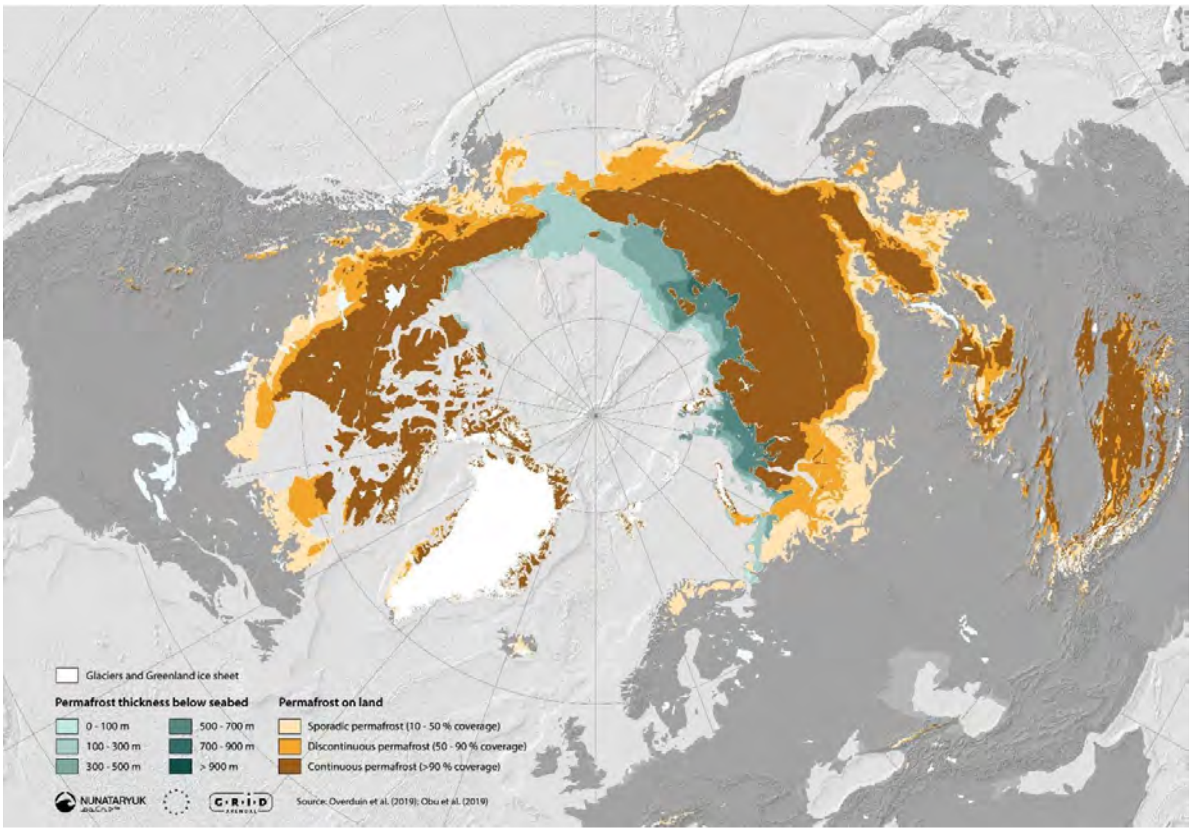


Figure 21. Extent of permafrost on the Northern Hemisphere

This map has been graciously adapted by G. Fylakis from GRID-Arendal based on data from Overduin *et al.* (2019) and Obu *et al.* (2019) and a product of the NUNATARYUK project in collaboration with GRID Arendal

Permafrost occurs on land in polar and high mountain areas, and as submarine permafrost in the bottom sediments of shallow shelf regions of the polar oceans (Figure 21). Estimating its total coverage is challenging because permafrost occurrence is spatially heterogeneous and difficult to measure remotely. For example, the permafrost region (including permafrost-free patches) of the Northern Hemisphere is estimated to be 21 million km² (22 percent of exposed land area, brownish colors in Figure 21), but modelling studies indicate that only 13.9 million km² of this area is actually underlain by permafrost (Obu *et al.*, 2019). Lowland (non-alpine) permafrost accounts for 10.1 to 19.6 million km², mountain (alpine) permafrost accounts for 3.6 to 5.2

million km², and subsea permafrost accounts for about 2.5 million km² (Obu *et al.*, 2019; Overduin *et al.*, 2019). The Southern Hemisphere has three orders of magnitude less permafrost than the Northern Hemisphere, most of which occurs in Antarctica, where 21 700 km² is underlain by permafrost (IPCC, 2019). The Tibetan Plateau is the largest alpine permafrost area outside the polar regions, covering 1.1 million km² (IPCC, 2019). The 2.5 million km² of submarine permafrost formed when sea level was more than 100 m lower during past glacial periods. Though it has been degrading since inundation, subsea permafrost persists in areas of the Arctic continental shelves (Figure 21 blue-greenish colors, Overduin *et al.*, 2019).

3. Global carbon stocks and additional carbon storage potential

The cold temperatures and unique soil processes of permafrost have led to the accumulation of deep deposits rich in organic matter (Figure 20 and Figure 22, Table 20, Hugelius *et al.*, 2014). Understanding the amount and degradability of soil organic matter stored in permafrost is crucial as increasing temperatures in northern high latitudes lead to permafrost thaw and loss (Figure 23 and

Figure 24). This permafrost degradation can accelerate decomposition of organic matter previously stored in permafrost. Microbial decomposition produces carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), the three most influential long-lived greenhouse gases (Schuur *et al.*, 2015; Voigt *et al.*, 2020).

Globally, permafrost regions store ~1460–1600 Gt[7] of soil organic carbon (SOC; Hugelius *et al.* 2014, IPCC, 2013, 2019, Schuur et al 2015; Figure 22, Table 20). This represents approximately twice as much carbon as is currently present in the atmosphere (Figure 22). The rest of Earth's biomes, excluding the Arctic and Boreal regions, are estimated to contain 2 050 to 2 800 Gt SOC in the top 3 m of soil (Schuur *et al.*, 2015, Jackson *et al.*, 2017). This means that even though these northern regions account for only 15 percent of global soil area, they contain approximately 42 percent of global soil carbon (taking the 2 050 Gt from Schuur *et al.*, 2015). Recent studies suggest that up to half of the global soil carbon pool (estimated at 2 800 Gt C to a depth of 3 m; Jackson *et al.*, 2017) is stored in the permafrost region (Figure 22). In addition to these relatively well-constrained SOC pools, there could be an additional deep permafrost pool of 350-465 Gt C (mean ~400 Gt, Figure 22). This would be in addition to the already included deep SOC from yedoma (Strauss *et al.*, 2017) and Arctic delta estimates. This additional pool is estimated using a depth interval of 3-10 m and carbon content of 11–14 kg C/m³ (Schuur *et al.*, 2015).

Most of the SOC in permafrost regions occurs in circumarctic ecosystems (Figure 21). However, we estimate that alpine permafrost zones outside the circumarctic contain 83.2 Gt SOC (Table 20). This estimate includes SOC in global mountain permafrost (IPCC, 2019) and an updated estimate of SOC in the top 3 m of the Tibetan Plateau (36.6 Gt C; Ding *et al.*, 2019). We note that 46 percent of this Tibetan C is estimated to be in permafrost. There is less SOC in alpine permafrost compared to circumarctic permafrost because of its smaller area and lower C density (kg C/m³) (IPCC, 2019; Hugelius *et al.*, 2014). The same elevational pattern holds

[7] 1Gt = 1 billion tons

within the circumarctic, with mountain regions showing 50 percent less C density compared to tundra lowlands (Schuur *et al.*, 2015; Strauss *et al.*, 2017).

The permafrost coverage can be patchy and discontinuous, especially in the southern edge areas of the permafrost zone and/or areas of lower altitude. Because of this, only ~1000 Gt C (derived from Hugelius *et al.*, 2014, Strauss *et al.*, 2017, and mountain permafrost estimate in IPCC, 2019) of the global permafrost region C stock is stored in permafrost, while up to ~600 Gt C are stored in permafrost-free soils or sediments within the region (Table 20).

Besides C, nitrogen (N) stocks of permafrost soils are estimated to range between 22 to 106 Gt N, with a best estimate of 66 Gt N (Harden *et al.*, 2012). This N is of concern because it could constrain the loss and uptake of C and potentially cause a climate feedback via N_2O. If only a minor portion of this soil N is released as N_2O during nitrification and denitrification, the climate feedback loop from permafrost thaw and resulting greenhouse gas production would be even larger.

Table 20. Soil organic C stocks reported for permafrost

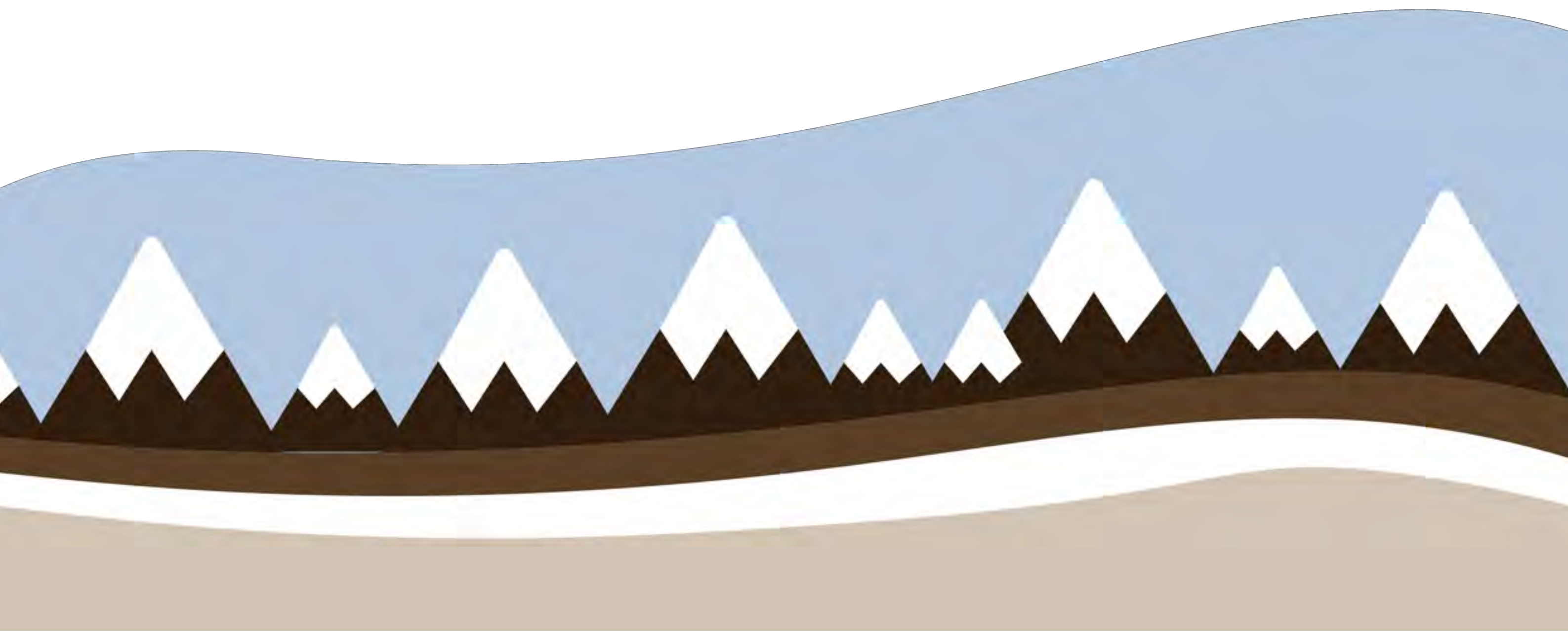
Unit	Depth (cm)	Region	SOC stock (Gt C)	stock uncertainty range (Gt C)	Reference
Turbels	0–300	lowland permafrost	476	359–593	Hugelius *et al.* (2014)
Orthels	0–300	lowland permafrost	98	61–135	Hugelius *et al.* (2014)
Histels	0 –300	lowland permafrost	153	139–167	Hugelius *et al.* (2014)
Histosols	0 –300	lowland permafrost	149	130–167	Hugelius *et al.* (2014)
Non-Gelisols, mineral	0–300	lowland permafrost	158	131–185	Hugelius *et al.* (2014)
Permafrost deep peatlands	>300	lowland permafrost	32	21–43	Hugelius *et al.* (2020)
Deltaic alluvium	>300–5400	lowland permafrost	91	39–143	Hugelius *et al.* (2014)

Unit	Depth (cm)	Region	SOC stock (Gt C)	stock uncertainty range (Gt C)	Reference
Yedoma region*	>300–5000	lowland permafrost	297	297–436	Strauss *et al.* (2017)
Mountain permafrost excl. Tibetan plateau	0–300	high altitude	47	na	IPCC (2019)
Tibetan plateau	0–300	high altitude	37	34–39	Ding *et al.* (2019)
Frozen in permafrost**		global	1024	920–1132	Hugelius *et al.* (2014) combined this synthesis;
Total permafrost region		global	~1538	1460–1600	This synthesis; IPCC (2019), Schuur *et al.* 2015
additional other deep deposits***	300–1000	lowland permafrost	400	unknown	Schuur *et al.* (2015)

*Lower boundary of the yedoma region minus the uppermost 3 m causes the difference to Strauss *et al.* (2017) estimate for full 0–50m yedoma pool (327 Gt C).

**Estimated assuming an active layer depth of 30 cm or more in all Gelisols/High Arctic soils and 46 percent of the Tibetan Plateau C perennial frozen.

***Rough estimate of potential permafrost carbon in regions with additional thick sedimentary overburden. Not included in any calculations yet due to very high uncertainties.



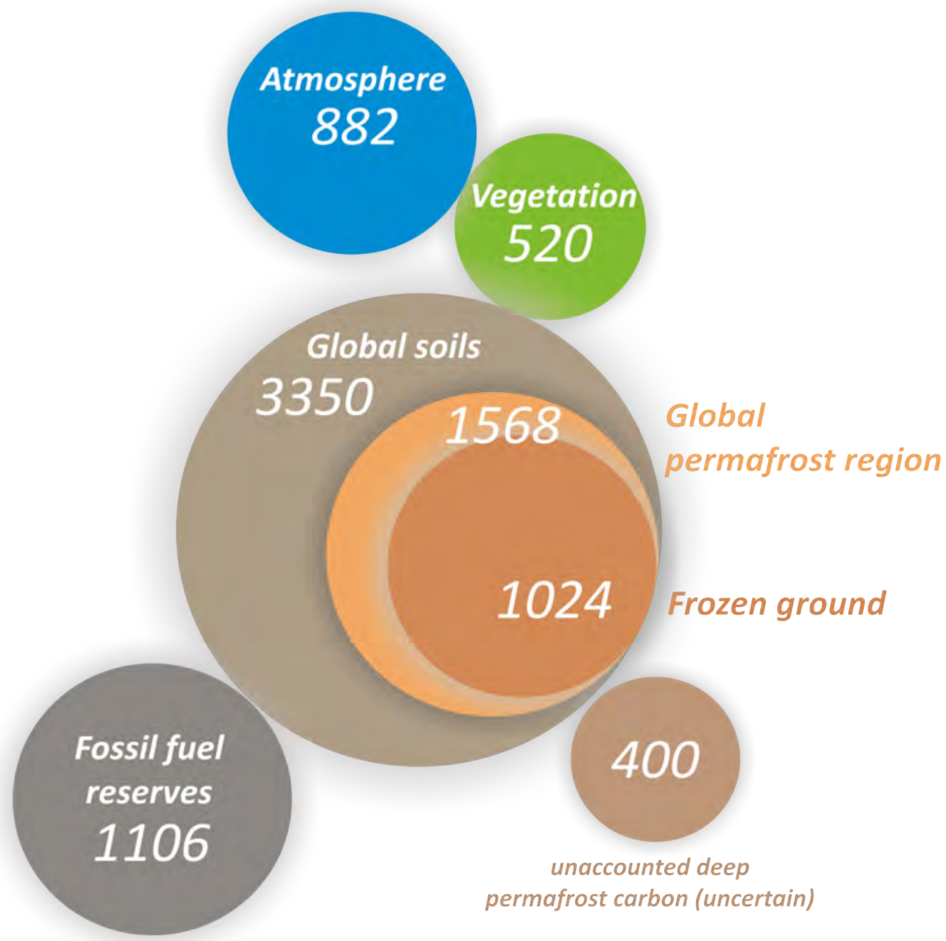


Figure 22. Terrestrial carbon stocks and atmospheric carbon in relation to the carbon stored in the permafrost region

The size of the circles is proportional to the size of the carbon stock. The stocks are given in gigatons (Gt)

The global soil estimate (3350 Gt) is based on soils to 3 m (2800 Gt) as well as other pools in deep permafrost (500 Gt) and tropical peatlands (50 Gt; Jackson *et al.*, 2017)

(Adapted and updated from Strauss *et al.*, 2017). Based on data from different International Panel on Climate Change (IPCC) reports (e.g. IPCC, 2019) and Hugelius *et al.* (2014; 2020)

Following IPCC 2013, the ocean stocks (not visualized) contain 900 Gt in the surface ocean, 37100 Gt in the intermediate and deep sea, 3 Gt in the marine biota and 700 Gt as dissolved organic carbon. For the ocean floor sediments 1750 Gt are estimated

3.1. Potential mechanisms for additional C storage

While permafrost ecosystems typically support relatively low net primary productivity and total living biomass compared to temperate and tropical ecosystems (Abbott *et al.*, 2016), permafrost soils have sequestered C over tens of millennia through different natural mechanisms. The active layer of permafrost soils is exposed to seasonal cycles of freeze and thaw, which cause complex soil mixing processes called cryoturbation. Over time, cryoturbation incorporates SOC from the surface into deeper soil, where SOC is protected from decomposition, eventually becoming part of the permafrost. This is a key mechanism leading to the large SOC stocks in the soil sub-order Turbels (Table 20). Peat accumulation, both with and without permafrost, has also led to large C stocks in both Histels and Histosols (Table 20). While permafrost peatlands lose C to the atmosphere when they thaw, there is also potential for increased rates of C accumulation in existing peatlands associated with vegetation changes and the formation of new peatlands. The latter would require additional areas with suitable conditions, such as drained thermokarst lakes (Walter Anthony *et al.*, 2014) or newly exposed, poorly drained surfaces such as areas of coastal uplift following glacial recession (Treat *et al.*, 2019), or changes in environmental conditions that promote widespread peat formation. However, given that the formation of peat is a slow process, current projections suggest that C loss from thawing and draining peatlands will likely be larger than the gains for several centuries (Hugelius *et al.*, 2020).

In addition to cryoturbation and peat formation, substantial SOC accumulation occurred during the Pleistocene and Holocene from wind, water, and colluvial transport. These processes buried SOC in deep sediments, such as ice-rich yedoma deposition in the Late Pleistocene (Strauss *et al.*, 2017; Treat *et al.*, 2019). Solifluction (flow of soil downslope (Figure 24) buried and continues to bury surface C in valley bottoms. However, it is unclear how important this mechanism will be for organic matter preservation because solifluction areas are most prominent on moderately steep slopes where SOC density is often lower. Permafrost C can also be eroded, transported, and sequestered in river, delta, and ocean sediments (Figure 24), although the relative stability and residence time of this C is poorly constrained.

Increased vegetation growth in the permafrost region due to increasing air temperature and CO_2 fertilization may increase ecosystem C storage, but the uncertainty about this potential C sink is large. Stock observations show that the upper active layer of Tibetan alpine permafrost currently functions as a substantial regional C sink, implying that C losses of deeper and older permafrost C might be offset by increases in upper-active-layer SOC stocks. Other studies in Alaska found a net C loss due to losses from deep soils, despite enhanced vegetation growth with permafrost thaw, suggesting that there may be limits to vegetation C uptake in Arctic and Boreal regions (e.g. Schuur *et al.*, 2009). A simple C budget based on a complete biome shift suggests that vegetation could take up 11 Gt total, assuming a complete shift of all Arctic Tundra becoming Boreal Forest and all Boreal Forest becoming Temperate Forest (Abbott *et al.*, 2016), which is substantially less than projections from current models. Overall, whether increased vegetation growth is enough to compensate for the potential C losses with increased soil warming and permafrost thaw is an open question. The absolute size of the permafrost soil C pool versus the size of the current global vegetation C pool (Figure 21) suggests that a vegetation C sink may only provide a limited capacity to counter permafrost C losses.

3.2. Soil organic carbon loss potential

Ground temperature is increasing rapidly in all of the permafrost regions, particularly since the early 1980s. There has been a global mean increase of 0.3 ± 0.1 °C per decade at the depth of no seasonal temperature fluctuation (Figure 20) (Biskaborn *et al.*, 2019; IPCC, 2019). The mean warming of global permafrost has also been 0.3 °C per decade since 2007, based on a global network of permafrost boreholes, with the rate of increase varying regionally (IPCC, 2019). The warming and thawing of permafrost is projected to lead to widespread disturbance and disappearance of Boreal, Subarctic, and alpine permafrost during this century and large decreases of near-surface permafrost in the Arctic (Figure 23). This could have substantial consequences for the global climate. By 2100, the near-surface (0–3 m) permafrost area may decrease by 2–66 percent for the

International Panel on Climate Change (IPCC) mitigation scenario (RCP2.6) and 30–99 percent for the high-emission scenario (RCP8.5) (IPCC, 2019). Between 2010 and 2300, simulations indicate a decrease of 6 to 16 million km^2 in permafrost area for the high-emission scenario (RCP8.5).

Projections of SOC stability are substantially more uncertain than projections of permafrost degradation. For the high warming scenario (RCP8.5), projected losses in SOC vary between 74 and 652 Gt C (mean loss of 341 Gt C; McGuire *et al.*, 2018). For this scenario, the C uptake by vegetation C is likely not large enough to compensate for the losses of permafrost C, with net changes in ecosystem C ranging from a 641 Gt C loss to a 167 Gt C gain (mean, 208 Gt C loss) (McGuire *et al.*, 2018). Under moderate warming (RCP4.5), gains in vegetation C across the circumarctic could result in overall net gains in ecosystem C by the year 2300 (-8 to 244 Gt C gains; RCP4.5 scenario; McGuire *et al.*, 2018). It is important to note that the spread between model results is very large and that many current models have only rudimentary representation of permafrost C and mechanisms of its mobilization across depths. This introduces uncertainty and potential underestimation of SOC mineralization.

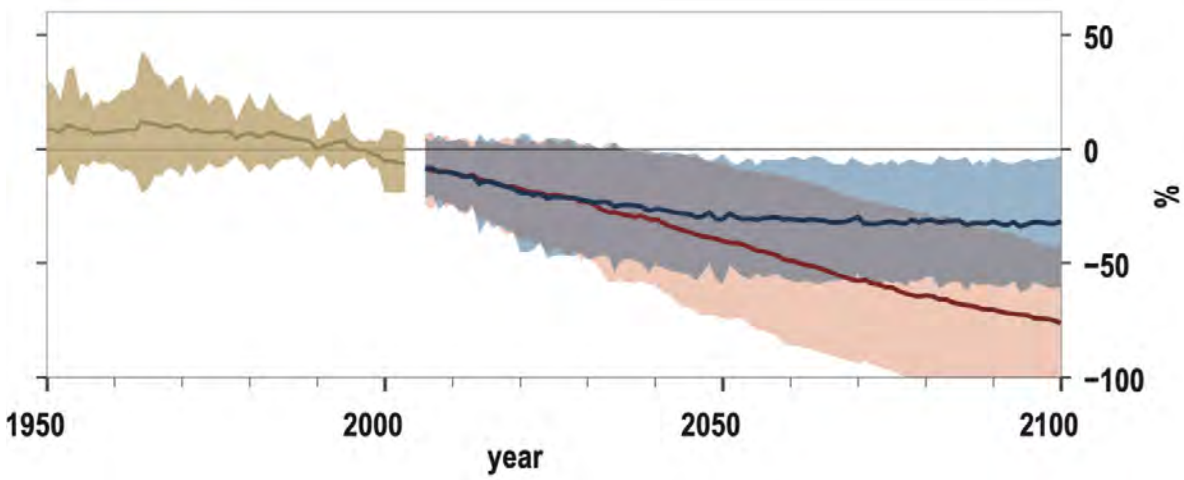


Figure 23. Projected permafrost areal change (x-axis) of the topmost 3 m until 2100

The high-emission scenario is illustrated in red (RCP8.5), the low-emission scenario (RCP 2.5) in blue. The greyish areas represent the overlap in the ranges

A reduction of up to 75 percent of the permafrost area, meaning a loss of more than 10 million km^2, is possible. (Adapted from IPCC, 2019)

One of the specific limitations of current modelling approaches is that models only simulate gradual, top-down thaw via a deepening of the active layer from the surface. Observations now show that permafrost containing high and moderate amounts of ground ice is affected by abrupt thaw events, such as thermokarst and thermo-erosion. These events can be triggered gradual warming, wildfires, excess rainfall, shore and hillslope erosion, human disturbance or other factors (Grosse *et al.*, 2011; Turetsky *et al.*, 2020). Abrupt permafrost disturbances are widespread across the permafrost distribution classes (i.e. continuous, discontinuous, etc.; Figure 21), including relatively warm and very cold permafrost regions (Nitze *et al.*, 2018). Thermokarst and thermo-erosion processes alter surface topography, hydrology, vegetation, soils, and C cycling. Thermokarst formation can create lakes (Figure 20, left side), mobilizing SOC previously stored in surrounding and underlying soil, but also acting as a C sink on centennial to millennial timescales (Turetsky *et al.*, 2020). Hydrological reorganization can cause inundation of surface soils, releasing CH_4 and CO2. Regions vulnerable to abrupt thaw include ice-wedge polygons in tundra lowlands (IPCC, 2019), ice-rich yedoma regions (Strauss *et al.*, 2017), and northern peatlands (Hugelius *et al.*, 2020). C loss from permafrost and thawed permafrost can also occur along rivers and coasts. Here the transport of dissolved and particulate C takes place with up to 20 m of lateral erosion per year (Fuchs *et al.*, 2020). Peatlands impacted by thermokarst also have high potential for N_2O emissions (Voigt *et al.*, 2020).

Given projections of increasing permafrost degradation during the 21st century, a corresponding loss of freeze-locked SOC together with increases in greenhouse gas emissions is anticipated (Schuur *et al.*, 2015; McGuire *et al.*, 2018; Hugelius *et al.*, 2020). Observations have shown that the magnitude of C loss and pathways (aerobic and anaerobic) is strongly related to the hydrology, and whether sites become wetter or drying upon thaw (Schuur *et al.*, 2015). To predict the moisture regime following thaw is complex and more progress is needed in the mapping of ground ice as well as model development to better project future changes.

Land use change and human impacts in permafrost regions may also alter soil C stocks. The degradation of permafrost can occur directly as a result of wildfire or land use in which the upper permafrost layer is disturbed. The construction of buildings, traffic routes and pipelines as well as agricultural activities can trigger gradual and abrupt permafrost degradation. As shown by Iwasaki *et al.* (2018), when forest was converted to arable land in Central Yakutia, a significant decrease in the total C content of the soil was observed, mainly due to mechanical disruption, decomposition, and removal of plant residues. As a result, there was only 41 percent of the SOC content in the cultivated soil compared to the original forest. After cessation of agricultural activity, vegetation recovery gradually restored some of the SOC. Pioneer species such as grasses and shrubs reestablished SOC over a 20-year period. However, new forest growth on some abandoned arable land follows the tendency of decreasing total C content due to a low level of productivity and a suppressive effect on grass vegetation. Yet, there is no data on the impact of land use change and human impacts on soil N stocks in permafrost regions.

Better integration of direct human disturbances, such as land use change, needs to occur to improve model estimates of the permafrost climate feedback. Widespread human activity in areas such as the Siberian boreal regions is rarely taken into account in predictions of SOC response (Crate *et al.*, 2017). Human activity reduces SOC via (I) use of thermokarst basins as pastures and hay making areas, (II) increased emission of CO_2 from moderately humid and humid grasslands in hot summers, and (III) significant CH_4 emissions from temporary flooded grasslands and thaw processes beneath thermokarst lakes and ponds that formed following deforestation or intensive agriculture in areas of ice-rich permafrost.

4. Importance of permafrost conservation for the provision of specific ecosystem services

The Arctic may seem remote and disconnected from current events, but the unprecedented environmental changes occurring there have important consequences for our global society. The loss of permafrost and associated greenhouse gas release could weaken the permafrost zone's service as a long-term C storage and sink (Schuur and Mack, 2018; IPCC, 2019). Thaw and release of just a fraction of this frozen C in the form of greenhouse gases into the atmosphere would accelerate and magnify global climate warming. This destabilizing feedback could cause further degradation of permafrost in both polar and mountain areas (Schuur *et al.*, 2015). It is unlikely that such large thaw induced losses could be compensated by increased plant growth or northward shifts in biomes. Because these permafrost feedbacks are still not incorporated into IPCC projections, current climate policy may not achieve desired targets.

In addition to the global consequences of GHGs emissions, permafrost thaw and degradation affects local habitats, degrading some of the last pristine areas on Earth. These local dynamics affect human communities living on permafrost through water quality and quantity, natural hazards, and stability of infrastructure and land loss. Changes in ground stability and weather patterns are altering travel routes, impeding access to culturally significant hunting and gathering areas and travel to other communities. Reliable transportation and timing of resources are fundamental to northern indigenous livelihoods.

Another ecosystem service that could be threatened by climate change is freshwater storage. Ground ice in the permafrost zone contains a globally-significant volume of freshwater: 22 to 300 × 10^3 km^3, which represents up to 90 cm sea level rise (Abbott *et al.*, 2019). While complete ground ice melt is not a realistic scenario for the 21st century, the projected widespread loss of near-surface permafrost, where most of the ground ice is located, suggests that this is a factor to be accounted for over the next few centuries.

In summary, permafrost is no longer permanent. Climate change and human disruption of the soil are causing irreversible changes to circumpolar and alpine permafrost areas.

4.1. Minimization of threats to soil functions

The only viable way to reduce permafrost soil threats is to reduce anthropogenic climate change. It appears that much of the SOC of the permafrost zone can be protected if human emissions are actively reduced. Specifically, greenhouse gas release, lateral C export, and disturbance such as wildfire and thermokarst are all reduced when human emissions are rapidly reduced (Abbott *et al.*, 2016; Turetsky *et al.*, 2020). Otherwise, because of its vast size and remote location, on-the-ground interventions are not feasible for most of the permafrost zone. Ice-rich permafrost, like the yedoma region, and steep mountain permafrost areas are particularly prone to hazards because permafrost and ground ice exert strong controls on ground stability (Krautblatter *et al.*, 2013, IPCC, 2019; Strauss *et al.*, 2017; Turetsky *et al.*, 2020). Projected permafrost thaw will affect Arctic hydrology and wildfire, with impacts on vegetation and soil. About 20 percent of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50 percent by 2100 for RCP8.5 (Turetsky *et al.*, 2020). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in permafrost may lead to soil drying (IPCC, 2019) as the landscape loses its frozen underpinning. In mountain permafrost regions, permafrost degradation has changed some alpine ecosystems through altered soil temperature and permeability, decreasing the climate regulating service of a vast region and leading to lowered groundwater and new and shrinking lakes on the Tibetan Plateau. Minimizing these threats requires coordinated global action to limit anthropogenic warming as much as possible (IPCC, 2019).

4.2. Increases in production and food security

Food and water security have been and will be negatively impacted by changes in snow cover, lake and river ice, and permafrost in many Arctic regions. These changes have disrupted access to herding, hunting and fishing grounds, and caused the instability of agricultural land (IPCC, 2019).

Lowland permafrost is expected to contain a significant amount of natural mercury, which may be released into the environment after thaw, affecting drinking water and ecosystem food webs (IPCC, 2019). In some high mountain areas, water quality has been affected by contaminants, particularly mercury, released from melting glaciers and thawing permafrost already (IPCC, 2019). The release of heavy metals and other legacy contaminants currently stored in glaciers and permafrost, is projected to reduce water quality for freshwater biota as well as human household and agricultural use. Additionally, permafrost degradation can enhance the release of other elements (e.g., aluminum, manganese and nickel) (IPCC, 2019). Permafrost degradation is also a major and increasing source of bioavailable dissolved organic C, which can degrade drinking water and affect food webs in aquatic and marine ecosystems. The release of metals, C, and nutrients could consequently affect the food security of humans living in the permafrost zone.

4.3. Improvement of human well-being

The combination of thawing permafrost, loss of sea ice, extreme weather events, and rising sea level has multiple negative impacts on Arctic livelihoods Climate-driven environmental change harms the livelihoods, wellbeing, and cultural identity of all Arctic residents (AMAP, 2017; IPCC, 2019). In some Arctic regions, tipping points may have already been reached such that adaptive practices can no longer insulate local peoples from the worst effects of climate change. People displaced by the collapsing ground and eroding coastlines of the permafrost zone are among the first climate refugees. Coastal erosion and thawing permafrost forced entire villages to relocate at enormous economic and cultural cost (Welch, 2019).

Another risk from permafrost soil is the potential for thawing permafrost to release ancient pathogens (Legendre *et al.*, 2015, non-pathogenic in this case). A 2016 outbreak of anthrax likely from frozen ground on the Yamal Peninsula in Siberia led to the culling of more than 200 000 reindeer and the death of one human (Hueffer *et al.*, 2020). The potential for viruses and diseases to be revived from permafrost should be of concern in the context of global warming, though it is unclear how widespread or common such events could be.

Wildfire frequency and intensity are projected to increase during this century across most tundra and boreal regions (Abbott *et al.*, 2016), and also in some mountain regions. Interactions between climate and shifting vegetation will influence future fire intensity and frequency (Schuur and Mack, 2018; IPCC, 2019; Holloway *et al.*, 2020). The years 2019 and 2020 were characterized by extraordinary intense wildfire seasons in Siberia (NASA, 2020), as well as extreme heat waves in northern high latitudes. In Verkhoyansk, located in the northern part of the Republic of Sakha (Yakutia), a record temperature of 38 °C was measured in June 2020 (WMO, 2020). Fires endanger infrastructure and human well-being by reducing air quality. They also burn surface soil organic matter, causing an immediate release of soil C to the atmosphere. On longer timescales, wildfire can remove the insulating layer on top of permafrost soils, degrading permafrost and enhancing soil organic C decomposition (Holloway *et al.*, 2020).

Another challenge is that permafrost decline alters the frequency, magnitude and location of most of the natural hazards. Exposure of people and infrastructure to natural hazards has increased due to growing population, tourism and socio-economic development. Seventy percent of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence by the year 2050 (IPCC, 2019). Even cold Arctic permafrost in northern Siberia is projected to be affected by thaw subsidence by the end of the 21st century (Nitzbon *et al.*, 2020). In May 2020 the largest reported diesel spill to date in the Arctic region from a tank facility at a power plant in Norilsk was linked to infrastructure damage furthered by permafrost thaw likely caused by human disturbance.

Permafrost thaw also has negative impacts on infrastructure in high mountain areas (IPCC, 2019). Cable cars, mountain huts, power lines, and rockfall or avalanche protections built on permafrost in the European Alps, mostly found in the high mountain region above 2.500 m, have been destabilized by permafrost thaw (Krautblatter *et al.*, 2013). On the Tibetan Plateau, deformation or damage has been found on roads, power lines and an oil pipeline. Tourism and recreation activities such as hiking, skiing and mountaineering have been negatively affected by permafrost thawing. In several regions, worsening trail safety has reduced mountaineering opportunities and will further endanger subsistence and recreational activities in mountainous areas.

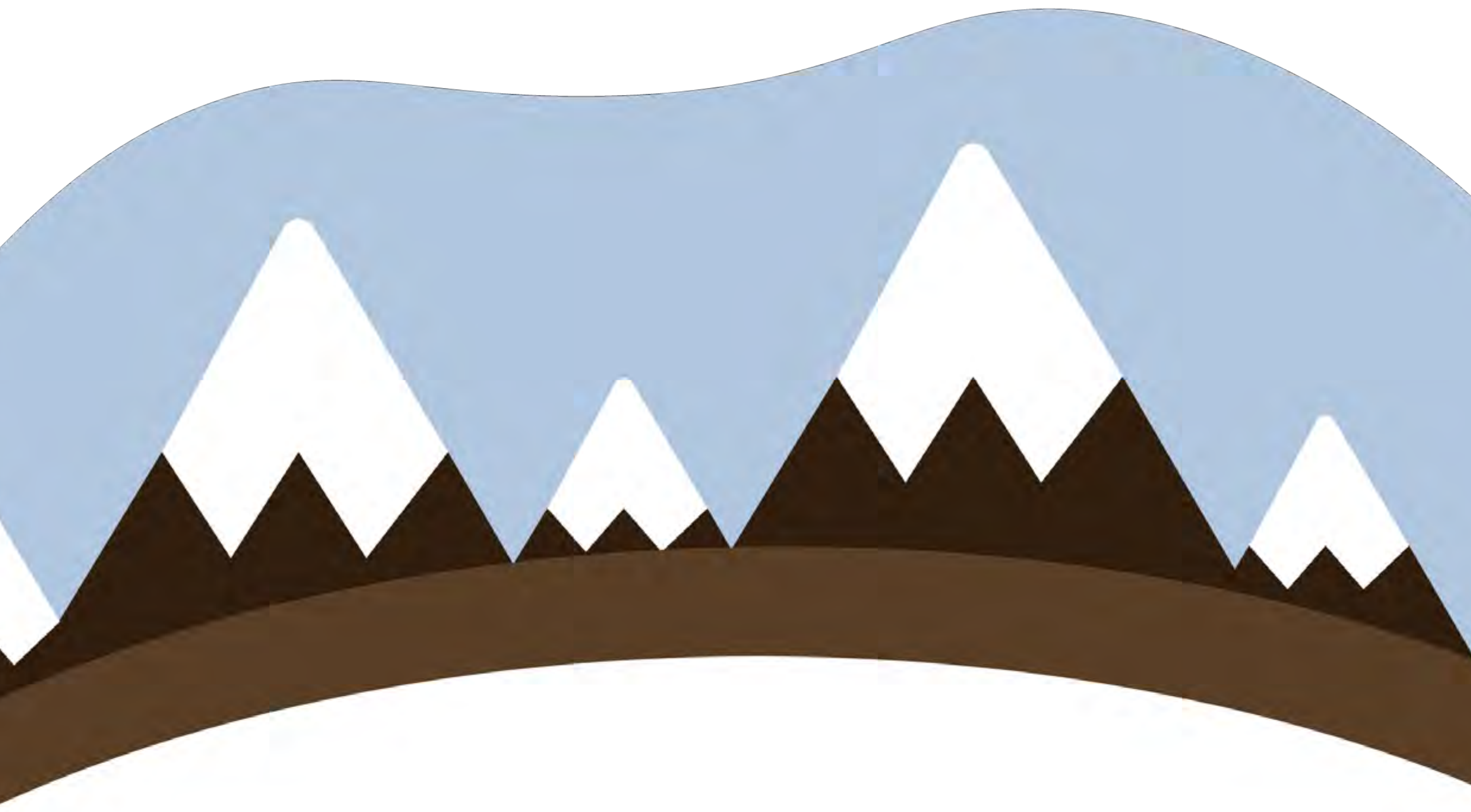
4.4. Mitigation of and adaptation to climate change

Arctic residents, especially indigenous peoples, have adjusted the timing of important activities and practices to respond to changes in seasonality and safety of land, ice, and snow travel conditions. Municipalities and industry are beginning to address infrastructure failures associated with flooding and thawing permafrost and some coastal communities are planning village relocations. Retrofitting and redesigning infrastructure has the potential to halve the costs arising from permafrost thaw and related climate-change impacts by 2100. For infrastructure on permafrost, engineering practices suitable for polar and high mountain environments have been developed to support adaptation (Doré *et al.*, 2016). It is suggested that effective mitigation efforts during the remainder of this century could attenuate the negative consequences of the permafrost climate feedback.

5. General challenges and trends

Permafrost thaw is expected to be irreversible on time scales relevant to human societies and current ecosystems. Long response times of decades to millennia mean that the permafrost region is committed to long-term change even after anthropogenic greenhouse gas and radiative forcing stabilize. Thawing of permafrost involves thresholds that allow for abrupt responses to ongoing climate warming. These characteristics pose risks and challenges to adaptation. The cryosphere also amplifies climate changes through snow, ice and permafrost feedbacks. The permafrost C feedback is a self-reinforcing one (Schuur *et al.*, 2015).

Global-scale permafrost thaw is projected to continue in the near-term (2031–2050) due to surface air temperature increases, ocean water temperature increases, and the ice-free season extension, with unavoidable consequences for river runoff and local hazards such as surface subsidence or coastal erosion. This leads to loss of soil stability, threatens livelihoods and potentially release of additional C into the atmosphere. By 2100, projected near surface (within 3–4 m) permafrost area shows a decrease of 24 ± 16 percent for the mitigation scenario (RCP2.5) and 69 ± 20 percent for higher emission (RCP 8.5) scenarios (IPCC, 2019). This last scenario leads to the cumulative release of substantial permafrost C as CO_2 and CH_4 to the atmosphere by 2100 with the potential to exacerbate climate change. Even larger emissions are projected from processes not yet included to models, such as abrupt thaw (Nitzbon *et al.*, 2020; Turetsky *et al.*, 2020) and fine-scale ecological interactions (Keuper *et al.*, 2020). Lower emissions scenarios dampen the response of C emissions from the permafrost region. CH_4 contributes a small fraction of the total additional C release but is significant because of its higher warming potential (28–36-fold warming potential compared to CO_2 over 100 years, Schuur *et al.* 2015). Increased plant growth is projected to replenish or partly offset soil C losses in the short-term, but will not match C releases over the long term or at high rates of C loss. The present-day N2O emissions of permafrost soils are estimated at up to 7 percent of the total N2O emissions from natural soils (Voigt, 2020), but the future release is yet poorly constrained. It has been shown, however, that climate-change related disturbances favor N2O production and release (Elberling *et al.*, 2010; Voigt *et al.*, 2017)



Future climate-induced changes in permafrost will drive habitat and biome shifts (Schuur and Mack, 2018), with associated changes in the ranges and abundance of many species. Even as the overall regional water cycle is projected to intensify, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in permafrost may lead to soil drying with consequences for ecosystem productivity.

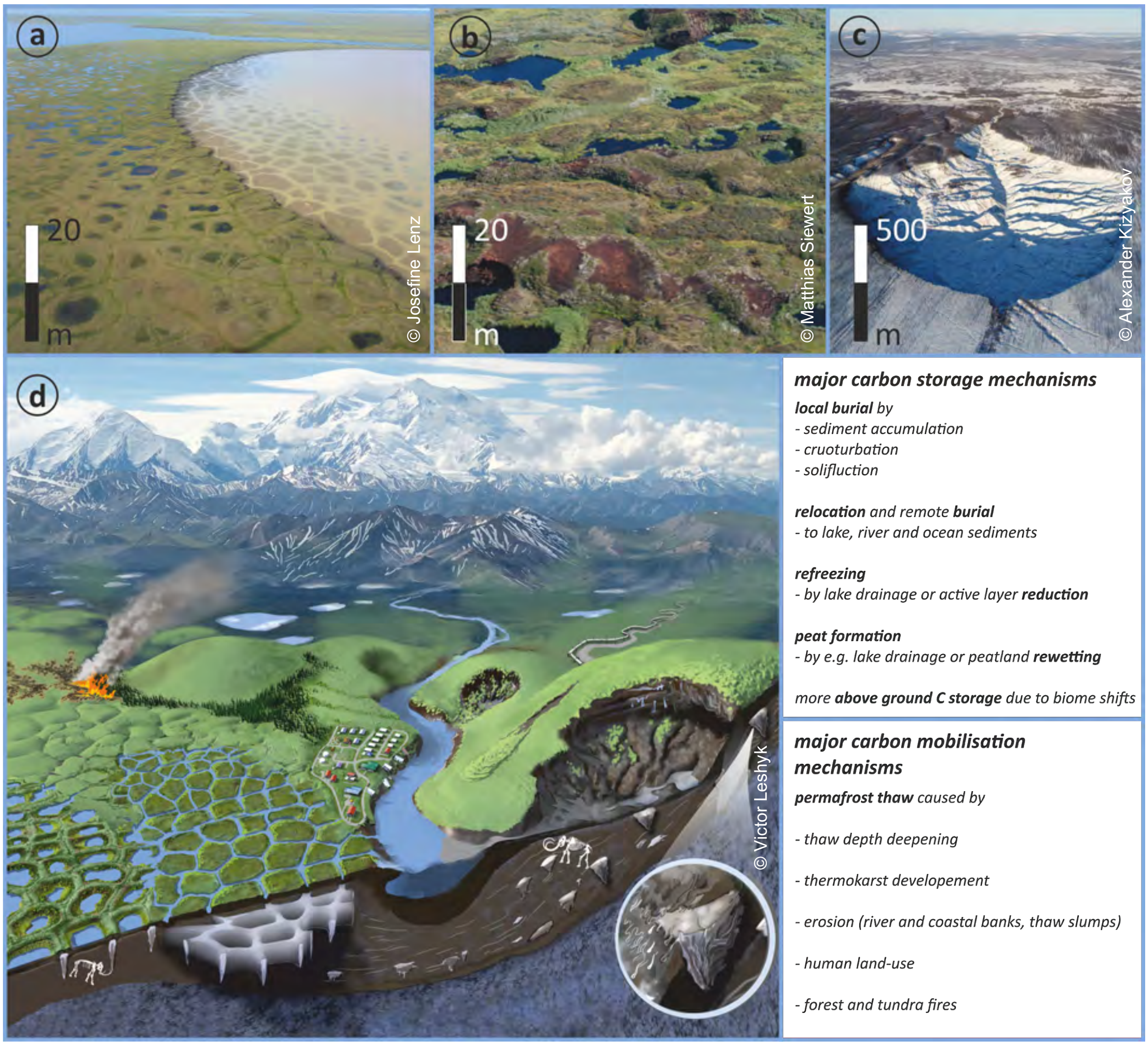


Figure 24. Permafrost degrades as the ice in the ground melts in response to e.g. climate warming, human disturbance, or more wildfires. The resulting ground collapse causes permafrost ecosystems to subside and erode. Previously frozen permafrost soil carbon can escape to the atmosphere via microbial action or be carried away by water. This image depicts features of a permafrost landscape with a focus on lowland permafrost of the Northern Hemisphere

a) Thermokarst degradation by lake expansion in northern Alaska

b) Palsa peatland complex in Tavvavuoma, Sweden

c) Batagai thaw slump in the boreal zone of Yakutia, Russia. The slump is more than 900 meters wide

d) Cartoon of major processes and landscape features in Schuur and Mack (2018)

6. Related terminology

6.1. Soil related terminology

Turbels: cryoturbated permafrost soils

Orthels: non-cryoturbated permafrost-affected mineral soils

Histels: organic permafrost soils

6.2. Permafrost specific terms

Simplified from van Everdingen *et al.* 2005

Active layer: top layer of ground subject to seasonal thawing and freezing in areas underlain by permafrost

Cryoturbation: soil movements causes by to freeze-thaw cycles, including expansion and contraction due to temperature changes and the growth and disappearance of ground-ice bodies,

Ice wedge: A massive, generally wedge-shaped body with its apex pointing downward. Ice wedges occur in thermal contraction cracks in which water from melting snow penetrates in the spring. Repeated annual contraction cracking of the ice in the wedge, followed by freezing of water in the crack, gradually increases the width and depth of the wedge

Lowland permafrost: Permafrost existing in high latitudes and outside alpine areas

Mountain permafrost (also alpine permafrost): Permafrost existing at high altitudes, also occurring in middle and low latitudes

Permafrost: Ground (including soil or rock) that remains at or below 0 °C for at least two following years

(Ice wedge) polygons: A type of patterned ground consisting of a closed, roughly equidimensional figure bounded by more or less straight sides. Causes by soil shrinking, water infiltration and thick wedged shape ice bodies (ice wedges) in the ground.

Solifluction (also frost creep): Slow downslope flow of saturated unfrozen earth materials

Talik: A layer or body of unfrozen ground within or through permafrost

Thaw subsidence: Drop in elevation of the ground surface due to ice volume loss caused by thaw

Thermo-erosion: The erosion of ice-rich permafrost by the combined thermal and mechanical action of moving water

Thermokarst: Process: melting of excess ground ice and subsequent thaw settlement, often caused by a water body (thermokarst lake); Landform: topography resulting from the melting of excess ground ice and subsequent thaw settlement. Thermokarst terrain is so named because of its superficial resemblance to the karst topography typical of limestone regions

Yedoma: Pleistocene ice-rich permafrost with syngenetic ice-wedges. Widespread in Siberia, Alaska, and Yukon (Canada) and prone to rapid-thaw processes.

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