doi:10.1038/nature14338

Climate change and the permafrost carbon feedback

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Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain. Here we find that current evidence suggests a gradual and prolonged release of greenhouse gas emissions in a warming climate and present a research strategy with which to target poorly understood aspects of permafrost carbon dynamics.

In high-latitude regions of Earth, temperatures have risen 0.6 °C per decade over the last 30 years, twice as fast as the global average[1]. This is causing normally frozen ground to thaw[2–4], exposing substantial quantities of organic carbon to decomposition by soil microbes. This permafrost carbon is the remnant of plants and animals accumulated in perennially frozen soil over thousands of years, and the permafrost region contains twice as much carbon as there is currently in the atmosphere[5,6]. Conversion of just a fraction of this frozen carbon pool into the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) and their release into the atmosphere could increase the rate of future climate change[7]. Climate warming as a result of human activities causes northern regions to emit additional greenhouse gases to the atmosphere, representing a feedback that will probably make climate change happen faster than is currently projected by Earth System models. The critical question centres on how fast this process will occur, and recent publications differ in their outlook on this issue. Abrupt releases of CH_4 forecast to cause trillions of dollars of economic damage to global society[8] contrast with predictions of slower, sustained greenhouse gas release that, although substantial, would give society more time to adapt[1,9]. This range of viewpoints is due in part to the wide uncertainty surrounding processes that are only now being quantified in these remote regions.

Here we provide an overview of new insights from a multi-year synthesis of data with the aim of constraining our current understanding of the permafrost carbon feedback to climate, and providing a framework for developing research initiatives in the permafrost region[10,11]. We begin by reviewing new research, much of it published since the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5)[1], on the size of the carbon pool stored in the permafrost region. Synthesis research has enlarged the number of observations in the permafrost region soil carbon pool database tenfold[12], and confirms that tremendous quantities of carbon accumulated deep in permafrost soils are widespread[5,6]. We then discuss new long-term laboratory incubations of these permafrost soils that reveal that a substantial fraction of this material can be mineralized by microbes and converted to CO_2 and CH_4 on timescales of years to decades, which would contribute to near-term climate warming. Initial estimates of greenhouse gas release point towards the potential for substantial emissions of carbon from permafrost in a warmer world, but these could still be underestimates. Field observations reveal that abrupt thaw processes are common in northern landscapes, but our review shows that mechanisms that speed thawing of frozen ground and release of permafrost carbon are entirely absent from the large-scale models used to predict the rate of climate change.

Bringing together this wealth of new observations, we propose that greenhouse gas emissions from warming permafrost are likely to occur at a magnitude similar to other historically important biospheric carbon sources (such as land-use change) but that will be only a fraction of current fossil-fuel emissions. At the proposed rates, the observed and projected emissions of CH_4 and CO_2 from thawing permafrost are unlikely to cause abrupt climate change over a period of a few years to a decade. Instead, permafrost carbon emissions are likely to be felt over decades to centuries as northern regions warm, making climate change happen faster than we would expect on the basis of projected emissions from human activities alone. This improved knowledge of the magnitude and timing of permafrost carbon emissions based on the synthesis of existing data needs to be integrated into policy decisions about the management of carbon in a warming world, but at the same time may help temper the worst fears about the impact of carbon emissions from warming northern high-latitude regions.

Permafrost carbon pool

The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone[6,7,13]. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (>1 m) in permafrost, below the traditional zone of soil carbon accounting[14]. Deeper carbon measurements were initially rare, and it was not even possible to quantify the uncertainty for the permafrost carbon pool size estimate. However, important new syntheses continue to report large quantities of deep carbon preserved in permafrost at many previously unsampled locations, and that a substantial fraction of this deep

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permafrost carbon is susceptible to future thaw[15]. The permafrost carbon pool is now thought to comprise organic carbon in the top 3 m of surface soil, carbon in deposits deeper than 3 m (including those within the yedoma region, an area of deep sediment deposits that cover unglaciated parts of Siberia and Alaska[16–18]), as well as carbon within permafrost that formed on land during glacial periods but that is now found on shallow submarine shelves in the Arctic. Recent research has expanded our knowledge considerably while at the same time highlighting remaining gaps in our understanding of this vulnerable carbon pool[19].

Surface carbon

The new northern permafrost zone carbon inventory reports the surface permafrost carbon pool (0–3 m) to be 1,035 ± 150 Pg carbon (mean ± 95% confidence interval, CI)[12,20] (where 1 Pg = 1 billion tons) (Fig. 1a). This estimate supported the original studies while improving precision by increasing the number of deeper (>1 m) sampling locations tenfold. This surface permafrost carbon pool is substantial. The rest of Earth's biomes, excluding the Arctic and boreal regions, are thought to contain 2,050 Pg carbon in the surface 3 m of soil[21]. Even though these northern regions account for only 15% of global soil area, the 0–3 m global soil carbon pool is increased by 50% when fully accounting for the carbon stored deeper in permafrost zone soil profiles.

Deep carbon in yedoma

Processes that accumulate carbon deep into permafrost soils do not stop at 3 m depth, and our previously limited understanding of those deep carbon deposits (>3 m depth) has been improved. In particular, several new estimates have emerged for carbon that accumulated during, and since, the last Ice Age in the yedoma region in Siberia and Alaska[16–18]. These new data support previous findings of relatively high carbon concentrations in permafrost soil at depth, but revised the understanding of total carbon stock by improving the estimates of spatial extent, type of deposit, sediment depth, and ground ice content. These deep, perennially frozen sediments are particularly ice-rich, where ice occupies 50%–80% of the ground volume[22,23]. Although this excess ice does not alter soil carbon concentration, it affects the total carbon inventory contained in a particular volume of soil, decreasing carbon stocks per unit soil volume by 22%–50% compared to previous estimates[24]. Because of the continued difficulty of measuring total ground ice content and total sediment depth, carbon pool estimates for the yedoma region still range by twofold even as new data from this region have accumulated. This region is now thought to contain between 210 ± 70 Pg carbon (ref. 16) and 456 ± 45 Pg carbon (ref. 18), still supporting the original accounts of several hundred billion tons of carbon stored deep in the permafrost even when recalculated with new observations.

Deep carbon outside the yedoma region

While new measurements of deep carbon have been largely focused on the 1.2 million square kilometres of the yedoma region in recent years, other areas in the northern permafrost zone with thick loose sedimentary material may also contain substantial organic carbon pools in permafrost (Fig. 1b). The major Arctic river deltas are now thought to contain 91 ± 39 Pg carbon (95% CI)[12], while carbon contained in the approximately 5 million square kilometres of thick (>5–10 m) sediments overlying bedrock outside the yedoma and river delta regions remain largely unknown. Taking the spatial extent of these poorly known permafrost areas, along with an estimated thickness in the tens of metres (similar to that of yedoma), and average carbon content of a few deep borehole soil samples, there could be an additional deep permafrost carbon pool of 350–465 Pg C outside the yedoma region (calculated using a depth interval of 3–10 m and carbon content of 11–14 kg C m^{-3}, which accounts for ground ice[25]).

Subsea permafrost carbon

Much of the inventory until this point has focused on terrestrial ecosystems where permafrost is currently sustained by cold winter air temperatures. But permafrost also exists below Arctic Ocean continental shelves, in particular the East Siberian Arctic Shelf, the largest and shallowest shelf on Earth. This permafrost is an extension of the terrestrial permafrost that existed during the last Ice Age, but became submerged when sea level rose during the late Pleistocene–Holocene transition, and at the beginning of the Holocene epoch. The shallow shelf area exposed as dry land in the area around Alaska and Siberia during the last Ice Age (<125 m current ocean depth), at almost 3 million square kilometres, is about 2.5 times the size of the current terrestrial yedoma region[16,26]. But the quantity of organic permafrost carbon stored beneath the sea floor is even more poorly quantified than on land and could be lower than it once was[27,28]. Subsea permafrost as a whole has been slowly degrading over thousands of years as relatively warm ocean water has warmed the newly submerged sea floor. Frozen sediments are thickest near the shore, where submergence with seawater occurred more recently than on the outer shelf, which is now underlain by discontinuous, patchy permafrost[29,30]. During this time of thaw, organic carbon was mineralized by microbes within the sediment in low-oxygen conditions that promote the formation of CH_4, reducing the pool of permafrost carbon remaining under the sea.

Taken together, the known pool of terrestrial permafrost carbon in the northern permafrost zone is 1,330–1,580 Pg carbon, accounting for surface carbon as well as deep carbon in the yedoma region and river deltas, with the potential for ~400 Pg carbon in other deep terrestrial permafrost sediments that, along with an additional quantity of subsea permafrost carbon, still remains largely unquantified.

Carbon decomposability

Permafrost carbon stocks provide the basis for greenhouse gas release to the atmosphere, but the rate at which this can happen is also controlled by the overall decomposability of organic carbon. Conceptual models and initial data on decomposability suggested that a portion of permafrost carbon is susceptible to rapid breakdown upon thaw[13,31]. But it has not been clear to what degree this could be sustained on the decade-to-century timescale of climate change, or what degree of variation exists within soils across the vast landscape of the permafrost zone. New research has confirmed that initial rates of permafrost carbon loss are potentially high, but continued observation reported declines in carbon loss rates over time, which might be expected as more labile carbon pools are exhausted[32]. This has highlighted the need for long-term observation under controlled conditions to estimate the potential decomposability of permafrost carbon. New data from a 12-year incubation of permafrost soil from Greenland showed that 50%–75% of the initial carbon was lost by microbial decomposition under aerobic and continuously unfrozen laboratory conditions over that time frame[33]. This experiment, of unprecedented length for permafrost soils compared to typical incubations that might be only weeks to months long[34,35], was then extended geographically in a new synthesis of long-term (>1 year) permafrost zone soil incubations. Soils from across the permafrost region showed similarly high potential for microbial degradation of organic carbon upon thaw in the laboratory, with a wider range of decade-long losses projected to be 1%–76% (Fig. 2a) under laboratory conditions[36].

A major cause of landscape-scale variation in decomposability across soils was linked to the carbon to nitrogen ratio of the organic matter, with higher values leading to more greenhouse gas release. This simple metric (the carbon to nitrogen ratio) is in part illustrated by grouping soils as organic ($>20\%$ C) with mean decade-long losses of 17%–34% (lower-to-upper 97.5% CI) and mineral ($<20\%$ C) with mean decade-long losses of 6%–13% (Fig. 2a). The metric takes into account the ability of microbes to process permafrost carbon for metabolism by breaking down organic carbon for energy, and to grow by acquiring nutrients such as nitrogen released during the decomposition process. Because carbon and nitrogen are often measured in soil surveys, maps of permafrost carbon pools can then be combined with the findings from laboratory incubations to project potential carbon emission estimates across the permafrost region to determine which regions could be emission hotspots in a warming climate. The location of such potential emission hotspots is expected to be affected by both the total pool of permafrost carbon and the potential for that carbon to be broken

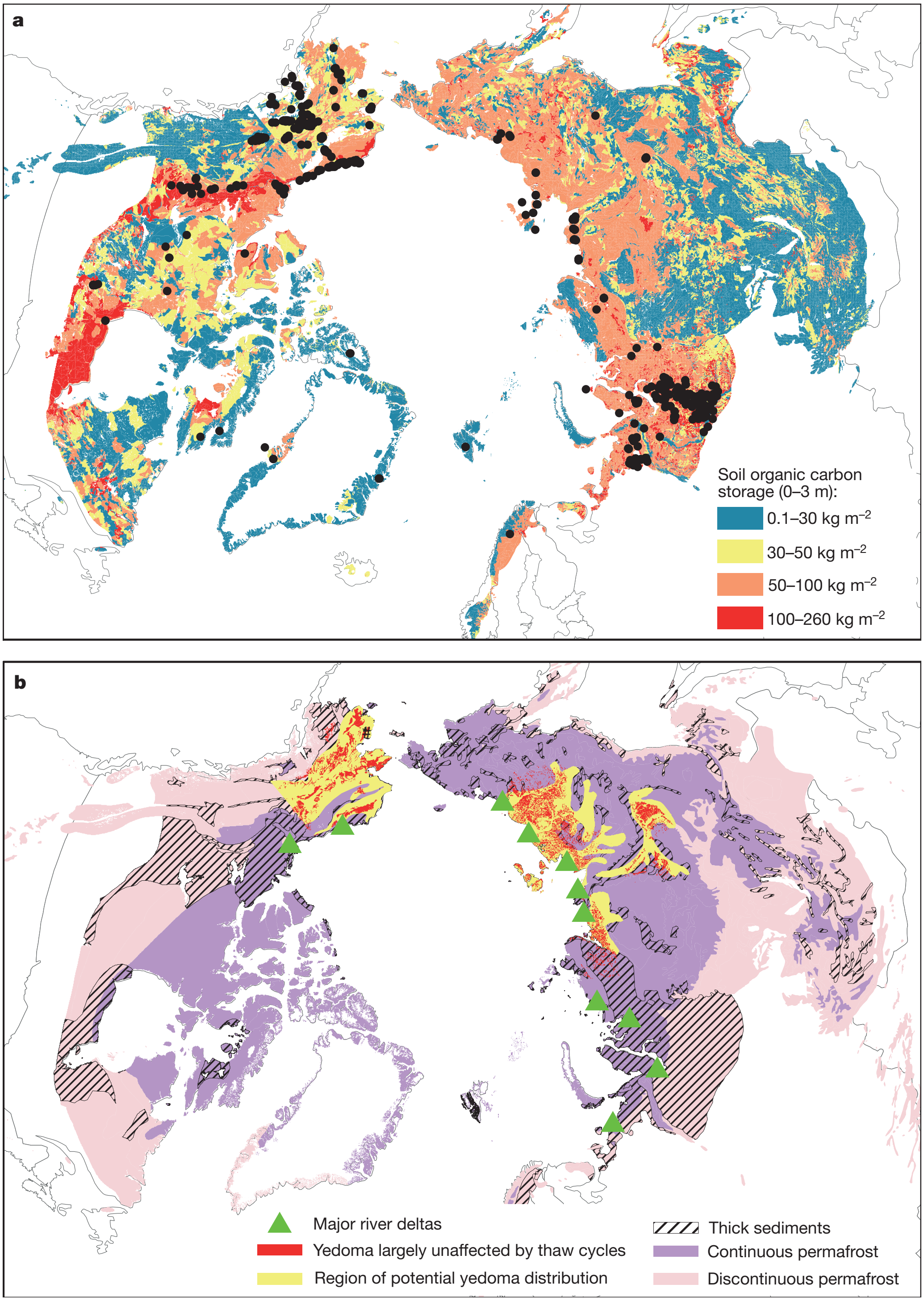


Figure 1 | **Soil organic carbon maps.** **a**, Soil organic carbon pool (kg C m^{-2}) contained in the 0–3 m depth interval of the northern circumpolar permafrost zone[12]. Points show field site locations for 0–3 m depth carbon inventory measurements; field sites with 1 m carbon inventory measurements number in the thousands and are too numerous to show. **b**, Deep permafrost carbon pools (>3 m), including the location of major permafrost-affected river deltas (green triangles), the extent of the yedoma region previously used to estimate the carbon content of these deposits[13] (yellow), the current extent of yedoma region soils largely unaffected by thaw-lake cycles that alter the original carbon content[17] (red), and the extent of thick sediments overlying bedrock (black hashed). Yedoma regions are generally also thick sediments. The base map layer shows permafrost distribution with continuous regions to the north having permafrost everywhere (>90%), and discontinuous regions further south having permafrost in some, but not all, locations (<90%)[96].

down by microbes after thaw as controlled by the energy and nutrients contained within the organic matter.

The inherent range of permafrost carbon decomposability across soil types also intersects with environmental conditions, and aerobic decomposition is only part of the story for northern ecosystems. While temperature control over decomposition is implicit when considering permafrost thaw, this region is characterized by widespread lakes, wetlands, and soils waterlogged as a result of surface drainage restricted by underlying permafrost. The lack of oxygen in saturated anaerobic soils and sediments presents another key control over emissions from newly thawed permafrost carbon. Comparing the results from the aerobic permafrost soil incubation synthesis[36] with those from another circumpolar synthesis of anaerobic soil incubations[37]

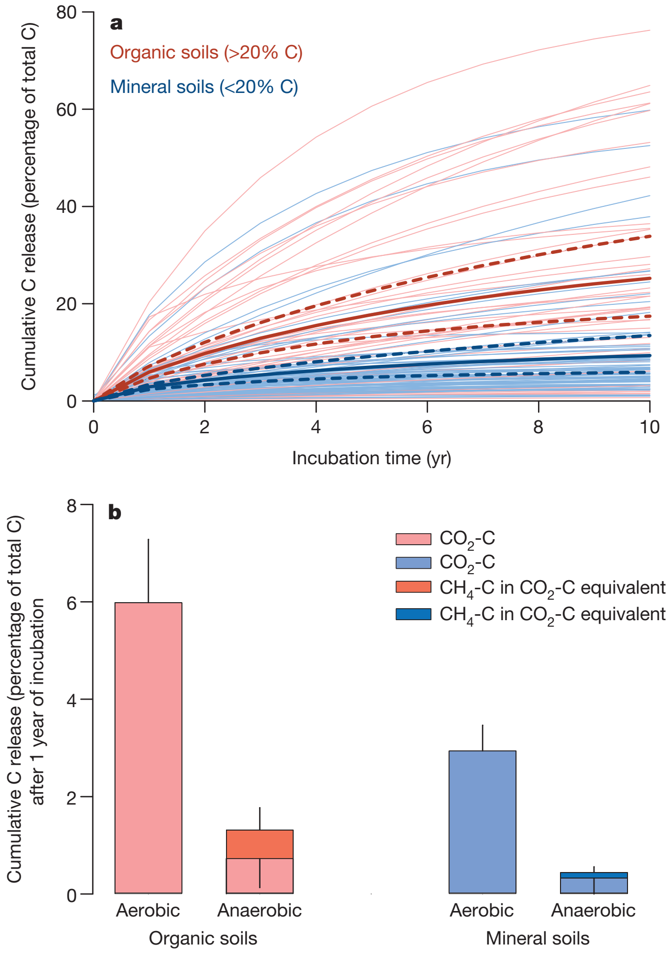


Figure 2 | Potential cumulative carbon release. Data are given as a percentage of initial carbon. **a**, Cumulative carbon release after ten years of aerobic incubation at a constant temperature of 5 °C. Thick solid lines are averages for organic (red, $N = 43$) and mineral soils (blue, $N = 78$) and thin solid lines represent individual soils to show the response of individual soils. Dotted lines are the averages of the 97.5% CI for each soil type. **b**, Cumulative carbon release after one year of aerobic and anaerobic incubations (at 5 °C). Darker colours represent cumulative CH_4-carbon calculated as CO_2-carbon equivalent (for anaerobic soils) on a 100-year timescale according to ref. 38. Positive error bars are upper 97.5% CI for CO_2-carbon and negative error bars are lower 97.5% CI for CH_4-carbon. $N = 28$ for organic soils and $N = 25$ for mineral soils in anaerobic incubations. Aerobic cumulative carbon release is redrawn from ref. 36 and anaerobic cumulative carbon release is calculated based on ref. 37.

shows that cumulative carbon emissions, over an equal one-year incubation time frame, are, on average, 78%–85% lower than those from aerobic soils (Fig. 2b). Specialized microbes release CH_4 along with CO_2 in these environments, and the more potent (that is, it affects climate change more powerfully) greenhouse gas CH_4 in the atmosphere can partially offset a decreased decomposition rate. While mean quantities of CH_4 are 3% (in mineral soils) to 7% (in organic soils) that of CO_2 emitted from anaerobic incubations (by weight of carbon), these mean CH_4 values represent 25% (in mineral soil) to 45% (in organic soil) of the overall potential impact on climate over a 100-year timescale when accounting for CH_4 (ref. 38). Across the mosaic of ecosystems in the permafrost region, controlled laboratory observations brought together here imply that, in spite of the more potent greenhouse gas CH_4, a unit of newly thawed permafrost carbon could have a greater impact on climate over a century if it thaws and decomposes within a drier, aerobic soil as compared to an equivalent amount of carbon within a waterlogged soil or sediment.

Controlled laboratory work is critical for identifying the key mechanisms for potential greenhouse gas release from permafrost carbon, but some important processes are difficult to address with incubation experiments. For example, CH_4 generated from permafrost carbon can be oxidized in aerobic soil layers above the water table and released to the atmosphere as CO_2 instead. This effect can be modified by vegetation, for example, sedge stems acting as pipes provide a pathway for CH_4 to avoid oxidation and to escape to the atmosphere[39]. A synthesis of field CH_4 emission rates showed that sedge-dominated sites had emission rates 2–5 times higher[40], due in part to sedges allowing the physical escape of CH_4, as well as providing more decomposable carbon to the microbial community[41,42]. But even with sedges, it is likely that CH_4 oxidation as a whole would decrease the warming impact of permafrost carbon decomposing in a waterlogged environment compared to what was measured from a laboratory potential. Incubation results, while needing to be interpreted carefully, are useful for scaling the potential of permafrost soils to release greenhouse gases upon thaw, and also for helping to quantify the fraction of soil carbon that is likely to remain relatively inert within the soil after thaw.

Projecting change

A number of ecosystem and Earth system models have incorporated a first approximation of global permafrost carbon dynamics. Recent key improvements include the physical representation of permafrost soil thermodynamics and the role of environmental controls, in particular the soil freeze/thaw state, on decomposition of organic carbon[43–45]. These improved models, which specifically address processes known to be important in permafrost ecosystems but that were missing from earlier model representations, have been key for forecasting the potential release of permafrost carbon with warming, and the impact this would have on the rate of climate change. Model scenarios show potential carbon release from the permafrost zone in the range 37–174 Pg carbon by 2100 under the current climate warming trajectory (Representative Concentration Pathway RCP 8.5), with an average across models of 92 ± 17 Pg carbon (mean ± s.e.) (Fig. 3)[45–52]. Furthermore, thawing permafrost carbon is forecasted to impact global climate for centuries, with models, on average, estimating that 59% of total permafrost carbon emissions will occur after 2100. While carbon releases over these time frames are understandably uncertain, they illustrate the momentum of a warming climate that thaws near-surface permafrost, causing a cascading release of greenhouse gases as microbes slowly decompose newly thawed permafrost carbon. At the scale of these models not all differentiated between CO_2 and CH_4 loss, but expert assessment, a method for surveying expert knowledge, placed CH_4 losses at about 2.3% of total future emissions from the permafrost zone[53,54]. This has the effect, in the expert assessment, of increasing the warming potential of released carbon by 35%–48% when accounting for the more potent greenhouse gas CH_4 over a 100-year timescale.

Within the wide uncertainty of forecasts, some broader patterns are just beginning to emerge. Models vary widely when predicting the current pool of permafrost carbon, which is the source of future carbon emissions in a warmer world. The model average permafrost carbon pool size was estimated at 771 ± 100 Pg carbon (mean ± s.e.), about half as much as the measurement-based estimate, potentially related in part to the fact that models mostly represented carbon to only 3 m depth. A smaller modelled carbon pool could, in principle, constrain forecasted carbon emissions. Normalizing the emissions estimates from the dynamic models by their initial permafrost carbon pool size, 15% ± 3% (mean ± s.e.) of the initial pool was expected to be lost as greenhouse gas emissions by 2100[55]. This decrease in the permafrost carbon pool is similar, but somewhat higher, than the 7%–11% (95% CI) loss predicted by experts[53,54], and the relatively constant fraction across model estimates does hint at the importance of pool size in constraining carbon emissions. However, sensitivity to both modelled Arctic climate change, as well as the responses of soil temperature, moisture and carbon dynamics, are important controls over emissions predictions within these complex models, not pool size alone[44,56,57]. Full diagnosis of the important parameters that regulate the permafrost carbon feedback is not currently possible from the small number of modelling studies that exist, but the estimates do seem to converge on a vulnerable fraction of permafrost carbon that seems to be in line with other approaches.

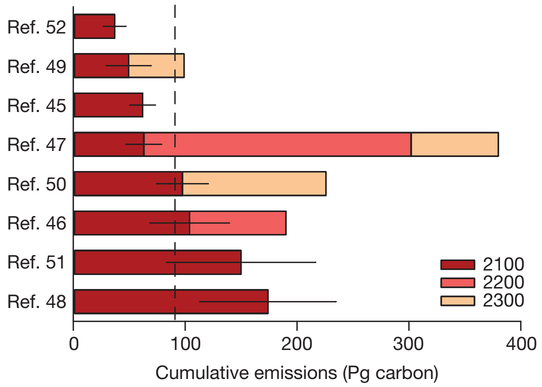


Figure 3 | Model estimates of potential cumulative carbon release from thawing permafrost by 2100, 2200, and 2300. All estimates except those of refs 50 and 46 are based on RCP 8.5 or its equivalent in the AR4 (ref. 97), the A2 scenario. Error bars show uncertainties for each estimate that are based on an ensemble of simulations assuming different warming rates for each scenario and different amounts of initial frozen carbon in permafrost. The vertical dashed line shows the mean of all models under the current warming trajectory by 2100.

These dynamic models also simultaneously assess the countering influence of plant carbon uptake, which may in part offset permafrost carbon release. Warmer temperatures, longer growing seasons, elevated CO_2, and increased nutrients released from decomposing organic carbon may all stimulate plant growth[58]. New carbon can be stored in larger plant biomass or deposited into surface soils[59]. A previous generation of Earth system models that did not include permafrost carbon mechanisms but did simulate changes in plant carbon uptake estimated that the vegetation carbon pool could increase by 17 ± 8 Pg carbon by 2100, with increased plant growth also contributing to new soil carbon accumulation of similar magnitude[60]. The models reviewed here that do include permafrost carbon mechanisms (as well as many of the mechanisms that stimulate plant growth that were used in the previous generation of models) generally indicate that increased plant carbon uptake will more than offset soil carbon emissions from the permafrost region for several decades as climate becomes warmer[45,46,48]. Over longer timescales and with continued warming, however, microbial release of carbon overwhelms the capacity for plant carbon uptake, leading to net carbon emissions from permafrost ecosystems to the atmosphere. Modelled carbon emissions projected under various warming scenarios translate into a range of 0.13–0.27 °C additional global warming by 2100 and up to 0.42 °C by 2300, but currently remain one of the least constrained biospheric feedbacks to climate[1].

Abrupt permafrost thaw

Recent progress towards predicting change in permafrost carbon dynamics focuses mostly on gradual top-down thawing of permafrost. However, increasing evidence from the permafrost zone suggests that abrupt permafrost thaw may be the norm for many parts of the Arctic landscape[17,18,61,62] (Fig. 4). Abrupt permafrost thaw occurs when warming melts ground ice, causing the land surface to collapse into the volume previously occupied by ice. This process, called thermokarst, alters surface hydrology. Water is attracted towards collapse areas, and pooling or flowing water in turn causes more localized thawing and even mass erosion. Owing to these localized feedbacks that can thaw through tens of metres of permafrost across a hillslope within only a few years, permafrost thaw occurs much more rapidly than would be predicted from changes in air temperature alone. This raises the question of whether key complexity is missing from large-scale model projections that are based on first approximations of permafrost dynamics.

Abrupt thaw occurs only at point locations but often causes much deeper permafrost thaw to occur more rapidly. This is in contrast to top-down thawing, which occurs across the entire landscape but affects only the permafrost surface. New regional research is beginning to reveal that a large fraction of permafrost carbon is vulnerable to abrupt thaw. For example, since the end of the last Ice Age, thermokarst thaw-lake cycles have affected 70% of the yedoma permafrost deposits in Siberian lowlands[17]. These cycles occur when abrupt permafrost thaw forms lakes that can drain over time, allowing sediments and carbon to refreeze into permafrost, while elsewhere new thaw lakes form and repeat this cyclic process (Fig. 4a, c). Abrupt thaw in upland regions, where water does not generally pool and form lakes, often creates gullies and slump features that can erode permafrost carbon into streams, rivers and lakes (Fig. 4b, d). These thaw features can also be widespread but are not as well recognized as are thaw lakes; over 7,500 upland thaw features were mapped within a 1,700-square-kilometre foothill region of Alaskan tundra[49]. Studies such as these illustrate a widespread influence of abrupt thaw in both upland and lowland permafrost landscapes, even though they do not provide a chronology of change.

Climate change is expected to increase the initiation and expansion of abrupt thaw features, potentially changing the rate of this historic disturbance cycle[62–65]. Wetland expansion due to abrupt thaw has affected 10% of a peatland landscape in northwestern Canada since the 1970s, with the fastest expansion occurring in the past decade[66]. Landscape lake cover is also affected by abrupt thaw, with net change being the sum of both lake expansion and drainage. The area of small open-water features around Prudhoe Bay on the Alaskan tundra has doubled since 1990 (ref. 67). In northwestern Alaska, lake initiation has increased since 1950, while lake expansion rates remained steady[68]. In general, landscape lake cover is currently believed to be stable or increasing within the continuous permafrost zone, whereas there is a tendency for lake drainage and vegetation infilling to dominate over lake expansion in the discontinuous permafrost zone[68–72].

Abrupt thaw influences carbon emissions to the atmosphere by exposing previously frozen carbon to microbial processes, and also by altering the hydrology that is critical for determining the balance of CO_2 and CH_4 emissions. Some of the highest CH_4 emissions in the permafrost region have been observed in lakes and wetlands formed through abrupt thaw[40,73]. At the same time, accumulation of new carbon under anaerobic conditions in peat[74] and in lake sediments[18] can be greater than permafrost carbon losses, at least in some ecosystems. In this way, anaerobic environments replace freezing temperatures as a mechanism for soil carbon stabilization, keeping greenhouse gas emissions lower than they would otherwise be[75]. In contrast, abrupt thaw processes in other landscapes clearly accelerate carbon loss. Drained lakes and lowered water tables will expose previously waterlogged carbon to microbial decomposition in aerobic conditions with relatively higher rates of carbon emissions. Also, lateral movement of permafrost carbon by leaching or erosion into lakes, rivers and the ocean[76–78] can increase loss, as carbon may be more readily mineralized through microbial and photochemical processes after mobilization[79,80]. How carbon cycling at the landscape scale will change under a warming climate will depend critically on how much of the landscape becomes wetter or drier, a question difficult to answer. It is clear that abrupt thaw is an important mechanism of rapid permafrost degradation, with widespread but varying influences on hydrology and carbon cycling. Yet abrupt thaw is not included in large-scale models, suggesting that important landscape transformations are not currently being considered in forecasts of permafrost carbon–climate feedbacks. This is in part due to the fact that we do not know at this stage what the relative importance of abrupt to gradual thaw across the landscape is likely to be.

Subsea carbon emissions

A majority of the observations and all of the modelling to date has focused on potential emissions from permafrost carbon on land. This is in part because subsea permafrost is buffered from recent climate change by the overlying ocean, and because ocean incursion at the end of the Ice Age has already been thawing and potentially reducing the pool of permafrost carbon under the sea. However, aside from organic carbon stored in permafrost, the sea bed underlying Arctic shelves also accumulated fossil CH_4 stored either as free CH_4 gas or as clathrates (CH_4-ice lattices that are stable at pressures and temperatures found at depth in this region). Layers of permafrost may serve as a physical barrier to the release of this CH_4 gas from the sediment into the water column and eventually the atmosphere. These

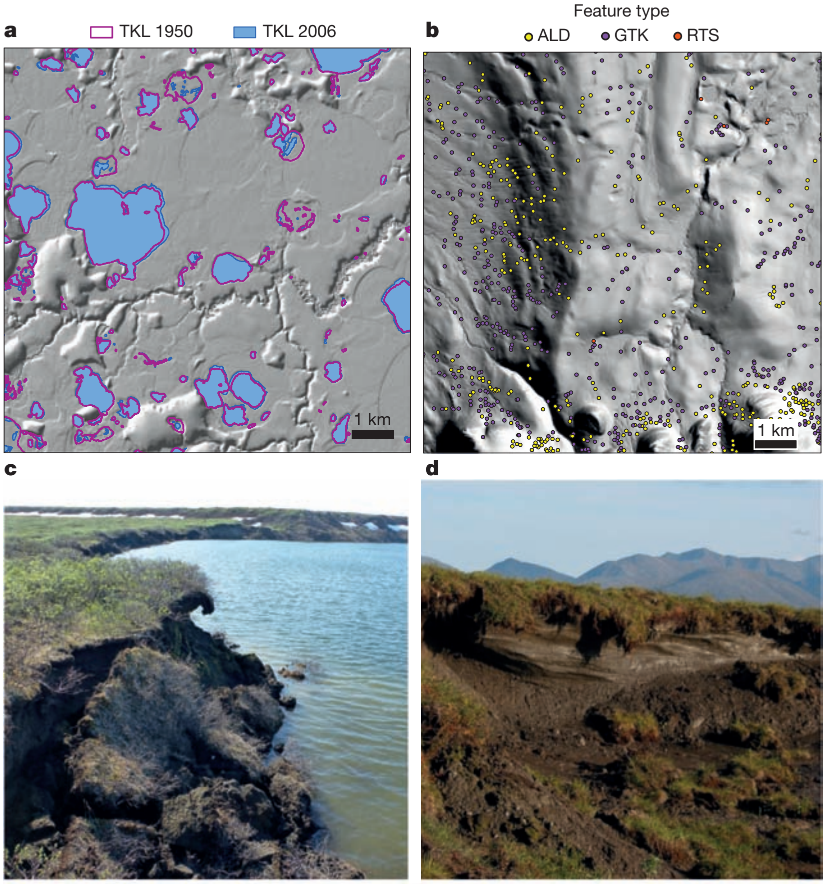


Figure 4 | Abundance of abrupt thaw features in lowland and upland settings in Alaska. Left panels (**a**, **c**) show thermokarst lake (TKL) abundance, expansion, and drainage on the Seward Peninsula, Northwest Alaska, between 1950 and 2006[68], with collapsing permafrost banks (photo credit G.G.). Right panels (**b**, **d**) show extensive distribution of ground collapse and erosion features (ALD, active layer detachment slide; RTS, retrogressive thaw slump; GTK, thermal erosion gullies) in upland tundra in a hill slope region in Northwest Alaska[61], and thawing icy soils in a retrogressive thaw slump (photo credit E.A.G.S.).

shallow shelves are also depositional areas for carbon from the erosion of coastal permafrost carbon and from inland permafrost carbon transported by Arctic rivers[81]. Together, these processes form ocean hotspots that are documented sources of high CH_4 emissions to the atmosphere[82,83], similar to hotspots formed in Arctic lakes on land[58]. New quantification has estimated that 17 Tg of CH_4 per year (where 1 Pg = 1,000 Tg) is emitted from the East Siberian Arctic Shelf after accounting for both diffusive and point-source bubble emissions[83]. Although this amount represents an increase from what was previously estimated for this region[27], this is probably because of improved observations of these emissions that may have been persistent over the thousands of years of land submergence. Climate warming, sea-ice decline, and increasing storminess have been linked to a 2.1 °C increase in bottom water (<10 m depth) temperature since the mid-1980s in this region[84]. Degradation of subsea permafrost from above by climate warming, and also from below by ongoing geothermal heat, will tend to increase new pathways between CH_4 storage areas deeper in the sediments and the sea floor[30]. But it is not known whether meaningful increases in CH_4 emissions via these processes could occur within this century, or whether they are more likely to manifest over a century or over millennia[84]. What is clear is that it would take thousands of years of CH_4 emissions at the current rate to release the same quantity of CH_4 (50 Pg) that was used in a modelled ten-year pulse to forecast tremendous global economic damage as a result of Arctic carbon release[8], making catastrophic impacts such as those appear highly unlikely[85–87].

Permafrost and the global carbon cycle

Carbon pools in permafrost regions represent a large reservoir vulnerable to change in a warming climate. While some of this carbon will continue to persist in soils and sediments over the long term, our understanding that a substantial fraction of this pool is susceptible to microbial breakdown once thawed has been verified at the landscape scale (Box 1 and the Box 1 Figure). The exponential nature of microbial decomposition and CO_2 and CH_4 release over time means that the initial decades after thaw will be the most important for greenhouse gas release from any particular unit of thawed soil. Our expert judgement is that estimates made by independent approaches, including laboratory incubations, dynamic models, and expert assessment, seem to be converging on ~5%–15% of the terrestrial permafrost carbon pool being vulnerable to release in the form of greenhouse gases during this century under the current warming trajectory, with CO_2-carbon comprising the majority of the release. There is uncertainty, but the vulnerable fraction does not appear to be twice as high or half as much as 5%–15%, based on this analysis. Ten per cent of the known terrestrial permafrost carbon pool is equivalent to ~130–160 Pg carbon. That amount, if released primarily in the form of CO_2 at a constant rate over a century, would make it similar in magnitude to other historically important biospheric sources, such as land-use change (0.9 ± 0.5 Pg carbon per year; 2003–2012 average), but far less than fossil-fuel emissions[88] (9.7 ± 0.5 Pg carbon per year in 2012). Considering CH_4 as a fraction of permafrost carbon release would increase the warming impact of these emissions. At these rates, the observed and projected emissions of CO_2 and CH_4 from thawing permafrost are unlikely to occur at a speed that could cause abrupt climate change over a period of a few years to a decade[1,9]. A large pulse release of permafrost carbon on this timescale could cause climate change that would incur catastrophic costs to society[8], but there is little evidence from either current observations or model projections to support such a large and rapid pulse. Instead, permafrost carbon emissions are likely to occur over decades and centuries as the permafrost region warms, making climate change happen even faster than we project on the basis of emissions from human activities alone. Because of momentum in the system and the continued warming and thawing of permafrost, permafrost carbon emissions are likely not only during this century but also beyond. Although never likely to overshadow emissions from fossil fuel, each additional ton of carbon released from the permafrost region to the atmosphere will probably incur additional costs to society.

Next steps for model–data integration

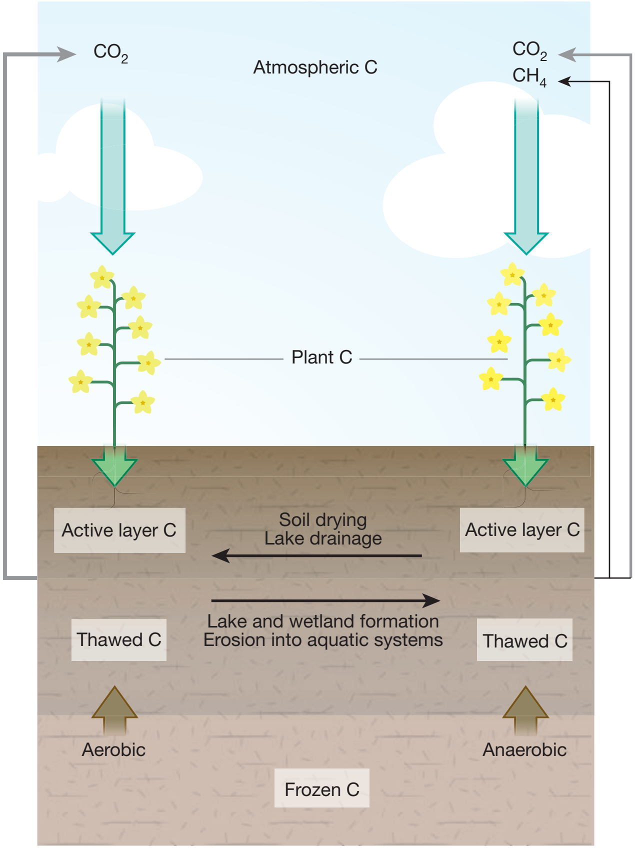
The Earth system models analysed for the IPCC AR5[1] did not include permafrost carbon emissions, and there is a need for the next assessment to make substantive progress analysing this climate feedback. It is clear, even among models that are currently capable of simulating permafrost carbon emissions, that improvements are needed to the simulations of the physical and biological processes that control the dynamics of permafrost distribution and soil thermal regime[43,44,57]. The initial model projections we review here are based on a range of different model formulations, many of which are known to lack key structural features. Critical next steps that are being achieved by the research community include a permafrost carbon model intercomparison using standard driving variables to improve model formulations and conceptualization. Initial intercomparison results point towards several key structural features that should be implemented by models attempting to forecast permafrost carbon emissions. These include explicitly defining the vertical distribution of carbon in permafrost soils to account for the way atmospheric warming at the surface propagates through the soil, causing permafrost thaw and carbon decomposition at depth. Additionally, many large-scale models do not distinguish CH_4 versus CO_2 release and project only total carbon emissions. This partitioning depends on explicitly describing the interactions between permafrost thaw and surface hydrology and is critical to produce credible projections of the effect of permafrost carbon on climate. A first-order issue is whether the terrestrial landscape in the permafrost region, already interspersed with thaw lakes, wetlands and waterlogged soils, becomes wetter or drier in a warmer world[89]. Lastly, new modelling formulations for describing abrupt thaw are being developed. These are needed to understand how gradual warming from the surface, occurring across the entire landscape as currently modelled, compares to hotspots on the landscape where permafrost undergoes catastrophic ground collapse and rapid thaw. These issues go beyond temperature sensitivity alone and are at the forefront of current ecosystem model development and research.

Models are useful tools for making projections, but need to use observations more effectively for benchmarking and parameterization. Current models show a wide range of results when compared against benchmark data sets of permafrost soil temperatures[44], soil carbon stocks[90], and high-latitude carbon fluxes[91], emphasizing the high uncertainty in these projections. Now, new data sets on decomposability (reviewed here) are available and should be used to parameterize key aspects of model carbon feedbacks. The databases on decomposability however, remain two orders of magnitude smaller than surface (<1 m) carbon pool data sets. Increasing the number of laboratory incubations will help to constrain uncertainty regarding the potential for permafrost carbon to remain stable under different environmental conditions and will allow researchers to understand which controls over decomposition are most important for the slow turnover pools that comprise a large fraction of the total permafrost carbon pool. At the same time, further work is required to quantify the permafrost carbon pool itself better. Despite substantial recent progress, remote regions such as the Canadian High Arctic, central Siberia, and the subsea continental shelves remain poorly represented, with very few data points deeper than 1 m. Other data sets synthesizing field observations of CH_4 emissions and CO_2 exchange provide process-level understanding available for model validation as well[40,91–93]. Model–data fusion using these newly created databases from both laboratory and field observations is urgently needed to evaluate which models can credibly represent the permafrost region and thus help reduce the uncertainty in forecasting the permafrost carbon feedback.

BOX 1

Permafrost carbon feedback to climate change

As shown in the Box 1 Figure, carbon stored frozen in permafrost, once thawed, can enter ecosystems that have either predominantly aerobic (oxygen present) or predominantly anaerobic (oxygen limited) soil conditions. Across the permafrost region, there is a gradient of water saturation that ranges from mostly aerobic upland ecosystems to mostly anaerobic lowland lakes and wetlands. In aerobic soils, CO_2 is released by microbial decomposition of soil organic carbon, whereas both CO_2 and CH_4 are released from anaerobic soils and sediments. Microbial breakdown of soil organic carbon can happen in the surface active layer, which thaws each summer and refreezes in the winter, and in the subsurface as newly thawed carbon becomes available for decomposition after it has emerged from the perennially frozen pool. The decomposability of soil organic carbon varies across the landscape depending in part on the plant inputs as well as the soil environment, and also with depth in the soil profile. The landscape mosaic of water saturation is also affected by permafrost thaw. Gradual and abrupt thaw processes such as top-down thawing of permafrost (increasing the thickness of the active layer) and lake draining can expose more carbon to aerobic conditions. Alternatively, abrupt thaw processes can create wetter anaerobic conditions as the ground surface subsides, attracting local water. Carbon can also be mobilized by erosion or by leaching from upland soils into aquatic systems or sediments. Plant carbon uptake can be stored in increased plant biomass or deposited in the surface soils, which in part can offset losses from soils.



Box 1 Figure | Key features regulating the permafrost carbon feedback to climate from new, synthesized observations.

High-latitude warming and the emission of permafrost carbon remains a likely global carbon cycle feedback to climate change. The sheer size of these frozen carbon pools and the rapid changes observed in the permafrost region warrant focused attention on these remote landscapes. The observations and modelling steps outlined here will help in forecasting future change. At the same time, it is imperative to continue developing effective observation networks, including remote sensing capability[94], to adequately quantify real-time CO_2 and CH_4 emissions from permafrost regions[95]. While increased permafrost carbon emissions in a warming climate are more likely to be gradual and sustained rather than abrupt and massive, such observation networks are needed to detect the potential emissions predicted here, and also to provide early warning of phenomena and potential surprises we do not yet fully appreciate or understand. The combination of robust observations with appropriate modelling tools for forecasting change is essential to properly evaluate permafrost carbon sources. The quantification of carbon sources in addition to those that are a direct result of human activity is necessary when developing and evaluating climate change mitigation policies.

Received 14 July 2014; accepted 12 February 2015.

1. IPCC in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*) 1535 (Cambridge Univ. Press, 2013).
2. Brown, J. & Romanovsky, V. E. Report from the International Permafrost Association: state of permafrost in the first decade of the 21st century. *Permafr. Periglac. Process.* **19,** 255–260 (2008).
3. Romanovsky, V. E. *et al.* Thermal state of permafrost in Russia. *Permafr. Periglac. Process.* **21,** 136–155 (2010).
4. Romanovsky, V. E. *et al. Permafrost* (Arctic Report Card 2011) http://www.arctic.noaa.gov/report11/ (2013).
5. Zimov, S. A., Schuur, E. A. G. & Chapin, F. S. Permafrost and the global carbon budget. *Science* **312,** 1612–1613 (2006).
6. Tarnocai, C. *et al.* Soil organic carbon pools in the northern circumpolar permafrost region. *Glob. Biogeochem. Cycles* **23,** GB2023 (2009).
7. Schuur, E. A. G. *et al.* Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *Bioscience* **58,** 701–714 (2008).
8. Whiteman, G., Hope, C. & Wadhams, P. Climate science: vast costs of Arctic change. *Nature* **499,** 401–403 (2013).
9. National Research Council. *Abrupt Impacts of Climate Change: Anticipating Surprises* (The National Academies Press, 2013).
10. Schädel, C. *et al.* Short communication on network related activities: research coordination network on the vulnerability of permafrost carbon. *Frozen Ground* **37,** 7 (2013).
11. Schuur, E. A. G. *et al.* Research coordination network on the vulnerability of permafrost carbon. *Frozen Ground* **35,** 6 (2011).
12. Hugelius, G. *et al.* Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences* **11,** 6573–6593 (2014).
    Revised and updated current state of knowledge on permafrost soil organic carbon stocks at circumpolar scales.
13. Zimov, S. A. *et al.* Permafrost carbon: stock and decomposability of a globally significant carbon pool. *Geophys. Res. Lett.* **33,** L20502 (2006).
14. Ping, C.-L. *et al.* High stocks of soil organic carbon in the North American Arctic region. *Nature Geosci.* **1,** 615–619 (2008).
15. Harden, J. W. *et al.* Field information links permafrost carbon to physical vulnerabilities of thawing. *Geophys. Res. Lett.* **39,** L15704 (2012).
    Provides cumulative distributions of active layer thickness under current and future climates and estimates the amounts of newly thawed carbon and nitrogen.
16. Strauss, J. *et al.* The deep permafrost carbon pool of the yedoma region in Siberia and Alaska. *Geophys. Res. Lett.* **40,** 6165–6170 (2013).
    Quantifies the organic carbon pool for yedoma deposits and thermokarst deposits in Siberia and Alaska.
17. Grosse, G. *et al.* Distribution of late Pleistocene ice-rich syngenetic permafrost of the Yedoma Suite in east and central Siberia, Russia. *US Geol. Surv. Open File Rep.* **2013–1078,** 1–37 (2013).
18. Walter Anthony, K. M. *et al.* A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature* **511,** 452–456 (2014).
19. Mishra, U. *et al.* Empirical estimates to reduce modeling uncertainties of soil organic carbon in permafrost regions: a review of recent progress and remaining challenges. *Environ. Res. Lett.* **8,** 035020 (2013).
20. Hugelius, G. *et al.* The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions. *Earth Syst. Sci. Data* **5,** 3–13 (2013).
21. Jobbágy, E. G. & Jackson, R. B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **10,** 423–436 (2000).
22. Schirrmeister, L. *et al.* Late Quaternary paleoenvironmental records from the western Lena Delta, Arctic Siberia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **299,** 175–196 (2011).
23. Kanevskiy, M., Shur, Y., Fortier, D., Jorgenson, M. T. & Stephani, E. Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure. *Quat. Res.* **75,** 584–596 (2011).
24. Schirrmeister, L. *et al.* Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic. *J. Geophys. Res. Biogeosci.* **116,** G00M02 (2011).
25. Hugelius, G. *et al.* High-resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, European Russian Arctic. *J. Geophys. Res. Biogeosci.* **116,** G03024 (2011).
26. Brosius, L. S. *et al.* Using the deuterium isotope composition of permafrost meltwater to constrain thermokarst lake contributions to atmospheric CH_4 during the last deglaciation. *J. Geophys. Res. Biogeosci.* **117,** G01022 (2012).
27. McGuire, A. D. *et al.* Sensitivity of the carbon cycle in the Arctic to climate change. *Ecol. Monogr.* **79,** 523–555 (2009).
28. Walter, K. M., Edwards, M. E., Grosse, G., Zimov, S. A. & Chapin, F. S. Thermokarst lakes as a source of atmospheric CH_4 during the last deglaciation. *Science* **318,** 633–636 (2007).
29. Romanovskii, N. N., Hubberten, H. W., Gavrilov, A. V., Eliseeva, A. A. & Tipenko, G. S. Offshore permafrost and gas hydrate stability zone on the shelf of East Siberian seas. *Geo-Mar. Lett.* **25,** 167–182 (2005).
30. Nicolsky, D. J. *et al.* Modeling sub-sea permafrost in the East Siberian Arctic Shelf: the Laptev Sea region. *J. Geophys. Res. Earth Surf.* **117,** F03028 (2012).
31. Dutta, K., Schuur, E. A. G., Neff, J. C. & Zimov, S. A. Potential carbon release from permafrost soils of Northeastern Siberia. *Glob. Change Biol.* **12,** 2336–2351 (2006).
32. Knoblauch, C., Beer, C., Sosnin, A., Wagner, D. & Pfeiffer, E.-M. Predicting long-term carbon mineralization and trace gas production from thawing permafrost of Northeast Siberia. *Glob. Change Biol.* **19,** 1160–1172 (2013).
33. Elberling, B. *et al.* Long-term CO_2 production following permafrost thaw. *Nature Clim. Change* **3,** 890–894 (2013).
34. Kirschbaum, M. U. F. Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry* **48,** 21–51 (2000).
35. Kätterer, T., Reichstein, M., Andren, O. & Lomander, A. Temperature dependence of organic matter decomposition: a critical review using literature data analyzed with different models. *Biol. Fertil. Soils* **27,** 258–262 (1998).
36. Schädel, C. *et al.* Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Glob. Change Biol.* **20,** 641–652 (2014).
    Synthesizes the decomposability of permafrost organic matter using incubation data and calculates potential carbon loss for high-latitude soils.
37. Treat, C. *et al.* A pan-Arctic synthesis of CH_4 and CO_2 production from anoxic soil incubations. *Glob. Change Biol.* doi:10.1111/gcb.12875 (in the press).
38. Myhre, G. *et al.* in *Climate Change 2013: The Physical Science Basis. Contributions of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*) 659–740 (Cambridge Univ. Press, 2013).
39. Verville, J. H., Hobbie, S. E., Iii, F. S. C. & Hooper, D. U. Response of tundra CH_4 and CO_2 flux to manipulation of temperature and vegetation. *Biogeochemistry* **41,** 215–235 (1998).
40. Olefeldt, D., Turetsky, M. R., Crill, P. M. & McGuire, A. D. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. *Glob. Change Biol.* **19,** 589–603 (2013).
    Synthesis of data on growing-season CH_4 emissions from terrestrial ecosystems across permafrost zones.
41. Treat, C. C. *et al.* Temperature and peat type control CO_2 and CH_4 production in Alaskan permafrost peats. *Glob. Change Biol.* **20,** 2674–2686 (2014).
42. Ström, L., Tagesson, T., Mastepanov, M. & Christensen, T. R. Presence of *Eriophorum scheuchzeri* enhances substrate availability and methane emission in an Arctic wetland. *Soil Biol. Biochem.* **45,** 61–70 (2012).
43. Lawrence, D. M., Slater, A. G., Romanovsky, V. E. & Nicolsky, D. J. Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *J. Geophys. Res. Earth Surf.* **113,** F02011 (2008).
44. Koven, C. D., Riley, W. J. & Stern, A. Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth system models. *J. Clim.* **26,** 1877–1900 (2013).
    Analysis of Earth system models projections of permafrost change in response to climate change scenarios.
45. Koven, C. D. *et al.* Permafrost carbon-climate feedbacks accelerate global warming. *Proc. Natl Acad. Sci. USA* **108,** 14769–14774 (2011).
46. Schaefer, K., Zhang, T., Bruhwiler, L. & Barrett, A. P. Amount and timing of permafrost carbon release in response to climate warming. *Tellus B* **63,** 165–180 (2011).
47. Schneider von Deimling, T. *et al.* Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences* **9,** 649–665 (2012).
48. MacDougall, A. H., Avis, C. A. & Weaver, A. J. Significant contribution to climate warming from the permafrost carbon feedback. *Nature Geosci.* **5,** 719–721 (2012).
49. Burke, E. J., Jones, C. D. & Koven, C. D. Estimating the permafrost-carbon climate response in the CMIP5 climate models using a simplified approach. *J. Clim.* **26,** 4897–4909 (2013).
50. Schaphoff, S. *et al.* Contribution of permafrost soils to the global carbon budget. *Environ. Res. Lett.* **8,** 014026 (2013).
51. Burke, E. J., Hartley, I. P. & Jones, C. D. Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere* **6,** 1063–1076 (2012).
52. Zhuang, Q. *et al.* CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophys. Res. Lett.* **33,** L17403 (2006).

53. Schuur, E. A. G., Abbott, B., &. the Permafrost Carbon Network. Climate change: high risk of permafrost thaw. *Nature* **480,** 32–33 (2011).
54. Schuur, E. A. G. *et al.* Expert assessment of vulnerability of permafrost carbon to climate change. *Clim. Change* **119,** 359–374 (2013).
State of knowledge on changes in permafrost distribution and soil organic carbon stocks in response to climate warming based on expert survey.
55. Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G. & Witt, R. The impact of the permafrost carbon feedback on global climate. *Environ. Res. Lett.* **9,** 085003 (2014).
56. Lawrence, D. M., Slater, A. G. & Swenson, S. C. Simulation of present-day and future permafrost and seasonally frozen ground conditions in CCSM4. *J. Clim.* **25,** 2207–2225 (2012).
57. Slater, A. G. & Lawrence, D. M. Diagnosing present and future permafrost from climate models. *J. Clim.* **26,** 5608–5623 (2013).
58. Shaver, G. R. *et al.* Global warming and terrestrial ecosystems: a conceptual framework for analysis. *Bioscience* **50,** 871–882 (2000).
59. Sistla, S. A. *et al.* Long-term warming restructures Arctic tundra without changing net soil carbon storage. *Nature* **497,** 615–618 (2013).
60. Qian, H., Joseph, R. & Zeng, N. Enhanced terrestrial carbon uptake in the northern high latitudes in the 21st century from the Coupled Carbon Cycle Climate Model Intercomparison Project model projections. *Glob. Change Biol.* **16,** 641–656 (2010).
61. Krieger, K. E. *The topographic form and evolution of thermal erosion features: A first analysis using airborne and ground-based LiDAR in Arctic Alaska*. MSc thesis, Idaho State Univ. (2012).
62. Jorgenson, M. T., Shur, Y. L. & Pullman, E. R. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophys. Res. Lett.* **33,** L02503 (2006).
63. Christensen, T. R. *et al.* Thawing sub-arctic permafrost: effects on vegetation and methane emissions. *Geophys. Res. Lett.* **31,** L04501 (2004).
64. Johansson, T. *et al.* Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing. *Glob. Change Biol.* **12,** 2352–2369 (2006).
65. Osterkamp, T. E. Characteristics of the recent warming of permafrost in Alaska. *J. Geophys. Res. Earth Surf.* **112,** F02S02 (2007).
66. Baltzer, J. L., Veness, T., Chasmer, L. E., Sniderhan, A. E. & Quinton, W. L. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. *Glob. Change Biol.* **20,** 824–834 (2014).
67. Raynolds, M. K. *et al.* Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. *Glob. Change Biol.* **20,** 1211–1224 (2014).
68. Jones, B. M. *et al.* Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *J. Geophys. Res. Biogeosci.* **116,** G00M03 (2011).
69. Smith, L. C., Sheng, Y., MacDonald, G. M. & Hinzman, L. D. Disappearing Arctic lakes. *Science* **308,** 1429 (2005).
70. Riordan, B., Verbyla, D. & McGuire, A. D. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *J. Geophys. Res. Biogeosci.* **111,** G04002 (2006).
71. Roach, J., Griffith, B., Verbyla, D. & Jones, J. Mechanisms influencing changes in lake area in Alaskan boreal forest. *Glob. Change Biol.* **17,** 2567–2583 (2011).
72. Sannel, A. B. K. & Kuhry, P. Warming-induced destabilization of peat plateau/thermokarst lake complexes. *J. Geophys. Res. Biogeosci.* **116,** G03035 (2011).
73. Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D. & Chapin, F. S. III. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* **443,** 71–75 (2006).
74. Jones, M. C., Grosse, G., Jones, B. M. & Walter Anthony, K. Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. *J. Geophys. Res.* **117,** G00M07 (2012).
75. Zona, D. *et al.* Increased CO$_2$ loss from vegetated drained lake tundra ecosystems due to flooding. *Glob. Biogeochem. Cycles* **26,** GB2004 (2012).
76. Olefeldt, D. & Roulet, N. T. Permafrost conditions in peatlands regulate magnitude, timing, and chemical composition of catchment dissolved organic carbon export. *Glob. Change Biol.* **20,** 3122–3136 (2014).
77. Feng, X. *et al.* Differential mobilization of terrestrial carbon pools in Eurasian Arctic river basins. *Proc. Natl Acad. Sci. USA* **110,** 14168–14173 (2013).
78. Vonk, J. E. & Gustafsson, O. Permafrost-carbon complexities. *Nature Geosci.* **6,** 675–676 (2013).
79. Vonk, J. E. *et al.* High biolability of ancient permafrost carbon upon thaw. *Geophys. Res. Lett.* **40,** 2689–2693 (2013).
80. Cory, R. M., Crump, B. C., Dobkowski, J. A. & Kling, G. W. Surface exposure to sunlight stimulates CO$_2$ release from permafrost soil carbon in the Arctic. *Proc. Natl Acad. Sci. USA* **110,** 3429–3434 (2013).
81. Vonk, J. E. *et al.* Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia. *Nature* **489,** 137–140 (2012).
82. Shakhova, N. *et al.* Geochemical and geophysical evidence of methane release over the East Siberian Arctic Shelf. *J. Geophys. Res. Oceans* **115,** C08007 (2010).
83. Shakhova, N. *et al.* Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. *Nature Geosci.* **7,** 64–70 (2014).
Quantitative assessment of bubble-induced CH$_4$ emissions resulting from subsea permafrost degradation in the coastal area.
84. Dmitrenko, I. A. *et al.* Recent changes in shelf hydrography in the Siberian Arctic: Potential for subsea permafrost instability. *J. Geophys. Res. Oceans* **116,** C10027 (2011).
85. Parmentier, F.-J. W. *et al.* The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. *Nature Clim. Change* **3,** 195–202 (2013).
86. Notz, D., Brovkin, V. & Heimann, M. Arctic: uncertainties in methane link. *Nature* **500,** 529–529 (2013).
87. Parmentier, F.-J. W. & Christensen, T. R. Arctic: speed of methane release. *Nature* **500,** 529–529 (2013).
88. Le Quéré, C. *et al.* Global carbon budget 2013. *Earth Syst. Sci. Data* **6,** 235–263 (2014).
89. Avis, C. A., Weaver, A. J. & Meissner, K. J. Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geosci.* **4,** 444–448 (2011).
90. Todd-Brown, K. E. O. *et al.* Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. *Biogeosciences* **10,** 1717–1736 (2013).
91. McGuire, A. D. *et al.* An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences* **9,** 3185–3204 (2012).
92. Belshe, E. F., Schuur, E. A. G. & Bolker, B. M. Tundra ecosystems observed to be CO$_2$ sources due to differential amplification of the carbon cycle. *Ecol. Lett.* **16,** 1307–1315 (2013).
93. Ueyama, M. *et al.* Upscaling terrestrial carbon dioxide fluxes in Alaska with satellite remote sensing and support vector regression. *J. Geophys. Res. Biogeosci.* **118,** 1266–1281 (2013).
94. National Research Council. *Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop* http://dels.nationalacademies.org/Report/Opportunities-Remote-Sensing/18711 (The National Academies Press, 2014).
95. Schaefer, K., Lantuit, H., Romanovsky, V. E. & Schuur, E. A. G. *Policy Implications of Warming Permafrost* (United Nations Environment Program, 2012).
96. Brown, J., Ferrians, O. J. J., Heginbottom, J. A. & Melnikov, E. S. *Circum-Arctic Map of Permafrost and Ground-Ice Conditions*. Version 2, http://nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/index.html (National Snow and Ice Data Center, 2002).
97. IPCC in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change* (eds Solomon, S. D. *et al.*) (Cambridge Univ. Press, 2007).

Acknowledgements Initial funding was provided by the National Science Foundation Vulnerability of Permafrost Carbon Research Coordination Network Grant number 955713, with continued support from the National Science Foundation Research, Synthesis, and Knowledge Transfer in a Changing Arctic: Science Support for the Study of Environmental Arctic Change Grant number 1331083. Author contributions were also supported by grants to individuals: Department of Energy Office of Science, Office of Biological and Environmental Sciences Division Terrestrial Ecosystem Sciences program (DE-SC0006982) to E.A.G.S.; National Science Foundation Long Term Ecological Research Program (1026415) to A.D.M.; Department of Energy (DE-AC02-05CH11231, NGEE Arctic, BGC-Feedbacks SFA) to C.D.K.; Regional and Global Climate Modeling Program (RGCM) of the US Department of Energy's Office of Science (BER) Cooperative Agreement (DE-FC02-97ER62402) to D.M.L.; European Research Commission (338335) to G.G.; The Netherlands Organization for Scientific Research (863.12.004) to J.E.V.; National Science Foundation Polar Programs (1312402) to S.M.N.; National Science Foundation Polar Programs (856864 and 1304271) to V.E.R.; National Oceanic and Atmospheric Administration (NA09OAR4310063) and National Aeronautics and Space Agency (NNX10AR63G) to K.S.; Nordforsk (DEFROST; 23001), EU FP7 (PAGE21; 282700) and FORMAS (Bolin Climate Research Centre; 214-2006-1749) to G.H. and P.K.; Department of Energy Biological and Environmental Research (3ERKP818) to D.J.H.; National Science Foundation, Division of Environmental Biology (724514, 830997) to M.R.T. and A.D.M.; U.S. Geological Survey Climate and Land Use Program to J.W.H. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Author Contributions This manuscript arose from the collective effort of the Permafrost Carbon Network (http://www.permafrostcarbon.org); all authors are working group leaders within the network. E.A.G.S. and A.D.M. wrote the initial draft, with additional contributions from all authors. C.S. provided assistance with final editing and submission of the manuscript, and helped to organise the Permafrost Carbon Network activities that made this possible. Figure 1 was prepared by G.H., Fig. 2 by C.S., Fig. 3 by K.S., Fig. 4 by G.G. and the Box 1 Figure by E.A.G.S.

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