and set their marine communities up for a persistent collapse. Furthermore, to some species, changes in feeding interactions may mean a shift to less energy-rich prey. If the energy received from prey decreases, many species will experience a decline in body condition. With these examples, Griffith and colleagues warn that the detected resilience of Arctic food webs could be short-lived.

This work[1] provides another piece of the puzzle in the quest to understand Arctic resilience to climate change[3,7]. By providing a warning that the detected food web resilience may be eroded by other Arctic changes, the results emphasize that complexity of the Arctic makes it challenging to forecast change. To a large part, the resilience of the Arctic as a region will depend on how climate effects and adaptations at different scales interact and affect each other: species, ecological communities, physical environment, local societies and global human community. At best, more adaptive Arctic systems can strengthen the resilience of less adaptive parts of the region. For example, local people can take additional pressure off species that are highly affected by climate change with rotational switching of resource use, if supported by regional and global policies[8]. On the other hand, climate responses may form reinforcing feedbacks that decrease the overall Arctic resilience: environmental degradation (such as weak sea ice) can reduce the ability of young people to learn local skills for living sustainably in the Arctic environment, or to perceive the need for climate mitigation[8].

Understanding Arctic resilience to climate change requires multiple perspectives and research methods. Incorporating the findings of Griffith and colleagues[1] into the wider literature, and continuing to investigate changes in Arctic marine food webs[2–4], will provide much-needed lessons in how to strengthen Arctic resilience and, in so doing, strengthen planetary resilience to climate change[7,9]. ❒

Johanna Yletyinen
Manaaki Whenua Landcare Research, Lincoln, New Zealand.
e-mail: yletyinenj@landcareresearch.co.nz

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BIOGEOCHEMISTRY

Arctic loses carbon as winters wane

Warming in the Arctic is causing soils to decompose more rapidly, even during winter. Now, estimates of winter carbon dioxide loss indicate that it can offset carbon gains during the growing season, meaning that the region is a source of carbon.

John L. Campbell

The pan-Arctic permafrost region is one of the most difficult places on Earth to do fieldwork. The area is remote, and the environment is harsh, particularly in winter when it is enshrouded in darkness and temperatures are at their coldest. Despite these challenges, data from this region are crucially important for understanding climate change impacts because warmer air temperatures are causing permafrost (the layer of ground frozen year-round) to thaw, resulting in the release of CO_2 to the atmosphere[1]. Determining the amount of CO_2 emitted to the atmosphere has been difficult, because of a lack of data, especially during winter. However, measurements of CO_2 are increasingly being made throughout the year. Writing in *Nature Climate Change*, Susan Natali and colleagues[2] present an analysis of CO_2 data from the northern circumpolar permafrost region and show that the flux during winter is larger than previously thought, changing our understanding of the Arctic carbon balance.

Fig. 1 | A flux tower on the North Slope of Alaska. The sensor has an on-demand heating system so that gas exchange between the ecosystem and atmosphere can be measured throughout the year[9]. Credit: Salvatore Losacco

Air temperatures are warming faster in the Arctic than anywhere else in the world[3]. This amplified warming has been attributed to several factors, including an increase in the amount of heat transported from the Equator poleward and a decline in reflectance due to melting snow and sea ice, causing more heat to be absorbed[4]. Arctic soils store vast amounts of carbon, much of which is non-reactive because it is locked in a layer of permafrost[5]. However, rapid warming in the Arctic is causing permafrost to thaw, exposing the long-buried carbon[6]. Microbes in the soil decompose the newly exposed organic matter and produce CO_2 in the process. Because CO_2 is a greenhouse gas, if more is emitted to the atmosphere through permafrost thaw, it creates a feedback that accelerates warming[6].

Carbon decomposition can occur in cold soils, even at temperatures well below freezing, as long as there are unfrozen microsites that contain carbon and water available to microbes[7]. Consequently, microbes continue to metabolize carbon throughout the winter; however, there is much uncertainty about how much CO_2 is lost from the Arctic permafrost region during winter and how it will change in the future. This uncertainty stems from a lack of field data due to difficulties in measuring CO_2 flux during winter and poor spatial coverage because of access challenges in this remote region. Field measurements are the most direct method for quantifying CO_2 flux and can be combined with other types of data, such as observations from satellites, to scale values up from individual sites to broader regions. Field data are also essential for developing and benchmarking the simulation models used to predict current patterns and future change.

The Arctic is increasingly recognized as a vital link in the global carbon cycle, and CO_2 flux from permafrost sites is being tracked more closely as methods and equipment improve (see Fig. 1) and monitoring networks expand. Natali et al.[2] compiled winter CO_2 flux data collected from more than 100 sites in the pan-Arctic permafrost region and evaluated factors that influence carbon degradation in the winter. They identified important environmental and ecological controls on winter CO_2 production (such as air temperature, soil temperature, soil moisture and vegetation type) from weather maps and data obtained from satellites. This information was then used to estimate how much CO_2 is emitted annually from the entire Arctic permafrost region.

The contemporary winter CO_2 loss of 1,662 TgC that Natali and colleagues[2] report is higher than previously published values. This new estimate is noteworthy because it exceeds the estimated 1,032 TgC taken up by vegetation during the growing season, suggesting that the region is a source of carbon to the atmosphere and therefore contributes to further warming. To take this a step further, the authors used a model to simulate how winter CO_2 emissions in this region might change in the future. Their analyses reveal that carbon loss during winter could increase by as much as 41% by the end of the century under the most extreme climate change scenario, and by 17% under a more moderate scenario that includes mitigation strategies.

Although the new estimate of winter CO_2 loss from the Arctic permafrost region is based on the best available data, the uncertainty in the value is large (813 TgC). Part of this uncertainty is due to the variety of methods used to measure CO_2 and could be improved by standardizing protocols. Increasing the spatial coverage and density of sites where CO_2 is measured year-round would also reduce the uncertainty, as would improvements to the remote sensing data used to model emissions across the region. Despite the uncertainty in the estimate, high winter CO_2 losses from Arctic permafrost have important implications for the carbon balance. Recently, there has been much emphasis on 'Arctic greening' — warming-induced increases in vegetation that enhance carbon uptake[8]. Results from the study by Natali and colleagues suggest that increases in the vegetation carbon sink could be offset by higher losses of CO_2 during winter.

Quantifying CO_2 emissions from the Arctic permafrost region is essential for evaluating climate feedbacks that influence the magnitude of future warming. Winter is often considered a period of dormancy with little biological activity, so the large loss of CO_2 reported by Natali and colleagues[2] during this season is surprising and alarming, given that CO_2 emissions are expected to increase as temperatures continue to rise. Although it is challenging to measure winter CO_2 flux, these data are key to understanding the impacts of the dramatic changes that are occurring in this rugged, yet remarkably vulnerable landscape. ❐

John L. Campbell
USDA Forest Service, Durham, NH, USA.
e-mail: john.campbell2@usda.gov

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ARCTIC HYDROLOGY

Engineering challenges of warming

Observations reveal recent Arctic warming, but future societal impacts are poorly understood. Now research identifies potential abrupt thaw-driven soil moisture shifts, with consequences for northern development including more intense wildfires and rainfall.

Barret L. Kurylyk

In Arctic landscapes, ground temperatures control water flow and storage because frozen ground is relatively impermeable. Subsurface water flow in cold regions is predominantly restricted to a seasonally thawed zone that maintains wet shallow soil conditions[1]. In contrast, in warmer sub-Arctic regions, the deeper summer thawed zone allows for a deeper water table and drier near-surface soils. Hydrologists studying northern water resources must therefore consider how climate change will affect subsurface temperatures and water flowpaths. Writing in *Nature Climate Change*, Bernardo Teufel and Laxmi Sushama[2] show that Arctic permafrost thaw may lead to a rapid transition between regimes with shallow or deep thawed zones (Fig. 1), drying soils and causing cascading environmental impacts.

Permafrost (ground that remains below 0 °C for at least 2 years) does not reach the land surface, because shallow soil warms above 0 °C in the summer. This shallow zone, known as the active layer, experiences seasonal freezing and thawing and separates the permafrost table from the land surface (Fig. 1). Darcy's Law, the foundation of hydrogeology, states that groundwater flow is proportional to the hydraulic conductivity, a measure of permeability. When the active layer thaws in the summer, its hydraulic conductivity can increase by up to 10 million times[3], opening subsurface flow pathways that remain closed in the winter.

Multidecadal hydrological changes are superimposed on these seasonal changes. As the climate warms, permafrost responds by first warming to the freezing temperature