PACIFIC CLIMATE IMPACTS CONSORTIUM

PCIC SCIENCE BRIEF: ON THE LOSS OF CO_2 IN THE WINTER OBSERVED ACROSS THE NORTHERN PERMAFROST REGION

As the Arctic warms, the rate at which microbes in Arctic soil digest soil organic matter increases and, with it, the release of carbon dioxide into the atmosphere also increases. The amount of carbon released into the atmosphere from permafrost in this region is significant and so it is important to measure it accurately and be able to make credible projections of it.

Publishing in *Nature Climate Change*, Natali et al. (2019) use observations of CO_2 flux from Arctic and Boreal permafrost soil to create a model that allows them to estimate winter (October through the end of April) soil carbon flux over the 2003-2017 period. They also drive their model with global climate model output, to make projections of future CO_2 flux in the region. They estimate that approximately 1.7 gigatonnes of carbon (GtC) were released each winter over the 2003-2017 period. The authors also find that, of the variables that they tested, soil temperature had the largest relative influence on CO_2 flux. Their projections show future winter Arctic soil fluxes of about 2.0 GtC per year by 2100, for a moderate emissions scenario, and about 2.3 GtC per year, assuming a high-emissions scenario.

Introduction

Arctic soil is home to a highly diverse range of microbial communities[1]. The bacteria that make up these communities play a number of roles in nutrient cycling, such as drawing down and fixing nitrogen into the soil. They also produce and release greenhouse gases such as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) into the atmosphere as they decompose organic matter in the soil. As climate change causes soil in the Arctic to warm, the decomposition of organic matter by microbes living in that soil increases.

Measuring the release of CO_2 from Arctic soil is challenging because of the limited amount of data and the limitations of current ecosystem models. There is a lack of satellite and airborne data for the winter and the spatial coverage of Arctic air monitoring stations is sparse. In order to estimate the winter (October to April) flux of CO_2 from Arctic soil, Natali and coauthors turn to in situ measurements of carbon dioxide flux from 104 sites in the Arctic and use these to train a machine learning model.

The authors then use output from a set of global climate models (GCMs) to create future projections of winter CO_2 emissions from Arctic soil.

Winter CO_2 Flux and Arctic Soil

Bacteria and fungi in Arctic soil break down large biomolecules containing carbon and, through a complex set of interactions between organisms, release greenhouse gases, such as CO_2 into the atmosphere. (The actions of these organisms also serve to fix carbon into the soil in various compounds, fix and release nitrogen, and release other compounds into the soil, containing elements such as iron and manganese.)

Observed warming in the Arctic has been of roughly twice the magnitude of the global average, a phenomenon known as polar amplification[2]. This warming is greatest in the autumn and winter months and allows for greater de-

1. The picture presented here is a simple one, but these communities are complex, as are the interactions between the microorganisms that they contain. For instance, some microorganisms produce methane while others utilize methane as a source of carbon. The abundance, diversity and distribution of Arctic microbes vary greatly over distance and are sensitive to a variety of factors, from vegetation to soil acidity. For an overview, see Malard and Pearce (2018) and Kwon et al. (2019).
2. This phenomenon has several causes. One of the main factors is that warming causes the loss of sea ice and, because open ocean reflects less light than sea ice, the ocean can absorb more radiation when the ice melts—this, in turn, causes further warming. A variety of other mechanisms have been proposed, including increasing water vapour and cloud cover in the Arctic, reduced air pollution in the region and changes to the overall rate of temperature change with height (termed the "lapse rate") in the atmosphere.
3. Though warmer temperatures see an increase in such decomposition, it is important to note that some amount of decomposition occurs even at very low temperatures, down to about -20 °C, because tiny regions of soil, called microsites, remain unfrozen at these temperatures, allowing microorganisms to continue their metabolic processes.

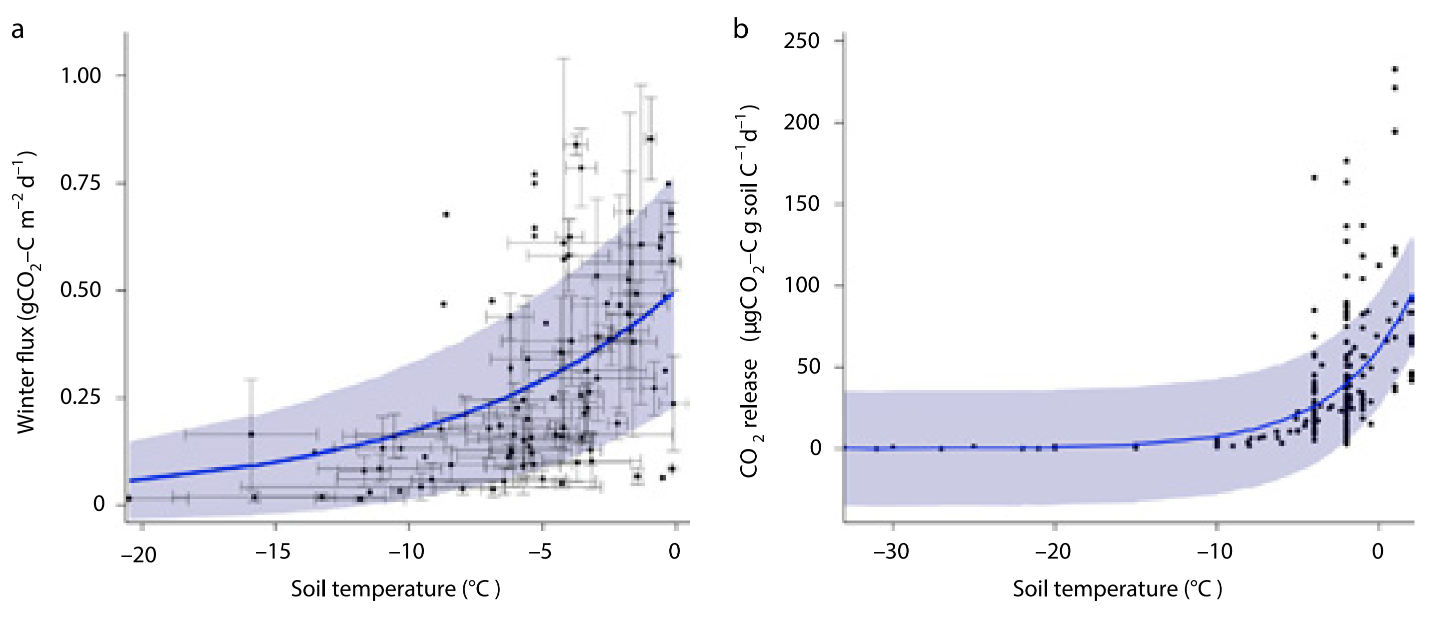

Figure 1: CO_2 Flux From Soil Versus Soil Temperature (from Natali et al., 2019).
This figure shows the relationship between (a) field measurements of winter CO_2 flux and soil temperature (here taken at an average depth of 10 centimetres) and (b) CO_2 released from soils in laboratories and soil temperature. Shading indicates the standard deviation of an exponential model that was fit to CO_2 flux.

composition[3] of organic matter in soils by the microorganisms that live in them.

Observations of airborne carbon dioxide data and carbon dioxide flux are relatively sparse for the Arctic in the winter. While satellite measurements are available from a pair of satellites Greenhouse Gases Observing Satellite[4] (GOSAT) and GOSAT2, these data only go back to 2009. There is also a global network of micrometeorological tower sites known as FLUXNET that measure carbon dioxide flux, but their coverage is sparse in the highest latitude regions.

Estimating Historical Arctic Winter Soil CO_2 Flux

In order to estimate the influence of temperature on the flux of CO_2 in the Arctic during the winter, Natali and coauthors use earlier studies and some unpublished data from the Permafrost Carbon Network, which were made up of direct measurements of CO_2 flux using a variety of methods[6]. These data comprised over 1000 aggregated monthly fluxes that were taken from 104 sites. They also use station measurements of air temperature and precipitation, reanalysis[7] data for air and soil temperature and field measurements of soil carbon[8]. The authors use satellite measurements of the soil moisture, vegetation cover, soil surface litter, and snow cover[8].

The authors use these data to train a machine-learning model[9] that they employ to estimate the influence of each input on Arctic winter CO_2 flux from soil and to make projections of how this flux could change under two future emissions scenarios, using GCM projections of future conditions in the area.

4. For more information on GOSAT and GOSAT2, including some data products, see the project's website: http://www.gosat.nies.go.jp/en/.
5. More information on FLUXNET, including publications and data products, can be found on the project's website: https://fluxnet.fluxdata.org/about/.
6. Several different types of measurements were used by the authors. Some of these were made by placing a chamber on the soil (either on top of the snowpack, or on the soil directly, in some cases prior to snowfall or by digging a pit through accumulated snow) and directly measuring changes in the gas concentration in the chamber, or by placing soda lime in the chamber and measuring the amount of carbon dioxide deposited onto the soda lime. Others were made by measuring gas concentrations in the snow pack or in the air above the snowpack (taking into account the effects of small-scale air circulation).
7. A reanalysis is a representation of the historical climate that is created from historical observations that are "assimilated" into a global weather forecast model that is run in a hindcast mode. The authors specifically use the National Aeronautics and Space Administration's Modern-Era Retrospective Analysis for Research Applications, version 2 (MERRA-2). For more information on MERRA-2, see the project's website: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/.
8. For more information on the various datasets used by the authors, see the supplemental material to their paper, Natali et al. (2019).

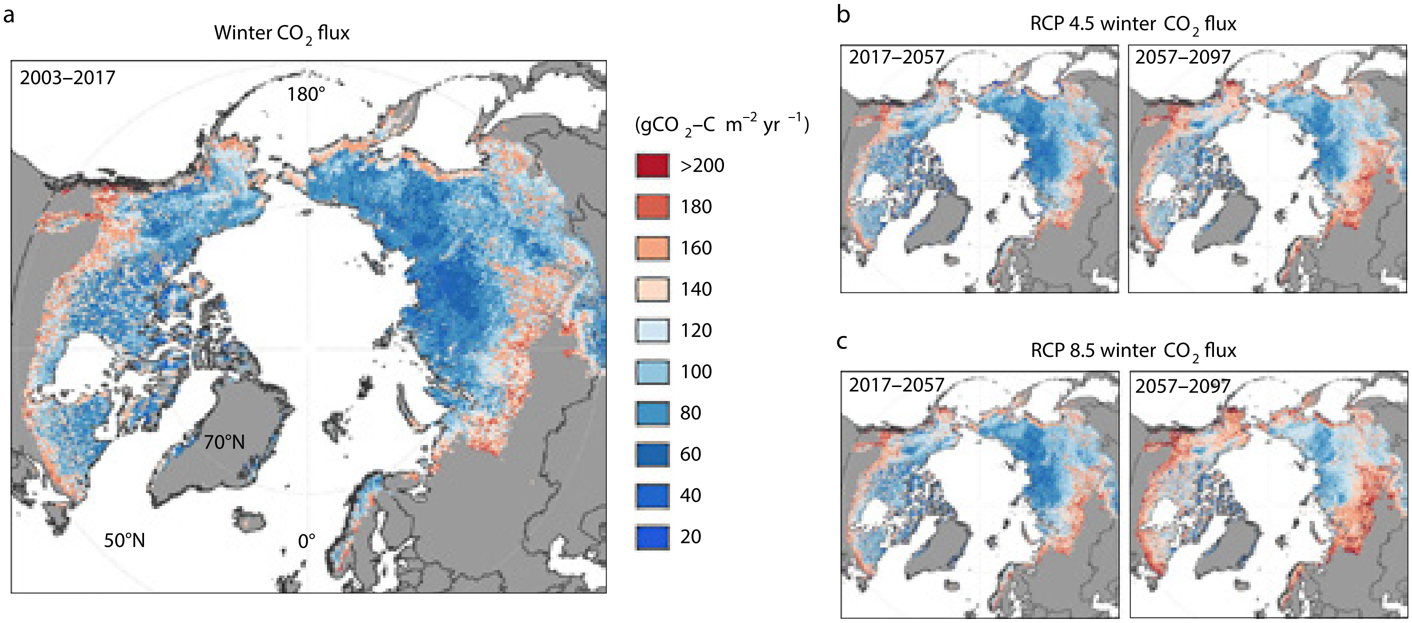

Figure 2: Observed and Projected Arctic Winter Soil Fluxes (adapted from Natali et al., 2019).
This figure shows (a) the observed annual average winter CO_2 flux over the 2003-2017 period, and the projected winter CO_2 fluxes for (b) RCP4.5 and (c) RCP8.5 (time periods as marked in panels and reported on an annual basis).

Natali and coauthors estimate the relative influence[10] that various factors had on Arctic winter (here October to April) CO_2 flux over the 2003-2017 period and find that air and soil temperature had the largest relative influence, at 32% (Figure 1), followed by vegetation type (15%), summer leaf area index (11%), tree cover (10%) and the amount of carbon drawn down into the ecosystem through photosynthesis in the previous year (termed, "gross primary productivity," 8.5%). The authors note that soil type was another important factor, because fine soils contain more unfrozen water than coarse soils, allowing more respiration to occur.

In addition to estimating the relative influence of various factors on Arctic winter CO_2 flux, Natali et al. also come up with an estimate of the flux itself over this period. They find that the northern permafrost region has released about 1,700 teragrams (Tg, this means 10^{12} grams; 1,700 Tg is equivalent to 1.7 gigatonnes) of carbon[11] into the atmosphere each winter. The authors note that their results are larger than an earlier in situ estimate made for a sub-region within the Arctic permafrost region. Whereas the earlier estimate found a winter soil flux of between about 24 and 41 grams of carbon per square metre (gCm^{-2}), Natali and coauthors arrive at an estimate of about 64 gCm^{-2} for this sub-region (and about 94 gCm^{-2} for the overall Arctic permafrost domain, see Figure 2a). They note that their measurements are in better agreement with an atmospheric inversion[12] estimate for the same sub-region, that finds a winter flux of between 27 and 81 gCm^{-2}.

9. Natali and coauthors use a boosted regression tree model. Regression trees are a way of modelling non-linear mathematical relationships between elements within a dataset. Regression trees are especially useful for datasets in which the data tends to cluster. Boosting techniques make weighted combinations of multiple models of varying quality and then evaluate the results, iteratively adjusting the weighting or "say" of the simple models in the output, until a final, satisfactory composite model is made that optimally combines the simpler models in order to make predictions from new data. For more on regression trees, see Breiman et al. (1984). For more on boosted regression trees in the context of statistical modelling, see Friedman, Hastie and Tibshirani (2000).
10. Relative influence has a specific meaning in the context of boosted regression trees. Relative influence is a measure of the contribution of a particular variable in improving the model's ability to predict a given outcome.
11. It is important to distinguish between grams of carbon and grams of carbon dioxide. The authors provide their results in grams of carbon. Because the atomic mass number of carbon is 12 (for the 6 protons and 6 neutrons that make it up) and the atomic mass number of CO_2 is 44, to determine how much carbon is in a given mass of carbon dioxide, one can multiply by 12/44 (about 0.27). Similarly, to determine the mass of carbon dioxide released for a given mass of carbon, one can multiply by 44/12 (about 3.7). So, a gigatonne of carbon released in molecules of CO_2 would mean a release of about 3.7 gigatonnes of CO_2.
12. Atmospheric inversion estimates use a knowledge of where sources and sinks of gasses are, along with observations of atmospheric concentrations of gases and an atmospheric model, in order to determine the surface-to-atmosphere flux of the gases.

Natali et al. then compare their estimate of winter CO_2 flux with those from five process-based models and one machine learning model[13], for the whole permafrost region. The flux that the authors estimated, about 1,700 Tg, is larger than the estimates from any of the models that the authors examine. These ranged from 380 Tg for another machine learning model to between 500 Tg and 1,300 Tg for the process-based models. The authors explain that the wide variation in estimates from the models they considered could arise from how the models treat soil temperature, unfrozen water and substrate effects[14] on CO_2 production.

Future Projections of Arctic Winter Soil CO_2 Flux

The authors then develop projections of future Arctic winter CO_2 flux by driving their machine learning model with output from 15 GCMs participating in the fifth phase of the Coupled Model Intercomparison Project[15] (CMIP5). The climate models were driven using two different emissions scenarios[16], one that leads to approximately a doubling of the preindustrial concentration of carbon dioxide in the atmosphere by 2100 (RCP4.5) and one that is more emissions intensive, leading approximately to a quadrupling (RCP8.5).

The authors' projections show an increase in Arctic winter CO_2 flux under both scenarios (Figures 2, panels b and c, and Figure 3), with a larger increase under the higher emissions scenario. For RCP 4.5, soil temperatures increase by 0.04 °C per year and the flux increases 17%, to about 2,000 Tg of carbon per year ($TgCyr^{-1}$), by 2100. This results in a cumulative flux of 150 petagrams of carbon (Pg, this means 1015 grams and 150 Pg is equivalent to 150 gigatonnes), which is 15 Pg more carbon emitted due to the increased forcing than would be emitted up to the year 2100 if emissions remained constant at their current (2003-2017 average) level. For RCP 8.5, soil temperatures increase by 0.08 °C per year and the flux increases 41%, to about 2,400 $TgCyr^{-1}$, by 2100. The cumulative Arctic winter carbon flux for RCP 8.5 is 162 Pg, which is 27 Pg more carbon emitted due to the increased forcing than would be emitted up to the year 2100 if emissions remained constant at their current level.

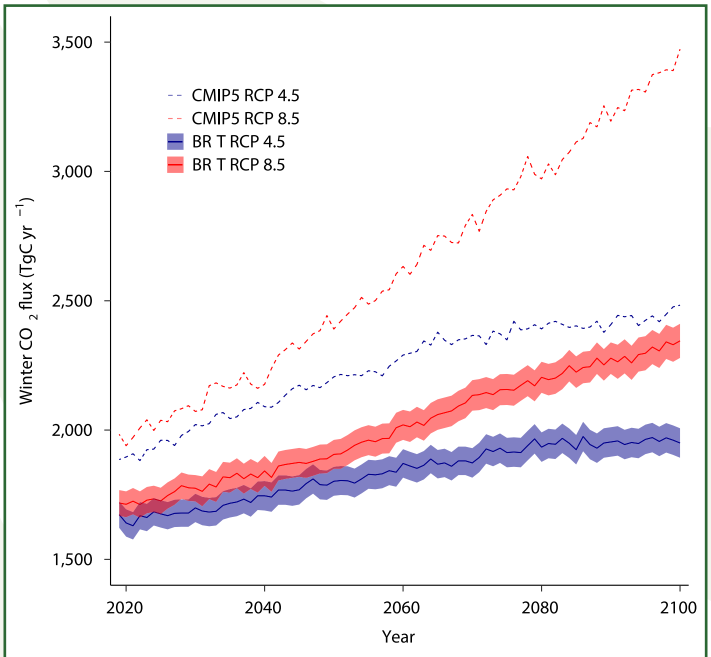

Figure 3: Projected Winter CO2 Flux (from Natali et al., 2019).
This figure shows the winter soil CO_2 flux from Natali et al.'s boosted regression tree model (solid lines) and the CO_2 emissions from respiration in the soil from the CMIP5 model ensemble mean (dashed lines). Red lines indicate projections for RCP8.5 and blue lines indicate projections for RCP4.5. Shading indicates 95% confidence intervals.

The authors note that the losses that these emissions represent are comparable in size to 70% of the carbon stored in the current near-surface (top 30 centimetres of the) permafrost layer. The authors also find that the leaf area index and amount of carbon dioxide that plants draw down during photosynthesis increases over the whole period.

The GCMs that Natali and coauthors use also internally simulate soil carbon fluxes. The authors take advantage of this to compare their findings to the carbon fluxes that the GCMs simulate. They find that, while the estimates from their machine learning model fall within the ranges of out-

13. Process-based models work directly from the basic physical equations (and simplified forms of these equations) that are thought to govern physical systems and create their simulations through calculating the answers to these equations. Machine learning is a method of developing models that recognize patterns and relationships in data without the models being explicitly programmed to do so. For a list of the models used by the authors, see the supplementary material for Natali at al. (2019).
14. The substrate here is the soil that the microbial communities live in. Because these microbes live in a network of pores in the soil, dependent upon the available material that surrounds them, including organic matter and minerals, substrate changes can effect the composition of the microbial community and the rate of decomposition in the soil.
15. For more information on CMIP5, see Taylor et al., 2012.
16. The IPCC used four trajectories of atmospheric greenhouse gas concentration, known as Representative Concentration Pathways (RCPs), for its Fifth Assessment Report. The four trajectories are denoted the radiative forcings that would result from each concentration, e.g. RCP 2.6 would result in warming effect of 2.6 Watts per square meter as compared to the preindustrial period (taken to be the year 1750). For more information on the RCPs, see: van Vuuren et al. (2011).

put from the GCMs, their estimates are somewhat smaller than the average fluxes from the GCMs. This is true over the historical period and for the future projections (Figure 3). As a starting point for comparison, Natali et al. arrived at an estimate of Arctic winter soil carbon flux of about 1,700 TgCyr-1 over the 2003-2017 period. The GCMs provide a result of about 1,700 ± 1,000 TgCyr-1 over the 2003-2005 period. By 2100, the GCMs show emissions of about 2,500 ± 1,400 TgCyr-1 for RCP 4.5 (versus Natali et al.'s estimate of about 2,000 TgCyr-1) and roughly 3,500 ± 1,700 TgCyr-1 for RCP 8.5 (versus Natali et al.'s estimate of about 2,300 TgCyr-1), increases of 37% and 86%, respectively.

The authors speculate that, on the one hand, their estimates may be lower than those from the GCMs because their model was trained on current soil flux observations, and so may be missing important aspects of the future environmental response to the changing climate. On the other hand, they suggest that the GCMs may be simulating too large of a flux because they do not capture negative feedbacks that would temper their soil carbon fluxes. The authors call for greater long-term monitoring of winter fluxes in the region and emphasize the importance of working to reduce uncertainties in the process-based models' representations of growing season and winter CO_2 exchange.

The authors note that some of the projected increase in Arctic winter soil CO_2 flux could be offset by plants drawing down more CO_2 as they respond to increasing atmospheric concentrations of the gas. They also point out that their results do not account for: carbon drawn down during the early and late winter periods; changes to fire frequency; changes in the distribution of snow and permafrost; or hydrologic changes, such as the draining of lakes. The authors also make clear that, while the work in their paper is focused on soil CO_2 flux, this is only part of the picture of greenhouse gas fluxes in the region; emissions of CH_4 from land and emissions of CO_2 and CH_4 from inland waters are important parts of the regional carbon budget. Finally, the authors stress that, while CO_2 fluxes in the region are likely to increase, this can be mitigated by a reduction in anthropogenic greenhouse gas emissions.

Summary

The authors used measurements of CO_2 flux from Arctic and boreal permafrost soil to develop a model to estimate the total winter (October through the end of April) soil carbon flux in the region over the 2003-2017 period. They then use their model, along with GCM output, to make projections of future CO_2 flux in the region under two emissions scenarios, RCP 4.5 and RCP 8.5.

They estimate that approximately 1.7 gigatonnes of carbon (GtC) were released each winter over the 2003-2017 period. The authors find that, of the variables that they tested, soil temperature had the largest influence on CO2 flux. They estimate future fluxes by 2100 of about 2.0 GtC each winter, for RCP 4.5, and about 2.3 GtC for RCP 8.5. They also find that these figures are somewhat lower than the equivalent fluxes taken straight from the climate models for the same emissions scenarios.

While there is some permafrost in Northeastern British Columbia, the findings of Natali et al. are primarily relevant for BC insofar as their results improve our understanding of the effects of different factors on Arctic winter CO_2 flux and can be used to improve GCM projections.

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