PLOS CLIMATE

OPINION

Bridging gaps in permafrost-shrub understanding

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OPEN ACCESS

Citation: Wilcox EJ, Bennett KE, Boike J (2024) Bridging gaps in permafrost-shrub understanding. PLOS Clim 3(3): e0000360. https://doi.org/10.1371/journal.pclm.0000360

Editor: Jamie Males, PLOS Climate, UNITED KINGDOM

Published: March 11, 2024

Funding: The authors received no specific funding for this work. This work is a contribution to the Cluster of Excellence 'CLICCS - Climate, Climatic Change, and Society', contributing to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg (EJW). Contributions to this work from KEB was supported by the Next Generation Ecosystem Experiment (NGEE) Arctic project, funded by the Office of Biological and Environmental Research in the U.S. Department of Energy's Office of Science. Funding for JB was provided within the German Federal Ministry of Education and Research project MOMENT (BMBF # 03F0931B). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Permafrost, permanently frozen ground which underlies much of the Arctic and sub-Arctic, is influenced by deciduous shrubs, yet our understanding of permafrost-shrub interactions is limited. This is largely due to a lack of widespread, long-term, high-quality observations across Arctic and sub-Arctic systems, which are difficult to study due to their remote locations. Shrubs are rapidly expanding in many areas of Arctic tundra and can either amplify or inhibit permafrost thaw [1,2], making it crucial that we can understand and predict permafrost-shrub interactions. As we have limited time and resources to make observations, we must design our field campaigns to be as impactful as possible. Below we outline the current state of knowledge and give suggestions about how we can maximize our fieldwork's impact.

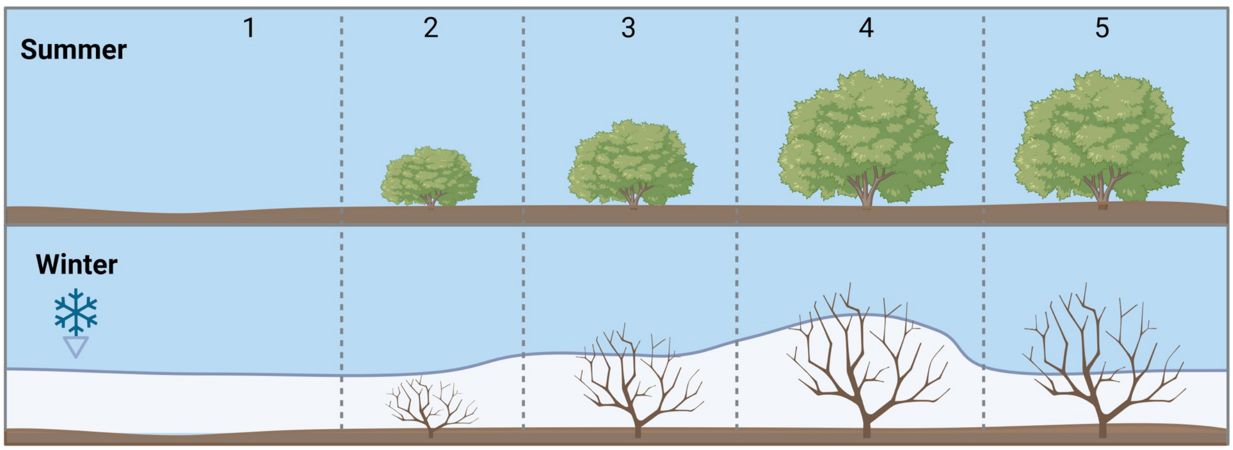
From field studies conducted around the Arctic, we know that shrubs generally have a cooling effect on permafrost in the summer, largely caused by the shrub canopy shading the soil. However, summertime cooling can be counteracted by a warming effect in winter, caused by the trapping of blowing snow by shrubs, which leads to increased snow depths [3]. In addition to these commonly observed effects, both observations and models [4] show that other local factors such as climate, soil, snow, and disturbances can interact to cause *contrasting* dominant effects on permafrost temperatures. For example, shrubs that protrude through the snowpack have been observed to cool permafrost in winter via thermal bridging between the air above the snow and the soil below [5]. However, at other research sites, protruding shrubs lower the surface albedo and cause earlier snowmelt in spring, amplifying permafrost thaw by exposing the soil to thawing earlier [2]. Protruding shrubs have also been observed to induce snow melt in autumn, creating ice layers at the snow surface that prevent further snow accumulation and eliminate the ability of shrubs to trap blowing snow, thereby reducing the winter warming effect [6]. While we understand the physical processes that lead to these effects, we cannot explain why we observe different effects between sites.

By synthesizing literature of past field studies, researchers have been able to qualitatively compare the dominant effects shrubs can have on permafrost conditions, generating diagrams that illustrate the interactions between shrubs, permafrost and other environmental components [3,7]. As we continue to discover dominant effects between shrubs and permafrost, we should design our field measurements not only with the intent to *describe* how shrubs and permafrost interact, but also with the goal that our measurements generate knowledge that can be used to *quantify* and *predict* how shrubs are influencing permafrost, using shrub properties and other local factors we have found to be important.

Competing interests: The authors have declared that no competing interests exist.

First, we should collect our data in as standardized a way as possible, while ensuring we collect data about all the variables we know can influence permafrost. A protocol for monitoring permafrost thaw created by Boike et al. [8] is accessible for non-experts while also providing an opportunity to contribute data to an open archive. We also need to integrate ecological and geophysical investigations (which are often completed independently) so we can link the physical properties of shrubs (e.g. leaf area index, stem density, spatial variability) to their influence on permafrost. While we have observed many different ways that shrubs can influence permafrost, we know little about how changes to the properties of shrubs alter their effect on permafrost. The integrated approach described above will not only help us to better quantify shrub-permafrost interactions via more powerful statistical analyses, but will also help those seeking to understand the dynamics of shrub expansion, which is affected by abiotic variables linked to permafrost (e.g. soil temperature, soil moisture).

We can also increase the impact of our fieldwork by coordinating with those who are developing models, so we may collect our data in a way that aids them; field data that are necessary



Stage	1	2	3	4	5
Soil shading	N/A	+	++	+++	+++
Snow depth enhancement	N/A	N/A	N/A	+++	N/A
Snowmelt advancement	N/A	?	+	–	?

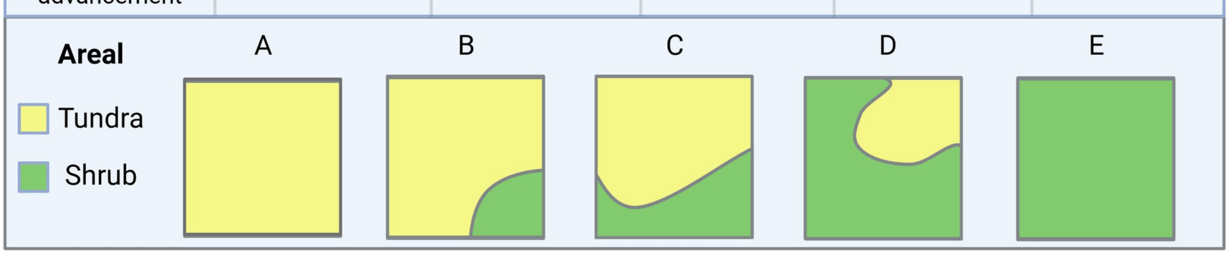


Fig 1. Five stages of shrub expansion at which different shrub-permafrost interactions become "activated", with the presence and relative magnitude of the effect outlined for each stage. The bottom of the figure characterises the areal expansion of shrubs, which can occur independently of the vertical expansion of shrubs. Stages 1–4 represent the effects of purely vertical shrub expansion, while Stage 5 is caused by the areal expansion of tall shrubs to a degree that snow redistribution by wind is impeded. This framework can help us categorize the changing presence and magnitude of shrub-permafrost effects, and can help us explain the complex effects of shrubs on permafrost that we have observed. Figure designed by Lauren Thomas.

https://doi.org/10.1371/journal.pclm.0000360.g001

for using or developing models may not be useful or apparent to collect for field-based studies. Currently, earth system models (ESMs) operating at the global scale only offer one type of shrub-tundra, with only one exception [9]. We must represent shrub-permafrost interactions within ESMs, given the large number of different shrub-affected processes that can combine to either amplify or hinder permafrost thaw, and given that permafrost thaw and shrub expansion can lead to feedback loops which sustain one another. Beyond ESMs, there are other techniques for combining models, field data and remote sensing data to estimate how shrubs affect permafrost conditions at much higher resolutions than are possible with ESMs (e.g. n-factors, [10]). When we link shrub properties to their effects on permafrost, we are also challenged with ensuring these properties can be estimated at a pan-Arctic scale. It is therefore necessary we are able to measure shrub properties relevant for permafrost thaw using scaling methods, such as remote sensing tools.

A framework that categorizes sites based on the presence and absence of different shrub-permafrost effects would also be beneficial. One can already hypothesize that shrubs which are not tall enough to trap snow may cool permafrost without a winter warming effect, as observed by Blok et al. [1]. But what happens once these shrubs grow tall enough to protrude through the snowpack–could shrubs then amplify permafrost thaw, as observed by Wilcox et al. [2]? Here we propose a framework that categorizes landscapes based on the presence or absence of three dominant effects of shrubs on permafrost: soil shading, snow trapping, and snow melt timing (Fig 1). The advantage of this framework is that it is easy to identify and quantify these categories in the field by simply observing the spatial patterns of snow depth and shrub heights present.

With these approaches, we can expedite the transfer of knowledge gained from fieldwork to systems used to predict how and where shrubs are altering permafrost thaw. It is time we move towards the more integrated, multi-expert, and communal approaches we describe, so we can reach our goal of predicting the influence of shrubs on permafrost via measurable properties.

Acknowledgments

We would like to thank the countless colleagues we have engaged with throughout our careers that have helped us to form the ideas we outline in this piece.

Author Contributions

Conceptualization: Evan J. Wilcox, Katrina E. Bennett, Julia Boike.

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