Improving permafrost thaw detection in Canada using multiple boreholes and temperature-derived metrics

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Permafrost monitoring

Permafrost temperature is one of three metrics used to monitor the **essential climate variable permafrost** by the Global Climate Observing System[1]. This metric is commonly described as mean annual ground temperature (**MAGT**) and measured near the depth of zero annual amplitude (**DZAA**), where the annual temperature fluctuations are minimal.

In Canada, summaries of MAGT often rely on a **limited number of boreholes**, primarily located at sites **removed from regular human activity**. Trends in this metric have revealed permafrost warming; however, they provide **little insight** into permafrost thaw (i.e., the **loss of ice** in the ground).

In this study, we present data from boreholes located within and outside locations of human activity, along with **four metrics** designed to capture changes **in permafrost temperature and thaw**. This information is intended to substantiate evidence of permafrost thaw and contribute to generating **permafrost climate services**[2].

Ground temperature dataset

Data used in this study comes from unpublished sources and open-source servers, totalling 116 boreholes with data spanning a minimum five years (Figure 1). Boreholes are found in both natural environments (41%) and locations affected by human activity (59%). A QR code showing individual data contributions can be found below.

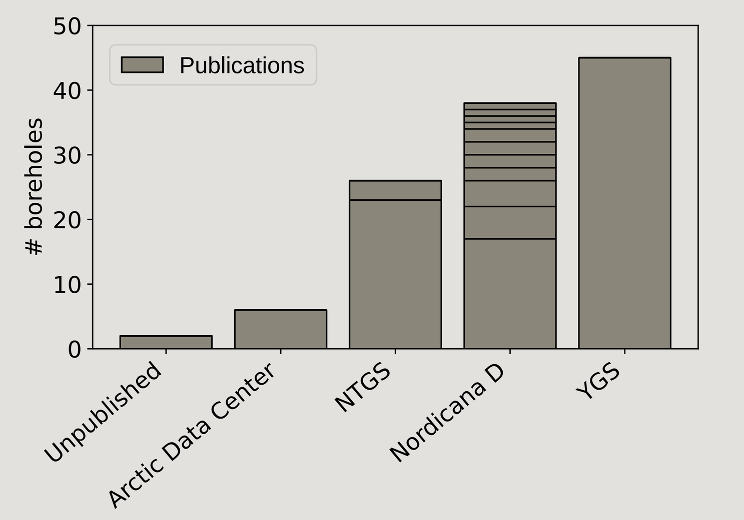

Figure 1. Number of boreholes with data per publication, organized by data server. Duration of data ranges from 5–24 years and maximum sensor depth ranges from 1.5–185 m with a mean of 14 m.

Metrics

We use **four metrics** to reveal permafrost thaw at each borehole site. These metrics were developed using simulated ground temperature data that resembles observations. Figure 2 provides a visualization of these four metrics alongside a common setup for a borehole.

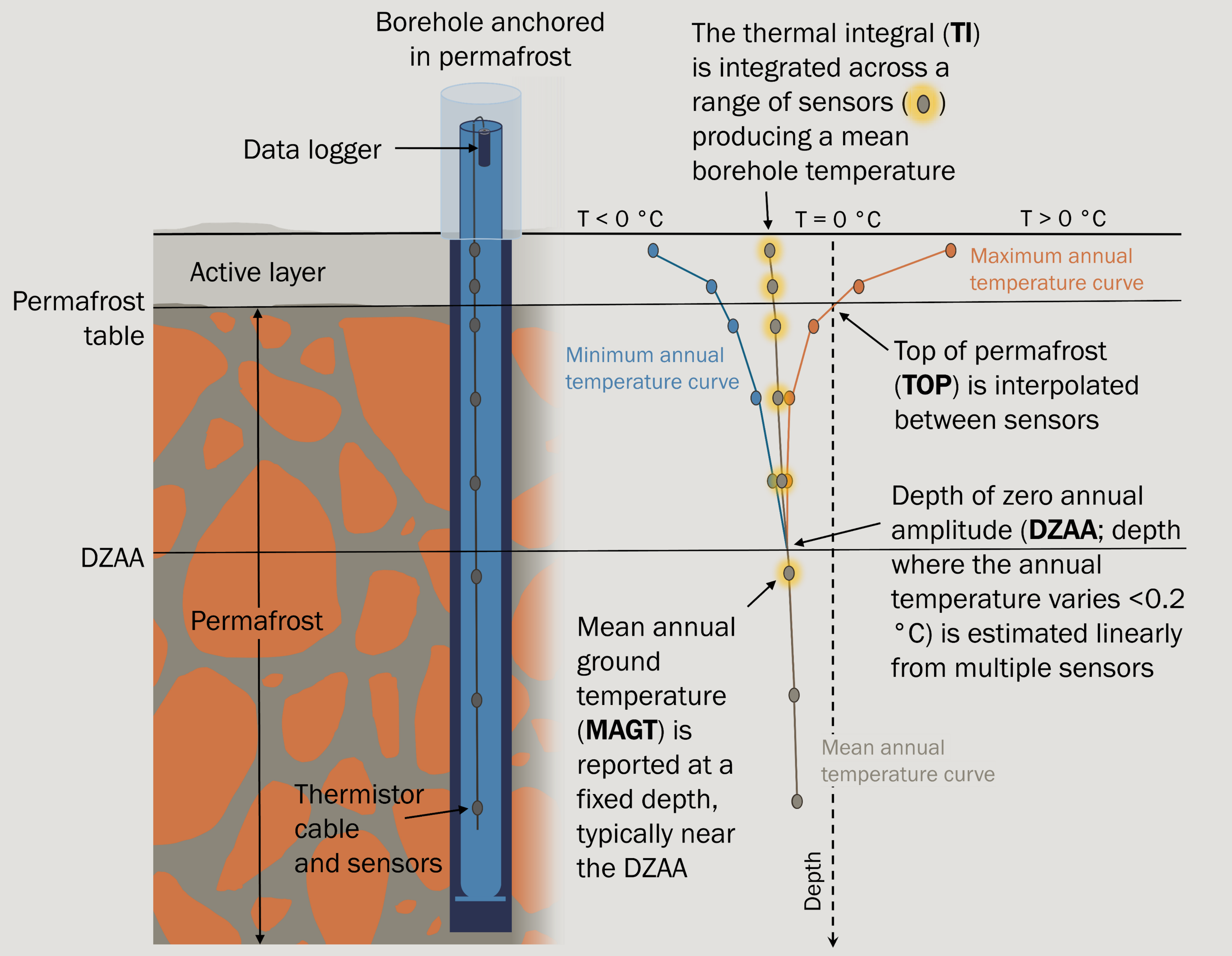

Figure 2. A borehole drilled into permafrost containing a thermistor cable and sensors records ground temperature at multiple depths (left). A trumpet curve (right) presents a typical thermal profile of permafrost including the minimum, maximum and mean temperatures at the specified depths. Metrics and their description are shown in bold print.

Interpreting metrics

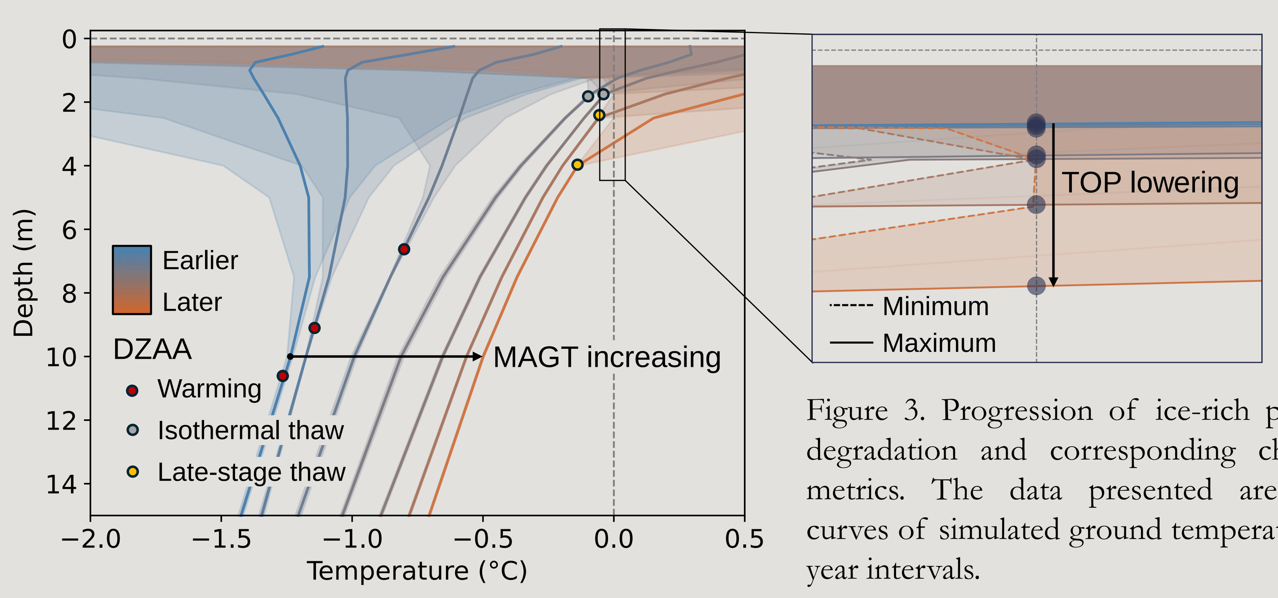

Figure 3. Progression of ice-rich permafrost degradation and corresponding changes in metrics. The data presented are trumpet curves of simulated ground temperature at 10-year intervals.

Comparing metrics

The trends in **TOP**, **TI**, and **DZAA** do not always correspond to those in **MAGT**; as such, they can offer additional evidence of permafrost changes (Figure 4).

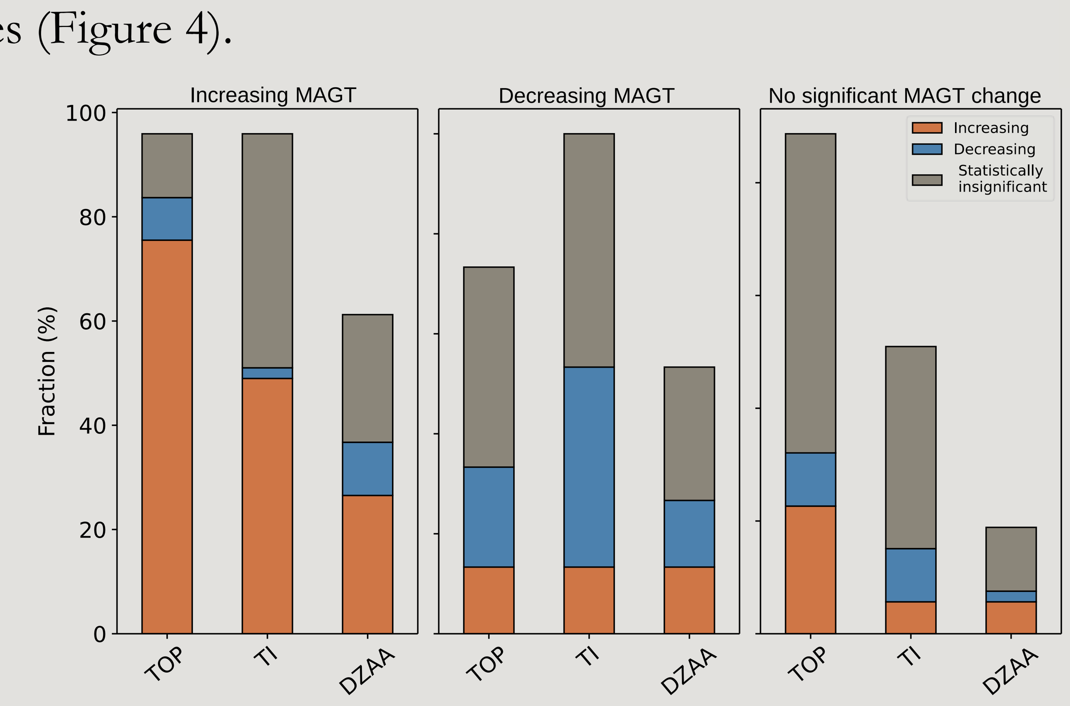

Figure 4. Comparing temporal change in metrics to MAGT trends. Shown are 49 significant positive MAGT trends (p-value ≤ 0.1), 15 significant negative trends, and 53 trends with no significant change. Bars do not reach 100% as data is not available for all metrics.

Trends across Canada

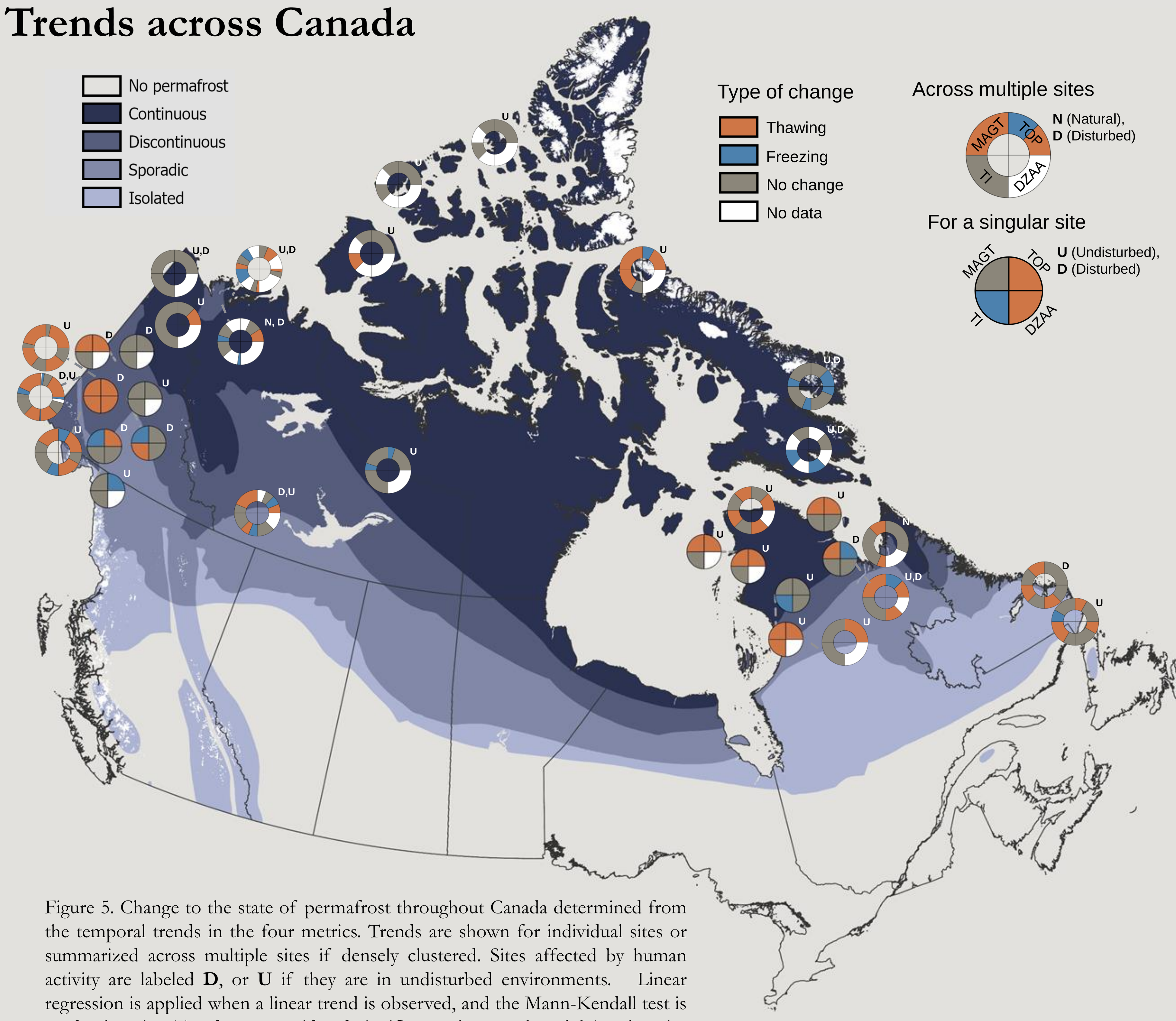

Figure 5. Change to the state of permafrost throughout Canada determined from the temporal trends in the four metrics. Trends are shown for individual sites or summarized across multiple sites if densely clustered. Sites affected by human activity are labeled **D**, or **U** if they are in undisturbed environments. Linear regression is applied when a linear trend is observed, and the Mann-Kendall test is used otherwise. Trends are considered significant when *p*-value ≤ 0.1, otherwise "no change" is reported.

Application

Metric trends show **permafrost conditions changing across Canada**. However, they **vary over short distances** (Figure 5) and, at times, the other metrics show evidence of permafrost change contrasting with the standard MAGT metric (Figure 4).

The **usefulness** of certain **metrics** and their temporal trends **varies**. For instance, the temporal trends in DZAA and TI–fluctuating more than MAGT–are difficult to detect and less intuitive over shorter time periods.

Overall, we see MAGT increasing (42%) more than decreasing (13%), but many of the borehole sites (45%) do not show significant MAGT trends. A lack of MAGT trend is primarily coupled with no change in TOP, DZAA, and TI.

Permafrost is changing both at sites impacted by human activity and in undisturbed environments. Since permafrost thaw can threaten the integrity of critical infrastructure and natural landscapes, we emphasize the **importance of monitoring and reporting changes in both types of environments**.

Future work

- Create a framework for establishing confidence in permafrost change.
- Investigate the influence of site-specific terrain and climatic factors on metrics, including the impact of human activity.
- Publish a dataset of compiled borehole temperature data.

References

[1]World Meteorological Organization. (2022). *The 2022 GCOS ECVs requirements* (GCOS-245). World Meteorological Organization.

[2]Gruber, S. (2024). Permafrost climate services. *Proceedings of the 12th International Conference on Permafrost, 2: Extended Abstracts*, 41–42.

[3]Heginbottom, J.A., Dubreuil, M.A., and Harker, P.T. (1995). *Canada, permafrost. The national atlas of Canada*. Natural Resources Canada, Geomatics Canada, MCR Series no. 4177. 5th edition.

Data references

Acknowledgments

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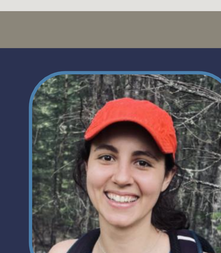

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