



Permafrost thaw follows spatially organized, nonlinear trajectories in ice-wedge terrain

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Abstract. Permafrost thaw is transforming Arctic landscapes, yet why thaw progresses differently across space and time remains poorly understood. Although ice-wedge degradation is widespread across the Arctic, its spatial organization and temporal evolution have not been well constrained, limiting our ability to forecast how the Arctic will change as it continues warming. Using a decadal time series of sub-meter satellite imagery and a U-Net deep learning classifier, we reconstructed fine-scale trajectories of ice-wedge degradation across a 50-km² Arctic landscape. Ice-wedge degradation did not follow a single progression toward advanced thermokarst. Instead, thaw evolved through multiple asynchronous and non-linear trajectories that were organized by geomorphic landforms across spatial scales. The location, timing, and severity of degradation varied systematically among landforms, indicating that millennia-scale geomorphic history sets the template for modern permafrost degradation trajectories. These spatial patterns suggest that climate warming is restructuring rather than homogenizing Arctic permafrost landscapes through interactions between inherited geomorphic setting and local ecohydrological feedbacks. Our framework of considering the spatial and temporal organization of permafrost thaw, not simply its extent or severity, provides a new basis for predicting Arctic landscape evolution and its hydrologic, ecological, and biogeochemical responses to continued warming.

20 1 Introduction

Arctic warming is reshaping permafrost landscapes, yet the processes governing where thaw emerges, how it expands, and why neighboring terrain follows contrasting trajectories remain poorly understood. As the ice wedges that form polygonal tundra melt, the land surface is altered in complex, difficult to predict ways: some ice wedges thaw rapidly and severely, leading to changing hydrology, ecology, and surface subsidence, while some stabilize and other ice wedges remain undisturbed (Jorgenson et al., 2015, 2022; Kanevskiy et al., 2017). These disparate thaw responses vary across meter, kilometer, and pan-Arctic scales (Abolt et al., 2024; Braun and Andresen, 2024; Frost et al., 2018; Liljedahl et al., 2016). Heterogeneous thaw complicates our assessment of the Arctic's future (Turetsky et al., 2020). Despite the abundance of ice wedges across the Arctic (Lara et al., 2018; Liljedahl et al., 2016; Udawalpola et al., 2022) and their environmental importance (Shur et al., 2025; Wickland et al., 2020), polygonal tundra is not represented in Earth System Models (Matthes et al., 2024). Understanding what



30 drives complexity in thaw dynamics and its distribution is essential for improving forecasts of how Arctic landscapes will evolve with continued warming.

Polygonal tundra is one of the most widespread and dynamic permafrost landscapes in the Arctic, where networks of massive ground ice cover millions of square kilometers (Lara et al., 2018; Leffingwell, 1915; Liljedahl et al., 2024). These landscapes are underlain by ice wedges formed through repeated winter frost cracking and ice accumulation over centuries to millennia (Lachenbruch, 1962; Mackay, 1993; Plug and Werner, 2002). These mm-wide cracks are infilled with liquid water in the summer which freezes the following fall. As ice wedges grow, they create semi-regular polygonal networks that typically span 5-30 m in diameter (Black, 1982; Liljedahl et al., 2016). These ground-ice networks create a patterned landscape that regulates surface hydrology, ecological gradients, and energy exchange, making the loss of ice-wedges through degradation a primary driver of environmental change across Arctic lowlands (Kanevskiy et al., 2017; Marcot et al., 2015; Schuur et al., 2015; Walker et al., 2022; Wickland et al., 2020; Wolter et al., 2016).

As the Arctic continues to warm at nearly four times the global average (Rantanen et al., 2022; You et al., 2021), ice wedges are thawing and inducing a range of ecosystem impacts. Ice-wedge thaw reorganizes surface topography and hydrologic connectivity as troughs deepen, trough ponds expand, and polygon centers become progressively drier. Warming and nutrient release from thawing permafrost can increase plant productivity and soil organic matter accumulation (Natali et al., 2012; Reyes and Loughheed, 2015), which eventually can produce sufficient insulation from warm summer air that the ice wedges and surrounding permafrost are stabilized from further thaw (Jorgenson et al., 2015; Kanevskiy et al., 2017). Collectively, these interacting ecohydrological feedbacks alter exchanges of carbon between the land and atmosphere, linking local thaw dynamics to regional and global climate feedbacks (Koch et al., 2018; Martin et al., 2018; Schuur et al., 2015; Wickland et al., 2020).

Given the widespread occurrence of ice-wedge degradation, remote sensing has become the primary tool for monitoring landscape change across the Arctic. Early studies focused on delineating flooded troughs using spectral thresholding (Fraser et al., 2018; Frost et al., 2018; Necsoiu et al., 2013; Swanson, 2016) or manual delineations (Steedman et al., 2017; Wickland et al., 2020), while ongoing advances in machine learning have substantially improved the detection and mapping of polygons (Abolt et al., 2019; Hasan et al., 2022; Zhang et al., 2018), trough networks (Rettelbach et al., 2021), and trough features (Witharana et al., 2021) across increasingly large spatial extents. These developments have transformed our ability to map degrading permafrost landscapes, with most studies emphasizing map production (Bhuiyan et al., 2020; Hasan et al., 2022; Li et al., 2022; Udawalpola et al., 2022; Witharana et al., 2021; Zhang et al., 2020) or quantifying change using landscape- or site-level averages, such as the expansion of flooded troughs or total degraded area (Abolt et al., 2024; Fraser et al., 2022; Frost et al., 2018; Steedman et al., 2017). These approaches have demonstrated that ice-wedge degradation is widespread across the Arctic, but the overall magnitude of thaw expansion represents only the cumulative outcome of landscape change.



Examining average thaw expansion provides limited insight into the processes that organize where degradation initiates, how it spreads, and why neighboring portions of the landscape often display markedly different responses to the same climatic forcing. Consequently, a fundamental challenge remains: understanding what processes generate the heterogeneous landscape patterns that govern future Arctic ecosystem responses to climate warming.

Landscape heterogeneity is a defining characteristic of ice-wedge degradation (Braun and Andresen, 2024), but how this heterogeneity emerges and evolves through time remains largely unknown. A prevailing conceptual model describes ice-wedge degradation as a permanent morphological transition from low-centered to flat-centered to high-centered polygons; this transition occurs as thaw and associated network rearrangement results in the erosion of trough rims, deepening of trough networks, and eventual drainage of the network, permanently transforming the tundra into a collection of dry, elevated high-centered polygonal terrain (Ellis et al., 2008; Liljedahl et al., 2016; MacKay, 2000; Shur et al., 2025). This framework has been widely adopted to represent degradation in process-based models (e.g., Nitzbon et al., 2019; Painter et al., 2023; Speetjens et al., 2024), or as space-for-time substitutions in the field (Wainwright et al., 2021; Wolter et al., 2016). However, polygon morphology represents the cumulative outcome of degradation over centennial timescales rather than the annual-to-decadal dynamics through which degradation unfolds. Furthermore, not all ice-wedge polygons originate as low-centered (Jones et al., 2025; Kanevskiy et al., 2013; Mackay, 1990), and individual polygons are commonly bounded by ice-wedge troughs at different stages of degradation that evolve asynchronously through time (Braun and Andresen, 2024; Jorgenson et al., 2022; Wickland et al., 2020). Consequently, existing morphological frameworks provide limited insight into how degradation develops across landscapes on decadal timescales. Characterizing the complex spatiotemporal trajectory of thaw is therefore essential not only for capturing the non-linear evolution of permafrost thaw but also for identifying the interacting geomorphic, ecological, and climatic processes that generate heterogeneous patterns of degradation across Arctic landscapes (Abolt et al., 2024; Frost et al., 2018; Kanevskiy et al., 2022) across timescales relevant for policymaking and carbon-climate feedbacks. Resolving these processes is fundamental to predicting how Arctic landscapes will evolve and reorganize under continued climate warming.

In this study, we reconstruct the decadal evolution of ice-wedge degradation across an Arctic landscape using high-resolution satellite imagery and deep learning to (i) quantify degradation trajectories, (ii) determine how thaw heterogeneity evolves through time, and (iii) evaluate how fine-scale geomorphic features organize distinct pathways of permafrost degradation.

2 Methods

2.1 Study site

The polygonal tundra terrain examined in this work is located on the Arctic Coastal Plain of Alaska west of miles 390 through 400 of the Dalton Highway on the traditional lands of the Inupiat. The study site is situated atop an alluvial terrace on the



western side of the Sagavanirktok River. The terrace is elevated between 1 and 3 meters above the modern channel and has an average slope of $\sim 0.27\%$. Geological mapping conducted 11.2 km inland of the Beaufort Sea on the same alluvial terrace (approximately 35 km north of the study site) radiocarbon-dated peat at the base of the Holocene alluvium to 4.640 ± 0.090 ka (Rawlinson, 1990).

2.2 Machine learning mapping of ice-wedge troughs

Ice-wedge troughs were identified in high-resolution, multispectral satellite imagery using a U-Net machine-learning image classifier across 2,900 km² of the Arctic Coastal Plain of Alaska. Peak-season (July-August), cloud-free, orthorectified, and radiometrically corrected Maxar satellite imagery was sourced from the Polar Geospatial Center. Multispectral images were pan-sharpened to match the resolution of the panchromatic band using the Intensity, Hue, Saturation (IHS) method in ArcGIS Pro 3.1.0. Four other pan-sharpening methods were tested and input into the trough classifier; these data input tests found no statistical difference in mapping accuracy based on the pan-sharpening method used to prepare imagery for classification (Figure S1), and thus the IHS method was chosen for all processing. Four spectral bands (B, G, R, and NIR) were used for classification. Each image was co-registered with 8-12 control points to the 2014 image, which had the greatest spatial overlap with the other images. Four images were selected from 2006, 2011, 2014, and 2023 to produce a 17-year time series (Table 1).

Table 1: Satellite image metadata, including number of training tiles produced for each image's bespoke U-Net machine learning classifier.

Date	Satellite	Resolution (m)	# of Training Tiles
08-15-2006	QuickBird-2	0.65	57
07-02-2011	QuickBird-2	0.74	55
07-07-2014	WorldView-2	0.50	63
08-05-2023	WorldView-2	0.47	50

The U-Net model is a convolutional neural network model, here built with four layers, that produces semantic segmentations (Ronneberger et al., 2015; Figure 1). The model segments images into three classes: dry troughs, flooded troughs, and non-trough areas. Troughs were separated into dry and flooded classes to allow examination of the shifting hydrological regime in degrading ice wedge terrain, as advancing degradation leads to increased flooding and formation of expanding trough ponds, and loss of trough water can occur during stabilization of degradation (Jorgenson et al., 2015; Kanevskiy et al., 2017). Training data for the machine learning model were manually digitized using the Pixel Editor toolbar in ArcGIS Pro. Training data were generated iteratively: the initial round of training data was focused on sites where field surveys and cm-scale drone



orthomosaics and digital elevation models (DEMs; Braun and Andresen, 2024) aided digitizers in accurately identify trough boundaries in satellite imagery; the model was then trained with the first round of training data and used to predict on a new region. Prediction results were examined to determine which areas required additional training data to improve model results, and then those portions of the model output were edited accordingly and incorporated as new training tiles into the second generation of model. This process was repeated with new prediction areas until the desired threshold of >90% pixel accuracy was achieved. Pixel accuracy describes the percentage of pixels accurately identified by the classifier in comparison to the reference data; classifier accuracy was also assessed using mean-Intersection-over-Union (mIoU) and Dice values, which both range from 0-1 and denote the proportion of spatial overlap between the reference feature and the classified feature (Table S2).

The U-Net workflow takes in a large satellite image and clips the raster into square tiles to match the size of the training tiles. Each tile was classified separately, then merged into the final output after classification. Training tiles for the machine learning model were 256 by 256 pixels in size. Tiles therefore differed in spatial extent depending on the resolution of the input imagery. This difference in image resolution also required that a distinct model be trained for each satellite image (e.g. Table 1); pixel accuracy, mIoU, and Dice values were lower when training data was pooled between years. The satellite images' original resolution was retained to preserve as much information as possible in later years when satellite image resolution improved.

Given that image classifiers tend to exhibit edge effect errors (Reina et al., 2020), the input image was clipped into tiles with 50% overlap. After classification, the output tiles were clipped to remove areas that overlapped with neighboring tiles and merged into a final ice-wedge trough map.

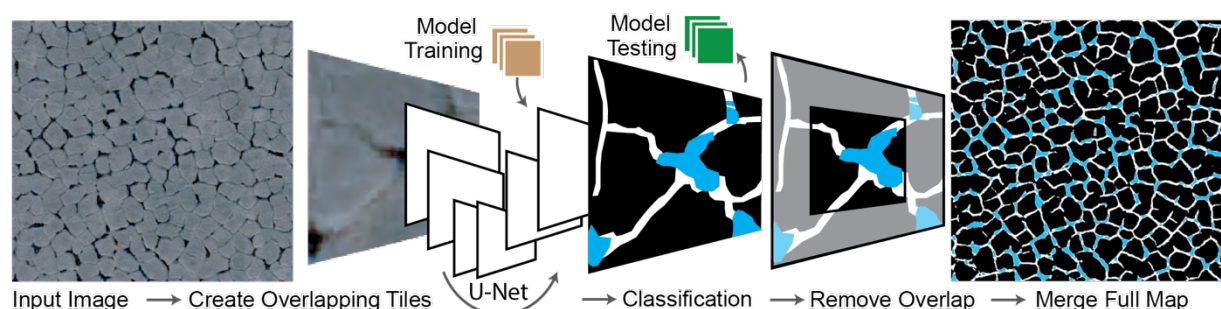


Figure 1: Machine learning U-Net algorithm architecture and workflow. Satellite images © Maxar 2014.

2.3 Assigning degradation classes

Three-class (flooded troughs, dry troughs, and non-trough) ice-wedge maps were produced from each satellite image. Ice-wedge trough metrics were spatially aggregated for each map within 30 m square grid cells to allow for comparison over time. Metrics included total trough area, dry trough area, flooded trough area, percentage of troughs that were flooded, total trough length, and average trough width. Trough length was calculated as the length of the centerline of the combined dry and flooded

troughs, produced using the “Thin Raster” tool in ArcGIS Pro. Average trough width was calculated by dividing total trough area (combined flooded and dry trough area) by the trough length within each 30 m aggregation cell.

150 Open water in lakes and stream channels was masked out of the maps to focus analysis on ice-wedge terrain (Lara et al., 2018).

Each cell of the spatial aggregation grid was assigned a dominant ice-wedge degradation stage for each year following the threshold method described in Braun and Andresen (2024): each cell was assigned a hydrogeomorphology classification based on the average trough width (morphology) and percentage of trough flooding (hydrology) within that cell (Figure 2). These hydrogeomorphology classes are associated with the dominant ice-wedge degradation stage present within the cell. Cells with wider, wetter troughs are assumed to contain mostly advanced degradation troughs; narrower, drier troughs are assumed to align with more undegraded troughs (Braun and Andresen, 2024).

A revision of the threshold levels used to distinguish hydrogeomorphology class was required for this project because the distribution of trough metrics differed compared to previously published ice-wedge trough maps. To identify appropriate threshold values for this classification method, we conducted a series of threshold simulations using a range of trough width thresholds and trough flooding percentage. Simulation methods and results are outlined in the supplement section 2. The final width threshold used for distinguishing between the undegraded and degradation stages was 1.5 m, while the final flooding threshold used for distinguishing between the initial and advanced degradation stages was 7.5%. These thresholds align with field observations of ice-wedge troughs (Braun and Andresen, 2024). Simulation test results show that small shifts in threshold value do not produce different spatial nor temporal patterns in degradation stages (Figure S5-8).

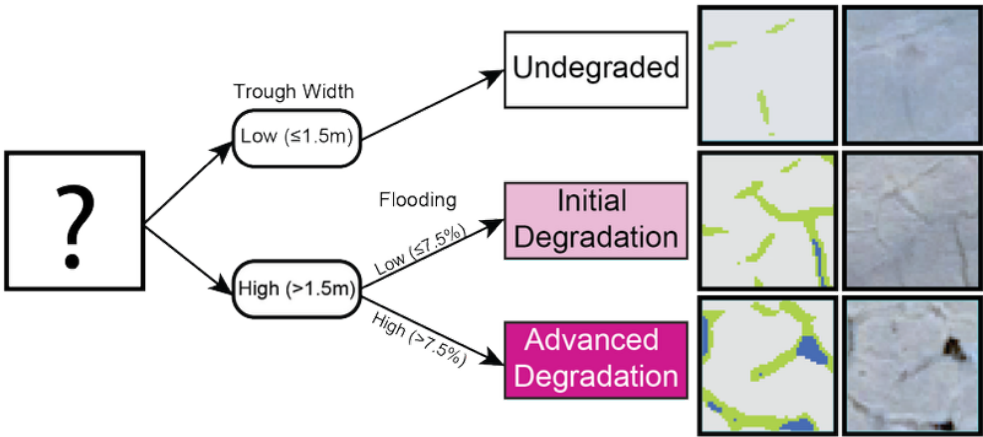


Figure 2: Assigning degradation stages to 30 m spatial aggregation cells using trough metric thresholding (adapted from Braun and Andresen, 2024). Satellite images © Maxar 2014.

170 Although ice wedges can transition into a stabilized stage following the accumulation of sufficient insulating material above previously degraded ice wedges (Jorgenson et al., 2015, 2022), we did not include stabilization as a hydrogeomorphic



classification in this study. In other locations, stabilization is characterized by widening troughs, reduced inundation, and vegetation shifts associated with trough drying (e.g., Wickland et al., 2020). However, these characteristics were not observed in our field surveys, suggesting that stabilization had not yet occurred within the study area. Instead of assigning a stabilization stage, we implemented a new approach that tracks temporal transitions among degradation stages to identify trajectories of ice-wedge degradation through time.

2.4 Assigning degradation trajectories

Degradation trajectories were computed and classified for each spatial aggregation cell that contained mapped data from all four satellite images, an area of 49.9 km² after the river corridor and lakes were removed from the analysis. This area is henceforth referred to as the overlap site.

The degradation trajectory is the temporal sequence of hydrogeomorphic stages assigned to a given cell. An example of a temporal stage sequence would be a cell assigned the undegraded, initial degradation, initial degradation, and advanced degradation stages in 2006, 2011, 2014, and 2023 respectively. As this cell is changing from a less degraded to more degraded stage through time, it is assigned the Advancing trajectory. All unique sequences of stages were computed, then the top 35 stage sequences (comprising 95% of all data at the overlap site) were assigned a qualitative trajectory label to describe how that cell was changing through time. If the stage remained the same through time, it was termed a Persistent trajectory and assigned that stage name (i.e., Undegraded, Initial Degradation, Advanced Degradation). If the cell changed from an undegraded stage to the initial degradation stage, it was assigned the Initiating trajectory. Cells changing from either undegraded or initial degradation to the advanced degradation were assigned to the Advancing trajectory. Cells that began in the advanced degradation category and ended in the initial degradation category were assigned the Drying trajectory. Cells that did not conform to these patterns were assigned the Oscillating trajectory. Stage sequences were cleaned to reduce noise associated with small magnitude fluctuations in threshold metric values prior to assigning trajectories (see Supplemental section 3).

In addition to degradation trajectories, we also identified when changes in stage occurred. For the changing trajectories, we identified the year when the cell first transitioned into the initial degradation and advanced degradation stage to track the timing of when the site was initiating and advancing in degradation between 2006 and 2023 (Table S6).

2.5 Landscape analyses: landforms and degradation trajectory patterns

Spatiotemporal patterns in ice-wedge degradation were examined in concert with landforms. Elevation data at the overlap site was sourced from a 2011 airborne LiDAR survey with >20 points per m² (Abolt et al., 2019); LiDAR data were interpolated into a 2 m resolution digital elevation model that was used for subsequent analyses. Distinct, fine-scale landforms were manually digitized at 1:3,000 scale through expert interpretation of both the LiDAR elevation data and satellite imagery at the



205 overlap site, and through reference to nearby surficial geology maps (Rawlinson, 1990). Landform features included aeolian deposits, alluvial terraces, abandoned channels, drained thaw lake basins, and active fluvial pathways.

210 The distribution of landform features within each degradation trajectory was calculated and compared to the site-level distribution by building a contingency table and calculating expected area values for each landform-trajectory class (Everitt, 1992). The difference between the observed and expected value was computed. The significance of those differences was not determined given that the nature of raster spatial data does not fit the assumptions of standard hypothesis testing (high spatial autocorrelation and arbitrary pixel size inflating n and p -values; Pontius et al., 2004). All analyses and visualizations were conducted in RStudio 2025.05.1+513 using R V4.5.1 (R Core Team, 2025) using packages tidyverse, sf, and patchwork (Pebesma, 2018; Pedersen, 2024; Wickham et al., 2019).

3 Results

215 3.1 Ice-wedge degradation follows nonlinear pathways

Ice-wedge degradation reorganized the landscape through multiple, asynchronous trajectories through time, rather than a single progression of thaw (Figure 3). The most striking landscape-scale transition was the near disappearance of undegraded terrain over the 2006-2023 study period. Areas classified as Undegraded declined from 38.5% of the landscape in 2006 to only 2.7% in 2023, while Initial Degradation became the dominant landscape state, expanding to 62.4% of the study area. In contrast, 220 Advanced Degradation occupied a relatively constant fraction of the landscape ranging between 27% in 2006 and 30% in 2023. Site-level summary statistics of degradation stages, while informative about the general transition of the landscape towards intensifying degradation, do not capture the complex and often nonlinear change occurring across individual ice-wedge troughs as the landscape evolves at fine spatial scales.

225 Trajectory analysis revealed the complexity in these landscape-scale trends. The overall most common pathway of degradation was the Initiating trajectory, representing areas that transitioned from the Undegraded to Initial Degradation stage during the period of study (Figure 4). Persistent trajectories, where the classified stage of degradation did not change over time, accounted for 34% of the landscape. Beyond these dominant trends, nonlinear pathways of thaw included drying and oscillation among degradation stages, which occurred across substantial portions of the landscape, demonstrating that permafrost thaw proceeds 230 through multiple modes of change rather than a single monotonic progression towards increased thaw.

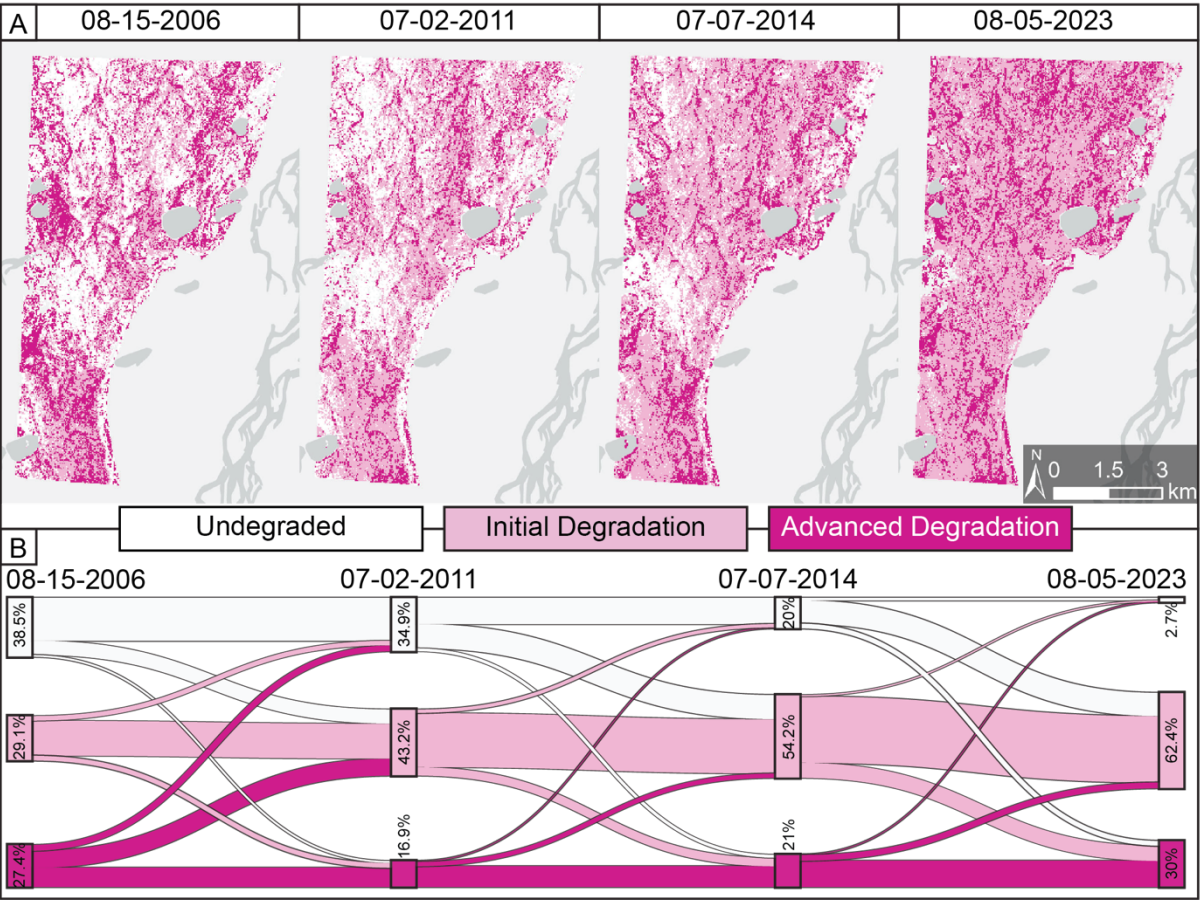


Figure 3: Decadal evolution of ice-wedge degradation reveals widespread landscape transition and multiple nonlinear degradation trajectories as permafrost thaws. A: Spatiotemporal evolution of ice-wedge degradation stages across the study landscape from 2006 to 2023, showing the progressive loss of undegraded terrain and expansion of initial and advanced degradation. Degradation stages are classified following the hydrogeomorphology approach (Braun and Andresen, 2024). B: Sankey diagram illustrates reorganization among degradation stages through time, revealing multiple, non-linear pathways of landscape change. Diagram stream widths are proportional to the area represented by each trajectory. The 5.1% of the study area without mapped ice-wedge troughs is excluded.

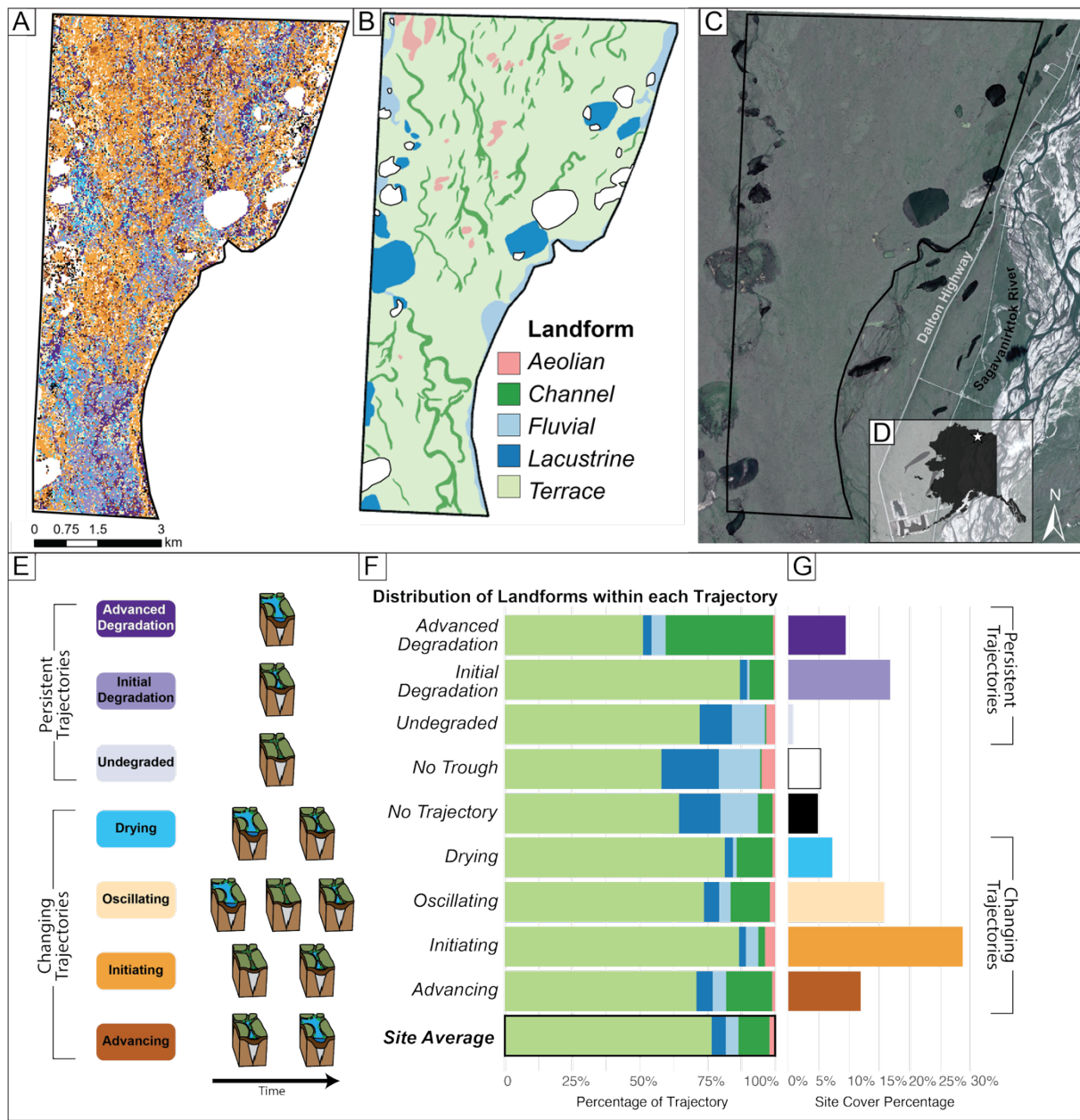


Figure 4: Fine-scale landforms spatially constrain the distribution of ice-wedge degradation trajectories. Maps of (A) degradation trajectories, calculated from the temporal sequence of mapped degradation stages and (B) geomorphic landform classes, digitized through interpreting high-resolution airborne LiDAR elevation data. (C) August 5, 2023, WorldView-2 satellite image (© Maxar), with (D) site location in Alaska. Summary of (E) degradation trajectories, and (F) Stacked 100% bar plots showing observed distribution of landform types within each trajectory class, with the site-level distribution of landforms bolded at the bottom. (G) Bar plot of cover percentage by trajectory class. Degradation trajectory color labels for the map in panel A are included in panel E.



3.2 Ice-wedge thaw is spatially constrained by landforms

Degradation trajectories were strongly influenced by geomorphic setting rather than being evenly distributed across the landscape (Figure 4). The most severe trajectories, Advanced Degradation and Advancing, were concentrated within
255 abandoned fluvial channels, where they occurred far more frequently than expected based on landform area. Although
abandoned channels comprise only 11% of the study area, they contained more than 40% of the Advanced Degradation
trajectory, which corresponds to an overrepresentation of 133 hectares relative to an even distribution (Figure 4f; Table S7).
Conversely, alluvial terraces accounted for 76% of the landscape but contained only 51% of the Advanced Degradation
trajectory, corresponding to an underrepresentation of 119 ha. Similar patterns were observed for the Advancing trajectory,
260 which was also disproportionately concentrated within abandoned channels and less common on the terraces. The abandoned
channels, more than any other landform at this site, contained far more of the severe degradation trajectories than expected.

In contrast, the extensive alluvial terraces were dominated by Initiating and Initial Degradation trajectories, indicating that
early, less severe stages of degradation were more widespread in these landforms. Although the Initial Degradation trajectory
265 was overrepresented on terraces by 87 ha, spatial patterns in the trajectory map reveal that these areas were often clustered
adjacent to abandoned channels (Figure 4a), suggesting a spatial progression of degradation beyond the channel boundaries.
The No Troughs and Undegraded trajectories were most common in fluvial and lacustrine landforms. These younger
geomorphic surfaces generally contain less developed ice-wedge networks and higher surface water cover. Overall, these
patterns demonstrate that geomorphic setting organizes not only the severity of ice-wedge degradation but also the trajectory
270 through which degradation unfolds across the landscape.

3.3 Temporal expansion of thaw across geomorphic features

The locations where changes in degradation stage occurred evolved systematically through time, indicating that ice-wedge
degradation expanded beyond initial hotspots rather than remaining confined to persistent hotspots (Figure 5). During the first
observation period (2006–2011), landscape change included widespread degradation initiating (6.4% of the study area), limited
275 degradation advancement (2.2%), and the greatest extent of trough drying observed during the study (5.4%). Areas undergoing
initiation and advancement were concentrated within a north–south-oriented zone in the northern portion of the study area;
advancing degradation was disproportionately associated with abandoned channels relative to their occurrence across the
landscape (Figure 5b). This pattern persisted through 2014, indicating that early degradation intensification was focused within
abandoned channel networks.

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After 2014, the spatial organization of advancing degradation changed. Although the total area of degradation continued to
increase, newly advancing terrain was distributed among geomorphic landforms in proportions similar to their landscape



abundance, indicating that degradation had spread beyond abandoned channels and became more broadly distributed across the study area. Consistent with this shift, the greatest overall expansion of degradation occurred between 2014 and 2023, whereas the most rapid rate of landscape change occurred between 2011 and 2014, when the Initiating trajectory expanded at 164 ha yr⁻¹.

The temporal evolution of degradation differed markedly between initiation and advancement. Early in the record, degradation advancement was disproportionately concentrated within abandoned channels, indicating that these landforms were initial hotspots of intensifying thermokarst. By 2014–2023, however, advancing degradation occurred across landforms in proportions increasingly similar to their landscape abundance, indicating that severe thaw had expanded beyond the geomorphic settings where it was initially concentrated. In contrast, degradation initiation remained consistently overrepresented on alluvial terraces and underrepresented within abandoned channels throughout all three observation periods. Thus, even as advancing degradation became more spatially widespread, new degradation continued to emerge preferentially on terrace surfaces.

Patterns of trough drying provide an additional dimension to this changing spatial organization. Drying reached its greatest extent during 2006–2011, when 5.4% of the landscape transitioned from more advanced to less flooded degradation states, but subsequently declined to less than 1% by 2023. Its geomorphic association also shifted, from predominantly terrace surfaces early in the record toward abandoned channels later in the study period. Together, these patterns reveal a progressive redistribution of degradation across geomorphic settings: intensification initially clustered within vulnerable abandoned channels before expanding more broadly across the landscape, while initiation continued to emerge preferentially on terraces. Thaw therefore spread beyond its initial hotspots without erasing geomorphic structure, producing increasingly widespread but persistently organized landscape heterogeneity.

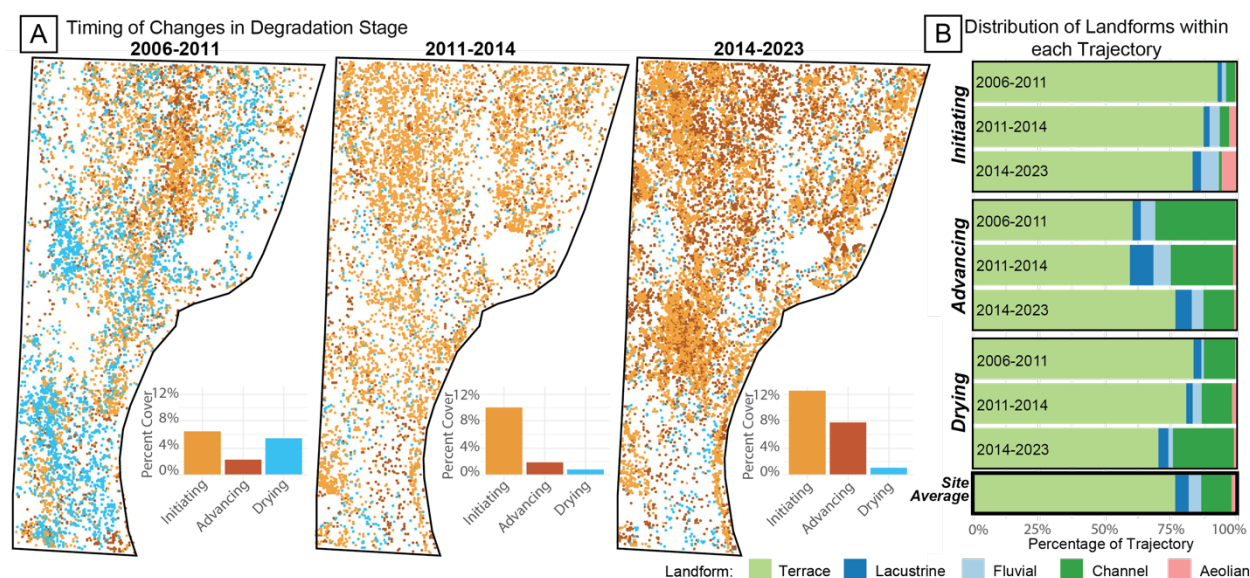


Figure 5: Degradation trajectories emerge and expand asynchronously across the landscape, producing a continually evolving mosaic of thaw states rather than a uniform progression toward advanced thermokarst. A: Timing of degradation-stage transitions across the study area, showing 30m pixels that initiated, advanced, or dried during each observation period. B: Distribution of geomorphic landforms associated with each trajectory and observation period, illustrating how the spatial organization of degradation evolves through time.

4 Discussion

Understanding how permafrost degradation restructures Arctic landscapes from an undisturbed to a thawed state remains a central challenge for predicting ecosystem responses to climate warming. Conceptual models of ice-wedge degradation are largely focused on processes operating within individual ice-wedge polygons or troughs (Jorgenson et al., 2015; Liljedahl et al., 2016), yet how these local processes scale up to produce landscape-wide patterns of heterogeneous thaw remains poorly understood. Here, we extend beyond static representations of thaw by tracking transitions among degradation states through time and relating those trajectories to their fine-scale geomorphic setting. Our results demonstrate that permafrost thaw is heterogeneous and this complexity extends from the polygon to the landscape scale, where degradation progresses through spatially organized and temporally nonlinear trajectories rather than as a uniform landscape response to climatic warming. Within a single 50 km² landscape, ice wedges degraded at different rates, transitioned through different stages, and followed distinct trajectories of change, producing an evolving mosaic of thaw through time. These trajectories were strongly structured by fine-scale geomorphic features, with degradation initially concentrated within vulnerable landforms before progressively expanding across the surrounding terrain. Together, these findings support a conceptual model in which landscape history governs where degradation begins, local feedbacks determine how it evolves, and the interaction of these processes drives the spatiotemporal evolution of Arctic ice-wedge terrain (Figure 6). By linking landscape history to contemporary thaw dynamics,

our framework provides a mechanistic basis for predicting how continued warming will reshape hydrologic, ecological and biogeochemical processes in Arctic landscapes.

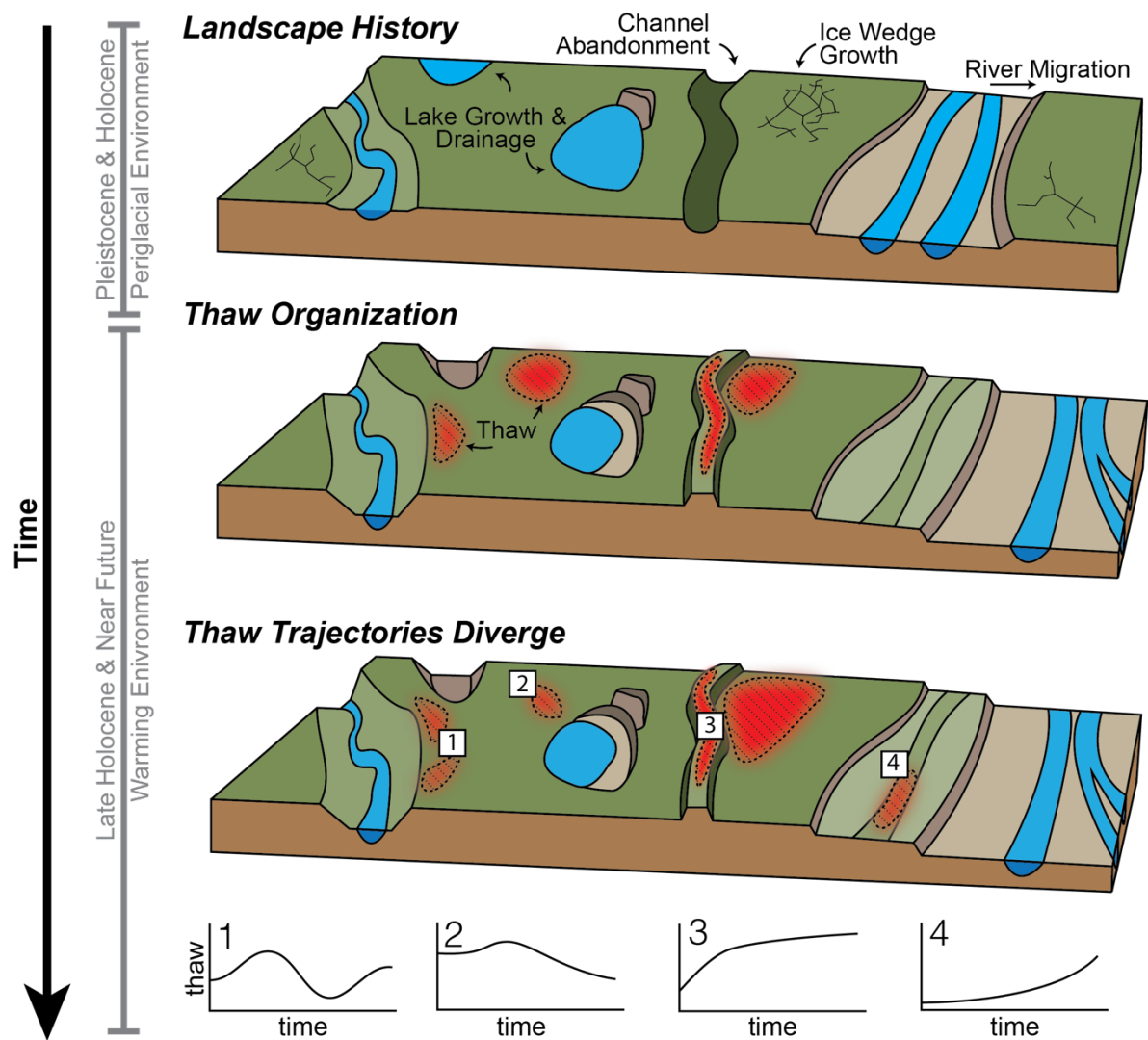


Figure 6: Modern thaw trajectories are spatially constrained by landscape history. Our results show spatiotemporal patterns in the thawing of ice-wedges are linked to the hectare-scale landforms that compose the landscape. Different periglacial landforms are created at different points in time from distinct geomorphic processes over millennia. Ice-wedge networks then grow through repeated thermal contraction cracking, which is modulated by both the winter temperature regime and the coefficient of thermal expansion of the subsurface material. Distinct landforms appear to have differing susceptibility to network growth, indicated by the differing density of ice-wedge trough networks across the landscape. As the Arctic has warmed over recent decades, hotspots of ice-wedge thaw form, preferentially located in certain landforms more than others. As warming continues, thaw expands over greater portions of the landscape, following nonlinear thaw trajectories. In this way, the millennia-scale evolution of the landscape governs modern Arctic thermokarst development.



340 4.1 Nonlinear trajectories of thaw reveal complex landscape response to warming

Recent Arctic warming has primarily expanded the footprint of degradation by recruiting new terrain into long-lived intermediate thaw stages, while simultaneously intensifying degradation within already affected areas. By 2023, undegraded terrain had nearly disappeared while initial degradation became the dominant landscape state (Figure 3), implying that Arctic ice-wedge terrain may spend prolonged periods in intermediate stages of degradation before progressing to more advanced thermokarst. This pattern suggests that recent warming has primarily transitioned undegraded terrain into the earliest stages of thermokarst rather than abruptly converting existing degraded terrain into advanced states. At the same time, troughs continued to widen, expand, and become increasingly inundated, with the most rapid intensification occurring after 2011, consistent with other studies in the region that have found indications of major degradation occurring in the early 2010s (Abolt et al., 2024; Liljedahl et al., 2016; Wickland et al., 2020). The acceleration observed after 2011 across multiple degradation metrics suggests that ice-wedge degradation may respond nonlinearly to sustained warming and/or episodic climatic extremes (e.g. rain, heat). Although the regional trajectory is one of initiating degradation, this aggregate trend masks substantial variation in how individual portions of the landscape evolve.

A defining feature of ice-wedge degradation at this site is the coexistence of multiple degradation trajectories occurring simultaneously across the landscape. Although degradation generally expanded and intensified during the study period, approximately one-quarter of the landscape followed Persistent trajectories that did not transition between degradation stages, while an additional quarter exhibited Oscillating or Drying trajectories that departed from a monotonic progression of thaw (Figure 4). Rather than representing isolated exceptions, these trajectories demonstrate that landscape evolution proceeds asynchronously, with different portions of the landscape initiating, intensifying, oscillating, or persisting at different times. Similarly asynchronous degradation trajectories are prevalent at other locations across the Arctic, as well, as other time series mapping of ice-wedge degradation has found that some ice wedge sites are degrading rapidly over the past several decades, as evidenced by increasing thaw pond area, while others are holding steady, oscillating between high and low thaw pond areas, or declining over time (Abolt et al., 2024; Frost et al., 2018; Steedman et al., 2017). Warming across the Arctic is reconfiguring ice-wedge terrain through multiple concurrent pathways rather than driving a uniform progression toward increasingly degraded conditions. Importantly, this transformation maintains substantial spatial heterogeneity even as the regional landscape transitions on average toward more degraded states (Figure 6). In other words, the landscape is becoming more degraded overall, but it is not becoming more homogeneous. Because landscape evolution under warming produces a heterogeneous mosaic of hydrologic, ecological, and biogeochemical states whose interacting feedbacks may amplify, dampen, or offset one another, their net influence on regional ecosystem function and carbon cycling remains difficult to predict. This complexity may not be captured by approaches that rely on spatially aggregated or mean landscape responses, highlighting the need to represent the processes that generate landscape heterogeneity rather than treating it as unresolved variability.



Although seasonal fluctuations in surface water can influence the apparent flooding of ice-wedge troughs (Koch et al., 2018; Thompson and Woo, 2009), the observed Drying and Oscillating trajectories are unlikely to result primarily from seasonal hydrologic variability. Consistent with common practice in remote sensing studies of ice-wedge degradation and Arctic surface-water dynamics (e.g., Abolt et al., 2024; Andresen and Lougheed, 2015; Frost et al., 2018; Liljedahl et al., 2016), imagery was restricted to the peak summer period (July through mid-August), when surface-water conditions are relatively stable and less influenced by snowmelt or fall freeze-up. Additionally, all trajectories were subject to sensitivity testing that only registered a change in degradation stage over time if that change in stage was accompanied by a sufficiently large shift in degradation metric (Table S3). Trough width and trough area did not exhibit systematic decreases; subsidence and widening associated with degradation are not reversible on decadal timescales (Frost et al., 2018; Wolter et al., 2016). Furthermore, while loss of surface water can indicate recovery or stabilization from thaw, as degradation continues, ice-wedge networks can become sufficiently connected that surface water laterally drains to lower elevation areas, leaving portions of the landscape newly dry (Liljedahl et al., 2024; Rettelbach et al., 2021). The detected reductions in surface water at this site are more consistent with the progressive hydrologic changes of degrading ice-wedge networks, where increasing connectivity promotes lateral drainage and redistributes water across the landscape rather than reversing degradation.

Ice-wedge degradation is governed by a suite of interacting hydrologic, ecological, and geomorphic feedbacks that can limit further thaw and drive local heterogeneity. Field observations and process-based models suggest that degradation should become increasingly self-limiting as near-surface excess ice is depleted and stabilizing feedbacks including peat accumulation, vegetation succession, and increased snow insulation reduce continued thaw (Jorgenson et al., 2015; Kanevskiy et al., 2017; Nitzbon et al., 2021; Ward Jones et al., 2020). Under this framework, older degradation hotspots would be expected to exhibit slower rates of change than terrain that began degrading more recently. Conceptually, degradation cannot progress indefinitely; early theories proposed that continued ice-wedge thaw would lead to widespread pond expansion and eventual thermokarst lake formation (Billings and Peterson, 1980), but subsequent studies have shown that this outcome is not a universal trend in ice-wedge terrain (Ellis et al., 2008; Painter et al., 2023), although it has been documented in some settings (Bouchard et al., 2020). Our trajectory analysis provides little evidence that these stabilizing mechanisms currently constrain landscape evolution at this site (Figure S9). More specifically, comparing between the Advancing and Persistent Advanced Degradation trajectories provides insight into how degradation is evolving across decadal periods; troughs in the Advancing trajectory were observed transitioning to the advanced stage after 2006, while troughs in the Persistent Advanced Degradation trajectory entered the advanced stage before 2006. Both recently initiated and long-established degradation trajectories have comparable rates of thaw intensification, which suggests that ice-wedge degradation has not yet become self-limiting at this site. Instead, local positive feedbacks to thaw continue to outweigh stabilizing mechanisms, allowing degradation to spread across the landscape while simultaneously intensifying within older thermokarst features. Consequently, the landscape remains poised for continued persistence of spatially heterogeneous thaw under the coming decades of future warming.



4.2 Millennial-scale landscape processes constrain modern thaw trajectories

The pronounced spatial clustering of degradation trajectories indicates that permafrost thaw is not random but instead constrained by geomorphic features. Ice-wedge terrain is known to respond variably to warming, with explanatory factors including climatic conditions, surficial geology, and regional topography often identified as primary controls on regional thaw patterns across the Arctic (Abolt et al., 2024; Frost et al., 2018; Liljedahl et al., 2024). Rather than responding uniformly to climate forcing, degradation trajectories at our site were consistently organized by hectare-scale landforms, indicating that these features formed over millennia govern where thaw initiates, persists, and intensifies today (Figure 6). In particular, the expansion of degradation from abandoned channels toward a more widespread distribution further supports that landscape evolution under thaw follows a process of hotspot expansion rather than uniform intensification (Figure 5). This transition suggests that degradation may originate in vulnerable geomorphic locations before spreading into less vulnerable adjacent terrain, possibly because the ongoing impacts of warming increased sufficiently to supersede the mechanisms that originally concentrated severe thaw in the abandoned channels, where thaw originated. Overall, our findings indicate that warming is not increasing degradation uniformly across the site but is instead driving a progressive restructuring of the landscape through the emergence and expansion of distinct degradation hotspots (Figure 6).

To understand the spatial organization of permafrost thaw and its vulnerability to degradation, we must contextualize modern degradation by examining the history of landscape formation and evolution. The surficial geology at this site is dominantly fluvial in origin; the abandoned alluvial terrace system was formed over the Holocene period as the Sagavanirktok River migrated east (Rawlinson, 1993). Thaw lakes appeared on this terrace and a portion of these lakes drained over time, producing a range of ages of drained thaw lake basins in which new, relatively young ice-wedge networks could form (e.g., Jones et al., 2022; Mackay and Burn, 2002; Plug and Werner, 2002); these thaw lake basins today, then, have fewer and smaller ice wedges available to thaw, leading to less severe thaw impacts as the Arctic warms. Two active fluvial systems drain this landscape on the western and eastern edges of the site. The areas surrounding these fluvial systems show evidence of abandoned meanders that are now drier tundra. Similar to the drained thaw lake basins, these portions of the landscape are relatively new surfaces post-dating the formation of the alluvial terrace and thus contain younger, less developed ice-wedge networks and less severe thaw. The main hotspots of thaw at this site are present along the abandoned channel network, which, unlike active channels, is composed of surfaces that are either flush with the surrounding terrain or are ~0.5 m higher on the local landscape. This topographic inversion can be produced through preferential winnowing of finer-grained material outside the inverted features (Pain and Ollier, 1995) or through increased frost heave within the features during permafrost formation, similar to the uplift that can occur in recently drained thermokarst lake basins (French, 2017; Jones et al., 2022; Roy-Léveillé and Burn, 2016). The initiation of thaw within these abandoned channels and then the spatial expansion of thaw from the channels onto the fluvial terraces surrounding them implies that these landforms were the most vulnerable portion of this site to thaw. As distinct



landforms are of different ages and geomorphic providence, they have differing susceptibility to ice-wedge formation due to differences in sediment composition, ground ice content, and elevation (Haltigin et al., 2012; Mackay, 1993; Plug and Werner, 2002; Sletten et al., 2003), thus leading to differing volumes of wedge ice available to melt today. Likewise, subtle variations in elevation, vegetation, and soil moisture regimes across those landforms today would impact the transfer of heat into the permafrost (Engstrom et al., 2005; Jafarov and Schaefer, 2016), influencing the modern progression of thaw. Our results suggest that geomorphic history establishes the template for thermokarst, local ecohydrological feedbacks generate heterogeneous thaw trajectories, and contemporary warming drives their progression through time.

Similar associations between geomorphic setting and thermokarst across the Arctic suggest that the spatial organization of thaw observed here reflects a broader property of periglacial landscapes. Geomorphic history creates persistent differences in landscape vulnerability that shape where thaw emerges and the pathways through which it evolves. Although previous studies have primarily interpreted these observations as spatial differences in the magnitude of degradation across regional scales (Abolt et al., 2024; Farquharson et al., 2016; Fraser et al., 2018; Liljedahl et al., 2016), they collectively point to a broader pattern: thaw repeatedly concentrates within specific landforms influenced by geomorphic history. Outside of this site along the Sagavanirktok River, severe thaw is visibly concentrated in abandoned channels along other Arctic rivers including the Canning, Hulahula, and Okpilak. Across the Arctic Coastal Plain, differences in landscape age and sedimentary history create contrasting settings for ice-wedge development and subsequent degradation. Relict surfaces and drained thaw lake basins exhibit distinct polygon morphologies, while frost-susceptible marine silts promote high ground-ice contents that increase susceptibility to thermokarst (Farquharson et al., 2016; Kanevskiy et al., 2013; Munroe et al., 2007). In hillslope settings, landscape position determines the form of ice-wedge growth (Mackay, 1990), and degradation is visibly clustered on hilltops where meltwater runoff can accelerate subsidence rates and diffusive erosion removes insulating soil material (Abolt et al., 2024; Burn et al., 2021; Fraser et al., 2018). The influence of geomorphic history on ice-wedge network organization extends beyond Arctic ice-wedge terrain. In Antarctica, the complexity and geometry of sand-wedge networks, analogous to ice-wedge networks except for the medium of the wedge itself, increases with the relative age of surfaces (Sletten et al., 2003). Previous studies have attributed differences in thermokarst abundance, morphology and landform type among broad geomorphic settings to controls such as regionally varying ground ice, drainage, topography, and sedimentology (Abolt et al., 2024; Farquharson et al., 2016; Frost et al., 2018). Synthesizing our results with observations across periglacial landscapes, we propose a framework in which geomorphic evolution organizes ground ice, drainage, topography, and sedimentary properties across both regional and local scales, thus establishing a spatial template of vulnerability upon which contemporary climate-driven thaw unfolds.



5 Conclusion

470 Ice-wedge degradation across this Arctic landscape did not progress as a uniform expansion of thaw, but through multiple asynchronous and nonlinear trajectories operating simultaneously across fine spatial scales. Over nearly two decades, the location, timing, and severity of these trajectories differed systematically among landforms. Regional increases in degradation therefore represent the average response of multiple local thaw pathways, including thaw initiation, advancement, persistence, drying, and oscillation. Understanding permafrost landscape evolution at local scales thus requires moving beyond how much
475 degradation has occurred to consider where, when, and how thaw unfolds.

Climate warming does not act upon a uniform landscape; it acts upon a geomorphic template with differences in thaw susceptibility. Millennial-scale landscape evolution structures landforms, sediments, excess ground ice, and hydrologic connectivity, while contemporary climate forcing and local ecohydrological feedbacks determine how degradation evolves within that template. These interactions produce divergent trajectories even among neighboring ice wedges and demonstrate
480 that landscape heterogeneity is not simply variability around a common climatic response, but an emergent outcome of geomorphic history and contemporary local feedbacks.

Considered alongside observations from other polar periglacial landscapes, our findings suggest that this organization may provide a broader framework for understanding permafrost landscape evolution. Continued warming is likely to reorganize rather than homogenize Arctic landscapes, thus generating dynamic mosaics of hydrologic, ecological, and biogeochemical
485 states whose feedbacks may reinforce, dampen, or offset one another. Their cumulative effects on ecosystem function and greenhouse-gas exchange may therefore be difficult to infer from regional or average thaw extent alone. Predicting future Arctic change will require representing not only how much permafrost degradation occurs, but the landscape structure and feedbacks that govern where, when, and how thaw evolves.

490 Code and data availability

The data that support the findings of this study are being prepared for deposition in a public data repository.

Supplementary material

The supplementary material is available online as a separate file.



Author contributions

495 K.N.B contributed to the conceptualization, methodology, processing of data, and writing the original draft. J.M. contributed to the methodology and processing of data. C.G.A contributed to the conceptualization and methodology. All authors interpreted results and contributed to reviewing and editing the draft.

Competing interests

The authors have no conflict of interest to disclose.

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Review statement

515 The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.



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