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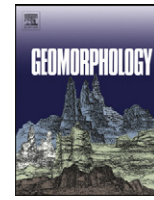

Transferability of regional permafrost disturbance susceptibility modelling using generalized linear and generalized additive models

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ABSTRACT

To effectively assess and mitigate risk of permafrost disturbance, disturbance-prone areas can be predicted through the application of susceptibility models. In this study we developed regional susceptibility models for permafrost disturbances using a field disturbance inventory to test the transferability of the model to a broader region in the Canadian High Arctic. Resulting maps of susceptibility were then used to explore the effect of terrain variables on the occurrence of disturbances within this region. To account for a large range of landscape characteristics, the model was calibrated using two locations: Sabine Peninsula, Melville Island, NU, and Fosheim Peninsula, Ellesmere Island, NU. Spatial patterns of disturbance were predicted with a generalized linear model (GLM) and generalized additive model (GAM), each calibrated using disturbed and randomized undisturbed locations from both locations and GIS-derived terrain predictor variables including slope, potential incoming solar radiation, wetness index, topographic position index, elevation, and distance to water. Each model was validated for the Sabine and Fosheim Peninsulas using independent data sets while the transferability of the model to an independent site was assessed at Cape Bounty, Melville Island, NU. The regional GLM and GAM validated well for both calibration sites (Sabine and Fosheim) with the area under the receiver operating curves (AUROC) > 0.79. Both models were applied directly to Cape Bounty without calibration and validated equally with AUROC's of 0.76; however, each model predicted disturbed and undisturbed samples differently. Additionally, the sensitivity of the transferred model was assessed using data sets with different sample sizes. Results indicated that models based on larger sample sizes transferred more consistently and captured the variability within the terrain attributes in the respective study areas. Terrain attributes associated with the initiation of disturbances were similar regardless of the location. Disturbances commonly occurred on slopes between 4 and 15°, below Holocene marine limit, and in areas with low potential incoming solar radiation.

1. Introduction

Increasing temperatures in arctic regions present new challenges for northern communities as permafrost is integral to the stability of arctic ecosystems and infrastructure built on perennially frozen ground (Kokelj and Jorgenson, 2013). Of particular concern is warming permafrost and thickening of the active layer because both can lead to thawing of ice-rich ground, terrain subsidence, and permafrost disturbance. Permafrost slope disturbance, in the form of active layer detachments (ALDs) and retrogressive thaw slumps (RTSs), have been observed with increasing frequency across the circumpolar arctic (Jorgenson et al., 2006; Lantz and Kokelj, 2008; Lamoureux and Lafrenière, 2009). These disturbances have implications for infrastructure (Nelson et al., 2002), drive shifts in terrestrial and aquatic ecosystems (Lafrenière and Lamoureux, 2013), and release carbon preserved in frozen ground (Grosse et al., 2011). To understand the potential for future permafrost slope disturbance, a better spatial understanding of where permafrost disturbances are likely to occur is needed.

One method used to assess the probability of future disturbances is the development of susceptibility models. Whereas susceptibility modelling does not explicitly imply a time frame because no assessment of the frequency of previous occurrences exist, the focus is placed on identifying disturbance-prone areas under the assumption that areas declared susceptible will have terrain conditions comparable to those in areas where disturbances have already occurred (JTC1, 2004). A site-specific statistically based susceptibility model of permafrost slope disturbances and map have recently been developed for one location in the Canadian High Arctic (Rudy et al., in press). Using a generalized additive model (GAM) fitted to disturbed and undisturbed locations and relevant GIS-derived predictor variables, the model accurately delineated areas across the landscape that were susceptible to ALDs. Local susceptibility maps of permafrost disturbance provide a first step in hazard and risk assessment and are promising for land management and decision making in remote areas where detailed information on the occurrence of disturbance is unavailable. The applicability of such a

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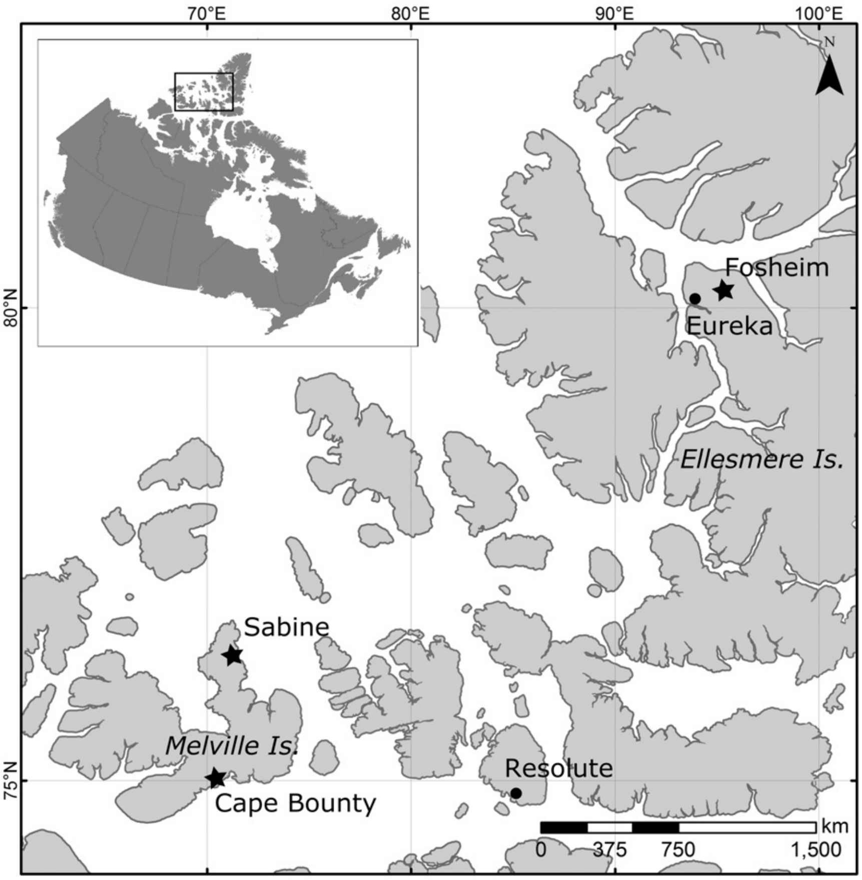

Fig. 1. Study sites are denoted by stars. Climate data were acquired from the weather stations denoted by the black circles. Inset of Canada outlines the region of interest.

model, developed in one context/locale and transferred to new locations, has the potential to improve our regional geomorphological understanding of permafrost disturbance and more importantly aid in hazard assessment through decreased logistical costs.

Transferability is the act of applying a model to data sets other than the one for which it was calibrated (Wenger and Olden, 2012). Transferability can be useful for identifying the types of relationships and patterns that exist between predictor and response variables; in other words, it can be used to distinguish whether terrain characteristics associated with disturbances are site specific or if more general characteristics can be attributable to the initiation of disturbance. A restricted range of variability within terrain characteristics, used to calibrate the model, often limits successful model transferability. Whereas, a model built with predictor variables that cover the same or wider range of terrain conditions than those that are found at the new location is likely to give better predictions (Hjort et al., 2014). Training sites were selected that covered the widest range of terrain variability. Another limitation is the use of predictor variables without a perceived mechanistic link to the response variable (Austin and Smith, 1989; Randin et al., 2006). Hence, the selection of relevant terrain attributes in susceptibility modelling that are transferable is important because they simplify potentially complex geomorphological processes while acting as surrogates for regional site characteristics.

Factors that impact susceptibility to disturbance can be grouped into two categories: (i) intrinsic variables that contribute to disturbance susceptibility, such as slope angle, soil moisture, drainage patterns, solar radiation; and (ii) extrinsic variables that trigger disturbances, such as increased thaw depths or large precipitation events (Wu and Sidle, 1995; Atkinson and Massari, 1998). Extrinsic variables, while important, are often difficult to estimate and may vary on short time scales. Intrinsic variables represent the properties that make an area inherently susceptible to failure and can be expected to change over a geomorphological time scale (Siddle et al., 1991). The spatial distribution of these intrinsic properties within a given region determines the relative disturbance susceptibility for that area (Carrara et al., 1995).

In this study we adopt a statistical approach to assess the transferability of a regional susceptibility model with intrinsic predictor variables developed using two locations in the Canadian High Arctic: the Sabine Peninsula, Melville Island, NU, and the Fosheim Peninsula, Ellesmere Island, NU. To assess the transferability of this model, a third independent location, Cape Bounty, Melville Island, NU, was used for validation. We utilized two statistical techniques, a generalized linear model (GLM), and a generalized additive model (GAM) to answer three questions: (i) Are susceptibility models fitted with GLMs and GAMs transferable in space? (ii) What influence does sample size have on model calibration and model transferability? (iii) What are the main factors driving the initiation of permafrost disturbances in different landscapes?

2. Study areas

Three study areas in this research extended from 75 to −80° North latitude (Fig. 1). Two locations, Cape Bounty (~75° N) and the Sabine Peninsula (~77° N) (hereafter referred to as the Sabine) are located on Melville Island, NU, whereas the third is located on the Fosheim Peninsula (~80° N) (hereafter referred to as the Fosheim), Ellesmere Island, NU. These locations were selected to calibrate and validate the regional model because they are part of the same broad geological and physiographic region in the Canadian High Arctic (Fig. 1).