Geomorphology 204 (2014) 165–176

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Transferability of geomorphological distribution models: Evaluation using solifluction features in subarctic and Arctic regions

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ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form 12 July 2013
Accepted 4 August 2013
Available online 13 August 2013

Keywords:
Extrapolation
Generalized linear model
Generalized additive model
Maximum entropy
Solifluction
Statistical modeling

ABSTRACT

Extrapolation potential of statistically-based geomorphological distribution models (GDMs) has not been scrutinized. Here, the possibility to transfer solifluction models within and between six study areas in subarctic and Arctic environments was examined. A generalized linear model, generalized additive model, maximum entropy and boosted regression tree methods were used in the analyses. The transferability success of the GDMs was assessed by the area under the curve of a receiver operating characteristic plot. Based on the results, slope angle, mean annual air temperature and a remote sensing based index of vegetation abundance were the most important variables contributing to the occurrence of solifluction at a landscape scale. In model extrapolation, over half of the calibrated solifluction models were transferable from one area to another. The topographical conditions of the study areas had a greater effect than climate conditions on the extrapolation potential. More precisely, it was more difficult to extrapolate the models to a high-relief environment than to an area with moderate topography. On the contrary, the models transferred within Arctic and subarctic areas were not better than the models between the Arctic and subarctic environments. In conclusion, (i) region specific geomorphological and environmental conditions may significantly affect the relative importance of variables in GDMs, (ii) solifluction models were transferable with certain limitations across areas, (iii) the range of the environmental conditions of the calibration area was a critical factor for transferability success and (iv) machine learning-based methods performed marginally better than parametric models in the model extrapolation. Extensive knowledge about the transferability of GDMs in space is needed before the models can be reliably used in climate change explorations.

1. Introduction

Modern Earth observation data acquisition techniques facilitate detailed mapping of land surfaces in various ways. For example, advances in laser scanning technologies and hyperspectral sensors have provided new surveying approaches (Bishop et al., 2012). Nevertheless, the exploration of the relationship between geomorphological processes and environmental drivers can be problematic in extensive and inaccessible areas (Harris et al., 2009). Statistically-based geomorphological distribution models (GDMs) provide an alternative approach to mapping and analyzing earth surface processes and landforms (Carrara, 1983; Guzzetti et al., 1999; Brenning, 2005; Hjort and Luoto, 2013).

The transferability or extrapolation potential of models at the regional scale has mostly remained unexplored. Predictive geomorphological models have often been evaluated utilizing semi-independent data sets, derived from splitting the study area into two or more subareas (Chung and Fabbri, 2003). This approach gives an indication of the robustness of the model in a particular environmental setting and is an estimation of interpolation rather than a true measure of extrapolation potential. Consequently, little effort has been put into assessing the extrapolation potential of GDMs. Better knowledge about the extrapolation potential would lead to the development of more robust models in geomorphology, which would eventually advance the understanding of geomorphological systems. Moreover, advanced knowledge concerning the possibilities to transfer models across space (i.e., regions and scales) would be highly important before the models can be reliably used to investigate the potential consequences of climate change on geomorphological processes and landforms (i.e., temporal extrapolation; e.g. Fronzek et al., 2006, 2011).

Solifluction is an important mass-wasting and denudation process, shaping the landscape slowly but extensively in high-latitude and high-altitude environments (French, 2007). Since the seminal paper of Andersson (1906), the occurrence and movement rates of solifluction have been the focus of interest in numerous laboratory and field-based studies (Matsuoka, 2001; Harris et al., 2009; Goodfellow and Boelhouwers, 2013). Recently, GDMs have also been applied to study the relationship between solifluction and environmental factors at local and landscape scales (e.g. Ridefelt et al., 2010).

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0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.08.002

In this study, we explored the possibility of extrapolating GDMs on a landscape scale, by analyzing the transferability of statistically-based solifluction models within and between six study areas in subarctic and Arctic regions. To assess the extrapolation potential, we utilized four different statistical techniques: the generalized linear model (GLM), generalized additive model (GAM), maximum entropy (MAXENT) and boosted regression tree (BRT) method. Moreover, GLMs and GAMs were calibrated using two different approaches, Akaike's Information Criterion (*AIC*) and Bayesian Information Criterion (*BIC*). Specifically, we focused on four main questions: (i) Which are the main factors affecting the occurrence of solifluction landforms in different environments? (ii) Are statistically-based solifluction models spatially transferable? (iii) How do the environmental conditions of the calibration and extrapolation area affect the transferability potential? (iv) Are complex machine learning-based models (BRT and MAXENT) more susceptible to a performance drop than parametric (GLM_{AIC} and GLM_{BIC}) models?

2. Study areas

A range of high-Arctic and subarctic areas with moderate to high-relief were selected for analysis (Fig. 1; Table 1). The study area in Adventdalen (235 km^2, Arctic with high-relief) covers the inner and southern part of a valley in the central part of Nordenskiöld Land, Spitsbergen (Fig. 1). The bedrock consists of flat-lying, sedimentary rocks of Triassic to Tertiary age, mostly sandstone, siltstone and shale (Dallmann et al., 2001). The surficial deposits in the central part of the valley mainly consist of till or fluvial material while the rest is dominated by solifluction- and weathering deposits. The vegetation is sparse and belongs to the mid- and high Arctic vegetation regions. The area belong to the zone of continuous permafrost and at Janssonhaugen, which is located within the study area, temperature at the depth of zero annual amplitude is c. −5 °C (Christiansen et al., 2010).

The Kvadehuksletta study area (17 km^2, Arctic with moderate relief) is located about 10 km NW of Ny-Ålesund in western Spitsbergen (Fig. 1). The area is a strandflat bounded by a steep scarp bordering a 300 m high dissected plateau. The bedrock of the area is dominated by Permo-Carboniferous limestone and marble and minor areas of younger clastic sediments. Surficial deposits mainly consist of till, weathering material and well-drained marine beach sediments (Tolgensbakk and Sollid, 1987). The area lies in the zone of continuous permafrost (Christiansen et al., 2010).

The Kåfjord study area (172 km^2, subarctic with high-relief) east of the Lyngen fjord in Troms, includes Nordmannvikdalen and Pilteridalen and the higher mountain areas surrounding the valleys (Fig. 1). The bedrock belongs to the Caledonian Kåfjord Nappe of the Reisadalen Nappe Complex and consists mainly of mica schist. Some of the highest mountains are made of quartz schist, while a minor area north of Pilteridalen consists of limestone (Zwaan, 1988). Due to high relief most of the hillsides are covered by colluvium while valley bottoms have till and higher plateaus are covered by weathered material and block fields (Tolgensbakk and Sollid, 1988). Below the climatic treeline at 250 m a.s.l. there is birch forest. Grass heath that is rich in lichens and moss dominates the higher lying areas. The lower permafrost limit is located at 800–900 m a.s.l. (Christiansen et al., 2010; Farbrot et al., 2013).

Nordre Andøya (135 km^2, subarctic with high-relief) is part of the northernmost island in the Vesterålen archipelago in Nordland (Fig. 1). Apart from a small area in southeast with Jurassic and Cretaceous sedimentary rocks, Nordre Andøya consists of autochthonous basement rocks of Precambrian age, a central area of granite surrounded by granitic gneiss and a zone of gabbros running diagonally NW–SE (Sigmond et al., 1984). The central part is dominated by an alpine relief with several large cirques, and this area is surrounded by lowland belonging to the strandflat. Most of the strandflat is covered by peat, but along the shore beach sediments and eolian material are also found. Till dominates the upland where solifluction landforms are found (Flakstad et al., 1985). Nordre Andøya does not have permafrost at present, but several relict rock glaciers indicate former permafrost presence (Lilleøren and Etzelmüller, 2011).

The Mållejus study area (143 km^2, subarctic with moderate relief) covers the border area between the counties Troms and Finnmark east of Reisa National Park (Fig. 1). The southern margin of the Caledonian Kalak Nappe Complex coincides with the southern part of the study area. Quartz schist and meta-arkose constitute most of the bedrock (Sigmond et al., 1984). Most of the area is covered by a thick layer of till and with few exceptions solifluction landforms are solely found in till deposits (Tolgensbakk and Sollid, 1983). Mållejus is well above the climatic treeline and vegetation cover is characterized by open heather communities. The area lies in the zone of sporadic and discontinuous permafrost (Christiansen et al., 2010; Farbrot et al., 2013).

Paistunturit (114 km^2, subarctic with moderate relief) is located in northernmost Finnish Lapland (Fig. 1). The area is characterized mostly by open uplands with forests of subalpine mountain birch *Betula pubescens* ssp. *czerepanovii*, shallow peat supporting mires, and gently sloping glacially sculptured fells (Hjort, 2006). Geologically, the study area belongs to the Pre-Cambrian c. 1.9 billion-year-old granulite complex (Meriläinen, 1976). Basal till is the predominant surficial ground material type of the Paistunturit study area. The climate is typically subarctic and permafrost is likely widespread at elevations above 500 m (Table 1; Christiansen et al., 2010).

3. Material and methods

3.1. Solifluction features

Solifluction was utilized in this transferability examination because it is a common, widespread mass-wasting process in cold environments, and solifluction features have successfully been modeled in previous GDM studies (e.g. Etzelmüller et al., 2001; Ridefelt et al., 2010). The occurrence of solifluction was determined using landforms considered as clear indicators of solifluction operation over a considerable period of time and/or at present (Tolgensbakk and Sollid, 1983; Flakstad et al., 1985; Tolgensbakk and Sollid, 1987, 1988; Tolgensbakk et al., 2000; Hjort, 2006).

In the two Svalbard study areas, non-sorted solifluction lobes and sheets are frequent on moderately inclined slopes. The abundance of these features is facilitated by the dominance of Mesozoic sedimentary rocks, producing relative fine-grained surface material. In such areas the active-layer soil is often a frost-susceptible sandy silt diamicton, containing coarser clasts. Harris et al. (2011) showed that the geotechnical properties reflect the soil granulometry with low values of plastic and liquid limits and low plasticity meaning that soil consistency is sensitive to moisture changes, which is typical for solifluction slopes where clay contents are low (Harris et al., 2011). Due to the continuous permafrost conditions two-sided freezing processes dominate the activity of the landforms (Harris et al., 2011).

In northern Norway, solifluction features are often found below the limit for discontinuous permafrost, but above the limit of sporadic permafrost. Both non-sorted lobes and sheets are common, and they are frequently found just below the regional permafrost limit, e.g. in the Kåfjord area at between 500 and 700 m a.s.l. There, the dominance of mica shists facilitates a silt-rich diamicton, susceptical to frost action. In the study areas of northern Norway, solifluction activity is governed by one-sided freezing, similar to what was reported from mountainous areas in southern Norway (Harris et al., 2008).

In the Paistunturit study area, the most common landform types are sorted solifluction sheets and streams and non-sorted terraces (Hjort, 2006). Lobe-like landforms are relatively rare in the area. The areal cover of sorted solifluction features is several times higher when compared to non-sorted features. One-sided freezing, frost creep and sorting