Received: 16 December 2022 | Revised: 18 May 2023 | Accepted: 14 June 2023

DOI: 10.1111/ejss.13393

RESEARCH ARTICLE

European Journal of Soil Science WILEY

# Soil moisture, stressed vegetation and the spatial structure of soil erosion in a high latitude rangeland

**N. A. Cutler**[1] | **G. Kodl**[2] | **R. T. Streeter**[2] | **P. I. J. Thompson**[3] | **A. J. Dugmore**[3,4]

[1]School of Geography, Politics & Sociology, Newcastle University, Newcastle upon Tyne, UK

[2]School of Geography & Sustainable Development, University of St Andrews, St Andrews, UK

[3]School of Geosciences, University of Edinburgh, Edinburgh, UK

[4]Graduate Center, City University of New York, New York City, New York, USA

**Correspondence**
N. A. Cutler, School of Geography, Politics & Sociology, Newcastle University, Newcastle upon Tyne, UK.
Email: nick.cutler@ncl.ac.uk

**Funding information**
Natural Environment Research Council, Grant/Award Number: NE/L002558/; University of St Andrews

## Abstract

Soil erosion has been a persistent problem in high-latitude regions and may worsen as climate change unfolds and encourages increased anthropogenic exploitation. We propose that soil moisture is likely to shape future erosion trends, as moisture stress reduces the capacity of vegetation cover to retard erosive processes. However, the spatial variability of soil moisture in high-latitude soils—and the ways in which this variability drives the spatial distribution of erosion features—is poorly understood. We addressed this knowledge gap with a study of andosol erosion in southern Iceland. Our study used a combination of high-resolution (<3 cm) remote sensing data (using normalised difference vegetation index (NDVI) and normalised difference red edge as metrics of plant vitality) and long-term, in situ measurements of soil moisture to unpick the relationship between moisture stress, vegetation vitality and patchy soil erosion. Mean NDVI increased with distance from eroded areas, varying from ~0.6 in vegetated areas on the margins of erosion patches to ~0.8 in areas >10 m from eroded terrain. We found lower moisture availability close to existing erosion features: mean volumetric soil moisture content varied from 17% (proximal to erosion patch) to 36% (distal to erosion patch). We also found that variability in soil moisture decreased with distance from eroded areas: the coefficient of variation (CV) in soil moisture varied from 0.33 (proximal to erosion patch) to 0.13 (distal to erosion). Our findings indicate that the margins of erosion patches have a stressful soil environment due to exposure to the atmosphere. The vegetation in these locations grows less vigorously, and the exposed soil becomes more vulnerable to erosion, leading to erosion patch expansion and coalescence. If these conditions hold more generally, they may represent a feedback mechanism that facilitates the lateral propagation of soil erosion in high-latitude regions.

KEYWORDS

aeolian erosion, andosol, biogeomorphology, NDVI, rofabard, soil degradation

https://doi.org/10.1111/ejss.13393

## 1 | INTRODUCTION

Soil erosion is a growing global crisis (Olsson et al., 2019). It is often conceptualised as a problem of low- and mid-latitude locations. However, soil erosion also occurs in high-latitude regions and may worsen as these regions warm and are subjected to increased anthropogenic exploitation (Grosse et al., 2011; Heindel et al., 2015; Hilton et al., 2015; Owczarek et al., 2022). Many factors combine to influence the extent and severity of high-latitude soil erosion, including climate, vegetation cover, parent material, soil type and land management (Arnalds, 2000; Grosse et al., 2011; Heindel et al., 2015). Soil moisture availability is likely to be particularly important, as water affects the physical, chemical and biological characteristics of soils and, by extension, their capacity to resist erosion. We explored the biogeomorphological dimensions of this phenomenon, focussing on the interaction between moisture availability, plant vitality and soil erosion. Water is a limiting resource for plant growth in many high-latitude terrestrial ecosystems (Kemppinen et al., 2019); the marginal conditions for plant growth in these habitats mean that even small variations in moisture availability can have a profound impact on ecosystem function (Kemppinen et al., 2018; Myers-Smith et al., 2015; Tyystjarvi et al., 2022). In the context of soil erosion, vegetation stressed by soil moisture conditions has a reduced capacity to retard soil loss. However, the spatial variability of soil moisture in high-latitude soils—and the ways in which this variability drives the spatial distribution of soil erosion—is poorly understood. Our research addresses this knowledge gap by using a combination of high-resolution (drone-acquired) remote sensing data and long-term, in situ measurements of soil moisture to unpick the relationship between moisture stress, vegetation vitality and patchy soil erosion in a sub-Arctic habitat.

High-latitude soil erosion is particularly prevalent in areas that support pastoral farming on marginal soils, e.g., southern Greenland (Jacobsen, 1987; Massa et al., 2012) and Iceland (Arnalds, 2015; Barrio et al., 2018; Dugmore et al., 2009, 2020; Gísladóttir et al., 2010; Ólafsdóttir et al., 2001; Streeter et al., 2015). These regions have experienced rapid environmental change in the last few decades, warming at 2–4 times the global average (Post et al., 2019; Rantanen et al., 2022). Climatic amelioration is likely to increase the exposure of high-latitude regions to human exploitation in the coming decades. Thus, soils here could face increased stress from climate change and increased anthropogenic impacts, both of which are likely to accelerate existing erosion or initiate erosion where it does not currently occur (e.g., Gísladóttir, 2006).

**Highlights**

- Connections among soil moisture, vegetation vitality and high-latitude soil erosion were investigated.
- A novel combination of remote sensing data and in situ measurements of soil moisture was used.
- A consistent relationship among soil moisture, vegetation cover and erosion was found.
- We propose a feedback mechanism that may shape the progression of high-latitude soil erosion.

Many factors combine to promote high-latitude soil erosion, including vegetation type and cover, soil type, spatiotemporal patterns of snow lie, the magnitude and frequency of freeze–thaw cycles, degree of exposure to winds and grazing by large herbivores. Soil moisture is a critical but frequently overlooked factor, as it has been shown to impact plant growth and—by extension—the ability of vegetation cover to retard erosion (Berdanier & Klein, 2011; Kemppinen et al., 2022). Drought is obviously stressful to plants (Grace, 1997), but variability in soil moisture levels (e.g., rapid cycling between soaked and parched conditions) can also lead to reduced growth and sparser cover (Kemppinen et al., 2019). Spatial variation in soil moisture conditions may be a factor in determining which areas are vulnerable to erosion and which are resilient. However, little is known about how patchiness in moisture stress drives the distribution of soil erosion in high-latitude habitats.

Our study aimed to unpick the spatial relationships among soil moisture, vegetation vitality and soil erosion on an eroded rangeland site in Iceland. The site is characterised by patches of eroded terrain surrounding vegetated 'islands' with thick soil cover. The boundaries between these two patches are low (a few metres high) scarps of exposed soil, named *rofabards* in Icelandic (Arnalds, 2000) (Figure 1a). Previous work in Iceland has argued for the importance of small erosion patches in triggering rofabard erosion (Dugmore et al., 2009; Gísladóttir, 2001). A recent study of erosion patch formation and growth in Iceland by Streeter and Cutler (2020) demonstrated that small openings in vegetation cover—incipient erosion patches indicative of stressed plants—cluster around large erosion patches. Based on this observation, we hypothesised that moisture stress decreases with increasing distance from the edge of the erosion patch, i.e., plants closer to the rofabard scarps

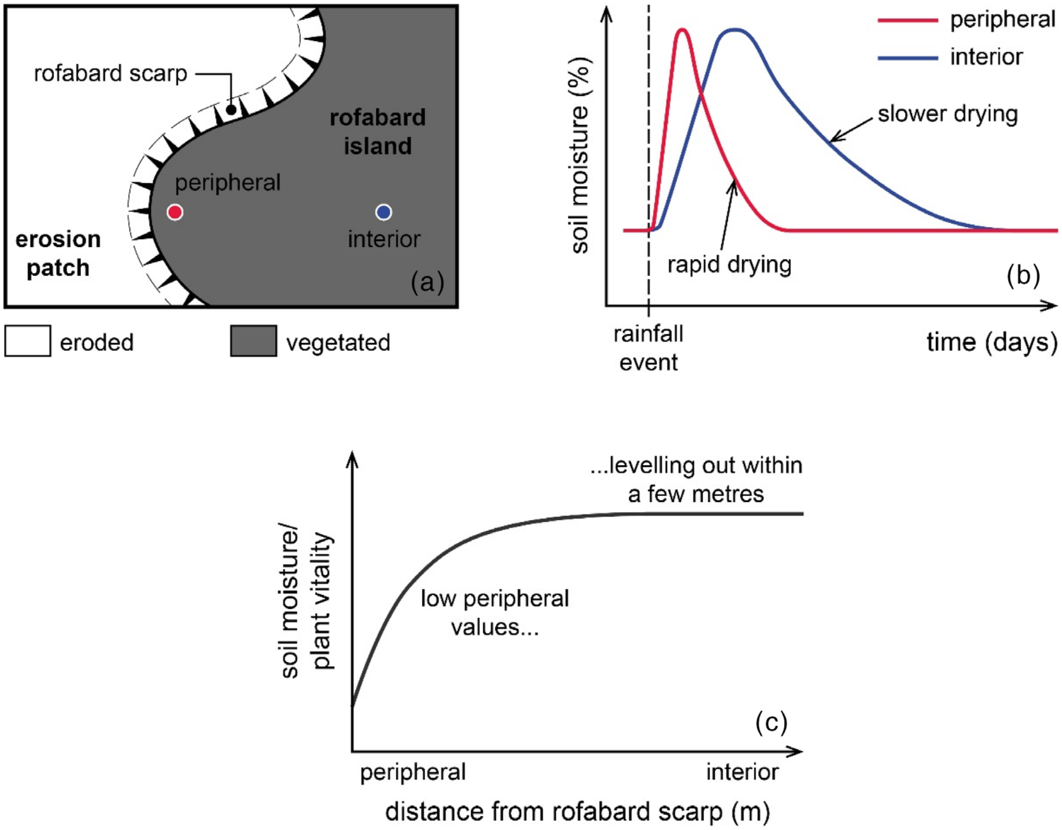

**FIGURE 1** Soil moisture and erosion (a) diagram illustrating Icelandic erosion features known as rofabards with indicative soil moisture sensor locations marked as red and blue circles (b) hypothesised changes in soil moisture following a rainfall event, according to distance from the edge of an erosion patch (delineated by the top edge of the rofabard scarp); peripheral locations close to the rofabard scarp are shown with a red line; interior locations are indicated with a blue line; (c) hypothesised relationship between plant vitality/moisture and distance from a rofabard scarp.

will be more stressed than those further away. This is because areas close to the rofabard scarp (peripheral areas) are likely to wet and dry more quickly than those further away (interior areas), due to their exposure to wind and driving rain. They are also likely to remain drier for longer due to evaporation from the exposed soils of the rofabard scarp (Figure 1b). We propose that the vitality of plants close to the rofabard scarp will be lower because of these soil moisture conditions (Figure 1c), although other factors, e.g., physical disturbance by sheltering sheep, may also contribute to stressful growing conditions.

We used two approaches, applied at different spatial scales, to investigate relationships among soil moisture, vegetation vitality and soil erosion:

1. At a landscape scale (10s–100 s m), we used normalised difference vegetation index (NDVI) and normalised difference red edge (NDRE) data, derived from multispectral uncrewed aerial vehicle (UAV) imagery, as a proxy for vegetation vitality.
2. At a fine scale (~10 m), we supplemented our UAV imagery with measurements of soil moisture, collected over 12 months.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

The study was conducted at Hamragarðaheiði (63.61393° N, −19.96424° E, approx. 200 m above sea level), a site on the western flank of Eyjafjallajökull, Iceland (Figure 2). The site was selected because (1) it has suffered soil erosion in the past; (2) the vegetated surfaces are relatively flat (so the impact of slope on soil hydrology in these areas is minimised) and (3) the vegetation cover is homogeneous (in terms of both structure and composition) at a landscape scale.

Hamragarðaheiði experiences cold winters and cool summers and receives around 1380 mm of precipitation each year (Figure 2d,e). Prevailing winds are from the

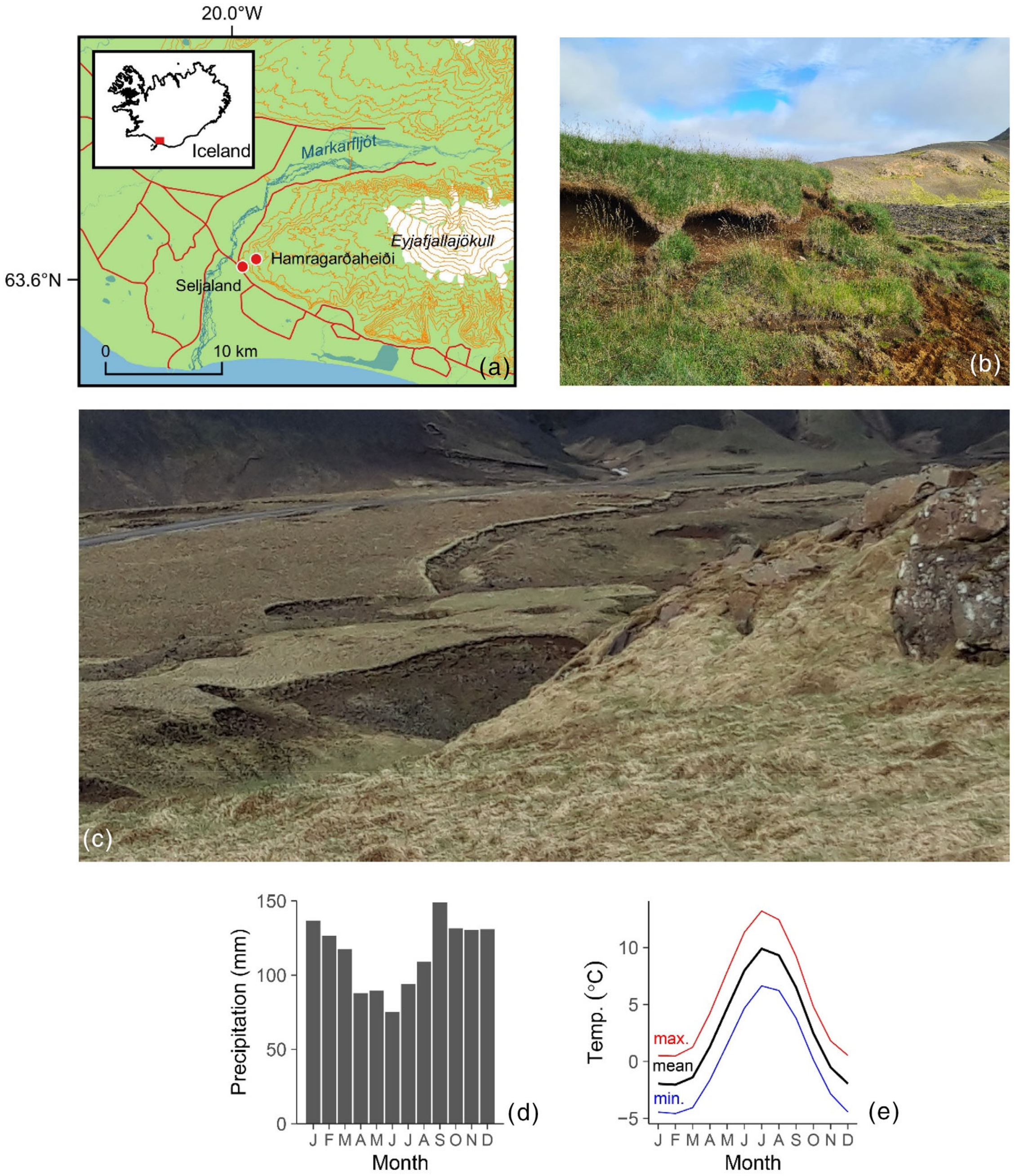

**FIGURE 2** Study site (a) location plan; (b) a rofabard scarp on the Hamragarðaheiði site; the low (approx. 2 m high) vertical face of andosol (left-hand side) is partially obscured by overhanging vegetation; blocks of detached vegetation can be seen in the foreground on a shallow slope of eroded sediment; eroded terrain is visible in the background (c) a view of the Hamragarðaheiði site looking SSE from 63.620° N 19.971° W; note the rofabard scarps; (d) mean monthly precipitation and (e) mean monthly temperatures for the Rangárvalla region of southern Iceland, 1991–2020 (World Bank Group, 2022).

east (Einarsson, 1984). Climate models suggest mean annual temperatures in Iceland will increase by 1.3–2.1°C by the mid-twenty-first century, coupled with small (1.2%–4.3%) increases in mean annual precipitation, probably concentrated in the late summer and early autumn (Icelandic Meteorological Office, 2023). In the future, one would therefore expect higher temperatures to promote evapotranspiration in summer, leading to soil moisture deficits during the growing season.

The Hamragarðaheiði site is grazed by sheep at low stocking densities from May to September. The soil cover in this region is Brown Andosol up to around 2 m thick. Brown Andosol is an Icelandic classification that corresponds to the World Reference Base for Soil Resources

(WRB) category of Haplic/Mollic Andosol (Arnalds, 2015). Icelandic Brown Andosols are derived primarily from tephra parent material and aeolian deposition rather than bedrock weathering, and they are correspondingly fine (the largest fractions are silt and sand-sized) and free-draining (Arnalds, 2004). Soil organic matter content is highly variable but is typically in the range of 5%–7% (Arnalds, 2005). The high proportion of Al and Si in the glassy parent material promotes the formation of allophane, a clay mineral with a high capacity for water retention. However, the allophane tends to form stable, silt-sized aggregates and Brown Andosols lack phyllosilicates that provide cohesion in other soils (Arnalds, 2005). Hence, Brown Andosols are friable when dry, rendering them vulnerable to erosion. The Hamragarðaheiði site has experienced severe soil erosion in the past, with many large (10s m) erosion patches. The patches expand at the margins by a few cm per annum, a process largely driven by aeolian erosion (Arnalds, 2000; Dugmore et al., 2020). Water retention in Brown Andosols is relatively high, but so is hydraulic conductivity (Arnalds, 2005); thus, a period of just a few weeks of low rainfall can be enough to trigger severe moisture stress (Arnalds, 2015).

The geomorphology of the Hamragarðaheiði site is characterised by ‘islands’ of vegetation surrounded by erosion patches (Figure 2b,c). The islands of vegetation are bounded by scarps and have flat tops covered by a thick, grassy sward. The adjacent eroded areas consist mostly of bare lava or sand and are generally not suitable habitats for vascular plants (Arnalds, 2015). In this study, we use the term ‘rofabard island’ to encompass both the erosion scarps *and* the flat-topped, vegetated areas that they surround.

## 2.2 | Remote sensing

We deployed a multispectral drone survey across the whole site (approx. 64,000 m$^2$) to assess spatial variation in NDVI. The survey was conducted in the latter part of the growing season (16 August 2021) and was carried out using a DJI Phantom 4 multispectral (P4m) quadcopter (refer to Supplementary Information for camera settings). Flight planning and execution followed the recommendations of the HiLDEN drone network protocol (Assmann et al., 2019). Seven ground control points (GCP) were deployed and geolocated with a Spectra Precision ProMark 120 GPS system (Spectra Geospatial, Westminster, CO). Additionally, photographs of the reflectance targets (Mapir Inc., San Diego) were taken during the survey for later radiometric calibration.

The survey was flown twice along parallel flight lines (the second set of survey lines was perpendicular to the first). The surveys were flown at an altitude of 48 m, resulting in an average ground sampling distance of ~2.6 cm. Images were acquired with 80% front and side overlap and close to solar noon with a mean absolute difference to solar noon of 1.5 h (max. 2 h). The weather conditions during the flight were overcast with continuous cloud cover.

The remote sensing data were processed using the Pix4D Mapper software (Pix4D SA, Switzerland). Photogrammetric procedures were applied along with georeferencing based on the GCPs and radiometric calibration based on photographs of the calibration targets (refer to Supplementary Information for details). The processed output comprised a digital surface model (DSM) and orthomosaics for each individual band. NDVI was calculated as the normalised difference between the near-infrared (NIR) and red bands:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

We additionally calculated the NDRE index:

$$NDRE = \frac{NIR - Rededge}{NIR + Rededge}$$

We calculated NDRE because it is more robust than NDVI against oversaturation (Nguy-Robertson et al., 2012). This is due to the lower absorption sensitivity of chlorophyll in the red edge region and its deeper penetration into vegetation canopies.

Analysis of the processed images was carried out with QGIS v 3.10. First, surface in the survey area was divided into rofabard islands (following our definition of scarps + flat, vegetated tops) and eroded areas. The rofabard islands had thick soils and continuous vegetation cover; the eroded areas lacked these characteristics. We used the following criteria to classify the rofabard islands:

- The area had an NDVI value >0.4.
- The area had to be connected to a multi-metre-scale vegetated area, not a small (less than metre-scale), isolated fragment of vegetation in an otherwise eroded area.
- The boundary of the rofabard island was defined by a break in slope, identified from a digital elevation map (DEM).

In addition, we cropped the vegetation cover in the northwest corner of the image, as visual inspection indicated it was recent, secondary regrowth on an eroded area, and thus qualitatively different from the vegetation cover on the top of the rofabard islands.

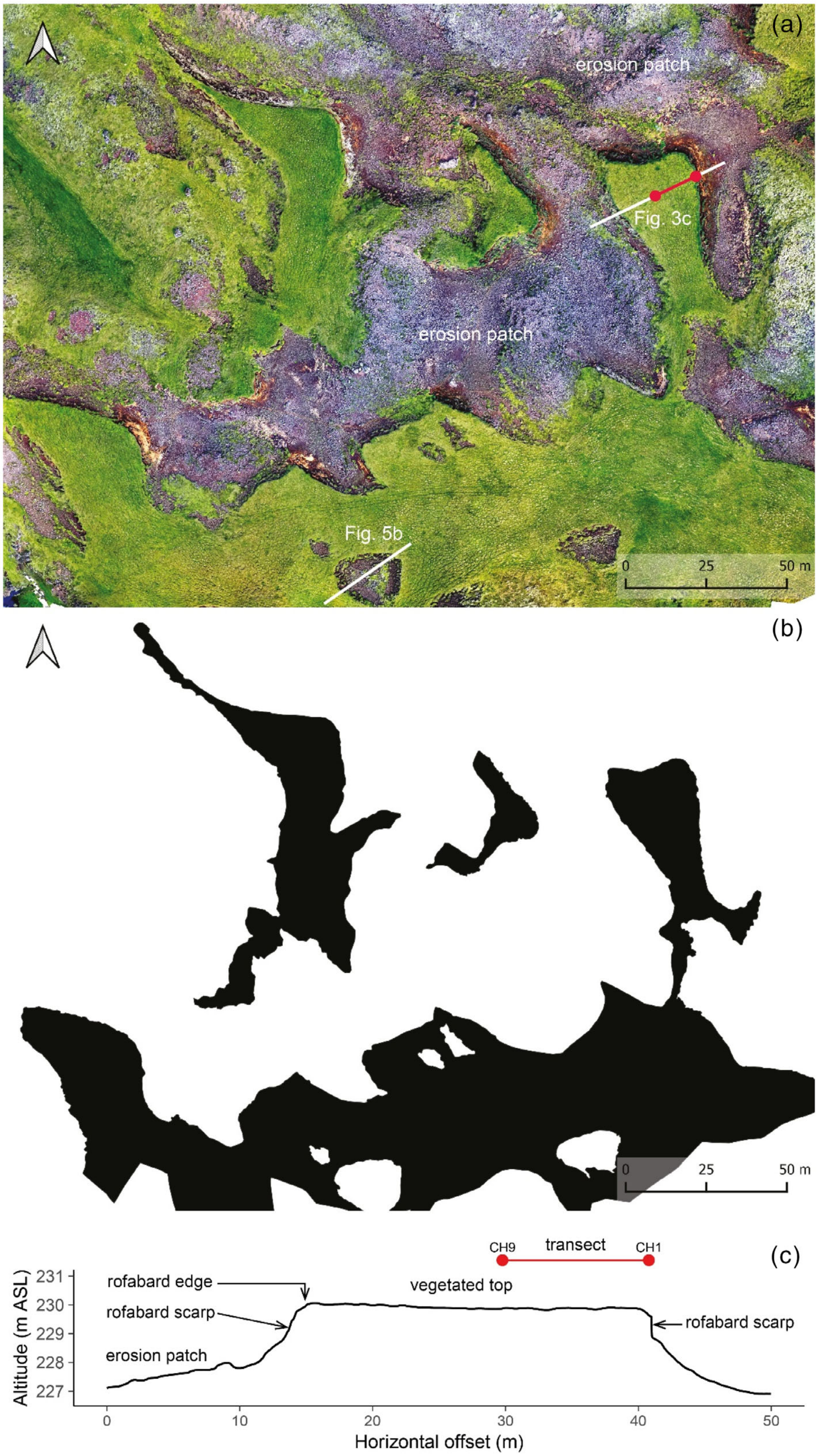

**FIGURE 3** Result of drone survey (a) an overview of the site, showing rofabard islands, eroded areas, and the moisture sensor transect (red dots connected with a red line); (b) the site after being classified into rofabard islands (black) and eroded (white) areas; (c) a section showing the transect location and the profile of the rofabard island on which it was installed (vertical scale exaggerated); note the flat top of the rofabard island.

The area classified as rofabard islands was clipped, and the distance to the nearest rofabard scarp was calculated for each pixel. The pixels were then placed in bins at 1 m intervals, and the mean NDVI and NDRE for each bin were calculated (Figure S1). To ensure that each bin had sufficient points for a representative estimated mean, the distance interval of the last bin was chosen so that its pixel count was at least 10% of the first bin.

### 2.3 | Moisture sensors

In June 2019, we established a transect of nine SMT150 soil moisture probes (Delta-T Devices, Cambridge, UK). The probes determined volumetric soil water content. They were designated CH1–CH9 and arranged along a transect running perpendicular to the edge of a rofabard scarp. This grassy area, like many others in Iceland, is covered with low (cm-scale) earth hummocks. The sensors were placed in the hollows between these hummocks. Probe CH1 was closest to the rofabard scarp (distance = 0.2 m), and Probe CH9 was furthest away (distance = 11.1 m). At each probe location, a small turf block was removed so that the sensors could be placed at a depth of 0.05 m below the surface (Figure S2). We chose a depth of 0.05 m because this placed the sensor in the rooting zone with sufficient soil cover but not so deep that excessive excavation was required. Once the sensor was installed, the turf and soil that had been removed were carefully replaced on top of the sensor to completely cover it. Measurements of soil moisture were made every hour over a 12-month period (1 October 2019–30 September 2020) and recorded on an in-situ Delta-T GP2 data logger (Delta-T Devices, Cambridge). In addition to compiling time series data, we also calculated soil moisture summary statistics, including the coefficient of variation as a metric of variability in soil moisture (Kemppinen et al., 2019). Vegetation composition along the transect was subsequently surveyed using contiguous 0.5 m × 0.5 m quadrats. All plant species present were recorded and quantified according to the Domin scale.

## 3 | RESULTS

### 3.1 | Remote sensing and vegetation survey

The results of the drone survey are shown in Figure 3a. The rofabard islands appear as bright green patches, and the intervening eroded areas as orange/grey patches of exposed sediment and lava. Figure 3b shows the sites divided into rofabard islands (black) and eroded (white) areas following classification (see also Figure S3). Rofabard islands account for 70% of the surveyed area. Visual inspection of the site indicated that the vegetation cover was homogeneous; this was supported by the results of a vegetation survey (Table S1). Briefly, vegetation cover was dominated by grasses (predominantly *Anthoxanthum odoratum*) and small forbs (e.g., *Thymus* sp., *Alchemilla* sp.) to a height of around 30 cm. There were some mosses in the understorey, but these were a minor component of the vegetation. There were also occasional patches of prostrate shrubs (notably *Empetrum nigrum* and *Salix* sp.) but these were small in stature and did not project above the grasses.

Analysis of our drone survey indicated that NDVI and NDRE values were generally lower close to rofabard scarps (Figure 4). Moving towards the interior of the rofabard island (i.e., away from the scarp), mean NDVI/NDRE increased over a distance of 4 m and then levelled out, with a slight increase from 12 m. Variability in NDVI/NDRE was also greatest closer to the rofabard edge (Tables S2 and S3).

The contrast in NDVI between vegetated and eroded areas is illustrated in Figure 5, which shows NDVI values along a transect cutting through an erosion patch. NDVI values in the vegetation surrounding the patch decrease from ~0.8 to ~0.6 on the patch margins, dropping to ~0.4 in the patch centre.

### 3.2 | Moisture sensors

Data from the soil moisture probes showed that locations close to the rofabard scarp were, on average, drier and more variable in terms of soil moisture than locations further away.

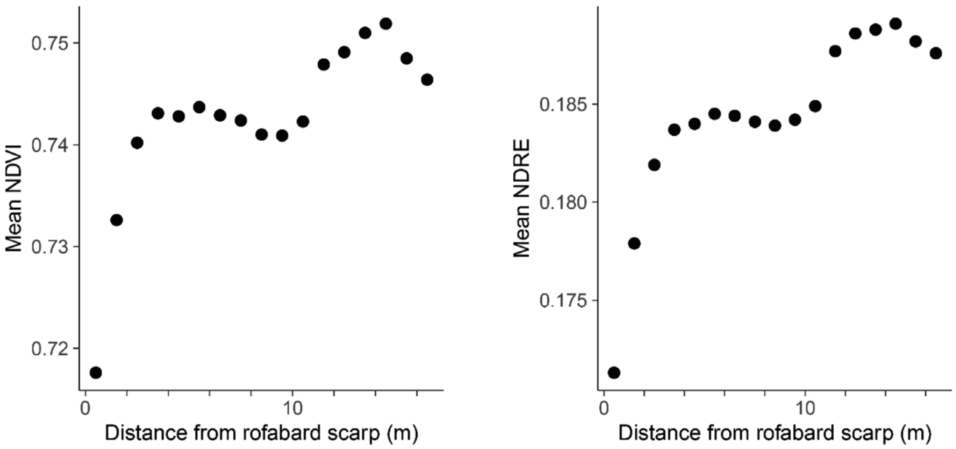

**FIGURE 4** Mean NDVI values (a) and NDRE values (b) plotted against distance from the rofabard scarp (SE values too small to show on this plot).

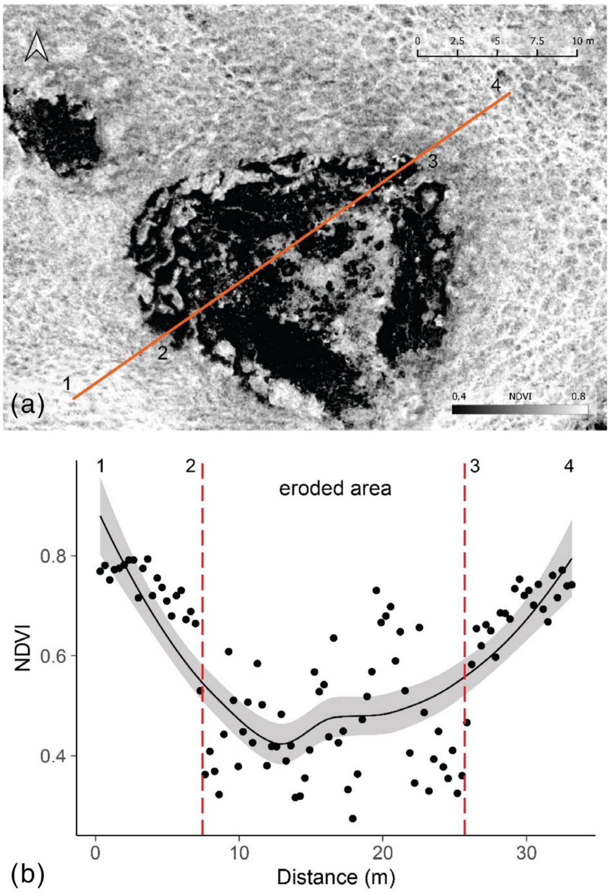

**FIGURE 5** Varying NDVI through an erosion patch: (a) the erosion patch highlighted in Figure 3, with tones representing NDVI values (low NDVI = dark tones, high NDVI = light tones); (b) variations in NDVI along the transect, showing a clear dip in the erosion patch in the centre.

Mean and median soil moisture increased with distance from the rofabard scarp. Mean soil moisture for each of the nine soil probes is shown in Figure 6a. Mean annual soil moisture levels varied by a factor of 2 from 17% to 36%. A quartile regression (Figure 6b) indicated an increase in median soil moisture along our transect. Probe CH2—0.6 m from the scarp—experienced drier conditions than probe CH1 (the probe immediately adjacent to the scarp) (see also Table S4). We calculated the coefficient of variation (CV) for the nine moisture sensors and observed a decrease in variability with distance from the erosion scarp (Figure 6c) for both the whole time series and a subset of recordings from the period May to September 2021, inclusive (i.e., during the growing season). Variability was somewhat lower during the growing season, but both datasets displayed a decrease in variability with increasing distance from the rofabard scarp. Other metrics (e.g., standard deviation) also showed a decrease in soil moisture variability with increasing distance from the scarp (Table S4). The interquartile range for each probe was similar (Figure 6b), indicating that the variability was driven by extreme values.

The importance of extreme values is illustrated by the time series data for individual probes. The moisture readings for probe CH1 (closest to the erosion scarp) and probe CH9 (furthest away) are shown in Figure 7. The peripheral probe (CH1, red line) recorded a much 'peakier' signal than the interior probe (blue line) and a much greater range of values (peripheral range = 66.6%, interior range = 36.5%), both high and low. In comparison, the interior probe exhibited more consistent values.

Differences among the probe locations can be seen clearly in response to (inferred) rainfall events, i.e., the abrupt spikes in the soil moisture record. We selected five rainfall events to study in detail, again comparing the soil moisture data from the ends of the transect (Figure 8). We chose week-long sections of the time series that appeared to represent discrete wetting events, i.e., periods characterised by a steep rising limb followed by a gradual decline to drier conditions. In each case, the signal from the peripheral probe was markedly more extreme (higher initial peaks). With the exception of Event 4, the shape of the peripheral and interior curves—especially the rising limb—was similar, although the slope of the falling limb was less steep in the interior location, suggesting slower drying. Event 4 probably resulted from a short, sharp wetting event (perhaps involving driving rain on the face of the scarp over several hours). The peripheral probe recorded a very steep but short-lived spike in moisture levels during Event 4; the response in interior locations was much more muted.

## 4 | DISCUSSION

Our results are consistent with the hypothesis that moisture stress decreases with increasing distance from eroded areas. The remote sensing data indicated that NDVI increased with increasing distance from the rofabard scarp into the vegetated areas, up to a range of 3–4 m. We interpret this observation as indicating higher plant vitality in areas away from the rofabard scarp. The spectral reflectivity of vegetation has been shown to reflect soil moisture conditions (Engstrom et al., 2008). We therefore propose that the increase in NDVI/NDRE we observed is at least partly explained by soil moisture, which increases and becomes less variable with distance from the rofabard scarp. To show a definitive link among these variables, we would need long-term experimental studies (of 3–5 years duration, say), repeated drone surveys and coupled measurements of soil moisture and

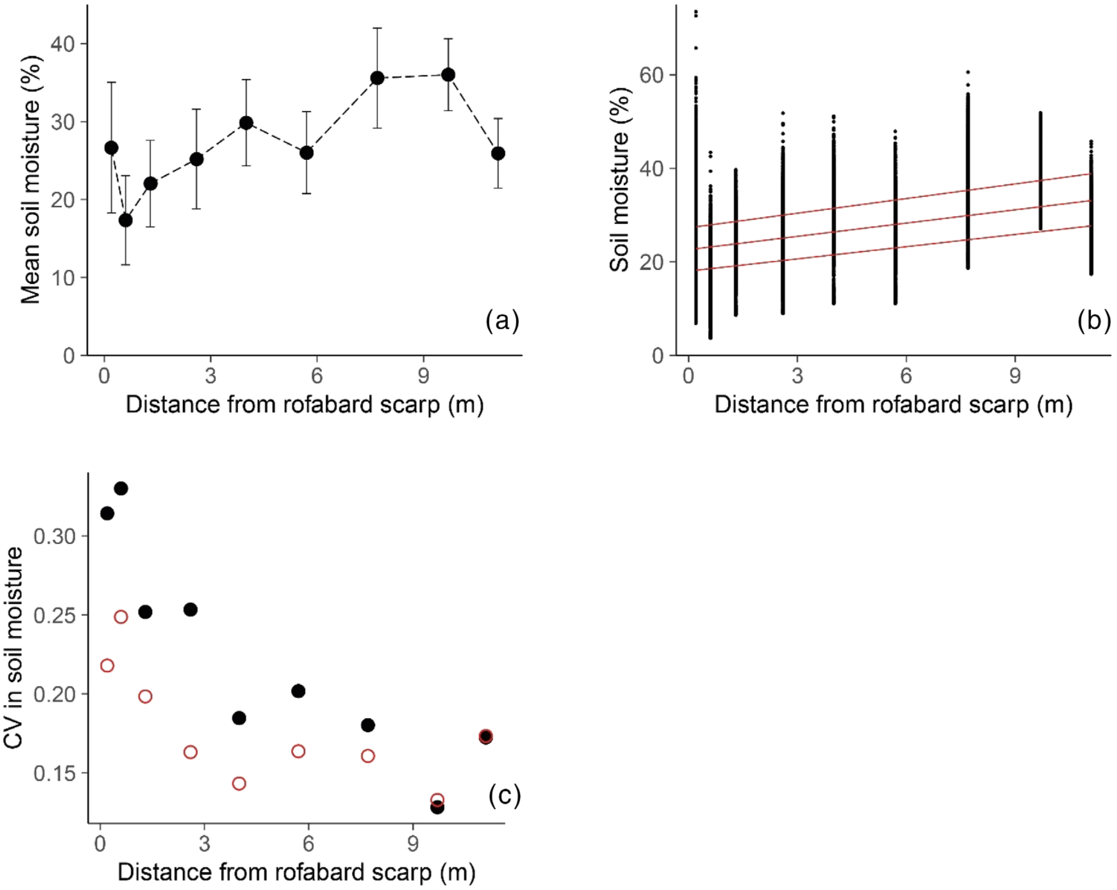

**FIGURE 6** Variation in soil moisture with distance from the rofabard scarp (a) mean soil moisture for the nine soil probes, i.e., CH1 (left-hand side, peripheral) to CH9 (right-hand side, interior); the error bars indicate ±1 SE (b) quartile regression of the soil moisture readings; from top to bottom, the red lines indicate the 75th quartile, the median and the 25th quartile (c) coefficient of variation (cv) for the nine probes; CV for the whole dataset is indicated with filled black points; a subset of values from May–September 2021 (i.e., from the growing season) is indicated with red circles.

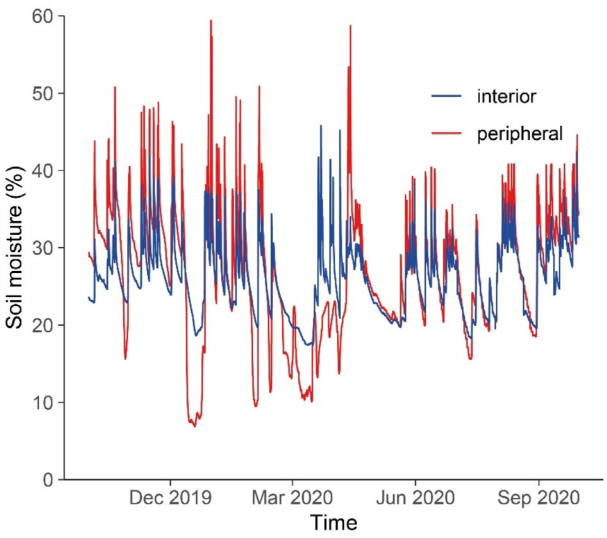

**FIGURE 7** Soil moisture data from the probe nearest the rofabard scarp (CH1, red line) compared with equivalent measurements from the probe furthest from the scarp (CH9, blue line).

vegetation growth along multiple transects. However, our study demonstrates a correlation between soil moisture and plant growth that merits further study.

## 4.1 | Remote sensing data

We observed a relationship between mean NDVI/NDRE and proximity to rofabard scarps. Generally, mean NDVI/NDRE was lower close to scarps and higher further away (Figure 4). The difference was most pronounced closest to the scarps: at distances >3 m from the scarps, mean NDVI did not vary much with distance.

Previous studies have demonstrated the usefulness of NDVI for estimating biotic parameters such as plant biomass, leaf area index (LAI) and $CO_2$ fluxes in high-latitude biomes (Boelman et al., 2003; Walker et al., 2003). For example, NDVI has been shown to be positively correlated with aboveground biomass in northern European tundra (Aalto et al., 2021).

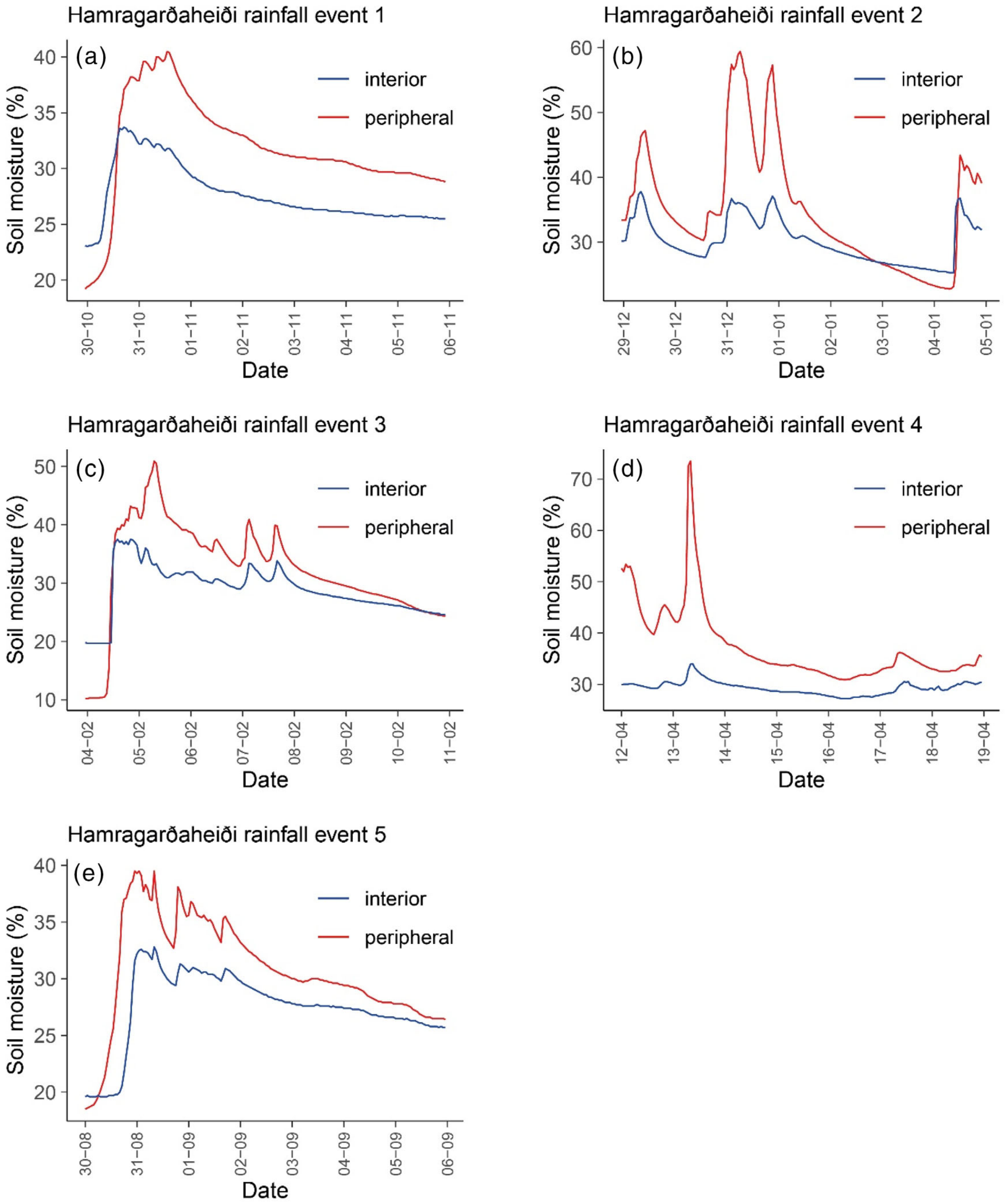

**FIGURE 8** Soil moisture data for selected 'rainfall events' between October 2020 and September 2021. The peripheral signal is from CH1, the probe nearest to the erosion scarp; the interior signal is from CH9, furthest from the erosion patch. Note the peakiness of the peripheral signal and the somewhat slower drying on the interior site.

Riedel et al. (2005) studied graminoids in the Alaskan tundra and demonstrated a positive linear relationship between NDVI and biomass. Climatic amelioration in tundra biomes is frequently associated with a marked 'greening', detectable by NDVI (Myers-Smith et al., 2020). In contrast, stressful conditions such as drought can lead to spectral 'browning' (Bjerke et al., 2014). We therefore attribute the increase in mean NDVI with distance to increased plant vitality.

While spectral vegetation indices like NDVI can contribute to understanding of biotic parameters, they are influenced by many additional factors—notably plant community composition and structure—that could confound interpretation. Plant community composition and structure (i.e., growth form and biomass) can influence the interpretation of the NDVI signal (Goswami et al., 2015). High-latitude vegetation is characteristically patchy, and plant community composition and structure can vary markedly over small spatial scales (e.g., the difference between lichen cover and adjacent deciduous shrubs). Moss cover—a common component of high-latitude vegetation—obscures the relationship between NDVI and biomass: in an ecosystem where bryophytes dominate, NDVI can only explain a small proportion of the variance in biomass (Cunliffe et al., 2020). Furthermore, the relationship between NDVI biomass—which is linear up to an NDVI value of ~0.8—becomes exponential at high NDVI readings, complicating interpretation (Aalto et al., 2021; Goswami et al., 2015).

We addressed these issues with a vegetation survey that indicated homogeneous cover of graminoids and forbs, with only sparse moss cover and no upright shrubs (Table S1). Vegetation cover was essentially homogeneous, with no major spatial variations in plant community composition and structure. NDVI values were <0.8, so saturation at high levels should not have been a problem. The rofabard tops were also more-or-less flat (Figure 3c, Figure S3), meaning that differences were not driven by microtopographic variation. We therefore believe that our NDVI values accurately reflect the vitality of the vegetation, rather than variations in vegetation cover or topography.

Our drone survey was a snapshot of conditions in the latter part of the growing season. We would expect NDVI patterns to vary temporally as well as spatially. We reasoned that the impact of soil moisture conditions would be most apparent well into the growing season, hence the timing of our survey. However, it is possible that the stress response of NDVI varies with the season; for example, soil moisture availability may be more or less critical according to phenology and is also likely to vary from species to species. To fully understand these factors, we would have to run repeat drone surveys at different times of the year, coupled with detailed studies of species-level NDVI.

In addition to moisture, it is likely there are other stresses for plants growing near rofabard scarps. For example, these locations are subject to enhanced fluxes of sediment from adjacent eroded areas (Streeter & Dugmore, 2013). Plant stems on the top of rofabard scarps might also be exposed to elevated mechanical stresses and abrasion from sediment carried by high winds. Even sheep using the rofabard to shelter from poor weather might damage exposed roots (Arnalds, 2015). In our opinion, the plant species characteristic of this environment are resilient in the face of these everyday stresses, and their overall impact is likely to be minor, compared to the effect of moisture stress.

## 4.2 | Soil moisture

Soil moisture levels are known to be highly variable in time and space. However, we appear to have detected systematic variation in likely soil moisture stress along our transect. Locations close to the erosion patch were generally dry but subject to highly variable conditions. Locations further away experienced wetter, less variable conditions (Figure 6). We suspect that the dryness of locations close to the rofabard scarp is due to evaporative losses to the atmosphere. Like many high-latitude locations, Iceland is extremely windy. The geometry of the rofabard scarps means that they catch the wind, and the exposed soil of the scarp lacks vegetation cover, which would shade it from the sun and wind. A previous study demonstrated that the scarp we focussed on was exposed to prevailing winds and is actively eroding (Dugmore et al., 2020). The scarp is also likely to influence the variability of soil moisture. The bare soil readily absorbs moisture, and the sparse vegetation cover does not intercept much rainfall. Hence, the soil adjacent to the scarp rapidly wets and dries, as demonstrated by our observations of inferred rainfall events (Figure 8). Sharp peaks in soil moisture in peripheral locations would be expected during rain showers, when moisture enters the soil laterally due to driving rain. Interior locations would not experience this effect.

## 4.3 | Implications

Our work has implications for understanding high-latitude soil erosion in Iceland and beyond. In an Icelandic context, the moisture gradients observed here provide a mechanism to explain the 'early warning signals' noted by Streeter and Dugmore (2013) in their study of changes in tephra layer thickness towards the edge of rofabard escarpments. The variations in tephra layers observed towards the edge of a rofabard are a reflection of vegetation changes (Cutler, Bailey, et al., 2016; Cutler, Shears, et al., 2016), which in turn are likely to be a reflection of moisture stress. The form and lateral erosion rate of rofabards are sensitive to the thickness of the soil mantle (Arnalds, 2015). Differences in soil thickness may affect the intensity of the soil moisture gradient at the boundary of vegetated areas and the erosion scarp. Soil thickness in Iceland is related to the frequency and magnitude of volcanic ash deposition as well as other sediment sources such as glaciers and soil eroded from elsewhere. Areas in the axial volcanic zone of Iceland, which stretches from the southwest to the northeast of the island, typically have the thickest soil mantles (up to 6 m in some locations in the south). Hamragarðaheiði is located within Iceland's volcanic zone, so it has a moderate soil mantle thickness. Thicker soil cover results in steeper and larger rofabard escarpments, which are generally more dynamic (Arnalds, 2015). Tall, steep scarps could have larger soil moisture gradients and greater moisture variability than the smaller, shallower scarps found outside the most volcanically active areas of Iceland. The lower overall height and lower prevalence of scarps in thinner mantled areas may result in more muted wetting and drying cycles than we observed. Further studies should explore how this edge effect may manifest itself in different soil thicknesses and climatic conditions within Iceland and in other similar Arctic environments.

Soil erosion in Iceland and Greenland is characteristically patchy (Dugmore et al., 2009; Heindel et al., 2015). The initiation of erosion is usually conceptualised as a threshold-crossing event (Kéfi et al., 2007; Streeter & Dugmore, 2013), driven by a large-scale deterioration in environmental factors. Global (in the sense of whole-site) factors, e.g., climate (quantity, timing and type of precipitation, windiness, etc.), no doubt play a role in determining whether a landscape will erode or not. However, the spatial structure of the landforms that subsequently develop is probably determined by small-scale processes. Previous research on the size and spatial distribution of Icelandic erosion patches has shown that (1) once initiated, isolated 'spots' of erosion have the potential to expand and coalesce (Ólafsdóttir & Guđmundsson, 2002) and (2) small erosion patches cluster around the margins of larger features (Streeter & Cutler, 2020). The research we present here provides a biogeomorphological mechanism—localised moisture stress—that might explain the spatially clustered distribution of small erosion spots. The erodibility of the margins is likely largely determined by the degree of stress experienced by individual plants, which is highly localised, although factors, such as soil structure (texture, presence of tephra layers, etc.), will also be a factor. On a landscape scale, the area under moisture stress is determined by the spatial structure (particularly edge length) of existing patches. It therefore appears that localised processes operating at the margins of large patches have the potential to drive landscape-scale patterns of erosion.

Our study of soil moisture prioritised spatial resolution over spatial coverage. Soil moisture sensors and data loggers are expensive, so trade-offs between extent and resolution are inevitable. To fully understand soil moisture dynamics on our sites, we would need replicate transects; sadly, such a survey was beyond our resources. As well as the lateral variation that we measured, soil moisture will also vary vertically. This would be significant if plants have different rooting depths, e.g., if the vegetation included a significant component of upright shrubs. If this were true on our sites, we would have to deploy sensors through the soil profile to fully understand moisture stress. However, the vegetation we observed was dominated by short-statured forbs and graminoids; similarities in growth form, functional type and overall stature indicated that the plants on our sites have similar—probably rather shallow—root structures. We are therefore confident that our moisture probes captured conditions relevant to the growth of plants on our sites.

## 5 | CONCLUSIONS

Understanding high-latitude soil erosion is important because these regions will be subject to abrupt climate change in the coming decades. Many of these changes will impact the soil environment. For example, climate change is likely to bring increased and more variable precipitation to many high-latitude locations, along with enhanced evapotranspiration and changes to the duration and extent of snow-lie, all of which will impact the soil moisture environment (Masson-Delmotte et al., 2021). Under current predictions, high-latitude soil moisture is predicted to become more variable (Berg et al., 2017). There is already evidence that increased instances of hot, dry days have increased soil erosion in Iceland (Owczarek et al., 2022). Higher variability in soil moisture will lead to increased moisture stress, compounded by reduced organic layer depths and reduced water retention capacity (Kemppinen et al., 2022). More frequent extreme weather—particularly rainstorms and periods of high winds—will increase erosive forces.

Our study provides a snapshot of the relationship between soil moisture, plant growth and erosion that should be applicable to other high-latitude regions, although the exact pattern will be sensitive to factors such as soil type. Most importantly, our results have relevance for understanding the spatial characteristics of high-latitude soil erosion. NDVI values and soil moisture are variable in time and space. However, in our study, both factors varied with distance from existing eroded areas. The margins of erosion patches have a stressful soil environment due to exposure to the atmosphere. The vegetation in these locations grows less vigorously, and the exposed soil becomes more vulnerable to erosion by wind and driving rain, leading to expansion of the erosion. If these conditions hold more generally, they may represent a feedback mechanism that facilitates the propagation of soil erosion in high-latitude regions, particularly those with similar andosols (e.g., the Kamchatka Peninsula and the Aleutian Islands).

## AUTHOR CONTRIBUTIONS

**N.A. Cutler:** Conceptualization; methodology; formal analysis; supervision; writing – original draft; writing – review and editing; visualization. **G. Kodl:**

Investigation; formal analysis; writing – original draft; writing – review and editing; visualization. **R.T. Streeter:** Conceptualization; methodology; investigation; supervision; writing – review and editing. **P.I.J. Thompson:** Investigation; writing – review and editing. **A.J. Dugmore:** Methodology; investigation; supervision; writing – review and editing.

## ACKNOWLEDGEMENTS

We are grateful to Dr Anthony Newton for assistance in the field and to an anonymous reviewer for their helpful suggestions. We gratefully acknowledge permission to access sites and support for the research from Kristján Ólafsson at Seljaland and Hálfdan Ómar Hálfdanarson at Ytra-Seljaland.

## FUNDING INFORMATION

Our research was supported by a NERC PhD studentship (ref: NE/L002558/) to Polly Thompson and a World-Leading Scholarship, funded by St Leonard's Postgraduate College, University of St Andrews, to Georg Kodl.

## CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript. We certify that the submission is original work and is not under review at any other publication.

## DATA AVAILABILITY STATEMENT

All data used in this paper are publicly accessible via the data.ncl site hosted by Newcastle University Library (https://data.ncl.ac.uk/).

## ORCID

*N. A. Cutler* https://orcid.org/0000-0003-1746-7769

## REFERENCES

Aalto, J., Niittynen, P., Riihimaki, H., & Luoto, M. (2021). Cryogenic land surface processes shape vegetation biomass patterns in northern European tundra. *Communications Earth & Environment*, *2*. https://doi.org/10.1038/s43247-021-00292-7

Arnalds, O. (2000). The icelandic 'rofabard' soil erosion features. *Earth Surface Processes and Landforms*, *25*, 17–28. https://doi.org/10.1002/(sici)1096-9837(200001)25:1<17::aid-esp33>3.0.co;2-m

Arnalds, O. (2004). Volcanic soils of Iceland. *Catena*, *56*, 3–20.

Arnalds, Ó. (2005). Icelandic soils. In C. Caseldine, A. Russell, J. Hardardóttir, & Ó. Knudsen (Eds.), *Iceland – modern processes and past environments* (pp. 309–318). Elsevier.

Arnalds, O. (2015). *Soils of Iceland*. Springer.

Assmann, J. J., Kerby, J. T., Cunliffe, A. M., & Myers-Smith, I. H. (2019). Vegetation monitoring using multispectral sensors – best practices and lessons learned from high latitudes. *Journal of Unmanned Vehicle Systems*, *7*, 54–75. https://doi.org/10.1139/juvs-2018-0018

Barrio, I. C., Hik, D. S., Thorsson, J., Svavarsdottir, K., Marteinsdottir, B., & Jonsdottir, I. S. (2018). The sheep in wolf's clothing? Recognizing threats for land degradation in Iceland using state-and-transition models. *Land Degradation & Development*, *29*, 1714–1725. https://doi.org/10.1002/ldr.2978

Berdanier, A. B., & Klein, J. A. (2011). Growing season length and soil moisture interactively constrain high elevation aboveground net primary production. *Ecosystems*, *14*, 963–974. https://doi.org/10.1007/s10021-011-9459-1

Berg, A., Sheffield, J., & Milly, P. C. D. (2017). Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters*, *44*, 236–244. https://doi.org/10.1002/2016gl071921

Bjerke, J. W., Karlsen, S. R., Hogda, K. A., Malnes, E., Jepsen, J. U., Lovibond, S., Vikhamar-Schuler, D., & Tommervik, H. (2014). Record-low primary productivity and high plant damage in the Nordic Arctic region in 2012 caused by multiple weather events and pest outbreaks. *Environmental Research Letters*, *9*. https://doi.org/10.1088/1748-9326/9/8/084006

Boelman, N. T., Stieglitz, M., Rueth, H. M., Sommerkorn, M., Griffin, K. L., Shaver, G. R., & Gamon, J. A. (2003). Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra. *Oecologia*, *135*, 414–421. https://doi.org/10.1007/s00442-003-1198-3

Cunliffe, A. M., Assmann, J. J., Daskalova, G. N., Kerby, J. T., & Myers-Smith, I. H. (2020). Aboveground biomass corresponds strongly with drone-derived canopy height but weakly with greenness (NDVI) in a shrub tundra landscape. *Environmental Research Letters*, *15*. https://doi.org/10.1088/1748-9326/aba470

Cutler, N. A., Bailey, R. M., Hickson, K. T., Streeter, R. T., & Dugmore, A. J. (2016). Vegetation structure influences the retention of airfall tephra in a sub-Arctic landscape. *Progress in Physical Geography*, *40*, 661–675.

Cutler, N. A., Shears, O. M., Streeter, R. T., & Dugmore, A. J. (2016). Impact of small-scale vegetation structure on tephra layer preservation. *Scientific Reports*, *6*. https://doi.org/10.1038/srep37260

Dugmore, A., Jackson, R., Cooper, D., Newton, A., Júlíusson, A. D., Streeter, R., Hreinsson, V., Crabtree, S., Hambrecht, G., Hicks, M., & McGovern, T. (2020). Continuity in the face of a slowly unfolding catastrophe: The persistence of Icelandic settlement despite large-scale soil erosion. In R. Riede & P. Payson Sheets (Eds.), *Going forward by looking back: Archaeological perspectives on socio-ecological crisis, response and collapse* (pp. 162–199). Berghahn.

Dugmore, A. J., Gisladóttir, G., Simpson, I. A., & Newton, A. (2009). Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. *Journal of the North Atlantic*, *2*, 1–18.

Einarsson, M. Á. (1984). Climate of Iceland. In H. van Loon (Ed.), *World survey of climatology: 15: Climates of the oceans* (pp. 673–697). Elsevier.

Engstrom, R., Hope, A., Kwon, H., & Stow, D. (2008). The relationship between soil moisture and NDVI near Barrow, Alaska. *Physical Geography*, *29*, 38–53. https://doi.org/10.2747/0272-3646.29.1.38

Gísladóttir, G. (2001). Ecological disturbance and soil erosion on grazing land in Southwest Iceland. In A. Conacher (Ed.), *Land degradation* (pp. 109–126). Kluwer Academic Publishers.

Gísladóttir, G. (2006). The impact of tourist trampling on Icelandic andosols. *Zeitschrift für Geomorphologie*, *143*, 53–70.

Gísladóttir, G., Erlendsson, E., Lal, R., & Bigham, J. (2010). Erosional effects on terrestrial resources over the last millennium in Reykjanes, Southwest Iceland. *Quaternary Research*, *73*, 20–32.

Goswami, S., Gamon, J., Vargas, S., & Tweedie, C. (2015). Relationships of NDVI, biomass, and leaf area index (LAI) for six key plant species in Barrow, Alaska. *PeerJ*, *3*. https://doi.org/10.7287/peerj.preprints.913v1

Grace, J. (1997). Plant water relations. In M. J. Crawley (Ed.), *Plant ecology*. Blackwell.

Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L., & Striegl, R. G. (2011). Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research-Biogeosciences*, *116*. https://doi.org/10.1029/2010jg001507

Heindel, R. C., Chipman, J. W., & Virginia, R. A. (2015). The spatial distribution and ecological impacts of Aeolian soil erosion in Kangerlussuaq, West Greenland. *Annals of the Association of American Geographers*, *105*, 875–890. https://doi.org/10.1080/00045608.2015.1059176

Hilton, R. G., Galy, V., Gaillardet, J., Dellinger, M., Bryant, C., O'Regan, M., Grocke, D. R., Coxall, H., Bouchez, J., & Calmels, D. (2015). Erosion of organic carbon in the Arctic as a geological carbon dioxide sink. *Nature*, *524*, 84–87. https://doi.org/10.1038/nature14653

Icelandic Meteorological Office. (2023). Climate report.

Jacobsen, N. K. (1987). Studies on soils and potential for soil erosion in the sheep farming area of South Greenland. *Arctic and Alpine Research*, *19*, 498–507. https://doi.org/10.2307/1551416

Kéfi, S., Rietkerk, M., Alados, C. L., Pueyo, Y., Papanastasis, V. P., ElAich, A., & de Ruiter, P. C. (2007). Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, *449*, 213–217.

Kemppinen, J., Niittynen, P., Aalto, J., le Roux, P. C., & Luoto, M. (2019). Water as a resource, stress and disturbance shaping tundra vegetation. *Oikos*, *128*, 811–822. https://doi.org/10.1111/oik.05764

Kemppinen, J., Niittynen, P., Happonen, K., Le Roux, P. C., Aalto, J., Hjort, J., Maliniemi, T., Karjalainen, O., Rautakoski, H., & Luoto, M. (2022). Geomorphological processes shape plant community traits in the Arctic. *Global Ecology and Biogeography*, *31*, 1381–1398. https://doi.org/10.1111/geb.13512

Kemppinen, J., Niittynen, P., Riihimaki, H., & Luoto, M. (2018). Modelling soil moisture in a high-latitude landscape using LiDAR and soil data. *Earth Surface Processes and Landforms*, *43*, 1019–1031. https://doi.org/10.1002/esp.4301

Massa, C., Bichet, V., Gauthier, E., Perren, B. B., Mathieu, O., Petit, C., Monna, F., Giraudeau, J., Losno, R., & Richard, H. (2012). A 2500 year record of natural and anthropogenic soil erosion in South Greenland. *Quaternary Science Reviews*, *32*, 119–130. https://doi.org/10.1016/j.quascirev.2011.11.014

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Myers-Smith, I. H., Elmendorf, S. C., Beck, P. S. A., Wilmking, M., Hallinger, M., Blok, D., Tape, K. D., Rayback, S. A., Macias-Fauria, M., Forbes, B. C., Speed, J. D. M., Boulanger-Lapointe, N., Rixen, C., Levesque, E., Schmidt, N. M., Baittinger, C., Trant, A. J., Hermanutz, L., Collier, L. S., … Vellend, M. (2015). Climate sensitivity of shrub growth across the tundra biome. *Nature Climate Change*, *5*, 887–891. https://doi.org/10.1038/nclimate2697

Myers-Smith, I. H., Kerby, J. T., Phoenix, G. K., Bjerke, J. W., Epstein, H. E., Assmann, J. J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P. S. A., Berner, L. T., Bhatt, U. S., Bjorkman, A. D., Blok, D., Bryn, A., Christiansen, C. T., Cornelissen, J. H. C., Cunliffe, A. M., Elmendorf, S. C., … Wipf, S. (2020). Complexity revealed in the greening of the Arctic. *Nature Climate Change*, *10*, 106–117. https://doi.org/10.1038/s41558-019-0688-1

Nguy-Robertson, A., Gitelson, A., Peng, Y., Vina, A., Arkebauer, T., & Rundquist, D. (2012). Green leaf area index estimation in maize and soybean: Combining vegetation indices to achieve maximal sensitivity. *Agronomy Journal*, *104*, 1336–1347. https://doi.org/10.2134/agronj2012.0065

Ólafsdóttir, R., & Guðmundsson, H. J. (2002). Holocene land degradation and climatic change in northeastern Iceland. *Holocene*, *12*, 159–167. https://doi.org/10.1191/0959683602h1531rp

Ólafsdóttir, R., Schlyter, P., & Haraldsson, H. (2001). Simulating Icelandic vegetation cover during the Holocene: Implications for long-term land degradation. *Geografiska Annaler*, *83*, 203–215.

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, D. J., & Stringer, L. (2019). Land degradation. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, et al. (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. IPCC.

Owczarek, P., Dagsson-Waldhauserova, P., Opala-Owczarek, M., Migala, K., Arnalds, O., & Schaetzl, R. J. (2022). Anatomical changes in dwarf shrub roots provide insight into aeolian erosion rates in northeastern Iceland. *Geoderma*, *428*, 116173. https://doi.org/10.1016/j.geoderma.2022.116173

Post, E., Alley, R. B., Christensen, T. R., Macias-Fauria, M., Forbes, B. C., Gooseff, M. N., Iler, A., Kerby, J. T., Laidre, K. L., Mann, M. E., Olofsson, J., Stroeve, J. C., Ulmer, F., Virginia, R. A., & Wang, M. Y. (2019). The polar regions in a 2 degrees C warmer world. *Science Advances*, *5*, eaaw9883. https://doi.org/10.1126/sciadv.aaw9883

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvarinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*. https://doi.org/10.1038/s43247-022-00498-3

Riedel, S. M., Epstein, H. E., & Walker, D. A. (2005). Biotic controls over spectral reflectance of arctic tundra vegetation.

*International Journal of Remote Sensing*, *26*, 2391–2405. https://doi.org/10.1080/01431160512331337754

Streeter, R., & Dugmore, A. J. (2013). Anticipating land surface change. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 5779–5784.

Streeter, R., Dugmore, A. J., Lawson, I. T., Erlendsson, E., & Edwards, K. J. (2015). The onset of the palaeoanthropocene in Iceland: Changes in complex natural systems. *Holocene*, *25*, 1662–1675.

Streeter, R. T., & Cutler, N. A. (2020). Assessing spatial patterns of soil erosion in a high-latitude rangeland. *Land Degradation & Development*, *31*, 2003–2018. https://doi.org/10.1002/ldr.3585

Tyystjarvi, V., Kemppinen, J., Luoto, M., Aalto, T., Markkanen, T., Launiainen, S., Kieloaho, A. J., & Aalto, J. (2022). Modelling spatio-temporal soil moisture dynamics in mountain tundra. *Hydrological Processes*, *36*. https://doi.org/10.1002/hyp.14450

Walker, D. A., Epstein, H. E., Jia, G. J., Balser, A., Copass, C., Edwards, E. J., Gould, W. A., Hollingsworth, J., Knudson, J., Maier, H. A., Moody, A., & Raynolds, M. K. (2003). Phytomass, LAI, and NDVI in northern Alaska: Relationships to summer warmth, soil pH, plant functional types, and extrapolation to the circumpolar Arctic. *Journal of Geophysical Research-Atmospheres*, *108*. https://doi.org/10.1029/2001jd000986

World Bank Group. (2022). Climate change knowledge portal: Iceland.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Cutler, N. A., Kodl, G., Streeter, R. T., Thompson, P. I. J., & Dugmore, A. J. (2023). Soil moisture, stressed vegetation and the spatial structure of soil erosion in a high latitude rangeland. *European Journal of Soil Science*, *74*(4), e13393. https://doi.org/10.1111/ejss.13393