ALBEDO ON A GLACIAL FORELAND AT GROUND LEVEL AND LANDSCAPE SCALE DRIVEN BY VEGETATION-SUBSTRATE PATTERNS

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ABSTRACT

Recent anthropogenic climate change has caused both glacial retreat and increased vegetative growth on Arctic and subarctic tundra landscapes resulting in changing albedo and energy budgets. Glacial forelands are topographically and ecologically heterogeneous landscapes comprising ice-contact and outwash deposits subject to primary succession. The most recent moraines on the foreland of the Skaftafellsjökull in southern Iceland are mostly unvegetated, but vegetation cover increases with the age in a general sense. Vegetated outwash channel terraces occur between the moraines, and a broad vegetated outwash plain occurs distal to the oldest moraine. Variations in albedo were measured at ground level to determine the specific role of vegetation types and varying substrates. Albedo and coverage by major plant groups were measured along transects established on moraines ranging in age from 20 to 130 years and the terrace of one outwash channel and three locations on the outwash plain. Total vegetation cover and coverage by mosses increases on the glacial moraines largely as a function of time but is subject to strong aspect effects. Total vegetation cover and moss cover are highest on outwash deposits, possibly due to a sheltered aspect and greater uniformity of the outwash surface. Measured albedo exhibits a modest positive correlation with total vegetation cover and a modest negative correlation with rock and soil exposure. The strongest positive correlation was found between albedo and moss cover. The differences in brightness between moraines and outwash deposits are evident visually at the landscape scale on satellite photographs and quantifiable by image-processing software.

Keywords: glacial foreland; glacial moraine; moss heath; outwash channel; outwash plain; primary succession

Introduction

It is well established that anthropogenic climate change over the last century has resulted in substantially greater warming at high latitudes compared to the global mean, causing the retreat of glaciers at both high latitudes and high altitudes (Hugonnet et al. 2021; Rounce et al. 2023). Moreover, the environmental impacts of this warming on Arctic regions include changes to the land energy budgets, decreasing snow cover and changing plant communities. Multiple studies have examined the transition of moss dominated tundras to shrub heaths and the increased growth of larger shrubs and trees, which presumably provide greater dark leaf area for absorption of solar radiation, thereby reducing albedo (Chapin et al. 2005; Sturm et al. 2005; Tape et al. 2006, 2012; Swann et al. 2009; Brown et al. 2010; Blok et al. 2011; Loranty et al. 2011; Pearson et al. 2013; Juszak et al. 2014; Williamson et al. 2016). However, the relationship between shrub vegetation and albedo is not always straightforward (Payette et al. 2001; Beck et al. 2011). Nonetheless, changes in the energy budget due to altered albedo have the potential to trigger climatic feedback, such as the oft-cited positive warming feedback in the Arctic climate system, which has the potential to cause accelerating permafrost thaw, glacial retreat and accelerated growth of shrubs on tundra (e.g. Blok et al. 2011; Pearson et al. 2013). At subarctic latitudes analogous studies have examined how anthropogenic climate change is causing the encroachment of boreal forest northward across the tundra-forest ecotone (Arnalds 1987; Robinson et al. 2008; Berner et al. 2013). Here again, this shift in community structure lowers the albedo of the landscape through the replacement of light-toned mosses with dark coniferous trees, providing positive feedback with the potential to accelerate.

The subarctic setting of Iceland offers an opportunity to test the effects of changing plant communities on albedo in landscapes that are unique in one respect. As the bedrock of the island consists almost entirely of mafic volcanic rock, glacial and fluvial deposits and soils derived from them consist largely of volcanic detritus (Arnalds 2008) that is dark when fresh, but lighter when weathered. Tanner and Vandewarker (2019) studied the differences of albedo due to successional vegetation encroachment on the Skeiðarársandur, the glacial outwash plain of the Skeiðarárjökull in southern Iceland. They found a strong positive correlation between albedo and the coverage of the plain by a moss-dominated heath, in which mosses are the dominant early colonizing plant species. Because the moss heath community has a higher albedo than the dark substrate, colonization and succession is causing albedo to increase.

In contrast to the topographic uniformity of the outwash plains of the Icelandic glaciers, or sandur, the land areas exposed by the retreating glaciers, or glacial forelands, are topographically heterogeneous, comprising multiple geomorphic elements, including recessional moraines, push moraines, outwash terraces and outwash plains. The study described herein examines the albedo of a glacial foreland, that of the Skaftafellsjökull in southern Iceland, by measurement at close scale at ground

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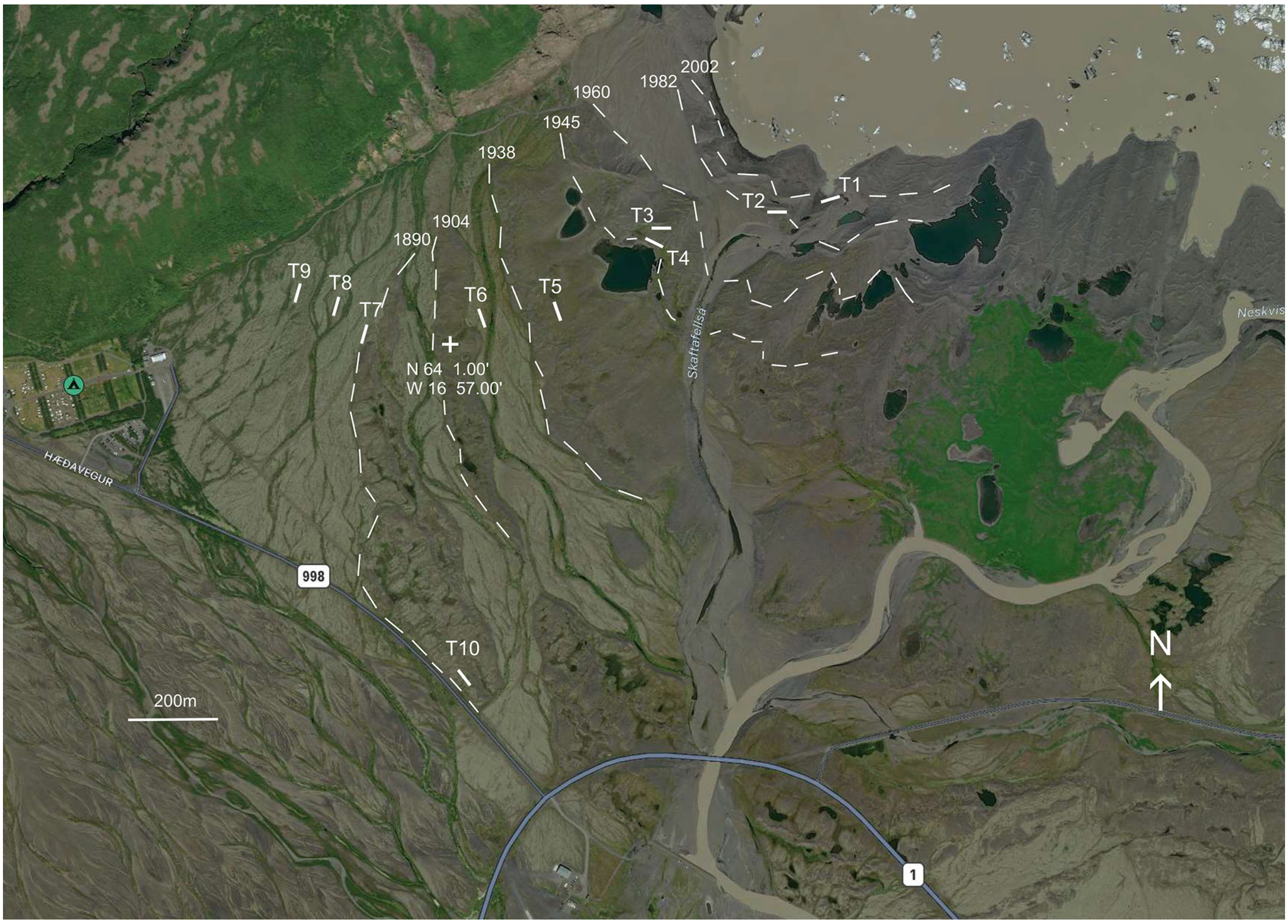

Fig. 1 Location of study area in southern Iceland (see arrow on inset map). Dates represent approximate locations of the ice front in the year indicated. Bold dashes represent specific transect locations. T = transect number. Brown areas are glacial moraines; pale green areas are moss-covered outwash deposits; dark green sinuous features are incised channels hosting downy birch; dark blue features are kettle ponds. Image downloaded from https://satellites.pro (by Google®).

level. We test the effect on albedo of the differences in the successional communities developed on the varying landforms in the glacial foreland and explore the causes for these differences. Additionally, we compare these ground-level measurements to observations of the landscape brightness as measured from satellite imagery.

Methods

Location

The study site is the foreland of the Skaftafellsjjökull, an outlet glacier of the Vatnajökull ice cap in southeastern Iceland (Fig. 1). Modern climate for this area of the Icelandic south coast is a mean annual temperature of ca. 5 °C and mean annual precipitation of 1400–1800 mm (Roeloffs 2022). Like most glaciers worldwide, the Skaftafellsjjökull, and the other outlet glaciers of the Vatnajökull have been in retreat since the end of the Little Ice Age. The Skaftafellsjökull reached its maximum modern extent at the close of the Little Ice Age in 1890 and has retreated ca. 3 km since (Baldursson et al. 2018). This retreat has exposed a foreland area with varying topography. Through the middle 20th century, the Skaftafellsjökull retreated consistently due to continued anthropogenic warming, leaving recessional moraines that have been dated accurately through continuous monitoring of the glacier terminus (Sigurðsson 2005). The most distal moraine of the Skaftafellsjökull that is clearly identifiable is dated to the position of the ice front in 1890. A much more pronounced topography is formed by a set of nested moraines that date from the position of the glacial front in 1945 (Fig. 1). The more proximal moraines date to the positions of the glacial front in 1954, 1960, 1982 and 2002 (Perrson 1964; Sigurðsson 2005; Hannesdóttir et al. 2014; Evans et al. 2017). Between the moraines are flatter areas formed by alluvial outwash terraces and incised channels. These outwash surfaces differ from the moraines in both their topography – the outwash deposits generally have horizontal surfaces in contrast to the slopes of the moraines – and in composition; the moraines consist of very poorly sorted deposits with protruding boulders, while the outwash consists mainly of sorted gravel-size clasts. The ages of these inter-moraine outwash channel and outwash plain surfaces generally are not well constrained, other than by the moraines that form their boundaries; i.e., the possibility of continued reactivation of the outwash channels over the course of many years removes age constraints. Consequently, the surfaces at Skaftafell can best be characterized as pre-1890, 1890–1904, 1904–1945, 1945–1960, 1960–1982, 1982–2002 and post-2002 (Fig. 1). Prior to 1967, the study area was used for sheep farming. This area was largely abandoned for grazing after the Skaftafell National Park (now incorporated within the Vatnajökull National Park) was established in 1967, and formally fenced off in 1987 (Vilmundardóttir et al. 2015).

Previous work

Multiple studies have been conducted on the foreland of the Skaftafellsjökull examining species diversity (Perrson 1964), soil properties (Tanner et al. 2013; Vilmundardóttir et al. 2015) and primary ecological succession (Glausen and Tanner 2019; Synan et al. 2021). Of these, Glausen and Tanner (2019), measured species richness on transects established on moraines at different distances from the current glacier terminus, representing different landscape ages, in addition to a glacial outwash channel terrace between moraines, and locations on the outwash plain distal to the oldest moraine. Their work suggested that following the pioneer stage, species richness and vegetation coverage both increased on the moraines through the mid-successional stages, but species richness decreased on the oldest portions of the landscape, even as total vegetation increased. In a general sense, total vegetative cover on the foreland increases with distance from the current glacial terminus. The most common component of the successional communities are mosses, primarily *Racomitrium lanuginosum* (hoary-fringe moss), followed by a low shrub community comprising *Empetrum nigrum* (black crowberry), *Calluna vulgaris* (scotch heather), *Arctostaphylos uva-ursi* (bearberry) and *Saxifraga oppositofolia* (purple saxifrage). Minor components include the dwarf trees *Betula pubescens* (downy birch), *Salix lanata* (wooly willow), *Salix phylicifolia* (tea-leaved willow), various graminoids, forbs, foliose and fruticose lichens and biological soil crusts.

Sampling design

This study was conducted in parallel with a reexamination of the study locations of Glausen and Tanner (2019) using the coordinates recorded by GPS in 2007 for the starting points of transects (Fig. 1). Transect 1 is the most proximal to the ice front, located on the glacial-facing slope (equals proximal aspect) of the most recent moraine, which is dated to the position of the ice front in 2002 (Fig. 2a; Hannesdóttir et al. 2014). Transect 2 is located southwest of Transect 1 on a flat at the top of a moraine associated with the ice position in 1982 (Fig. 2b). Transect 3 is situated on the northeast-facing slope (proximal aspect) of a moraine ridge that marks the position of the ice front ca. 1954 (Perrson 1964). Transect 4 is situated in a slight hollow on the southwest-facing slope (away from the glacier, or distal aspect) of the moraine ridge from 1954, overlooking a kettle pond in the 1945 moraine. Transect 5 is on a broad flat at the top of the 1945 moraine; the date of deglaciation of the site is estimated at 1938 (based on data from Sigurðsson 2005). Transect 6 is located on the terrace of a stream channel in a broad swale immediately east (toward the glacier) of the moraine associated with the ice position in 1904 (Sigurðsson 2005). However, this swale was occupied by an outwash channel active as recently as 1960 (Perrson 1964). Transect 7 is situated on the outwash plain adjacent to the margin of the oldest boulder moraine, associated with the position of the ice margin between 1904 and 1890 (Fig. 2d). Transects 8 and 9 are located on the outwash plain distal (west) of the 1890 ice front. The topography here is not entirely flat but consists instead of very subdued ridges and swales that are relics of the period when the outwash channels on the plain were occupied. Transect 10 (not studied by Glausen and Tanner 2019) is located to the south of the other transects on the distal side of the 1890 moraine (Fig. 2c).

At each site, a transect line was established parallel to the trend of the moraines with five measurement stations set 10 m apart. Starting points for stations were chosen without bias for substrate, i.e., individual stations may have included non-vegetated boulders. At each station, measurements were made using a 0.5 m × 0.5 m (= 0.25 m^2) quadrat that was rotated spatially to provide 1.0 m^2 of continuous coverage per station. Within each quadrat, the percentage of cover by each of the major vegetation groups (mosses, shrubs, dwarf trees, graminoids, forbs, lichens and biological soil crust), plus non-vegetated area were estimated for comparison with the data collected in 2007.

Spot measurements of albedo were calculated from measurements of ambient and reflected light from the ground surface using a Reed Instruments® SD-1128 Datalogger with light sensor measuring in units of lux (= lumens m^{-2}). The sensor was mounted on a flat board that was placed on the ground to measure ambient light intensity. Reflected light intensity was measured immediately following at the same location with the same sensor 1 m above the ground surface with the sensor oriented parallel to the ground surface. This measurement was repeated four times at each location (once in each quadrat). The mean of the resulting 20 measurements per transect presents an average value representative of the transect irrespective of the heterogeneity of the vegetation. Variations in intensity of ambient or reflected light due to cloud cover or time of day were effectively negated by the albedo calculation as incoming ambient and reflected light intensity were measured under identical conditions. The results are internally consistent with albedo varying as might be expected between sample sites on different types of surfaces. Moreover, they compare well with published values of albedo measured at ground

Fig. 2 Landscape features of the Skaftafellsjökull foreland. a) View of the 2002 moraine with negative aspect, or slope facing the ice front (Transect 1). Surface is covered mainly by soil and gravel. b) View near the crest of the 1982 moraine with positive aspect, or slope facing away from the ice (Transect 2). Surface is mostly vegetated, primarily by mosses. c) Location of Transect 10 on the 1890 moraine with view of positive aspect slope. Surface exposes protruding boulders but is largely covered by vegetation. d) Moss-covered bar top of outwash deposits at Transect 7. The downy birch to the right is mainly limited to the swale between the bars.

level on various landscape surfaces at high latitude (Petzold and Rencz 1975). The mean brightness of the land surface at each transect was approximated by analyzing the light intensity for an area approximating the transect area on a cloud-shadow free satellite photograph (Fig. 1; downloaded from https://satellites.pro by Google®) with ImageJ software, a public domain Java image processing program. The program performs measurements of mean brightness of an area defined on an image relative to the greyscale range of 0 (black) to 255 (white). Results for vegetative cover, moss cover, soil and rock exposure, albedo and mean transect brightness are presented in Table 1. Comparisons of albedo to vegetation surface cover data were analyzed by linear regression analysis using the statistical functions of Microsoft Excel®.

Results

Transect 1

The youngest land surface examined is the glacier-facing slope of a push moraine that is proximal to the present lagoon in front of Skaftafellsjökull (Figs 1, 2a). This surface is estimated to have been ice free since ca. 2002. The surface of this transect is dominated by exposed gravel, although coverage varies from station to station, from 41.3% to 92.5% (mean = 72.1%; SD = 20.3). Vegetative cover (includes mosses, lichens, willows, forbs, graminoids and biological soil crusts) is also greatly variable, from 7.8% to 58.5%, averaging 26.6% across the five stations (SD = 20.9). The vegetative component is dominated by mosses (13.3%). Measurements of mean albedo for the individual stations range from 0.15 to 0.17 (mean = 0.158).

Transect 2

The transect line was established on the west-facing slope (aspect oriented away from the glacier) of the second prominent push moraine ridge from the current lagoon. This surface is estimated to have been ice free since 1982 (Figs 1, 2b). Vegetative cover is more pervasive and more diverse on the surface of this transect, averaging 73% across all stations (SD = 17.9). The vegetation is dominated by mosses (mean = 42.8%), which vary from 4.5% to 80.0% (SD = 33.9); forbs, graminoids, low shrubs, willows, lichens and biological soil crusts also are present. Albedo measured at the five sets in this transect ranges from 0.15 to 0.21 (mean = 0.182).

Table 1 Measurements of ground cover and albedo for all stations. Station = transect and station number (transect locations shown in figure 1, each station is the mean of four quadrats); VC = total vegetation cover %; moss = % ground cover by undifferentiated mosses; r&s = rock and soil cover %; SD = standard deviation of albedo measurements at each station; mean = the mean albedo for the five stations in the transect; brightness is measured relative a greyscale value range of 0 (black) to 255 (white) across the entire transect area shown in Fig. 1 as measured by ImageJ software.

Transect	VC	moss	r&s	albedo	SD	mean albedo	Brightness
1–1	58.5	36.3	41.5	0.15	0.008	0.158	78.72
1–2	9.8	7.8	90.3	0.16	0.042		
1–3	16.3	2.1	83.3	0.15	0.006		
1–4	30.3	16.3	69.0	0.16	0.015		
1–5	7.8	4.0	92.8	0.17	0.019		
2–1	40.5	4.5	60.0	0.15	0.010	0.182	85.73
2–2	58.5	16.8	40.0	0.16	0.011		
2–3	75.8	37.5	27.5	0.18	0.004		
2–4	65.3	80.0	11.8	0.21	0.016		
2–5	88.0	75.0	12.0	0.21	0.019		
3–1	55.0	27.5	46.5	0.19	0.008	0.186	86
3–2	59.5	17.5	43.8	0.18	0.012		
3–3	58.0	37.5	43.8	0.19	0.009		
3–4	0.3	0.0	100.0	0.19	0.006		
3–5	87.5	62.5	13.0	0.18	0.010		
4–1	97.5	48.8	2.3	0.19	0.014	0.184	82.36
4–2	99.5	58.8	0.2	0.2	0.015		
4–3	70.5	20.0	29.5	0.17	0.010		
4–4	92.5	32.5	7.5	0.15	0.011		
4–5	99.0	75.0	1.0	0.21	0.008		
5–1	85.0	57.5	20.8	0.18	0.010	0.188	78.53
5–2	38.3	23.0	72.5	0.19	0.011		
5–3	100.0	77.0	17.3	0.2	0.010		
5–4	7.8	3.0	97.3	0.18	0.011		
5–5	26.3	11.3	75.0	0.19	0.014		
6–1	99.3	73.3	0.3	0.2	0.037	0.192	93.14
6–2	99.8	82.5	0.1	0.2	0.022		
6–3	87.3	48.3	13.0	0.21	0.024		
6–4	99.8	77.5	0.3	0.18	0.015		
6–5	97.3	93.8	2.6	0.17	0.011		
7–1	79.8	79.8	20.3	0.23	0.021	0.238	101.56
7–2	97.3	93.0	4.0	0.24	0.007		
7–3	97.8	87.0	2.0	0.24	0.024		
7–4	99.8	38.8	0.0	0.23	0.017		
7–5	87.5	78.8	13.8	0.25	0.037		
8–1	99.8	99.3	0.3	0.18	0.019	0.206	98.8
8–2	95.8	93.0	4.0	0.25	0.030		
8–3	95.3	84.0	7.3	0.2	0.016		
8–4	97.0	87.3	3.0	0.23	0.027		
8–5	25.0	9.8	75.0	0.17	0.022		
9–1	100.0	96.3	0.0	0.26	0.026	0.2666	99.12
9–2	100.0	91.8	0.0	0.27	0.019		
9–3	100.0	98.5	0.0	0.28	0.019		
9–4	98.8	61.3	1.3	0.23	0.004		
9–5	98.8	98.3	1.3	0.29	0.011		
10–1	95.8	35.0	9.0	0.18	0.023	0.194	84.57
10–2	96.5	45.0	4.8	0.19	0.014		
10–3	91.8	11.3	13.3	0.16	0.008		
10–4	70.0	31.3	59.3	0.22	0.023		
10–5	92.0	73.8	15.5	0.22	0.019		

Transect 3

This transect line is located near the crest of an older push moraine located between the glacial lake and several prominent kettles. The location is estimated to have been ice free since ca. 1954. Total vegetative cover (mean = 53.5%) slightly exceeds that of the exposed rock and soil surface but is highly variable (SD = 31.7%). Mosses account for most of the vegetation, ranging from absent (at station 4) to 62.5% (mean = 29%; SD = 23.3); the remaining vegetative components are similar to those in Transect 2. The non-vegetated surface comprises gravel to boulder size rock (37.3%) and bare soil (12.2%). Measurements of albedo on this transect occupy a narrow range of 0.18 to 0.19 (mean = 0.0.186).

Transect 4

Transect 4 is located proximal to a prominent kettle pond on the slope of the most distal push moraine facing away from the glacier. The date of exposure of this surface is estimated at 1945. All stations in this transect are well-vegetated, ranging from 70.5% to 99% (mean = 99.4%; SD = 12.2). Mosses are the dominant component of the vegetation, ranging from 20% to 75% (mean = 47%; SD = 21.6), with contributions by the groups observed at the younger transects in addition to downy birch (*B. pubescens*). Albedo measured at the stations ranges from 0.15 to 0.21 (mean = 0.184).

Transect 5

This transect is situated at the crest of a broad, gently sloping moraine distal to the younger push moraines and intervening kettles. The date of glacial retreat from this location is estimated at 1938. Vegetative cover is inconsistent between stations, ranging from 7.8% to 100% (mean = 53.5%; SD = 44.2). The cover is dominated by mosses, which vary from 3% to 77% of cover (mean = 34.4%; SD = 31.6), but exhibits similar diversity as Transect 4. Albedo measured at the stations in this transect ranges from 0.18 to 0.2 (mean = 0.188).

Transect 6

Transect 6 is located on the fluvial terrace of a glacial outwash channel between the broad moraine of Transect 5 and an older arcuate moraine dated to 1904. However, historical imagery suggests the area between the moraines was occupied by a glacial outwash stream as recently 1960 (Perrson 1964). The surface of the terrace is well-vegetated (mean = 100%; SD = 5.4) and dominated by hummocky mosses (mean = 75.1%; SD = 16.8). All other vegetation groups are present, although aside from low shrubs (mean = 18.5%), most are very minor components. The terrace is dissected by a narrow channel. In contrast to the terrace surface, the channel floor is occupied by a thicket of downy birch, visible on Fig. 1. Albedo measurements at Transect 6 stations range from 0.17 to 0.21, but cluster near 0.2 (mean = 0.195).

Transect 7

This transect is located on the outwash plain proximal and to the west of the oldest of the Skaftafellsjökull arcuate moraines, which dates to the most distal position of the glacier in 1890 (Figs 1, 2d). Although the age of the moraine is well established, there are no means for dating directly various locations on the outwash plain in the distal foreland. Satellite imagery demonstrates conclusively that the channels have been inactive at least since 1985, and the figures from Perrson (1964) illustrate this area of the outwash plain as free of active streams. Therefore, we embrace the interpretation that most of the outwash plain derives from the early stages of glacial retreat. In general, the outwash plain consists of a series of diamond to linguoid-shaped bars with relatively flat surfaces separated by narrow channels, the floor of which are commonly occupied by thickets of downy birch, as described for Transect 6. Presumably, the age of exposure of the bar surfaces equates to the date of deposition of the outwash. The surface at the stations in Transect 7 is consistently vegetated (mean = 100%; SD = 8.5) and dominated by mosses (mean = 75.5%; SD = 21.3). As on Transect 6, low shrubs are a significant component (mean = 16.5%), while other components are minor. Albedo measurements occupy a narrow range between 0.23 and 0.25 (mean = 0.238).

Transect 8

This transect, located approximately 125 m to the north-northwest of Transect 7, is also situated on the outwash plain of Skaftafellsjökull and shares a similar bar and channel topography. As with Transect 7, the age of exposure of the land surface is ambiguous.

The surface here is mostly vegetated, although total vegetative cover is variable, ranging from 23.8% to 99.8% (mean = 99.6%; SD = 32.2). Mosses dominate the vegetation, ranging from 9.8% to 99.3% of surface cover (mean = 74.7%; SD = 36.7), with low shrubs next most abundant (mean = 11.0%). Albedo measurements at individual stations range from 0.17 to 0.25 (mean = 20.6).

Transect 9

This transect is the most distal transect in the study, located on the outwash plain approximately 120 m west-northwest of Transect 8. Once again, the age of exposure of the surface is unknown, although hypothetically it could be older than the transects located closer to the oldest moraine (7 and 8). The surface at all stations in this transect are nearly fully vegetated (mean = 100%; SD = 0.7). The vegetative cover is dominantly moss (mean = 89.2%; SD = 15.9%), with low shrubs subordinate (mean = 8.1%). Measurements of albedo at the five stations range from 0.23 to 0.29 (mean = 0.266).

Transect 10

The transect is located on the distal side of the oldest arcuate moraine of the Skaftafellsjökull, dated to the maximum Little Ice Age glacial extent in 1890 (Figs 1, 2c). Vegetation covers most of the surface at all stations in the transect, ranging from 54% to 95.8% (mean = 95.7%; SD = 10.9). Mosses are common, but do not dominate the surface, ranging from 11.3% to 73.8% (mean = 39.3%; SD = 22.9), subequal with low shrubs (mean = 30.4%). Albedo at the stations in this transect varies from 0.16 to 0.22 (mean = 0.194).

Discussion

Primary succession on glacial deposits initiates by colonization, which as described by Glausen and Tanner (2019) for the Skaftafelljökull foreland, is dominated in the earliest stages by graminoids and mosses. Vegetative cover increases with time but is also subject to local conditions of favorable or unfavorable aspect. The vegetative cover on the youngest moraine on the foreland, from 2002 (Transect 1), is sparse (Fig. 2a) due to the young age of the surface and the aspect (facing the glacier) that exposes the surface to katabatic winds from the ice sheet. The aspect at Transect 2, facing away from the ice sheet, provides partial shelter to the surface (Fig. 2b), which combined with the greater age of exposure (from 1982) allows for vegetation coverage over the majority of the surface. As reported by Glausen and Tanner (2019), this transect is the youngest location studied in which the low shrub component of the community becomes common. The ground surface at Transect 3, near the crest of a push moraine from 1960, varies from horizontal to sloping toward the ice. Consequently, the location is poorly sheltered, accounting for the lower vegetative cover as compared to Transect 2, despite the greater time of exposure. The location of Transect 4 has a favorable aspect (i.e., facing away from the ice) for vegetation growth and as a result exhibits more complete vegetative cover than Transect 3 despite having been exposed for less than a decade longer. Transect 5 lies near the crest of a broad, gently sloping moraine where vegetation is poorly sheltered from the wind. Hence, surface cover by vegetation is incomplete here. The oldest moraine on the foreland, and most distal (ca. 3 km) from the ice front, was studied at Transect 10. The surface is well vegetated, but mosses constitute less than half of the community; most of the remainder consists of shrubs and lichens. The four transects on outwash deposits (6, 7, 8 and 9) are similar to each other in exhibiting nearly completely vegetated surfaces that are dominated (> 75%) by mosses.

Across all stations, albedo measured at the metre-scale exhibits a modest positive correlation with total vegetation cover ($R^2 = 0.25$; Fig. 3a). This stems from the fact that the glacial debris of the Skaftafellsjökull, both ice-contact and outwash deposits, are darker, because they are derived from mafic bedrock, than most of the successional vegetation. Therefore, the overall trend on the moraines of the Skaftafellsjökull foreland over time is of increasing albedo due to the increase in vegetative cover through plant colonization and primary succession. This is further demonstrated by the modest negative correlation between albedo and total rock and soil surface exposure ($R^2 = 0.25$; Fig. 3c). This is contrary to the trends on most Arctic and sub-Arctic landscapes where the conversion of moss heath to shrub heath lowers albedo (cf. Chapin et al. 2005; Blok et al. 2011; Loranty et al. 2011; Pearson et al. 2013; Juszak et al. 2014; Williamson et al. 2016). The strongest positive correlation was found between albedo and cover by mosses, which are primarily *Racomitrium* species ($R^2 = 0.50$; Fig. 3b), due the fact that the mosses generally are lighter in colour than the other components of the vegetative community. Total vegetation coverage and coverage by mosses increases on the glacial moraines largely as a function of time but is subject to aspect effects; surfaces exposed to the katabatic winds are less vegetated than surfaces on the sheltered. Hence, time and/or distance from the glacier of a moraine surface control albedo but are constrained by aspect.

Notably, albedo is higher on the outwash deposits (transects 6 through 9) than on the moraines, with the exception of Transect 10, which is nearly equal to the lowest mean albedo from an outwash location (Transect 6). The outwash surfaces have higher mean vegetative cover than the moraines, possibly due to the neutral aspect of the nearly horizontal outwash channel terrace and bar surfaces and the nature of the substrate. Glausen and Tanner (2019) speculated that colonization by mosses on the outwash surfaces limits recruitment of other vegetation by restricting seeding sites, thereby limiting community diversity. However, Burga et al. (2010) noted the importance of microsite variation, including substrate, in controlling successional trends. We point out here that the poorly sorted substrate of the moraines, in which fine-grained material occurs in the spaces between gravel and boulders, provides more seeding sites for vascular plants than the gravel-covered surfaces of the outwash bars and terraces. Hence, vascular plants have more opportunities for colonization and competing with mosses on the moraines. As mosses lack root systems, they can effectively grow over gravel-covered surfaces and dominate the outwash deposits to the exclusion of most vascular plants (i.e., low shrubs and dwarf trees).

In summary, the differences in the landforms and their substrates control the successional communities, which in turn control variations in albedo at the landscape scale. These differences are recognizable from satellite photographs as distinct variations in brightness between moraines and outwash deposits due specifically to the greater coverage by mosses. These brightness variations can be measured semi-quantitatively by image-processing software (Table 1). The mean greyscale brightness measured for all of the outwash transect locations (transects 6 through 9) have values of > 90, while all of the moraines (transects 1 through 5 and 10) have values of < 90. The brightness values obtained from the satellite photograph (Fig. 1) correlate well with the mean albedo for each transect as measured at ground level ($R^2 = 0.66$; Fig. 3d). These results demonstrate that measuring albedo at ground level can be used to establish the vegetative control of metre-scale albedo, and also show that these small-scale measurements can be related to observations at the landscape-scale by remote sensing.

Conclusions

The foreland of the Skaftafellsjökull consists of moraines with varied slopes and relatively horizontal outwash deposits. Primary succession since the retreat of the ice starting in 1890 has resulted in differences in the vegetation communities on the moraines compared to the outwash deposits, which also causes measurable differences in albedo. The moraines, which consist of poorly sorted materials, are incompletely vegetated after 130 years of exposure. Vegetation on the older moraines comprises a mix mainly of mosses, low shrubs, and dwarf trees. In a general sense, albedo of the moraines increases with time as vegetation increases, subject to local aspect controls, because most of the vegetation is lighter than the substrate of mafic composition. The deposits of outwash channel terraces and the distal outwash plain consist primarily of water-transported, gravel-size clasts. The outwash deposits are nearly completely vegetated by a low diversity community dominated by mosses that are lighter in colour than most other plants in the successional communities. Consequently, the outwash deposits have a higher mean albedo than the glacial moraines. The difference between the landforms in albedo as measured at ground level are also measurable as differences in greyscale brightness on satellite images, demonstrating that albedo measurements made at ground level are representative of differences in albedo at the landscape scale.

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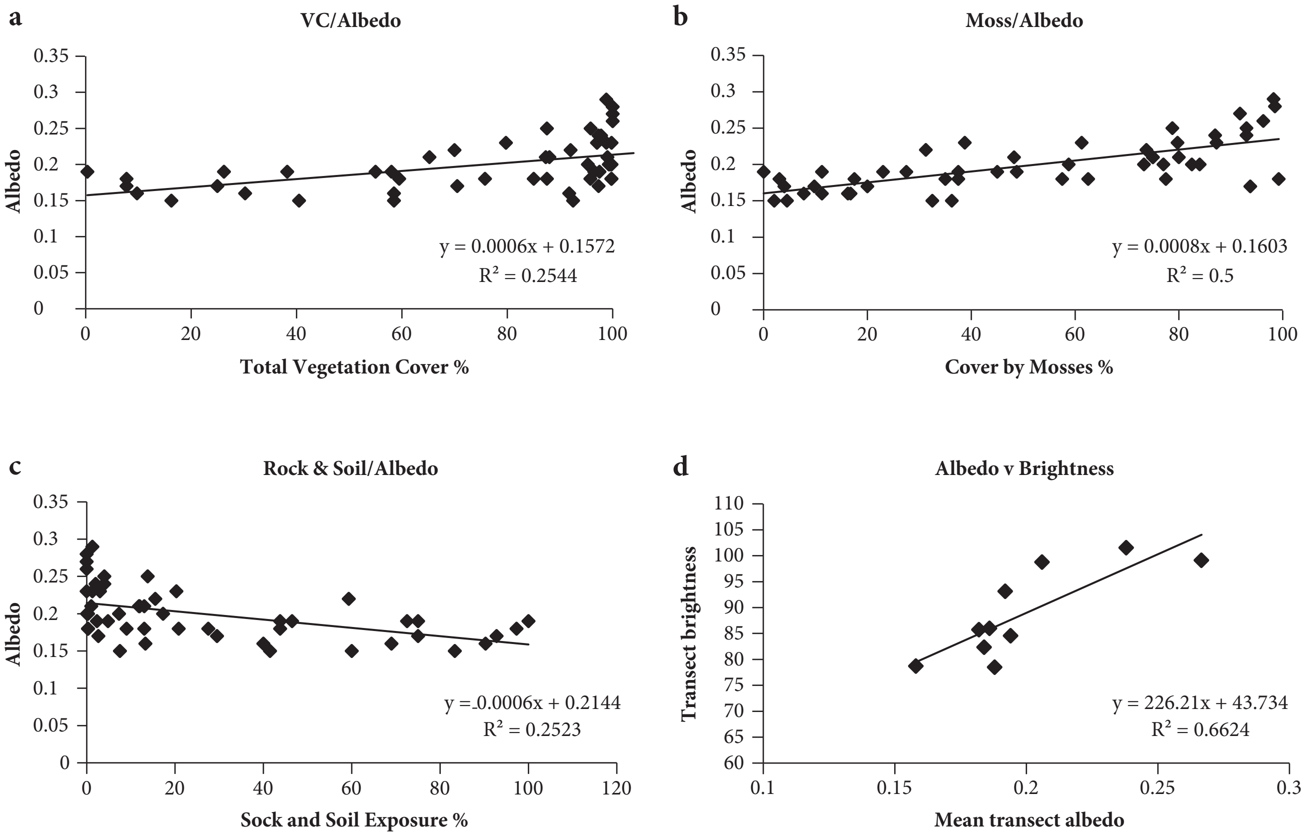

Fig. 3 Albedo scatter plots with linear regression. Each data point represents mean for 1 m² (four quadrats) at one station in transect. a) Albedo plotted against total vegetative cover (VC). b) Albedo plotted against percent of surface area covered by mosses. c) Albedo plotted against a total surface area consisting of exposed rock and unvegetated soil. d) Mean albedo for each transect (mean of five stations) plotted against greyscale brightness measured for transect location on satellite photograph using ImageJ software.

Data availability

The raw data generated in this study are available from the corresponding author on request. Summary data for all plant groups measured are presented as a Supplement.

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