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*Research article*

# Significance of vegetation cover differences on albedo and soil carbon on a basaltic sandplain in southern Iceland

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**Abstract:** Studies have documented that recent anthropogenic climate change has caused increased vegetative growth on arctic tundra landscapes, resulting in increased carbon storage (in biomass and soil), but decreased albedo and increased energy budgets. The glacial outwash sandplains (sandurs) of Iceland offer an interesting landscape comparison. Here, glacio-fluvial deposits of basaltic volcanic sands and gravels form a low albedo surface (mean 0.11) that stores little carbon (<0.1%). Conversion of the barren surface to a moss-dominated heath in recent decades increased albedo substantially (mean 0.24), contrary to the general trend on Arctic tundra landscapes, and also increased soil carbon (>0.2%). The environmental benefits of increased albedo and carbon sequestration highlight the importance of considering the specific processes of landscape change in projecting future environmental changes.

**Keywords:** albedo; sandur; moss heath; soil carbon

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**Abbreviations:** VC = vegetative cover

## 1. Introduction

It is well established that the anthropogenic climate change of the last century has resulted in substantially greater warming at high latitudes compared to the global mean [1]. Numerous studies have examined the environmental impacts of this warming on Arctic regions, including the effects on land energy budgets, of retreating glaciers, decreasing snow cover and changing plant communities. Specifically, the conversion of moss-dominated tundras to shrub heaths and the increased growth of larger shrubs and trees presumably provide greater dark leaf area for absorption of solar radiation, thereby reducing albedo [2–11], although the relationship between shrub vegetation and albedo has sometimes been oversimplified [12,13]. Nevertheless, the potential change in the energy budget thus provides a possible positive warming feedback in the arctic climate system with important consequences, such as accelerating permafrost thaw, glacial retreat and accelerated growth of shrubs on tundra. At lower latitudes, similar studies have examined the encroachment of boreal forest northward across the tundra-forest ecotone, also driven by anthropogenic climate change [14–16]. This shift in the biome similarly lowers landscape albedo due to the darkness of coniferous trees, producing an accelerating positive feedback. Overlooked in many of these studies, however are the consequent changes in carbon cycle dynamics, particularly the expansion of carbon sinks (soil and above-ground biomass) linked to increased primary productivity (Beck et al. [15] is an exception).

The subarctic setting of Iceland offers an opportunity to test the effects of changing plant communities on albedo and carbon storage on a unique landscape. Broad areas of the country are covered by dark, unvegetated surfaces comprised primarily of volcanically and glacially deposited sediments of mostly basaltic composition. Some of these are the outwash plains of glacial outwash rivers and streams (sandurs) in coastal areas, such as the Myrdalsandur and Skeiðarársandur on the south coast. Similar surfaces occur in the interior highlands, where the combination of low temperature, eolian processes and lack of particle cohesion prevent plant colonization. Other extensive barren areas were formed by anthropogenic processes, primarily erosion due to deforestation and overgrazing following settlement in the late 9th century [17]. In theory, plant colonization of these surfaces has the potential to both change the albedo of the surface and create a soil carbon reservoir. This study compares the albedo and soil carbon content of different portions of the Skeiðarársandur where the surface varies from completely vegetated to almost completely barren.

## 2. Methods

### 2.1. Location

The Skeiðarársandur, which is possibly the world's largest outwash plain at ca. 1000 km$^2$, is the outwash plain formed by the meltwater streams draining the Skeiðarárjökull (Figure 1), one of the largest outlet glaciers of the Vatnajökull ice cap [18]. The Skeiðarársandur is traversed by several streams that drain south to the coast, ca. 23 km to the south of the ice front; from west to east the major streams are Nupsvötn, Gígjuksvísl and Skeiðará. The sandur is separated from a partially inundated periglacial basin by a topographically complex set of push moraines that sits two to five kilometers south of the current ice front.

The Skeiðarársandur is not a completely unvegetated plain, however; substantial portions of the sandur are vegetated. Baldursson et al. [19] describe vegetation growth on the sandur as occurring primarily in three areas since the 1970s: a broad band stretching across much of the uppermost (i.e. northern) part of the sandur, including approximately two-thirds of the upper sandur between Gígjukvísl, and Skeiðará; an elongated but narrow band that stretches northeast to southwest across the central area; and a centrally located band near the coast (Figure 1). The vegetative cover (VC) in the study area is dominated by mosses, primarily *Racomitrium lanuginosum* (Hoary-fringe moss). Other plant species, including most prominently (in approximate decreasing order of abundance) *Empetrum nigrum* (Black crowberry), *Calluna vulgaris* (Scotch heather), *Arctostaphylos uva-ursi* (Bearberry), *Saxifraga oppositofolia* (Purple saxifrage), *Betula pubescens* (Downy birch), *Salix lanata* (Wooly willow) and various graminoids comprise up to 15% of VC at some individual stations, but generally are less than 5% of VC, the remainder consisting of moss, which forms mats two to three centimeters thick that trap aeolian sediments effectively (Figure 2A). The underlying sediment, poorly to moderately sorted gravelly sand (or sandy lag gravel [20]), displays very little evidence of pedogenic modification other than a silty mantle of variable thickness and likely aeolian origin. The substrate consists of the basaltic glacio-fluvial outwash of the Skeiðarárjökull, with occasional inputs of tephra. In the broadest sense, the soils belong to the order Andosols of the more specific type Cryand or Vitric Andosol [21]. Nevertheless, much of the sandur remains unvegetated; more than 70% of the land area bordered by Gígjukvísl, Skeiðará, the moraines and the coast has less than 10% vegetative cover (VC) [22].

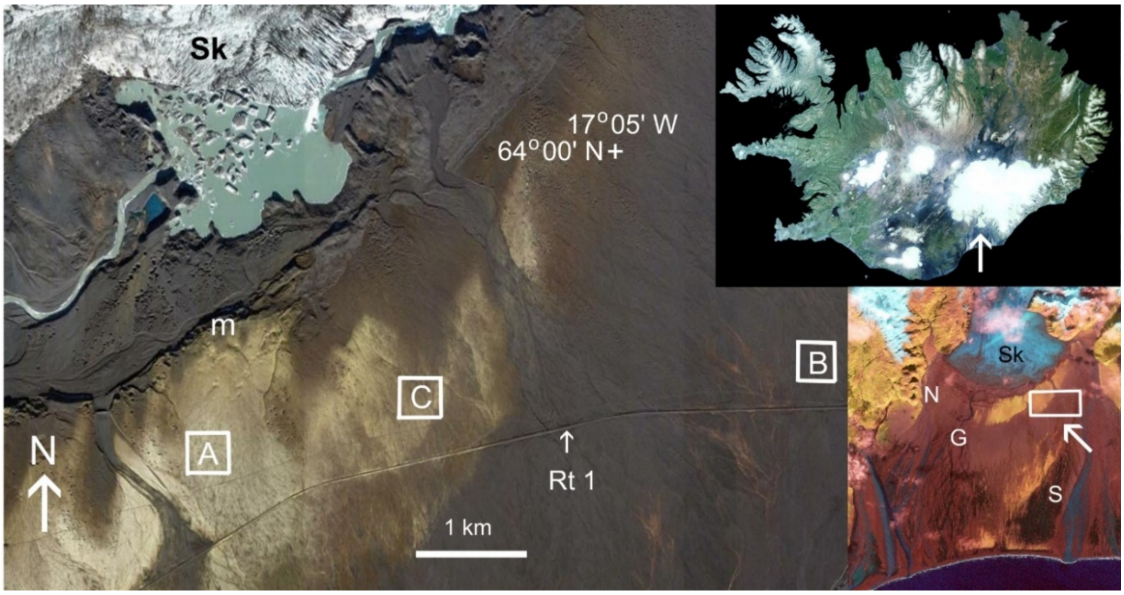

**Figure 1**. Map of the study area on near the south coast of Iceland. Upper inset map: arrow indicates area of study near the Vatnajökull ice cap. Lower inset map: false color Landsat image (vegetation appears bright; from NASA http://denali.gsfc.nasa.gov/islands/iceland/; also available from Wikipedia Commons). N = Nupsvötn, G = Gígjuksvísl, S = Skeiðará, Sk = Skeiðarárjökull, box indicates study area. Main figure identifies locations of sites A, B and C with boxes approximately the size of the sampling grid at each site. Rt 1 = Route 1, m = main moraine complex of the Skeiðarárjökull. Figure adapted from Google Earth ® image; satellite data acquired 2013.

**Figure 2.** Details of the sandur surface. A) View of Site A illustrating thickness of moss with pockets of aeolian sand trapped in depressions, and gravelly, sandy nature of the substrate. B) View of Site B illustrating gravel lag that armors the upper surface over a substrate similar to that at Site A.

In addition to normal meltwater discharge, the geomorphology and surficial characteristics of the sandur are affected by episodic jökulhlaups, or glacial outburst floods, the largest of which are triggered by subglacial eruptions of volcanoes beneath the Vatnajökull. The last major event was triggered by the eruption of Gjálp in November 1996. Meltwater from the eruption traveled southward 50 km beneath the ice before bursting forth from the front of the Skeiðarárjökull at a discharge rate of $45 \times 10^3$ $m^{-3}s^{-1}$ [19]. Approximately 3.5 $km^3$ of water inundated ca. 750 $km^2$ of the sandur in the space of two days [18], but as the ground was frozen at the time, there was only minor erosion of the vegetated portions of the sandur [19,23]. From comparison of Landsat satellite imagery from 1990 to 2006 SPOT imagery Shoopala [23] concluded that most of the area studied, ca. 26,500 ha, experienced no change in VC as a result of the jökulhaup, while VC increased across 6150 ha and decreased across only ca. 1000 ha. The increase was attributed to nutrient deposition in areas covered by floodwaters.

### 2.2. Sampling design

The Skeiðarársandur is traversed by Route 1 (also called the Ring Road), which provides multiple points of access. Three study locations were chosen to represent the range of surface cover by vegetation (Figure 1): Site A, located ca. 500 m north of Route 1 and 300 m east of the Gígjuksvísl is well vegetated, primarily by *Racomitrium* sp. moss with very localized patches of *E. nigrum*, *C. vulgaris* and *A. uva-ursi* (in order of decreasing abundance) and widely scattered individuals of *B. pubescens* and *S. lanata*; the VC is interrupted by unvegetated patches, typically from less than 0.25 $m^2$ to 0.5 $m^2$ in area, and outsize boulders (Figure 3A). Site B, situated ca. 6.5 km to the east of Site A and 200 m north of Rt. 1, was chosen to represent a surface almost completed devoid of vegetation; only scattered patches of (undifferentiated) graminoids occur (Figure 3B). Site C, located ca. 2 north-northwest of Site A, was selected to represent an intermediate site of partial VC; vegetation is similar in species to that at Site A, but the coverage is broken by large barren patches (Figures 1, 3C).

At each site location, a sampling grid was established consisting of five north-south oriented transect lines, each spaced 50 meters apart. Along each transect line five measurement stations were established, also spaced 50 meters apart, yielding a total of 25 stations per site. Each station on the transects consisted of a 10 m × 10 m (100 $m^2$) plot. Soils were sampled on each plot by removing five 20 cm length soil cores using a 3 cm-diameter hand auger; one core was drilled from near each corner of the plot and one from the approximate center of the plot,. Light measurements for albedo calculation and measurement of VC were made at the same locations as described below.

### 2.3. Measurements

Total VC for each station was determined by visually estimating VC within a 0.25 $m^2$ quadrat that was rotated three times to provide 1 $m^2$ of continuous coverage. This measurement was repeated at each corner and in the center of each plot, coincidental with the location of the soil sampling. In addition to simple VC, the proportions of different major plant species within the quadrat also were estimated.

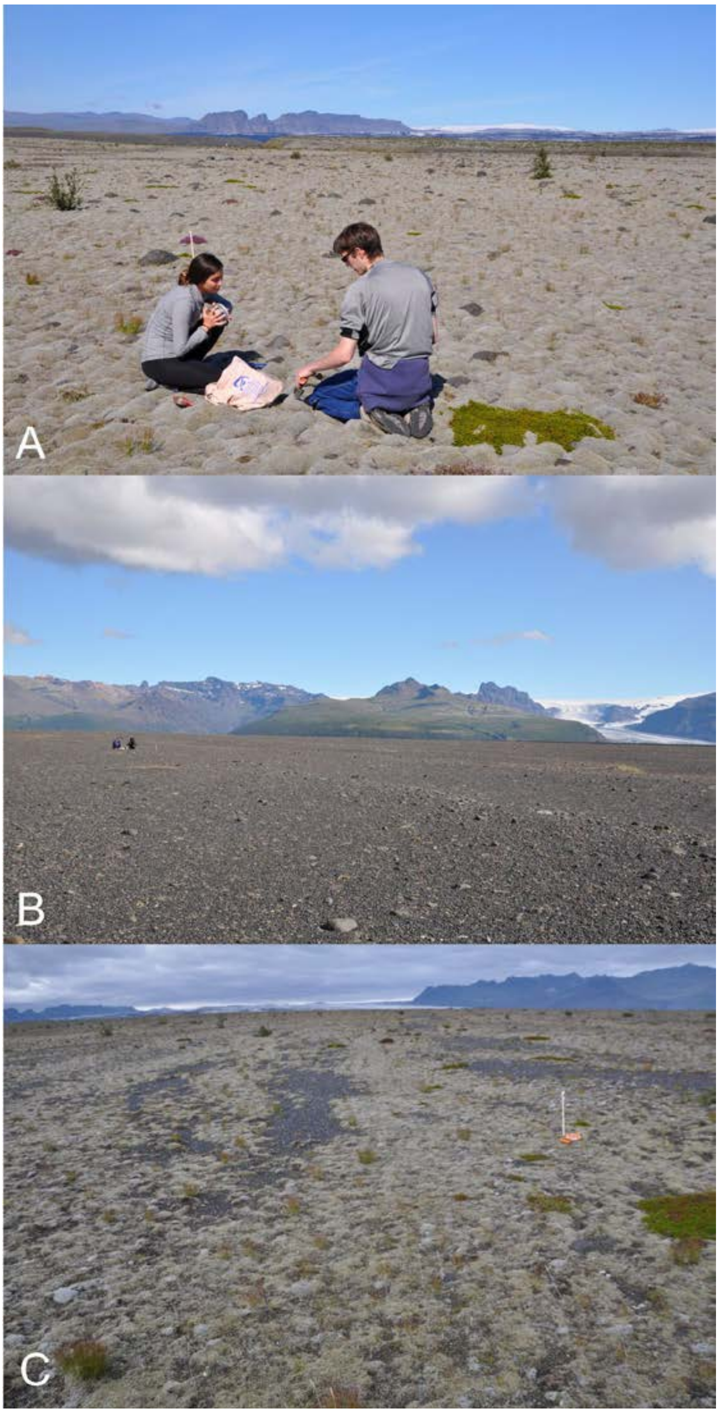

**Figure 3.** Representative views of the landscapes at sites A (fully vegetated), B (unvegetated) and C (partially vegetated), respectively.

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) one meter above the ground surface with the sensor oriented parallel to the ground surface. This measurement also was repeated four times at each location from which the soil cores were obtained (times five locations per station). The mean of the resulting 20 measurements per station presents an average value representative of the entire 100 $m^2$ area of the station, 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 level on various landscape surfaces at high latitude [24].

Soil carbon was measured from the cores collected in the field. The 20 cm core was divided into upper and lower 10 cm segments. The separated 10 cm segments of the five cores from each station were combined to produce composite samples representative of the upper and lower 10 cm of the soil for the entire plot. Bulk density of the soil was measured separately for the upper and lower core segments after drying. In the lab, the composite samples were sieved with a 2 mm screen, washed with 5% HCl (to remove inorganic carbon), rinsed, dried and pulverized in a ball mill. Carbon analyses were conducted on two replicates of each sample with a TruSpec CN carbon-nitrogen analyzer manufactured by Leco Corporation. Analyses consisted of combustion of the sample at 950 °C in a pure $O_2$ atmosphere with the $CO_2$ in the exhaust gas measured by an IR cell.

## 3. Results

### *3.1. Site A – Nearly fully vegetated*

Vegetation coverage at the 25 stations represented in the five transects at this site ranged from ca. 70% to 98%, with a mean of 89 ± 2%. Mean values of albedo for the stations at Site A were remarkably consistent, ranging from 0.20 to 0.24, but individual measurements at the stations ranged from 0.15 to 0.30, reflecting the small-scale variability of VC and plant species. The overall mean for Site A was 0.22 ± 0.003. The soil carbon content exhibits much greater variability, with station values ranging from 0.1 to 0.8% in the upper 10 cm; mean soil carbon = 0.24 ± 0.03% in the upper 10 cm, 0.16% at 10–20 cm. Mean bulk density of the soil was measured (dry) in the laboratory at 1.28 g $cm^{-3}$, yielding a carbon stock of 0.51 kg $m^{-2}$ (or 5.1 tC $ha^{-1}$) within the upper 20 cm. These values match well with those reported previously for Sandy Vitrisols in Iceland [25] although we note that carbon stocks cited in [25] are calculated for full profile thickness.

### *3.2. Site B - Unvegetated*

As described above, Site B, located 6.5 km east of Site A is largely devoid of vegetation, but not completely so. VC at the individual stations ranged from 0 to a maximum of 5% (mean = 1 ± 0.3%) and consisted almost entirely of graminoids. The surface is a gravel lag produced by aeolian deflation that protects a coarse gravelly sand beneath, as observed at Site A (Figure 2B). Individual measurements of albedo for this surface varied from a minimum of 0.07 to a maximum of 0.15, although the means for the stations were quite consistently between 0.10 and 0.12; the overall mean was 0.11 ± 0.001. As might be expected, the carbon content of the soil here is much lower than at Site A. Only two of the 25 stations recorded soil carbon >0.10% in the upper 10 cm, with a maximum value of 0.18%; nine samples were below detection limits. The mean carbon content was 0.04 ± 0.01% in the upper 10 cm and 0.01% in the 10 to 20 cm interval. The mean bulk density measured was 1.36 g $cm^{-3}$, yielding a carbon stock of 0.07 kg $m^{-2}$ (= 0.7 tC $ha^{-1}$).

### 3.3. Site C – Partially vegetated

Site C is located between sites A and B at 2.2 km west-northwest of Site A. Vegetation coverage is less continuous than at Site A, ranging from a minimum of 50% to a maximum of 85% (overall mean = 70 ± 2%), with patches of bare ground of various sizes and shapes and boulders interrupting the plant cover. The species of the plant community are the same as at Site A; although still dominated by mosses, vascular species form more substantial patches than at Site A, particularly *E. nigrum* and *C. vulgaris*, which account for 5% to as much as 7% of VC at some stations. As at Site A, the mean albedo for the 25 stations was relatively consistent with a range of 0.13 to 0.18, although individual albedo measurements varied greatly, from 0.10 to 0.20. The overall mean albedo for Site C was 0.15 ± 0.004. The substrate at this site does not differ substantially from that at Site A in texture or carbon content; the range of values and mean soil carbon in the upper 10 cm are nearly identical, 0.04% to 0.41% (mean = 0.25 ± 0.02%). The mean bulk density of the soil at Site C was slightly lower than at sites A and B at 1.11 g cm$^{-3}$, yielding a carbon stock (for the upper 20 cm) of 0.38 kg m$^{-2}$ (3.8 tC ha$^{-1}$).

### 3.4. Site comparisons

The results presented above indicate a relationship between VC and both albedo and soil carbon. Box plots for the three sites for albedo and soil carbon (Figure 4) demonstrate marked separation of sites A (fully vegetated) and B (unvegetated). Site C (partially vegetated) falls in an intermediate position between A and B for albedo, as might be expected, but is identical to A for soil carbon. This is not totally unexpected given the overlap in the range of VC between these sites. Both properties correlate positively with VC (Figure 5), although the correlation with albedo is stronger ($R^2 = 0.75$) than for soil carbon ($R^2 = 0.41$). Notably, the data from Site B, where VC was very low, clusters very tightly.

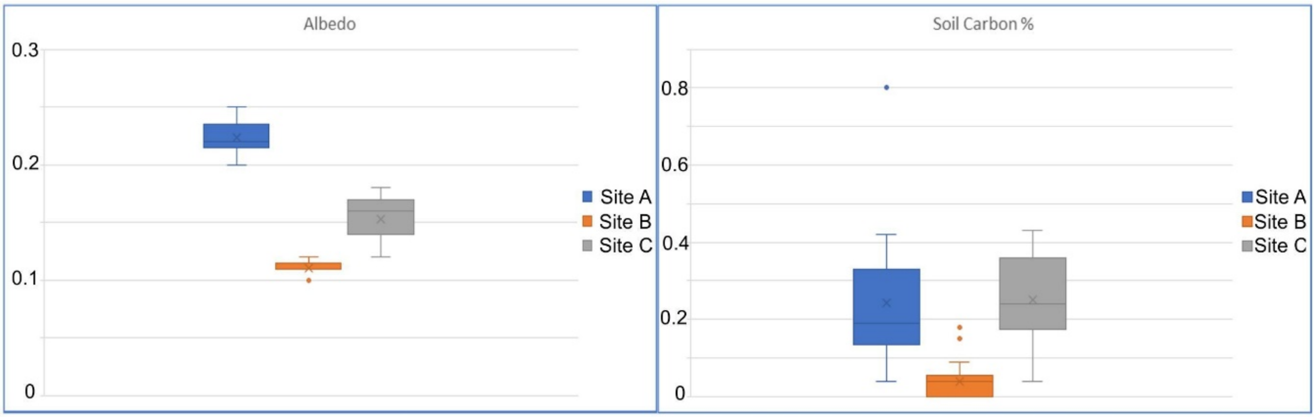

**Figure 4.** Standard box and whisker plots for albedo (left) and soil carbon content (right) for the three sites.

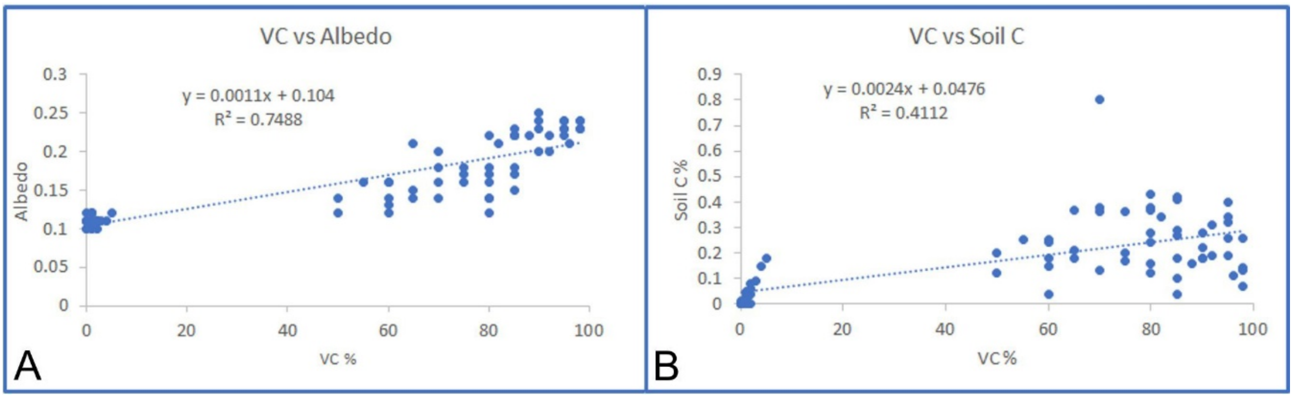

**Figure 5.** Scatter plots with best fit regression lines for vegetation cover vs. albedo (left) and soil carbon content (right).

## 4. Conclusions

The landscape change on the Skeiðarársandur in recent decades, by increasing the albedo of the land surface, is a temporal trend that is contrary to that observed on the Arctic tundra, where the climate-driven increase in shrub growth lowers albedo [2–11]. The moss heath cover of large areas of the Skeiðarársandur provides the environmental benefits of lowering the albedo, thereby lowering the local energy budget, and allowing increased storage of carbon in the underlying soils. Indeed, the soils of the Skeiðarársandur have the potential to sequester considerably more carbon than they do at present. Theoretically, complete coverage of the 1000 $km^2$ sandur to the same VC level as at Site A would (by extrapolation) cause sequestration of $5.1 \times 10^5$ tC. Moreover, if vegetative growth of the sandplains of Iceland is accelerated by ongoing climate change, the potential exists for future coverage of other unvegetated landscapes in Iceland, including both coastal sandplains and highland deserts. By extrapolation, such landscape changes could produce a more significant negative climate feedback through carbon sequestration and increased albedo. Admittedly, however, this effect would benefit only a limited portion of the arctic and near-arctic environment.

Interestingly, some areas of the Skeiðarársandur have become colonized by *B. pubescens* (Downy birch) in the last three decades [19,26,27]. By 2016, an estimated 34 $km^2$ of the sandur had been colonized by birch [19]. Aside from creating an above-ground biomass carbon stock, establishment of a forest of birch and other deeper rooted vascular species increases the potential for formation of thicker, more carbon-rich soils such as the Brown Andosols [28] that typically store carbon at more than order of magnitude greater than the Vitric Andosols that presently cover most of the Skeiðarársandur. However, a major increase in the amount of cover by the darker leaved birch or other shrubs at the expense of the lighter toned mosses, potentially driven by anthropogenic climate warming, will also cause a decrease in the albedo of the vegetated portions of the Skeiðarársandur and thereby increase the local energy budget, as has been documented in various studies of the Arctic [3–11].

Nevertheless, there remains the potential for jökulhlaups that could strip away the moss, or bury it in rapidly deposited outwash. Prior to the 1996 event, the last major flood event on the Skeiðarársandur was in 1938. As described above [19], the widespread development of the moss on the sandur did not occur until several decades later. It is not clear, however, if this delay was due to some autogenic properties or processes on this landscape, perhaps controlled by the nature of the substrate, or if the growth of the moss was related to climate warming during the late twentieth century. Fortunately, these large-scale jökulhlaups are infrequent (on the human time scale).

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## Conflicts of interest

Both authors declare that they have no conflicts of interest regarding the publication of this paper.

## Data availability

The raw data generated in this study are available from the corresponding author on request. Summary data (mean values for VC, albedo and soil carbon) are presented as a Supplement.

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