Soil development within glacier forelands, Southeast Iceland

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Dissertation submitted in partial fulfillment of a Philosophyae Doctor degree in Geography

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Abstract

Glaciers in Iceland have been steadily retreating since the end of the Little Ice Age ~1890, exposing surfaces where weathering and vegetation succession commences. This thesis presents the results from studies on soil development along chronosequences, a time for space substitution, within the fore-fields of Skaftafellsjökull and Breiðamerkurjökull outlet glaciers in SE-Iceland. The study showed that with increasing time since deglaciation and vegetation succession, bulk density and pH (H₂O) decreased, while concentrations of loss on ignition (LOI), soil organic carbon (SOC) and total nitrogen (N) along with pH (NaF) increased. There was a slow yet significant increase of ammonium oxalate extractable aluminium (Alox) and iron (Feox) in the oldest moraine at Skaftafellsjökull. Vegetation succession was initially slow but then the vegetation stratigraphy developed in two different directions. Dwarf shrubs and shrubs characterized the oldest moraines at Skaftafellsjökull but grasses at Breiðamerkurjökull where shrubs were completely absent. The rates of soil development were initially slow, reflecting the trend in vegetation succession, but the rates increased after the first 50 years. The highest rates of soil organic carbon accretion (SOC) were reached in the 120 yr-old moraine at Skaftafellsjökull, 9.1 g m⁻² yr⁻¹. The rates were considerably lower for Breiðamerkurjökull, reaching 4–4.5 g m⁻² yr⁻¹ in the 67–122 yr-old moraines. The rates of increase for both the study sites were considerably lower than compared to sites of revegetation or forestry. Topography affected both vegetation establishment and soil development, where the base of slopes significantly contained higher SOC, N, Alox and Feox concentrations. At Breiðamerkurjökull, avifauna had a point-centered impact on soil formation, creating hot spots within ‘bird hummocks’ on the summits of moraine ridges by adding nutrients through their droppings. The current annual increase in SOC stocks was estimated at 20.7 Mg C yr⁻¹ for Skaftafellsjökull and 19.7 Mg C yr⁻¹ at Breiðamerkurjökull.
Útdráttur

Jöklar á Íslandi hafa hörfað meira og minna frá lokum litlu ísaldar um 1890. Þar sem land verður íslauð of gróðurframvinda og efnavéðrun sem leiðir til jarðvegsmynndun. Þessi ritgerð fjallar um jarðvegsmynndun og gróðurframvindu fyrir framan tvo skriðjökla á Suðausturlandi, Skaftafellsjökul og Breiðamerkurjökul. Þar sem staða jökla á ákveðnum tíma er þekkt má nýta það til að rekja breytingar á gróðri og jarðvegi með auknum aldri yfirborðsins. Rannsóknir sínydu að breytingar á jarðvegi stjórnudust af aldri yfirborðs og gróðurframvindu; rúmþyngd og pH (H₂O) lækkudu með tíma en gleðitap (LOI), lífrænt kolefni (SOC) og köfnunarefni (N) ásamt pH (NaF), jukust með tíma. Til að byrja með var gróðurframvinda hæg, sem endurspeglaðist í hægri jarðvegsmynndun fyrstu 50 árin. Eftir það þróaðist gróðurfar við jöklana í sitt hvora áttina, þar sem smárrunnar og runnar einkenndu elstu jökulgarða við Skaftafellsjökul, en grös einkenndu elstu jökulgarða við Breiðamerkurjökul þar sem engir runnar voru. Mesti uppsöfnunarhraði kolefns reyndist vera í elstu jökulurðinni við Skaftafellsjökul, 9.1 g m⁻² yr⁻¹ eftir 120 ár. Söfnunarhraðinn var talsvert lærri við Breiðamerkurjökul eða 4−4.5 g m⁻² yr⁻¹ eftir 67−122 ár. Hann var talsvert lægri við jöklana tvo en mælst hefur í uppgreiðslum og í skógrækt hér á landi. Landslag hafði ahrif á jarðvegsmynndun þar sem lægdir innan jökullandslagins höfðu marktaðt hærri SOC, N, Alox og Feox gildi. Við Breiðamerkurjökul skipti fuglalíf sköpum þar sem ‘svalþúfur’ eða ‘fuglaþúfur’ höfðu myndast á toppum jökulgarða og þær reyndust vera ‘heitir reiti’ jarðvegsmynndunar í jökulurðinni. Árleg uppsöfnun SOC í jökulurðinni var áætluð 20.7 Mg C ár⁻¹ við Skaftafellsjökul og 19.7 Mg C ár⁻¹ við Breiðamerkurjökul.
Dedication

This thesis is dedicated to my two daughters, who had just been and were born on my walk along this road to PhD. Snæðís Erla and Valgerður Svana, keep on playing in the ‘dirt’ until you grow old and never stop asking questions about our amazing nature.
Landslag í Öræfum

Margan sumardag höfum við horft á blágræna jaka sigla um jökullónið fram á rauðanótt og hugsæð: á morgun eða hinn daginn mun sólinni auðnast að breyta örfoka sandi í frjóan svörð handa grængresi að halda sér í þegar nødingar geisa og jafnoft séð þessa djúpristu ísnökkva færast aftur í aukana með veturnóttum uns þeir urðu samfrosta við jökulspóðinn sem skriður yfir landið og eirir engu lifi. Nú bíðum við vorsins milli vonar og ótta eins og hér hefur lóngum verið á bæjum títt.

Einar Bragi
List of papers

This PhD project has been carried out at the Institute of Life- and Environmental Sciences, University of Iceland. Soil formation was studied in front of two retreating outlet glaciers, Skaftafellsjökull and Breiðamerkurjökull, SE-Iceland. This thesis is a compilation of four papers presenting the results from the two study sites from different aspects. Appendix I includes author contributions to the papers. In appendix II, published papers outside of this PhD thesis during the time of this study are listed. The papers will be referred in the text as follows:


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Abbreviations

LIA: The Little Ice Age
GHG: Greenhouse gas(es)
OM: Organic matter
SOM: Soil organic matter
SOC: Soil organic carbon
OC: Organic carbon
LOI: Loss on ignition
C: Carbon
N: Nitrogen
Al: Aluminum
Si: Silica
Fe: Iron
Ca: Calcium
El\textsubscript{ox}: Element extracted with ammonium oxalate solution
NaF: Sodium fluoride solution
ICP-OES: Inductively coupled plasma optical emission spectrometry
O, A, Bw, C, E: Soil horizons
CEC: Cation exchange capacity
BD: Bulk density
T: Thickness
S: Content of coarse fragments (vol. %)
ST: Soil taxonomy, soil classification system of the United States of America
WRB: World Reference Base for Soil Resources, soil classification system of IUSS-FAO (The International Union of Soil Sciences – Food and Agriculture Organization of the United Nations)
DEM: Digital elevation model
Lidar: Light detection and ranging; a remote sensing technique that uses laser pulses to measure surface topography
GPS: Global positioning system
ANOVA: Analysis of variance
REIS: The RapidEye Earth Images Scanning System
VI: Vegetation indexes
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My affection for this land fuels the devotion for this work.

Ever grateful,

Olga Kolbrún
Introduction

1.1 Background

1.1.1 Soil development and the soil forming factors

The importance of soils for life on Earth is great. With an increasing human population the importance of soil resources is likely to keep increasing since food production is largely dependent on soils. Soils are regarded as one of Earth’s non-renewable resources as they form over a long period of time (hundreds to thousands of years) and the need for sustainable use of this resource is rightfully receiving strong attention worldwide. Soils are both physical and a biological entities and can be viewed as a link between the physical and biological components of the landscape (Matthews, 1992). Where land emerges from beneath retreating glaciers they reveal moraines of raw materials, which over time are altered through physical- and chemical weathering and the input of plants colonizing the surface, slowly forming the thin soil layer upon which terrestrial ecosystems largely depend.

Soil formation is controlled by five factors. The soil as a whole or a particular soil property is dependent on, or a function of, the various soil forming factors: regional climate, organisms (the available biota), landscape or topography incorporating the water table, the nature of the parent material and time (Jenny, 1941). These factors play different roles in soil formation. Some may be regarded as passive, e.g. the parent material and landscape may remain unchanged, or active, such as some climatic and biotic variables, but time is the only independent factor (Matthews, 1992). In a chronosequence, a space for time substitution, time is the principal factor driving the soil development through vegetation succession and weathering processes. The pioneering chronosequence studies of soil development and vegetation succession from Glacier Bay, Alaska, (Crocker and Dickson, 1957; Crocker and Major, 1955) are an example of this approach. As a response to the impact of climate change causing glacial retreat worldwide, the number of published chronosequence studies from recently deglaciated areas has increased since 1980s. This study ranks in the same category.

Glacial recession since the end of the Little Ice Age (LIA)

During the LIA, a period from the Middle Ages till the close of the 19th century, glaciers in Iceland advanced and piedmont glaciers culminated between 1850 and 1890 (Björnsson and Pállsson, 2008). The terminal moraines, demarcating the maximum extent of glaciers at the end of the LIA, are generally dated to 1890. For the two outlet glaciers that were chosen for this chronosequence study, Skaftafellsjökull and Breiðamerkurjökull, their terminal moraines are dated to 1890, but as for most glaciers in Iceland, their recession until today has been interrupted with static periods and/or readvance. Hannesdóttir et al. (2014) studied the recession of Skaftafellsjökull (Fig 1.1) as well as the other outlet glaciers from Öræfajökull and reported a slow recession/advance after 1900 until ~1935 and again during the period from ~1965–1995. The variations in Breiðamerkurjökull’s glacier front (Figure 1.2) were studied by Guðmundsson (2014) but the glacier is
composite of three ice flows with the middle part, Esjufjallajökull, being the one exposing the area concerning this study. The Esjufjallajökull part of Breiðamerkurjökull slowly receded from 1890–1930, then the front receded rapidly but after that two periods of static front/advancement were reported: from around 1950–1965 and again after 1980–1995.

Both Skaftafellsjökull and Breiðamerkurjökull have receded considerably since 1890 and the distance to the terminal moraines is currently ~2.8 and 5 km, respectively. With the continued recession of Skaftafellsjökull a glacial lake is forming at the glacier front in the trench dug out during the advance of the glacier in the LIA (Magnússon et al., 2012). Two glacial lakes are in front of Breiðamerkurjökull, the larger Jökulsárlón to the east and Breiðárlón to the west. The proglacial area included in this study is at the western edge of Jökulsárlón (Figure 1.2). This recently deglaciated terrain in between the present day glacier terminus and the terminal moraines formed towards the end of the LIA, which herein will be referred to as glacier fore-field, proglacial area or glacier foreland. Since the end of the LIA, from 1890 to 2000, the glacial recession in Iceland is estimated to have exposed 1285 km² (Sigurðsson et al., 2013). Many of these deglaciated areas are now dynamic sites of chemical weathering and plant succession.

The power of plants
Vegetation colonization and increase in plant cover are probably the most obvious changes occurring within glacier fore-fields. Vegetation succession has been described for numerous glaciers but patterns of successional change differ between study sites. Vegetation colonization begins almost immediately after deglaciation and a full cover is often attained within 30–50 years. It is, however, highly dependent on local environmental factors, such as the nature of the substrate, the landscape and biological controls, such as patterns of immigration and species interaction (Matthews, 1992). In general, vegetation stratification is developed over time, with time-dependent sequence of herbs, shrubs and trees in specific regions such as the Alps and Alaska (Burga et al., 2010; Crocker and Major, 1955), and cryptogams appear to precede phanerogams at higher latitudes and in mid- and high-alpine zones (Hodkinson et al., 2003; Persson, 1964; Stork, 1963).

The input of plant detritus to the soil, chemical- and biological processes and physical changes of the parent material slowly forms a sequence of horizons within the soil profile. Typically, the biological activity in the surface material forms an A horizon on top of the relatively unaltered parent material (the C horizon). Where the input of organic matter is abundant or decomposition slow, an O horizon may form on top of or instead of the A horizon. Over time, a B horizon forms below the A horizon, representing a layer of chemical weathering and formation of clay minerals. In some cases, an E horizon of eluviations may form below the A horizon. This process of horizontation operates on the timescale of 100–200 years and has been described from various locations (Alexander and Burt, 1996; Crocker and Dickson, 1957; Dümig et al., 2011; Egli et al., 2010; He and Tang, 2008; Kabala and Zapart, 2012).
Figure 1.1 The Skaftafellsjökull proglacial fore-field. Above - a view eastward to Öræfajökull volcano and the outlet glaciers Skaftafellsjökull (left) and Svínafellsjökull (right) with Skaftafellsheiði heathland in the foreground. Below – a close up on the northern part of the proglacial fore-field. Photos: Snævarr Guðmundsson.
Figure 1.2 An aerial view of the Breiðamerkurjökull glacial fore-field. Above - Fjallsárlón glacial lake is closest, Breiðárlón in the middle and then Jökulsárlón with its blue color. The Atlantic Ocean is on the right. Below – a close up on the northern part of the pro-glacial fore-field. Photos: Snævarr Guðmundsson.
1.1.2 Why the SOC soil organic carbon?

Plants use the energy from the sun and carbon dioxide (CO$_2$) from the atmosphere to grow and reproduce, a process called photosynthesis. Their detritus is broken down and incorporated in the soil during decomposition (Figure 1.3). The organic matter (OM), or soil organic matter (SOM), plays various important roles in the soil as it provides water-holding capacities, cation exchange capacity (CEC), nutrients, especially nitrogen (N), and supplies energy for microorganisms (Brady and Weil, 2004). The OM is defined as the mixture of recognizable plant and animal parts and material that has been altered to the degree that it no longer contains its original structural organization. The non-recognizable material is called humus and makes up the bulk of SOM (Oades (1989) cited by Amundson (2001)). As all organic substances, OM contains carbon (C), and organic carbon in the soil is referred to as soil organic C (SOC). The OM in soils is on different stages of decomposition and on different forms where it becomes immobilized. SOM is stabilized through different mechanisms that may be categorized as biochemical recalcitrance, chemical stabilization and physical protection; for example, SOC may be bound to clay minerals and organo-mineral compounds or by forming stable soil aggregates (Christensen, 1996; Dahlgren et al., 2004).

The plant uptake of C from the atmosphere therefore leads to sequestration of soil organic carbon into the SOC stock, which comprises the largest terrestrial C pool of 1550 Pg (1 Pg = 10$^9$ Mg, 1 metric ton = 1 Mg) to 1 m depth (Figure 1.4). This ability of soils to sequester C from the atmosphere is now seen as a way to off-set the increased anthropogenic emission rates of greenhouse gases (GHG’s) until improved technology allows for a reduced use of fossil fuels (Lal, 2008).

![Figure 1.3 The carbon cycling process in soil. Source: ©FAO, 2005. The importance of soil organic matter – Key to drought-resistant soil and sustained food and production, p. 5, http://www.fao.org/3/a-a0100e.pdf, 22.6.2015.](image-url)
Different soil types contain different amounts of OM. Organic soils, such as Histosols and Gelisols (Soil Taxonomy, ST), are the soils of wetlands and regions of permafrost, and contain the highest amount of (OC), while Andisols, soils of volcanic origin, contain the highest amount of OC of the mineral soil orders (Brady and Weil, 2004). Intact soils store SOC but land use, soil erosion, draining of wetlands, especially peatlands, and the thawing of permafrost may deplete the SOC stock by making the C accessible to oxidation. In fact, since the settlement (870 AD), soil erosion has severely depleted the SOC stock in Iceland as a consequence of land-use, volcanism and climate deterioration (Gísladóttir et al., 2011; Gísladóttir et al., 2010; Ólafsdóttir and Guðmundsson, 2002). Óskarsson et al. (2004) estimated the amount of SOC eroded since the settlement at 120–500 Tg (1 Tg = 10^{12} g = 1 million t). This widespread soil erosion has led to stark differences in the SOC and N stocks between vegetated land and the eroded and barren areas. The soils of the barren areas are of poor quality with low SOC content and often low water holding capacity and rapid water infiltration in summer but the low N content is the major nutrient limiting the reestablishment of vegetation (Arnalds, 2008b; Bradshaw, 1997; Magnússon, 1997). During the 20th century up today, actions have been undertaken to prevent further erosion and stabilize eroded areas through revegetation and ecosystem restoration. Several methods have been used; grass seeding and fertilization, tree planting, lupine (Lupinus

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**Figure 1.4** The global carbon pools and fluxes between them. Adapted from Lal (2008), with kind permission from the Royal Society of Chemistry.
nootkatensis) dispersal, lyme grass (Leymus arenarius) seeding and prevention from sheep grazing to name a few (Arnalds et al., 2000). The purpose is to stabilize the barren areas and start a vegetation succession so that eventually a sustainable ecosystem will develop. As a result, the soil underneath will develop from being nutrient poor to feature characteristics beneficial to plants and animals, such as containing SOM, nutrients, secondary clay minerals, high water holding capacity, rapid hydraulic conductivity and infiltration (Arnalds, 2008b).

Today, land restoration and forestry are considered important options to contribute to the counteraction of the ongoing climate change as the soils and vegetation take up C from the atmosphere and store it in plant tissues and soil (Aradóttir et al., 2000; Arnalds et al., 2013; Kolka-Jónsson, 2011; Ritter, 2007; Snorrason et al., 2002). According to the United Nations Framework Convention on Climate Change, the net change in C stocks and GHG emissions by sources and removals by sinks, resulting from direct human-induced land-use change and forestry activities, is considered as an option for countries to meet the commitments of the Kyoto Protocol (UNFCCC, 2015). This includes, under article 3.4, any elected human-induced activities, which can be forest management, revegetation, cropland management and grazing land management. In a report from 2014, the net CO₂ removal due to afforestation, reforestation and deforestation were estimated to be 162 Gg in 2011 and 174 Gg due to revegetation in Iceland (Borgþórsdóttir et al., 2014). In some places natural processes are active that generate results of similar nature as what is being acquired with the restoration activities. These sites are occurring where the environment is considerably stable for plants to colonize the surface, as can be found in front of retreating glaciers. The proglacial areas and the chronosequences that can be established in front of them serve as excellent sites to evaluate the rate of SOC accretion and the increase in SOC stock following natural processes and can be regarded as a baseline or reference sites to compare the results of restoration actions.

1.1.3 From raw moraine material to soil

Chronosequence studies have shown that over time, changes occur in the moraines exposed, where morphological changes create soil horizons, bulk density (BD) and soil pH (H₂O) decrease with increase in time since deglaciation but the SOM, SOC and N contents increase as the time proceeds. Chemical weathering releases iron (Fe) and aluminum (Al) and silica (Si), secondary minerals form and with time it leads to the formation of B horizons. A compilation of the time induced changes has been published by Matthews (1992). Estimating and measuring soil properties and components is done both in the field and in laboratory but working with glacial moraines can pose challenges. A short introduction to some of the methods may therefore be relevant in this chapter.

BD is the weight of the soil per unit volume and is usually presented as g cm⁻³ or kg m⁻³ (Blake and Hartge, 1986). To determine stocks of elements, such as for SOC or N, it is essential to know the dry bulk density for the given soil. It is used as a multiplier for converting a measured amount of elements into weight by area (Lal and Shukla, 2004). The BD value may also provide information on the nature and properties of the soil itself, its composition and even quality. It is therefore widely used and the procedure of measuring BD is rather simple. What is needed is the volume of the sample, including pores, and the weight of the soil after drying for 24 hrs at 105°C. Gravelly soils do however pose challenges for measuring BD as the sample itself must represent the coarse fraction of the soil matrix. To measure bulk density of gravelly soils, excavation methods
are often used where a hole is dug into the soil and its volume measured by using sand, water or insulation foam to fill the holes (Blake and Hartge, 1986; Brye et al., 2004; Page-Dumroese et al., 1999; Stanich, 2013). The volume estimate of the sample is therefore done after retrieving the sample. The volume of the coarse fraction (> 2 mm) is determined with water displacement and must be included when calculating the stocks of elements.

The OM content of the soil is often determined through loss on ignition (LOI) where oven dried soil (105°C) is combusted at 550°C and the weight loss can subsequently be used to determine the SOM content. The SOM concentration may be used to estimate SOC concentration in soils and vice versa. Published SOC–SOM conversion factors for surface soils have varied from 1.724 to 2.0 but the appropriate factor must be determined experimentally for each soil by independent analysis of SOM and SOC (Nelson and Sommers, 1996). The SOM is the major contributor to SOC (50 to 58%) and nitrogen (N) contents but SOC and N are usually determined simultaneously to SOC. Soil pH (H₂O) is a commonly measured value as it affects a wide range of soil properties, for instance the availability for root uptake of elements, both nutrients and toxins. The accumulation of OM tends to lower the pH value of the soil, which facilitates leaching of cations and provides H⁺ from acid functional groups (Brady and Weil, 2004).

Andisols – soils of volcanic regions

Iceland is a volcanic island primarily consisting of igneous rocks of basaltic composition with frequent tephra fall and active eolian deposition (Arnalds, 2008b). Andisols (ST) or Andosols (WRB) developed from the volcanic ejecta comprise the primary soil order (Arnalds and Óskarsson, 2009). The glassy nature of basalts, especially the glassy tephra, has high weathering rates despite the prevalence of cool climate (Gislason et al., 2009). Through water-rock/tephra interaction, some minerals are dissolved completely and leached out of the parent material while others, such as Al, Fe and silica (Si) are tied up in the weathering residues of the primary mineral, such as clays and hydroxides (Gíslason, 2008). The most common weathering residuals of basalts comprise allophane and/or imogolite of variable Al:Si ratios and poorly crystalline iron oxide, ferrhydrite, all mostly amorphous and referred to as the ‘clay minerals’ of Andisols (Arnalds, 2004). The basaltic parent material favors formation of allophane and ferrhydrite, dominating the secondary clay mineral fraction, and their ability to stabilize OC is integral to the high SOC sink capacity of Andisols (Dahlgren et al., 2004). The formation of allophane is inhibited by the presence of large quantities of organic matter and by low pH (generally <5) as the organic materials form complexes with Al or Fe (Arnalds, 2004; Dahlgren et al., 2004). OM sorption to allophane, ferrhydrite and imogolite, the formation of stable Al/Fe-humus complexes and frequent burial of the topsoil by tephra fall all lead to the high SOC accumulation in Andisols. Allophane and ferrhydrite contents in volcanic soils are commonly determined by the indirect measure where Al, Si and Fe are extracted with ammonium oxalate (Al₀, Si₀ and Fe₀), which dissolves allophane, allophane-like materials, organic Al and Fe complexes as well as noncrystalline Al and Fe oxides and ferrhydrite (Wada, 1985). Soil reaction in sodium fluoride solution (pH NaF) is also used as an indicator of andic properties, as it usually correlates strongly with allophane content (Arnalds, 2008a).

1.1.4 The effects of vegetation and landscape on soil formation

Soil development is not simply a time-related factor but also influenced by vegetation and landscape, and these factors function on different scales (Burga et al., 2010). During the initial stages of plant succession, SOC and N concentrations in soils are closely related to
the extent and species composition of vegetation cover and depend upon the magnitude of litter accumulation and OM input between plant species and growth forms (Crocker and Major, 1955; Dahlgren et al., 2004; Rajaniemi and Allison, 2009; Su et al., 2004). Similarly, abiotic factors such as landscape form, slope aspect, grain size distribution and moisture content affect vegetation establishment and can enhance soil development in their initial stages (Burga et al., 2010; Egli et al., 2006; Houle, 1997; Jumpponen et al., 1999). The concurrent yet incongruent effect of biotic and abiotic factors entails spatial variation in the developing soil properties.

Table 1.1 REIS spectral bands and principal applications, modified from Lillesand et al. (2014).

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (nm)</th>
<th>Nominal spectral location</th>
<th>Principal applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>440–510</td>
<td>Blue</td>
<td>Designed for water body penetration, making it useful for coastal water mapping. Also useful for soil/vegetation discrimination, forest–type mapping, and cultural feature identification.</td>
</tr>
<tr>
<td>2</td>
<td>520–590</td>
<td>Green</td>
<td>Designed to measure green reflectance peak of vegetation for vegetation discrimination and vigor assessment. Also useful for cultural feature identification.</td>
</tr>
<tr>
<td>3</td>
<td>630–685</td>
<td>Red</td>
<td>Designed to sense in a chlorophyll absorption region aiding in plant species differentiation. Also useful for cultural feature identification.</td>
</tr>
<tr>
<td>4</td>
<td>690–730</td>
<td>Red–edge</td>
<td>Designed to facilitate the differentiation of vegetation types and conditions.</td>
</tr>
<tr>
<td>5</td>
<td>760–850</td>
<td>Near IR</td>
<td>Useful for determining vegetation types, vigor, and biomass content, for delineating water bodies and for soil moisture discrimination.</td>
</tr>
</tbody>
</table>

The proposed effects of vegetation and landscape on soil formation were the inspiration to estimate regional SOC stocks within the proglacial areas based on the chronosequences, vegetation cover and plant communities and SOC stock. However, vegetation maps for the two study sites were not available and other means of estimating vegetation cover were needed to pursue this goal. Remote sensing images have been used for regional vegetation mapping and images that contain spectral information on ,red-edge‘ and near infrared wavelengths have proven especially useful to detect different vegetation types (Lillesand et al., 2014). Remote sensing data have been used to classify vegetation cover and estimate biomass of aboveground vegetation via indices (VI’s). For example Eckert and Engesser (2013) compared different indices when assessing the vegetation cover and biomass within areas of land restoration in Iceland. They concluded that based on VI’s, vegetation cover within areas of low biomass could be classified with high accuracy using SPOT-5 images. The emerging proglacial areas feature extremely dynamic environments with active vegetation succession. Thus recent satellite images were required for the vegetation classification. The National Land Survey has been systematically collecting RapidEye images for the entire country and an image from 2012 was available for use in this research. The RapidEye Earth Images Scanning System (REIS) contains a five band multispectral imager that employs linear poosh broom scanning. The five spectral bands include the blue, green and red (440–510, 520–590, 630–685 nm) and the ,red-edge‘ and near-infrared bands detecting radiation of 690–730 and 760–850 nm wavelengths, respectively (Table 1.1) (BlackBridge, 2015; Lillesand et al., 2014). The use of the five
spectral bands, including the red-edge band has proven effective to classify the vegetation cover (Roslani et al., 2014; Schuster et al., 2012). Remote sensing and image classification have been used to assess SOC in the surface layers of bare soil (Chen et al., 2000; Gomez et al., 2008). However, estimates of SOC contents under vegetated surfaces must be based on established relationships between vegetation cover/types and SOC data.

1.2 Aims of the research

The overall objective of the research was to investigate vegetation succession and soil development on the glacial moraines since the end of the LIA, in front of two outlet glaciers, Skaftafellsjökull and Breiðamerkurjökull, SE-Iceland. The Skaftafellsjökull forefield represented an area with a seed source from birch woodlands right at its side. The Breiðamerkurjökull study site is within the vast plains being exposed by the recession of the glacier and is relatively isolated from seed sources as the closest birch woodlands are in 11–12 km distance. A chronosquence approach, a time for space substitution, was used to assess the developing vegetation stratigraphy, changes in soil properties and rates of soil formation, where the location of a glacier’s terminus is known in time. Morphological, physical and chemical properties of the soil were used to assess the soil development in relation with time, vegetation succession and topography as the soil forming factors. The accretion of SOC was emphasized as plant succession and soil forming processes transform atmospheric C into SOC, increasing the SOC stock.

The specific objectives of this PhD study were:

- To study soil formation on the glacial moraines along the two chronosequences established in front of Skaftafellsjökull and Breiðamerkurjökull, representing a time period of ~120 years. This was done by investigating morphological changes such as formation of soil horizons, changes in color, structure etc., and physical and chemical changes, such as BD, LOI, SOC and N accretion, changes in pH H2O and NaF and by extracting Al, Fe and Si in ammonium oxalate solution. Chapters 2 and 4.
- To study vegetation succession and changes in vegetation composition over time since deglaciation. Total vegetation cover was measured as well as the cover of plant groups and the relationship between total cover and plant group cover with time and soil properties analyzed. Chapters 3 and 4.
- To investigate the relationship between the soil forming factors, time, vegetation and landscape, and the developing soil properties. Chapter 3.
- To study the impact of avifauna on soil development where the great skua and the Arctic skua have brought in nutrients from the ocean to the terrestrial ecosystem developing within the Breiðamerkurjökull foreland. Chapter 4.
- To assess the regional SOC stock accumulating in the glacial fore-fields of Skaftafellsjökull and Breiðamerkurjökull using the chronosequence approach, vegetation cover, bulk density and SOC concentrations. Chapter 5.

The hypotheses tested in this research were that 1) the developing vegetation stratigraphy in front of Breiðamerkurjökull would be different from glaciers which are closer to seed sources and result in lower rates of soil formation, 2) the presence of avifauna enhanced vegetation growth and soil formation rates within restricted locations, and 3) the chronosequence setup along with vegetation and plant group cover and soil data could be used to estimate the regional SOC stock within the glacier forelands.
1.3 Methodology

1.3.1 Study sites

The two study sites were within the proglacial areas of two outlet glaciers flowing towards south from the Vatnajökull ice-cap in southeast Iceland (64°00'–05', W16°14'–57'). Skaffafellsjökull is a small piedmont glacier flowing down from the main ice-cap in between steep mountain ridges (Figure 1.5). The thick proglacial moraines are intersected by former and current river paths. Beyond the terminal moraine are vast outwash plains formed by the material transported by Skaffafellsá and Skeiðará glacial rivers. Breiðamerkurjökull is one of the largest outlet glaciers in Vatnajökull and its recession since the end of the LIA has exposed vast plains of moraines (Figure 1.6). The terminal moraines are located close to the ocean with the shortest distance being ~1 km but current distance from the terminus to the coast is ~5 km. The study site within the proglacial area was defined to be in between the distinct pathways of the two medial moraines, Mávabyggðará and Esjufjallarárd, that are evident along the recessional path of the glacier (Snævarr Guðmundsson, personal communication, see also Guðmundsson (2014)). The glacial lake Jökulsárlón also defined the study area to the east. Both sites are at low altitudes with an oceanic climate where summers are cool but winters mild (Einarsson, 1984). The mean annual temperature is around 5°C and is slightly higher for Skaffafellsjökull compared to Breiðamerkurjökull (Table 1.2). The glacial moraines mainly consist of volcanic basalt and hyaloclastite (Jóhannesson and Sæmundsson, 2009) along with tephra deposited both on glaciers and on the moraines from subglacial eruptions in Grímsvötn, Katla, Bárðarbunga and Óræfajökull (Óladóttir et al., 2011).

Table 1.2 General information for the two study sites.

<table>
<thead>
<tr>
<th></th>
<th>Skaffafellsjökull</th>
<th>/</th>
<th>Breiðamerkurjökull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>N 64°02'–64°00'</td>
<td>/</td>
<td>N 64°05'–64°02'</td>
</tr>
<tr>
<td></td>
<td>W 16°57'–16°53'</td>
<td>/</td>
<td>W 16°18'–16°14'</td>
</tr>
<tr>
<td>Elevation range</td>
<td>70–120 m a.s.l.</td>
<td>/</td>
<td>15–70 m a.s.l.</td>
</tr>
<tr>
<td>Mean annual temperature*</td>
<td>5.1°C</td>
<td>/</td>
<td>4.8°C</td>
</tr>
<tr>
<td></td>
<td>10.5°C</td>
<td>/</td>
<td>10.6°C</td>
</tr>
<tr>
<td></td>
<td>3.3°C</td>
<td>/</td>
<td>0.4°C</td>
</tr>
<tr>
<td>Mean annual rainfall*</td>
<td>NA</td>
<td>/</td>
<td>1800 mm</td>
</tr>
<tr>
<td></td>
<td>1500 mm</td>
<td>/</td>
<td>Kvikser: 3500 mm</td>
</tr>
<tr>
<td></td>
<td>Hali: 2250 mm</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>

*Based on unpublished data from the Icelandic Meteorological Office. Skaffafell weather station is the closest to the Skaffafellsjökull study site and spans the period from 1996–2007. Fagurhólsmýri weather station is midway between Skaffafellsjökull and Breiðamerkurjökull and the average values represent the period of 1949–2007. Hólar in Hornafjörður is the closest weather station to Breiðamerkurjökull to the east, values represent the period from 1949–2011. Additional precipitation data from Kvikser and Hali are also shown but those weather stations are located closer to Breiðamerkurjökull than Fagurhólsmýri and Hólar.

1.3.2 Field setup and sampling

Fieldwork at Skaffafellsjökull was done during summer of 2010 and 2011 along three moraines with a known time of deposition: 2003, 1945 and 1890 (Hannesdóttir et al., 2014). For each moraine six points were randomly selected on undisturbed sites. A 10-m transect was fixed parallel to the moraine ridge for each point. Soil samples were collected within three 0.25 m² quadrants per transect at 0–10 cm and 10–20 cm depths, in total 54 sampling sites. Soil
samples were also collected from nearby birch woodlands in Skaftafellsheiði (Figure 1.5) where downy birch (*Betula pubescens*) and willows (*Salix* spp.) are most abundant. The birch woodlands served as a reference area to compare the young soils with those in a mature ecosystem to which moraines may transform in the future. Fieldwork at Breiðamerkurjökull was done in summer of 2012 and included moraines exposed in 2012 (right in front of the terminus), 2004, 1994, 1982, 1960, 1945, 1930 and 1890 (Figure 1.6). Five random points were chosen for sampling within one 0.25 m² quadrant at 0–5 cm and 5–15 cm depths. Where the presence of seabirds had created distinct bird hummocks, one such site was chosen for sampling per moraine. In total 38 moraine samples were collected and 6 bird hummock samples. Similarly to the Skaftafellsjökull study, soils were also sampled in the most proximal birch forest at Stórihnaus close to the farm Kvísker west of the moraines.

![Figure 1.5](image-url) The location of the study site within the Skaftafellsjökull fore-field. Samples were collected along three known positions of the glacier terminus, 2003, 1945 and 1890. The 1890 moraine marks the maximum extent during the LIA. Circles represent location of sampling transects. Soil sampling was also done in the birch woodlands close to the Skaftafell visitor centre, and it served as a baseline on the reference area. Each circle represents a sampling zone in the forest. The map shows the developing glacial lake in 2011, drawn from airborne Lidar – digital elevation model (The Icelandic Meteorological Office), and the location of the terminus in 2012, drawn from RapidEye image. The locations of the glacier’s termini sampled in this study are redrawn based on the work of Hannesdóttir et al. (2014). K, G and Ö mark the location of the subglacial volcanoes Katla, Grímsvötn and Öræfajökull.

Prior to soil sampling, the landscape was classified using the geomorphic description and surface morphometry by Schoenberger et al. (2002): slope aspect, slope gradient, slope complexity, profile position, and landform (shape). The vegetation cover, total cover, bare ground and cover of plant groups, was estimated using a Braun-Blanquet cover scale (Goldsmith and Harrison, 1976). This applies to both the study sites.
**Figure 1.6** The study site at Breiðamerkurjökull. Lines mark the glacier position in 1890, 1930, 1945, 1960, 1982, 1994, 2004 and 2012, and are redrawn from S. Guðmundsson (personal communications and Guðmundsson (2014)). Dots mark soil sampling sites and stars mark sampling sites in bird hummocks. Soil samples were also collected in birch woodlands at Stórhnaus (reference area) 11 km southwest of the study site. The figure shows the location of the terminus as well as the distribution of lakes and rivers in summer 2013, drawn on aerial photographs from Loftmyndir Inc. (2013). The digital elevation model (from the Icelandic Meteorological Office), based on images from an airborne Lidar, shows the proglacial landscape in 2010. G, B, K and Ö mark the location of Grímsvötn, Bárðarbunga, Katla and Öræfajökull subglacial volcanoes.

### 1.3.3 Sample analysis

Bulk density of the fine earth fraction was measured for both depths using small cubical cores of known volume. The volume of coarse fragments was measured for the top 10 cm depth at Skaftafellsjökull and determined with an excavation method using insulation foam (Brye et al., 2004; Page-Dumroese et al., 1999) and reported by Stanich (2013). It is used here to calculate the SOC stocks in the glacier forelands. The volume of the coarse material (>2 mm) was estimated with water displacement. The bulk density of the fine earth fraction (<2 mm) was calculated after subtracting the weight and volume of the coarse fraction from the weight and volume of the total bulk density sample. Similarly, bulk samples were air dried and passed through a 2 mm sieve. Samples were combusted in a muffled furnace at 550°C for four hours to determine loss on ignition (LOI). SOC and N concentrations were determined by the dry combustion for the Skaftafellsjökull samples by using a Vario Max C-N elementar analyzer and for Breiðamerkurjökull samples on a Flash 2000 Elemental Analyzer. Samples were dried at 50°C prior to weighing. Soils were estimated to be carbonate free, therefore the measured C was assumed to be the SOC. Soil
pH (H₂O) was determined in water-soil suspension. Andic properties were evaluated by the indirect method of determining soil pH in 1 M NaF solution. For the Skaftafellsjökull samples, ammonium oxalate extraction was obtained in the dark by the shaking method (Blakemore et al., 1987), with oxalate solution buffered at pH 3.0. The Al, Fe, and Si extracted were determined by inductively coupled plasma optical emission spectrometry (ICP-PES). Concentrations of non-crystalline secondary clay minerals were calculated using the proportion of extracted Si and Fe as summarized by (Shang and Zelazny, 2008), the standard method for estimating the allophane and ferrihydrite content in Andisols.

1.4 Results

1.4.1 Development of selected soil properties within the glacial fore-fields (chapters 2, 3, 4 and 5)

Time and vegetation succession were the primary controls of soil formation on the glacial moraines inducing morphological, physical and chemical changes in the soil. With time, changes in texture occurred where the finest grains were removed from the top layer. Then, with the input of OM the proportion of fines increased again as an A horizon formed. A distinct A horizon was evident in 65–67 yr-old moraines exposed in 1945 although it was generally thicker at Skaftafellsjökull compared to Breiðamerkurjökull (Figure 1.7). The color of the A horizon was dark as expected from the basaltic parent material and accumulation of OM. The C horizon had a more grayish tone and had the appearance of an unsorted glacial till (chapters 2 and 4).

With increase in time since deglaciation, the BD decreased from being 1.2–1.4 g cm⁻³ in the youngest moraines decreasing down to 0.8–1.0 g cm⁻³ over 67–120 years depending on study sites. LOI concentration increased with increase in soil age but the values for the youngest moraines started at 0.6–0.8% indicating that some other material was being lost during combustion than OM. The pH H₂O was as high as 8.1 in the fresh moraines exposed in 2012 in front of Breiðamerkurjökull. It decreased rapidly and was the only value reaching a steady state (5.7–6.0) for the time span investigated. The SOC concentration increased with increase in moraine age from being 0.02–0.05 to reaching the maximum values of 2.7% in the oldest moraines of Skaftafellsjökull. Total N increased with increase in soil age from being around zero attaining a value of 0.07–0.1% in 120 and 82 yr old moraines for Skaftafellsjökull and Breiðamerkurjökull, respectively (chapters 2 and 4).

Both the chronosequences exhibited slow initial rates of soil formation with increasing rates after the first 52–67 years (chapters 3 and 5). For Skaftafellsjökull the highest LOI, SOC and N values were for the 120 yr-old terminal moraine but for Breiðamerkurjökull, the values were highest for the 82 yr-old moraine. The SOC stocks were estimated to have reached 1.1 kg C m⁻² in the 120 yr-old moraines at Skaftafellsjökull and 0.5 kg C m⁻² in the 122 yr-old moraines at at Breiðamerkurjökull. Rates of SOC accretion were 9.1 g C m⁻² yr⁻¹ in the 120 yr-old moraine at Skaftafellsjökull but peaked in the 67–82 yr-old soil at Breiðamerkurjökull with rates of 4.5 g C m⁻² yr⁻¹.
Figure 1.7 Soil profiles from moraine at Skaftafellsjökull exposed in 1890 (left) and from Breiðamerkurjökull exposed in 1930 (right). A much thicker A horizon is developing in the surface at Skaftafellsjökull.

There was a trend towards increase in Al$_{ox}$ concentration with increase in time and the concentration of Al$_{ox}$ was significantly higher in the 120 yr-old moraine of Skaftafellsjökull compared to that in the younger two. The trend of increase of Fe$_{ox}$ showed a significant increase in Fe$_{ox}$ between in the oldest moraine compared to the youngest (chapter 2). The increase may be reflected by higher pH NaF values for the older two moraines investigated. A clear trend of increase in pH NaF values for the Breiðamerkurjökull moraines may indicate such an increase in oxalate extractable Al and Fe (chapter 4).

1.4.2 Comparison to the birch woodlands (reference sites) (chapters 2, 3 and 4)

A comparison to nearby birch woodlands showed that the young soils on the moraines still need a long time to develop the properties of well drained Andisols. The BD values for the woodland soils (Figure 1.8) were much lower or 0.5−0.6 g cm$^{-3}$. LOI concentrations were much higher or 17−22%, SOC concentrations were 6.6−10% and total N was ~ 0.5%. pH NaF values were also higher with values of 9.2 and 10.1 and then the extracted Al$_{ox}$ and Fe$_{ox}$ were two to four times higher than compared to the 120 yr-old moraine soils of Skaftafellsjökull.

This indicated that the developing proglacial soils are still evolving and undergoing pedological transformation. The older moraines represented an A-C horizon sequence but a fine-grained cambic (Bw) horizon had not yet formed in the moraines. In addition, low SOC concentrations and oxalate extractable Al and Fe values did not meet the criteria for volcanic soils in ST or WRB systems of soil classification, whereas soils under the birch woodlands would likely be classified as Cryands (ST) or Silandic Andosols (WRB). If the Icelandic soil classification system is applied (Arnalds and Óskarsson, 2009), the moraine soils would be classified as Gravelly Vitrivols (the equivalent to Cryands, ST, and Vitric Andosol/Regosol/Leptosol, WRB).
1.4.3 Vegetation succession and the effects of vegetation and landscape on soil development (chapter 3 and 4)

The vegetation cover increased over time since deglaciation, from being completely absent on the moraines closest to the glacier, to reaching close to full cover in the oldest moraines (67–88%) (chapter 3 and 4). In the 8 yr-old moraines the vegetation cover was 1–6% on average where mosses and grasses were the pioneering plant groups. The vegetation cover progressively increased with increase in moraine age although large stones on the surface often inhibited the low growing plants to acquire full cover. Mosses comprised most of the vegetation cover for both study sites but at Skaftafellsjökull, biological crust and macrolichens increased their cover with increase in moraine age but the oldest moraines were characterized by dwarf shrubs. Low growing shrubs (Salix spp. and birch) covered 5–7% on average in the 65 and 120 yr-old moraines with average height 20 cm. Birch grew only within the oldest moraine. The vegetation succession at Breiðamerkurjökull was similar as where the cover of biological crust and macrolichens increased with moraine age, as did the cover of grasses, which characterized the vegetation of the moraines. However, dwarf shrubs were rare and shrubs completely absent.

The study from Skaftafellsjökull showed that landscape affected vegetation establishment and the distribution of plant groups and it was principally affected by two of the landscape parameters analyzed; profile position and landform (chapter 3). Footslopes and toeslopes (the base of slopes) and depressions allowed for denser vegetation cover predominantly comprising mosses and shrubs. On the other hand macrolichens predominated on ridges. Similarly, the two landscape parameters were significantly connected with several of the soil properties studied. Soils on backslopes had significantly higher pH (H2O) and lower SOC and N concentrations compared to soils on ridges and depressions. SOC and N concentrations along with Alox and Feox were generally higher at the base of slopes and in depressions within the landscape.
The relationships between the developing soil properties and vegetation cover showed that the age-dependent vegetation parameters correlated strongly with the soil parameters. For Skaftafellsjökull, total vegetation cover, mosses, macrolichens and dwarf shrubs showed the strongest relations with the soil properties. The concentrations of SOC, N and oxalate extractable Al increased significantly with increase in vegetation cover. Similar trends were observed for increase in cover by mosses, macrolichens and dwarf shrubs. For Breiðamerkurjökull, the underlying soil had lower bulk density, higher LOI, SOC and N concentrations and lower pH (H₂O) where the vegetation cover and moss cover was denser (chapter 3 and 4).

1.4.4 Soil development in bird hummocks (chapter 4)

Bird hummocks, sites where the great skua and the Arctic skua regularly perch and defecate, were on the tops of moraine ridges in particular but also occurring on more level surfaces. The hummock vegetation differed from the surroundings as they were fully covered by vigorous grasses and herbs (Figure 1.9). The vegetation formed zones of different species; grasses were dominant in the center, encircled by herbs and at last mosses and macro-lichens encircled the grasses and herbs. The hummocks occurred in all the moraine age groups studied, except for the two youngest moraines, although their size and prevalence were seemingly reduced in the younger moraines (chapter 4).

![Figure 1.9 An example of a ‘bird hummock’ in the terminal moraine deposited in 1890. Maria Svavarsdottir for scale.](image)

The soil under the hummocks featured thick A (or O) horizons with dense but fine root systems. The sandy texture of the soil indicated an eolian deposition and tephra from the Grímsvötn eruption in 2011 was evident in the sward layer. Soil properties of the bird hummocks were different from those of the surrounding moraine soils. BD was much lower within the 0–5 cm layer, maintaining below 0.8 g cm⁻³ and usually between 0.3–0.6 g cm⁻³, showing a trend towards decrease from younger to the older moraines. LOI values were much higher than in the moraine soils, reaching 40% in the 67 yr-old moraine. SOC and total N concentrations also reached the highest values of 18% and 1.1%, respectively, in the 67 yr-old moraine. These parameters were more comparable to what was measured
in the soil under the birch woodlands. Soil pH (H$_2$O) was considerably lower than that in the moraine soils as was the pH (NaF).

1.4.5 Regional SOC stock estimates (chapter 5)

The SOC stocks of densely vegetated surfaces were 53–65% higher than those of sparsely vegetated (<50%) surfaces. The total area of each glacial fore-field (undisturbed moraines only), for which the SOC stock was calculated, was 457 ha and 632 ha for Skaftafellsjökull and Breiðamerkurjökull, respectively (Figure 1.10). Thereof, densely vegetated areal extent was estimated to be 233 ha (51%) and 360 ha (56%). The regional SOC stocks for the two fore-fields were estimated at 1604.6 Mg C (0–10 cm) for Skaftafellsjökull in 2010, and 1105.9 Mg (0–5 cm) for the Breiðamerkurjökull study site in 2012 (chapter 5).

![Figure 1.10 The classification of vegetation cover based on RapidEye satellite images from 2012 and the defined time-zones used as an input to calculate the regional SOC stocks. Green areas represent sites with dense vegetation (cover >50%) and orange areas sites where vegetation is sparse (cover <50%).](image)

1.5 Discussion

1.5.1 Vegetation succession

The developing vegetation stratigraphy differed between the two study sites, as was expected due to the differences in distances to seed sources. Within both sites, mosses comprised most of the cover, but at Skaftafellsjökull dwarf shrubs and shrubs characterized the vegetation, whereas grasses characterized the moraines of Breiðamerkurjökull (chapters 3 and 4). The effects of other factors on the vegetation stratigraphy, such as the past and present land-use, or the regional topography affecting winds or precipitation still cannot be overlooked.

In comparison with the published data from Alaska, China and Switzerland, the vegetation succession on the proglacial area in Skaftafell occurred at seemingly slower rate. For
example, Crocker and Dickson (1957) reported a spruce forest development on the moraines after 100–120 years of soil exposure. He and Tang (2008) described development of a coniferous forest over 150 years and Egli et al. (2010) reported establishment of Larici-Pinetum cembrae forests after only 77 years. A shrub cover was forming in places closest to the seed source at Skaftafellsjökull, a future indicator of woodlands and was the most apparent in the 120 yr-old moraine (chapter 3). This trend was more comparable to a chronosequence from Norway at an elevation above the tree line, showing that dwarf shrubs along with Salix spp. and Betula nana have established after 60 years (Matthews and Whittaker, 1987). The development on the Breiðamerkurjökull moraines will likely experience an extended lag time until woodlands will develop on the Breiðamerkurjökull moraines (chapter 4), making the current status of the chronosequence more comparable to the development in glacial fore-fields in Svalbard, where vascular plants are slow to establish and represent only a small part of vegetation cover for the first 100 years (Hodkinson et al., 2003; Kabala and Zapart, 2012).

The relatively slow vegetation succession within the two fore-fields was probably a result of various environmental factors; frequent freezing and thawing cycles with concurrent cryoturbation, general species paucity in Iceland, strong winds, sheep grazing (for Skaftafellsjökull, sheep grazing ceased in the 1980’s (Ives, 2007)) and lack of soil moisture and available nutrients (Arnalds, 2008b; Magnússon, 1997; Þórhallsdóttir, 2010). The topography had an effect on the vegetation establishment where it was favored in depressions and at the base of slopes within the moraine landscape due to abiotic factors such as differences in soil moisture content and soil texture, shelter, snow cover and incident radiation (Fowler, 1986) (chapter 3).

### 1.5.2 Soil development

#### Physical and chemical weathering

The unsorted glacial moraines started undergoing changes as soon as the surface is deglaciated, where wind and water erosion and downward translocation removed the finest grains from the surface layer and sandy loam with gravel remained (Boulton and Dent, 1974; Romans et al., 1980) (chapters 2 and 4). The removal of the finer grains in conjunction with an increase in organic matter lowered the bulk density (Crocker and Dickson, 1957; He and Tang, 2008). The color changed from dark gray to a blacker hue in the oldest soils, similar to that reported by Arnalds and Kimble (2001) for Andisols of deserts in Iceland.

Abundant precipitation, basal meltwater and ground basaltic rocks of a wide range of grain sizes should provide an environment conducive to active chemical weathering (Gislason et al., 2009; Gíslason, 1993). There was a detectable but slow increase in Al\textsubscript{ox} and Fe\textsubscript{ox} concentrations in the moraine soils and the values were in accord with those reported by Arnalds and Kimble (2001) from Icelandic deserts. Dümig et al. (2011) also reported an increase in non-crystalline Al-phases with increase in time from 15 to 127 years for a chronosequence in front of the Damma glacier. However, concentrations of Al\textsubscript{ox} (0.02–0.08%, 15–140 years) and of Fe\textsubscript{ox} (0.04–0.14%, 15–140 years) are lower for the Damma glacier (Dümig et al., 2011) than those for the Skaftafellsjökull glacier at Al\textsubscript{ox} (0.35–0.55% and Fe\textsubscript{ox} 1.31–1.51% (8–120 years) (chapter 2). On the other hand, the Al\textsubscript{ox} and Fe\textsubscript{ox} presented in this study are lower in the glacial moraines than 1.22% Al\textsubscript{ox} and 2.08% Fe\textsubscript{ox} concentrations from barren areas in South Iceland (Arnalds et al., 2013).
Poorly crystalline phases of Al and Fe can stabilize organic matter and is one of the reasons of high SOC concentrations in Andisols (Dahlgren et al., 2004). This study shows a moderately strong correlation between extracted Al$_{ox}$ ($R^2 = 0.52$, $p < 0.001$) and Fe$_{ox}$ ($R^2 = 0.20$, $p < 0.001$) concentrations and SOC for the 120 yr-old moraine only, possibly an indication of increased potential for stabilizing OM as andic properties evolving in the young moraine soils (chapter 2). The increase in pH NaF values throughout the Breiðamerkurjökull chronosequence (with the exception of the 122 yr-old moraine) and between the 65 and 120 yr-old moraine also indicates the evolution of andic properties (chapters 2 and 4).

The pH in H$_2$O is the only soil property that has attained equilibrium when compared to the birch woodland soils. The pH values in the woodlands were slightly higher in the Skaftafell area compared to the adjacent moraines, but the woodland soils close to Kvísker (at Stórihnaus) had slightly lower pH values compared to those of the Breiðamerkurjökull moraines (chapters 2 and 4). In Iceland, pH H$_2$O values are generally maintained high due to eolian deposition (Arnalds, 2008b).

The accretion of SOM, SOC and N

Concentrations of SOC increased with increase in moraine age for both study sites. Initial rates of increase were low but after the first 50 years they increased, suggesting a threshold or lag-time which may be linked to the initial slow vegetation succession as previously discussed. The initial SOC concentrations were very low, 0.02–0.05% depending on the study site, and the origin of the SOC is unknown. The high LOI concentrations compared to the SOC concentrations for the youngest soils in both study sites indicate that in addition to SOM some inorganic volatile compounds were lost during the ignition (chapters 2 and 4).

The SOC stock at Skaftafellsjökull since 120 years after glacial retreat was estimated at 1.10 kg C m$^{-2}$ (0–10 cm) and 0.50 kg C m$^{-2}$ (0–5 cm) at Breiðamerkurjökull 122 years after glacial retreat (chapters 3 and 5). The stocks corroborated with other estimations: ~1–5.5 kg C m$^{-2}$ after 100–150 years (Egli et al., 2010), 0.55 kg C m$^{-2}$ after 120 years (Dümig et al., 2011), 2.0 kg C m$^{-2}$ after 130 yrs (He and Tang, 2008), and 2.5 kg C m$^{-2}$ after 122 yrs from Glacier Bay in Alaska (Crocker and Major, 1955). Different sampling protocols must still be regarded when comparing the SOC stocks.

Bulk density affected the calculated SOC stocks as was evident in the stocks calculated for the Breiðamerkurjökull moraines. There, past eolian activity has reduced the concentrations of SOC and increased the bulk density, resulting in higher SOC stocks when compared to for example the 82 yr-old moraine, which featured both higher SOC concentration and lower bulk density (chapter 5). The raw SOC concentration values are therefore often more informative of the soil properties than the actual calculated stocks and emphasizes the importance of measuring bulk density for the relevant study sites.

Comparison with SOC accretion rates from other chronosequences showed that the curves depicting the rate of increase differ in the way that in SE-Iceland the rates of increase were initially slow but increased after the first 50 years. This trend is in contrast to studies of soil formation from other glaciated regions such as from the Swiss Alps (Egli et al., 2010), Glacier Bay in Alaska (Crocker and Major, 1955), China (He and Tang, 2008), and Svalbard (Kabala and Zapart, 2012), where the reported rates were higher during the first
decades and then decreased. The reason for this anomaly may be linked to the slow vegetation succession in the first decades after deglaciation (chapters 3 and 4).

The concentrations of N from Skaftafellsjökull (~0.1%) after 120 years are similar to those reported by He and Tang, (2008), 0.2−0.4% of N in soils formed on 130 yr-old moraines, depending on the horizon sampled (chapters 2 and 3). The values were lower for Breiðamerkurjökull, reaching 0.07% N in the 82 yr-old moraine. N concentrations at Breiðamerkurjökull were first detectable in the 30 yr-old moraine, before they were zero and they remained at zero for the 5−15 cm depth throughout the chronosequence (chapter 4). At Skaftafellsjökull, N concentration of 0.004% in the 8 yr-old moraine was considerably higher than at Breiðamerkurjökull. The annual wet N deposition is typically rather low for Iceland, <1 kg N ha\(^{-1}\) yr\(^{-1}\) (Kleemola and Forsius, 2006). The higher values in the youngest moraine at Skaftafellsjökull is a probability an overestimation due to problems with the CN analyser and considerable error margin when dealing with such low quantities of N in the soil. In that regard, the N data from Breiðamerkurjökull is probably more reliable.

The SOC stocks in soils developed on lavas in S-Iceland under natural conditions showed that 0.21 kg C m\(^{-2}\) had accreted on a lava field formed in 1783 AD (McPeek et al., 2007), which is lower than the 0.50 and 1.1 kg C m\(^{-2}\) in front of Breiðamerkurjökull and Skaftafellsjökull in the 120−122 yr-old moraines. Preliminary results of a chronosequence study from restored birch forests in S-Iceland reported SOC concentration of 8.8−11% in the surface horizon of a 60 yr-old forest, 5.6−8.0% SOC of 5−15 yr-old forest, and 4.5−6.2% in unforested, fully vegetated land (Kolka-Jónsson, 2011). These concentrations are similar to those under the birch woodlands (chapters 3 and 4).

When comparing the SOC stock of the oldest moraines at Skaftafellsjökull to that under the birch woodlands, the unfilled C sink capacity for the surface layer (0−10 cm) was estimated at ~2.0 kg C m\(^{-2}\) (chapter 3) With the observed accrual rate of 9.1 g C m\(^{-2}\) yr\(^{-1}\) in the moraine soils, it may take an additional ~220 yrs to accrue SOC stocks comparable to those under the birch woodlands, or a total of 340 yr since deglaciation, given that the SOC stocks under the birch woodlands have reached a steady state for well drained Andisols of Iceland. These projections do not account for the fact that Icelandic Andisols, especially soils within the volcanic zone, tend to form thicker solum which contains SOC throughout the entire profile because of the specific pedological conditions of Andisols (Óskarsson et al., 2004).

The effects of vegetation and topography on the developing soils

Landscape seemed to favor soil development similar to that of vegetation establishment, and these two factors had synergistic effects in creating ‘hot spots’ or sites of relatively rapid soil development, where the accretion of SOC, N and oxalate extractable Al and Fe phases and therefore weathering, occur at faster rates than those at other locations (chapter 3). Similarly, Egli et al. (2006) proposed a basis for spatial modeling by assessing the effects of landscape on soil properties. They documented that various landforms correlated well with soil evolution, where slope, exposure and landform determined the soil development. On a larger scale, Yoo et al. (2007) have pointed out and modeled higher chemical weathering rates at the base of hillslopes due to weathering of parent material in situ and of material eroded and transported from upslope. Erosional and depositional
processes may also be at play in small scale landscape features as studied in the Skaftafellsjökull fore-field.

Vegetation itself also directly affected the underlying soil properties. As presented in chapters 3 and 4, an increase in vegetation cover and moss cover indicated lower bulk density, higher LOI, SOC and N and lower pH (H₂O) of the underlying soils. Studies from Svalbard and the Andes have shown that cyanobacterial crust starts to form 2–4 years after deglaciation and it plays a major role in C and N inputs to the sol system (Hodkinson et al., 2003; Schmidt et al., 2008). Preliminary results show that N₂ fixing moss associated cyanobacterial communities are important in Icelandic ecosystems (Jónsdóttir, 2014; Russi Colmenares et al., 2014). In the chronosequences, time and succession were dominant factors of soil formation and the strong time factor masked the relationship between vegetation cover and the soil properties to some extent (chapter 3). While examining the relationship between vegetation and soil within each time group indicated only a few parameters with significant relations. This relationship, as examined by analyzing the entire dataset, added important information on the effects of vegetation and soil development and along with the chronosequence concept served as a basis for the concept of chapter 5.

1.5.3 The effects of the avifauna on plants and soils

Within the Breiðamerkurjökull fore-field the presence of the great skua and the Arctic skua had great influence on the developing soils and vegetation. This was reflected in thick A (or O) horizons, dense but fine root system and high SOC and N concentrations (chapter 4). The bird hummocks were the hot spots for soil formation within the Breiðamerkurjökull fore-field, a result from the birds bringing nutrients from the sea to the terrestrial ecosystem, creating stark differences among sites of fertilization and the regular nutrient-poor surfaces (Bockheim and Haus, 2014). Verbeek and Boasson (1984) studied bird hummocks in the Pyrenees, France, and similarly reported significantly more N compared to the soils of their surroundings. As did Tomassen et al. (2005) for bird dropping sites in Irish bogs but those had significantly higher influxes of nutrients and showed more vegetation vigor than at reference sites without droppings. At Breiðamerkurjökull, the effects of nutrient input seemed to be much localized to the areas with direct manure inputs, affecting the biogeomorphic characteristics of the moraines. Such point-centered effects on the soil environment can also be allotted to individual trees, ants and termites, where they can change both physical and chemical properties in their closest vicinity, often raising the nutrient status (Donovan et al., 2001; Frouz and Jilková, 2008; Gersper and Holowaychuk, 1971; Rhoades, 1996).

The bird activity within the Breiðamerkurjökull moraines created the hot spots of soil formation on the tops of moraine ridges although also occurring on more level surfaces. This differed from Skaftafellsjökull, where sites of the most rapid soil development were related to depressional landforms, as a result from several abiotic factors such as textural differences in the soil, higher moisture content and shelter.

1.5.4 Regional SOC accretion and SOC accretion rates

Several reports on SOC accretion rates are available from sites of land reclamation treatments and forestry. Arnalds et al. (2000) reported a significant increase in SOC stock with increase in treatment age, with the average rate of increase of 0.027 kg C m⁻² yr⁻¹.
Arnalds et al. (2013) reported accretion rates for different reclamation methods, and concluded that sites revegetated by seeding of grasses with fertilization result in the highest SOC accretion rates (0.055–0.065 kg C m\(^{-2}\) yr\(^{-1}\)). Würsch (2012) reported the SOC accretion rates of 0.022 kg C m\(^{-2}\) yr\(^{-1}\) (0–20 cm) in sites revegetated by the nootka lupine. These results are substantially higher than the rates reported in chapter 3 and 5, where the accretion rates reached the highest average values of 0.009 and 0.005 kg in the Skaftafellsjökull (0–10 cm) and Breiðamerkurjökull (0–5 cm) moraines, respectively. The (IPCC, 2000) estimates the potential of restoring severely degraded land to be 0.03 kg C m\(^{-2}\) yr\(^{-1}\), which is similar or lower to what has been reported for the restored areas in Iceland, yet considerably higher than the SOC accretion within the glacier fore-fields.

In a restored birch forest, the SOC accretion rate was reported by Kolka-Jónsson (2011) as 0.12 kg C m\(^{-2}\) yr\(^{-1}\) in the top 0–5 cm. Within planted larch forests of 14–53 years, Ritter (2007) reports a non-clear trend of increase in SOC stock with time or −0.018–+0.023 kg C m\(^{-2}\) yr\(^{-1}\), probably because larch was planted in an already vegetated land. The accretion rates within the two forest types are considerably lower than those reported from the reclamation sites and the proglacial areas have the lowest SOC accretion rates compared to revegetation and forestry. Still, the rates of increase present background values that are generated via natural plant succession without human input. On the other hand, revegetation efforts generally require inputs depending on the method used. The most commonly used method in restoration is by seeding and fertilization where a mineral fertilizer is applied for the first years mainly supplementing N, P and K (50–100 kg N and 27 kg P\(_2\)O\(_5\) ha\(^{-1}\) (Arnalds et al., 2013; Arnalds et al., 2000).

The Soil Conservation Service in Iceland (SCSI) estimated the average net removal of CO\(_2\) from the atmosphere through land restoration (seeding and fertilizing, lupine, fertilizing) by soil formation to be 0.71 Mg C ha\(^{-1}\) yr\(^{-1}\) (2.6 Mg CO\(_2\) ha\(^{-1}\) yr\(^{-1}\)) (Guðmundur Halldórsson, personal communication). The areal extent of land restoration between 1990–2009 is estimated to be 115 000 ha, leading to the annual accumulation of SOC stock of 81 551 Mg C yr\(^{-1}\). The current annual increase in the moraine SOC stock was 20.7 Mg C yr\(^{-1}\) for Skaftafellsjökull and 19.7 Mg C yr\(^{-1}\) for Breiðamerkurjökull (chapter 5). From 1890 to 2000, the total decrease in glacial cover in Iceland has been estimated as 1285 km\(^2\) or by >11% (Sigurðsson et al. 2013). The total area of the two study sites is 18 km\(^2\), which is only ~1% of the entire area that is estimated to have been deglaciated between 1890 and 2000. The proglacial areas within Iceland probably differ greatly with regards to vegetation succession and SOC accretion rates, as shown by the comparison between the two study sites. In order to estimate the SOC stock within other glacial fore-fields, additional field data are needed for assessing the SOC content of the soils.

### 1.6 Conclusions

The overall objective of the research was to study the vegetation succession and soil development on the glacial moraines since the end of the LIA, in front of the two outlet glaciers Skaftafellsjökull and Breiðamerkurjökull, using a chronosequence approach. Changes in soil properties occurred with increasing surface age as a result from physical and chemical weathering and vegetation succession. With increasing age, bulk density and pH H\(_2\)O decreased, while concentrations of LOI, SOC, N, and ammonium oxalate extractable Al and Fe increased, as well as pH NaF (chapters 2 and 4). Despite these changes, the young moraine soils still featured values much different from soils under
Birch woodlands, the future climax ecosystem that may possibly develop on the moraines, which feature properties typical for well drained Andisols. The moraine soils at Skaftafellsjökull are expected to take another ~220 years to attain the SOC values of the adjacent birch woodlands given the current rate of SOC accretion. Vegetation succession differed between the two study sites (chapters 3 and 4) where at Skaftafellsjökull shrubs were colonizing the moraines but they were absent on the study site at Breiðamerkurjökull. This resulted in different rates of soil formation, where the slower rates at Breiðamerkurjökull were due to the different vegetation stratigraphy as a result from the long distance to seed sources and unstable environment showing past and present signs of eolian activity. Landscape features affected the soil formation by influencing the vegetation establishment and through abiotic factors, where the hot spots of soil formation were within depressional features in the landscape (chapter 3). The presence of the great skua and the Arctic skua had a point-centered effect on the soil development of the moraines of Breiðamerkurjökull by adding nutrients to the otherwise nutrient poor moraines. There, the hot spots of soil formation were within the bird hummocks, where the vigorous growth of grasses resulted in thick A (or O) horizons and high SOC and N concentrations (chapter 4). Vegetation cover and related SOC stock values allowed for the use of simple vegetation cover classification of two classes, >50% vegetation cover and <50% vegetation cover, to assess the regional SOC stocks. Comparison with sites of forestry and land reclamation showed that the rates of accretion are considerably lower (chapter 5), but the natural SOC accretion rates in front of the glaciers provide a background value for Iceland to compare with other sites of vegetation succession whether they are human-induced or natural. The results also show that soil formation in Iceland is a slow process, operating on the scale of centuries. This emphasizes the need for a sustainable use of the soil resource and for reducing the current extent of soil erosion.

In order to strengthen the knowledge with regards to the dynamic proglacial areas, based on our analyses, there are several aspects that need further investigation:

- Assessing the effects of vegetation and landscape on soil development by designing the sampling protocol with regards to vegetation cover, landscape position and moraine age, as it could further clarify the relationship between those factors.
- The nature of SOC being accreted in the moraine soils is not accounted for and information on whether and how SOC is being immobilized could be useful to understand the C dynamics within these young soils.
- Evaluating similar dynamics of N and the types of N present in the moraines and in the bird hummocks.
- Estimating the SOC accretion within proglacial areas for the entire country. For that, additional SOC data must be acquired from other outlet glaciers from other regions of the country, featuring different environmental conditions.
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2 Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland
Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland

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A B S T R A C T

Soil development was studied along a chronosequence in 2010 in a proglacial environment in SE-Iceland. We investigated morphological, physical, chemical and mineralogical changes in the soil representing over 120-year period. In total, 54 sampling sites were distributed along three moraines deposited in 1880, 1945 and 2003. For comparison, samples were collected from a nearby downy birch (Betula pubescens Ehrh.) forest, representing soils in a mature ecosystem likely to establish on the moraines in the future. After 120 years since deglaciation and formation of AC horizon sequence, bulk density decreased from 1.36 g cm⁻³ to 1.07 g cm⁻³. Concentrations of soil organic carbon (SOC) and total nitrogen (N) increased with time, from being ~zero up to 1.77% of SOC and 0.10% of N. Soil pH (H₂O) declined rapidly and was the only soil property that attained a steady state compared to that under the birch forest. The concentration of oxalate extractable Al and Fe increased over time although at a slower rate of change compared to that for other soil properties. Freshly exposed moraines contained a considerable amount of the extractable elements, indicating a relative abundance of poorly crystalline Al- and Fe-phases in the subglacial moraines. The data support the conclusion that after 120 years of soil formation, proglacial soils are still young and may yet need one or two centuries to develop properties typical of well drained volcanic soils.

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1. Introduction

Global climate change has caused significant glacier retreat since the mid 19th century, exposing moraines commencing weathering, plant succession and soil formation. In theory, soil development is governed by five principal factors: climate, topography, biota, parent material and time (Jenny, 1941). Time and climate are the primary determinants of the relative degree of weathering in the pedogenic environment (Ugolini and Dahlgren, 2002). Chronological sequences of glacial recession provide the settings for studying the impact of time on soil formation. In a pioneering work in glaciated areas in Alaska, Crocker and Major (1955) and Crocker and Dickson (1957) studied the rate of development of soil properties in relation to vegetation succession and as a function of time. Since climate change impacts vegetation distribution and increases chemical weathering rate, the rate of soil formation is likely to increase as well as that of soil carbon accretion (Dahlgren et al., 1997). It is precisely this notion which has been the driving force for more chronological studies from glaciated environments (e.g., Alexander and Burt, 1996; Douglass and Bockheim, 2006; Dümig et al., 2011; Egli et al., 2006a, 2006b, 2010; Haugland and Haugland, 2008; He and Tang, 2008; Mavis et al., 2010).

While the strong impact of climate change on glacial environments and subsequent soil formation has attracted global scientific interest (Goryachkin et al., 1999), research information on soil formation in proglacial areas in Iceland is rather limited. Persson (1964) briefly discussed the subject while investigating primary succession on the moraines of Skalafellsjökull, SE-Iceland. Proglacial areas are sites of high geochemical reactivity due to the abundance of ground permeable parent material and water percolation (Egli et al., 2010; Gislason, 2008). Thus, these are excellent sites for studying soil formation on a temporal scale, which is of primary interest to envision future soil development under specific climate scenarios. Icelandic glaciers have been retreating since the end of the Little Ice Age (LIA) almost continuously over the past 120 years, or since around 1890 when they reached their maximum extent (Björnsson and Pálsson, 2008; Sigurðsson et al., 2007). The recession is predicted to prevail over the next several decades with significant environmental impact along with the reduction in size of glaciers exposing vast areas, changing drainage patterns, increasing runoff volume and forming of new glacial lakes (Björnsson and Pálsson, 2008).

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For comparison, samples were collected from a nearby downy birch (Betula pubescens Ehrh.) forest, representing soils in a mature ecosystem likely to establish on the moraines in the future.

After 120 years since deglaciation and formation of AC horizon sequence, bulk density decreased from 1.36 g cm⁻³ to 1.07 g cm⁻³. Concentrations of soil organic carbon (SOC) and total nitrogen (N) increased with time, from being ~zero up to 1.77% of SOC and 0.10% of N. Soil pH (H₂O) declined rapidly and was the only soil property that attained a steady state compared to that under the birch forest.

The concentration of oxalate extractable Al and Fe increased over time although at a slower rate of change compared to that for other soil properties. Freshly exposed moraines contained a considerable amount of the extractable elements, indicating a relative abundance of poorly crystalline Al- and Fe-phases in the subglacial moraines.

The data support the conclusion that after 120 years of soil formation, proglacial soils are still young and may yet need one or two centuries to develop properties typical of well drained volcanic soils.
Iceland is a volcanic island primarily consisting of igneous rocks of basaltic composition. Andisols (Soil Taxonomy, ST) or Andosols (World Reference Base, WRB) developed from the volcanic ejecta comprise the primary soil order (Arnalds and Oskarsson, 2009). These soils exhibit some distinctive properties unique to the soil order, e.g. low bulk density and accumulation of soil organic carbon (SOC), which is largely due to the formation of noncrystalline secondary minerals (e.g., active Al- and Fe- allophane, imogolite, ferrihydrite, Al/Fe- humus complexes) (Dahlgren et al., 2004; Shoji et al., 1993). Nitrogen (N) is the major nutrient limiting establishment of plants in volcanic deposits within the volcanically active zones in Iceland (Gíslason and Eiríksdottir, 2004; Gíslason et al., 1996).

The glassy nature of basalts exhibits high weathering rates despite the prevalence of cool climate (Gíslason et al., 2009; Gíslason et al., 1996). Through water-rock/tephra interaction, some minerals are dissolved completely and leached out of the parent material while others are tied up in the weathering residues of the primary mineral, such as clays and hydroxides (Gíslason, 2008). The weathering of Ca-rich plagioclase (CaAl2Si2O8) (one of the most abundant primary mineral of basalt), to allophane (Al2SiO5·2.5·3H2O), an important secondary mineral in Icelandic soils, is shown in Eq. (1) (assuming that carbonic acid is the only important proton donor (Gíslason, 2008)):

\[
\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{CO}_2 + 5.53\text{H}_2\text{O} \rightarrow \text{Al}_2\text{SiO}_5 \cdot 2.5\text{H}_2\text{O} + \text{Ca}^{2+} + \text{H}_4\text{SiO}_4 + 2\text{HCO}_3^-
\]  

Ca and half of the Si in Eq. (1) are mobile, whereas Al is immobile and remains in situ along with half of the silica. The most common weathering residuals of basalts comprise of allophane and/or imogolite of variable Al:Si ratios and poorly crystalline iron oxide, ferrihydrite, all mostly amorphous and referred to as the 'clay minerals' of Andisols (Arnalds, 2004). The basaltic parent material favors formation of allophane and ferrithydrate, dominating the secondary clay mineral fraction, and their ability to stabilize organic carbon is integral to the high SOC sink capacity of Andisols (Dahlgren et al., 2004). The formation of allophane is inhibited by the presence of large quantities of organic matter and by low pH (generally <5) as the organic materials form complexes with Al or Fe (Arnalds, 2004; Dahlgren et al., 2004). Allophane and ferrithydrate contents in volcanic soils are commonly determined by the indirect measure where Al, Si and Fe are extracted with ammonium oxalate (Alox, Siox, and Feox), which dissolves allophane, allophane-like materials, organic Al and Fe complexes as well as noncrystalline Al and Fe oxides and ferrithydrate (Wada, 1989). Soil reaction in sodium fluoride solution (NaF) is also used as an indicator of anodic properties, as it is usually correlated strongly with allophane content (Arnalds, 2008a; Soil Survey Staff, 2010).

Here we present results from a study on an 8–120 year chronosequence in front of the Skæftafellsjökull glacier, SE-Iceland. The aim was to assess short-term (120 years) soil development in glacial till of basaltic origin through a selection of morphological, physical, chemical and mineralogical properties of the soil and to assess whether the young soils have developed the distinctive properties of Andisols.

2. Materials and methods

2.1. Study site

The study area lies within the recessional path of the Icelandic outlet glacier Skæftafellsjökull (the Icelandic term for glacier is jökull) (N64°00′, W16°55′), extending south from the Vatnajökull ice cap to the lowlands (Fig. 1). It is within the boundaries of the Vatnajökull National Park, established in 2008, before it was a part of the Skæftafell National Park established in 1967. Prior to 1967, traditional farming, with sheep grazing and hay-making, was practiced in the area (Ives, 1989; Arnalds, 2004). The basaltic parent material favors formation of allophane and ferrithydrate, dominating the secondary clay mineral fraction, and their ability to stabilize organic carbon is integral to the high SOC sink capacity of Andisols (Dahlgren et al., 2004). The formation of allophane is inhibited by the presence of large quantities of organic matter and by low pH (generally <5) as the organic materials form complexes with Al or Fe (Arnalds, 2004; Dahlgren et al., 2004). Allophane and ferrithydrate contents in volcanic soils are commonly determined by the indirect measure where Al, Si and Fe are extracted with ammonium oxalate (Alox, Siox, and Feox), which dissolves allophane, allophane-like materials, organic Al and Fe complexes as well as noncrystalline Al and Fe oxides and ferrithydrate (Wada, 1989). Soil reaction in sodium fluoride solution (NaF) is also used as an indicator of anodic properties, as it is usually correlated strongly with allophane content (Arnalds, 2008a; Soil Survey Staff, 2010).

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The predominant climate in the study area is maritime with cool summers and mild winters (Einarsson, 1980) with mean annual temperature of ~5 °C and mean annual precipitation of 1800 mm. Skæftafell responds to climatic conditions with a change in rate of advance or retreat as a result of changes in temperature (Sigurðsson et al., 2007). The recession is intersected by a few periods of glacial advance in response to changes in temperature (Sigurðsson et al., 2007). The terminus receded ~2 km between 1890 and 2003 and a lagoon has been forming in front of the glacier since ~2000.

The vegetation of the proglacial area is primarily comprised of mosses, dwarf shrubs and shrubs. The plant groups characterizing the oldest terrain are shrubs, willows (*Salix lanata* L. and *S. phylicifolia* L.) and downy birch (*Betula pubescens* Ehrh.), nomenclature follows that by Kristinsson (2010), dwarf shrubs and macrolichens (Fig. 2). When drawing closer to the glaciers’ present position, macrolichens and birch become less abundant and mosses predominate. In the youngest moraines, mosses and grasses make up for a sparse vegetation cover. Shrubs are the species that characterize climax ecosystems in Iceland, an example of which is found on the Skæftafellsheidi heathland west of the moraines (Fig. 1). Natural colonization of birch and willows is active on the sandur plains and moraines south of Vatnajökull where the forest in Skæftafellsheidi is an ideal source of seeds (Marteinsdóttir et al., 2007). Continuation of vegetation succession on the Skæftafellsjökull moraines may eventually lead to the development of a mature ecosystem.

Soils on young moraines such as in Skæftafell are generally classified as Cryands (ST) and range between Vitric Andosols, Regosols or Leptisols (WRB) (Arnalds and Óskarsson, 2009). Soils in well drained landscapes with shrub or heathland vegetation such as under the birch forest would be classified Cryands (ST) or as Silandic Andosols (WRB).

### 2.2 Field setup and soil sampling

Sample collection was carried out during summer of 2010 and 2011. Sample sites in the proglacial area were distributed along three end moraines with known time of deposition: 2003, 1945 and 1890 (Hannesdóttir et al., in review) (Fig. 1). The outline of the moraines was identified as GPS waypoints and six points were randomly selected for each of the moraines. The selection was stratified to ensure that points from both sides of the proglacial area were chosen since a gradient in vegetation could be expected because of much richer vegetation in the forested Skæftafellsheidi heathland west of the moraines. If the site of a

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**Table 1**

| General information about the Skæftafellsjökull proglacial study area. |
|-----------------|------------------|
| **Position**    | N 64°00’          |
| **Elevation range** | 90–120 m         |
| **Climate**     | Maritime, cool summers and mild winters |
| **Elevation range** | 33 °C            |
| **January**     | 3.3 °C            |
| **Mean annual temperature** | 5.1 °C           |
| **Mean annual precipitation** | 1800 mm         |
| **Geology/parent material** | Basalt, hyaloclastite, tephra |
| **Area**        | 7 km²             |

* Based on unpublished data from The Icelandic Meteorological Office. Temperature values are from the Skæftafell weather station, 1996–2007, and temperature and precipitation values from the Fagurhólmeyri weather station, 1949–2007 (numbers in parenthesis represent averages for Fagurhólmeyri, 1996–2007). See Fig. 1 for location of weather stations.
selected point exhibited any disturbance, such as dry riverbeds or flooded areas, the point was omitted and the next random point chosen instead. For each point, a 10 m transect was selected parallel to the moraine ridge (glacier’s terminus). Soil samples were collected on 0, 4 and 8 m distance for each transect within a 0.25 m² quadrant at two depths, 0–10 cm and 10–20 cm.

Because of the rocky nature of the material, conventional sampling methods were not applicable. Bulk density of the fine earth fraction was measured using small cubical cores of known volume by digging two holes within quadrant and the cores were applied perpendicular to the soil profile. The cores were of three sizes, 1.4 cm³ (n = 5), 7.9 cm³ (n = 3) and 19.5 cm³ (n = 2), and were used interchangeably during sampling. The larger two were preferred but the smallest size was preferred where the gravel content was large. Due to the small size of the cores, replicates (n) for each bulk density sample were collected to obtain an average value. This sampling method was compared to the results reported by Stanich (2013), who sampled the same soils using the cavity method with insulation foam to determine bulk density and gravel volume using much larger samples (~1000 cm³), a method usually applied to gravelly soils. The two methods resulted in similar bulk density values, which support the validity of the cubical core method. Bulk sample was collected from two holes, mixed in a bucket and bagged for further analysis. The soil profile was described by measuring the depth of horizons down to >20 cm, and the colors assessed on field moist soil using a Munsell soil color chart. At one transect for the 1890 and 1945 moraines, an intricate profile description was performed according to Schoeneberger et al. (2002).

Soils were also sampled in the birch forest of Skáfatfellsemi heathland (Fig. 1) to compare the young proglacial soils to those in a mature ecosystem. Samples were obtained in the southernmost part of the heathland at an elevation range of 100–160 m a.s.l. within an area of ~3.3 ha (220 × 150 m). The slope is convex with gradient ~27%. Sampling was divided into three zones along elevational contours (140–160 m, 120–140 m and 100–120 m a.s.l.). One soil profile was described and a composite sample was obtained with a core at two 10 cm depth increments for each zone. Each composite sample consisted of 15 cores collected randomly within the relevant zone. Bulk density samples were obtained for each of the three soil profiles at both depth intervals using the cubical cores.

2.3. Soil sample analysis

Soil samples were analyzed at The University of Iceland and at The Ohio State University, Ohio, USA. Bulk density samples were dried, gently ground and sieved through a 2 mm sieve. The volume of coarse fragments (≥2 mm) was determined by the water displacement technique. The bulk density of the fine earth fraction (≤2 mm) was calculated after subtracting the weight and volume of the coarse fraction from the weight and volume of the total bulk density sample. Similarly, bulk samples were air dried and passed through a 2-mm sieve. Samples were combusted in a muffled furnace at 550 °C for four hours to determine loss on ignition (LOI). Concentrations of SOC and total N were determined by the dry combustion method at 900 °C using a Vario Max C-N elemental analyzer, and the data were used to compute the C:N ratio. Soil pH was determined in water-soil suspension (1:1) and in 1 M NaF solution for estimation of andic properties of the soil following the method of Fields and Perrott as outlined by Blakemore et al. (1987). Ammonium oxalate extraction was obtained in the dark by the shaking method (Blakemore et al., 1987), with oxalate solution buffered at pH 3.0. The Al, Fe, and Si extracted were determined by inductively coupled plasma optical emission spectrometry (ICP-OES). Concentrations of non-crystalline secondary clay minerals were calculated using the proportion of extracted Si and Fe as summarized by Shang and Zelazny (2008), the standard method for estimating the allophane and ferrihydrite content in Andisols. The amount of ferrihydrite was calculated by multiplying the %Fe by a factor of 1.7. For estimating the allophane content %Si was multiplied by a factor f, where f depended on the Al:Si molar ratio. The factor was 5 for an Al:Si ratio of 1, 7 for Al:Si of 2, and 12 for an Al:Si ratio of 3. Intermediate factors were used for allophanes of intermediate composition. Since the moraine soils are very young and noncrystalline forms of Al and Fe are not necessarily in the form of allophane and ferrihydrite, the calculated values of the two secondary minerals must be considered with caution.

2.4. Statistical analysis

Descriptive statistics and correlation were performed using the JMP software (JMP, 2005). The relationship between soil properties and time since deglaciation was analyzed with one way ANOVA. Non-normal parameters were log-transformed prior to analysis. When transformation was not sufficient for normal distribution requirements, a non-parametric Wilcoxon/Kruskal-Wallis test was used. A Tukey-Kramer honestly significant difference test was used for pair wise comparison of means of the soil properties for each time group, and a Wilcoxon non-parametric test for each pair for the non-parametric properties. The correlation between two soil properties was determined with bivariate analysis.

3. Results

3.1. Morphological properties of the soil

For most of the soil profiles of the older two timelines (120- and 65-year-old soils) horizonation is evident and an A-horizon is gradually forming on top of the parent material (C-horizon) (Fig. 3a). The depth of the developing A-horizon increases with increase in time, from being absent in the youngest soil to 4.4 cm on average in the 65-year-old soil, and 8 cm for the oldest soil of 120 years (Table 2). The color of the horizons is dark, as is to be expected from the basaltic parent material, where the developing A-horizon has a very dark gray or black color and the color gradually becomes lighter with a more grayish tone towards the C-horizon.

The soil in the birch forest contains an A-Bw-C horizon sequence, interspersed with three to four thin, black colored tephra layers (Fig. 3b). The A-horizon has a granular structure and a dark color indicative of high organic matter content. The Bw horizon has a subangular blocky structure and a lighter and more reddish color than the overlying A-horizon. The A-Bw sequence is 32 cm thick (Table 2), resting upon a gravelly parent material and another black colored tephra layer. The origins of the tephra layers are unknown but the dark color indicates basaltic phreato-magmatic eruptions from the Grimsvötn or Katla subglacial volcanoes.

3.2. Bulk density and loss on ignition

The following results and discussion are focused on the 0–10 cm depth unless stated otherwise. The %LOI in the soil increases and the bulk density decreases with increase in time. The %LOI is very low for the initial stages of soil formation when vegetation cover is sparse, or 0.79% on average (Table 3). For the oldest soil, the average LOI is 2.67%. The average values for the 10–20 cm are similar for all the timelines. %LOI is significantly different between each of the three time points (p < 0.001, Wilcoxon/Kruskal-Wallis).

Bulk density decreases with time and after 120 years of weathering attained a value of 1.07 g cm⁻³, which is significantly lower than those in the younger two surfaces (p < 0.001) (Table 3). The bulk density is higher in the lower depth except for the youngest soil where there is little difference between the two depth intervals. The bulk density of the forest soil is 0.49 g cm⁻³ (Table 3).
groups (p < 0.001). In the youngest soil, the SOC is close to zero (0.05% on average) (Table 3). The average SOC value in 0–10 cm layer increased to 0.30% after 65 years of soil formation and to 1.77% SOC after 120 years. The rate of increase of SOC is much slower in the lower 10–20 cm layer. The SOC concentration under the birch forest was 6.6% in the 0–10 cm layer, almost four times higher than that of the oldest moraine soils.

Concentration of total N in the 0–10 cm layer increased with increase in time although still only 1/5th of that in the forest soil in the oldest moraine. The N content was frequently under detection limit for the 8-year-old soil. The general trend in C:N ratio shows an increase with increase in time from around 12–17 over the 120 years.

There is a significant inverse relationship between bulk density and SOC (R² = 0.48, p < 0.001) (Fig. 4). Examining each time group individually, the bivariate fit of bulk density and SOC shows a similar relationship, but the correlation coefficient is slightly lower for the 65- and 120-year-old soil (65 year: R² = 0.42, p < 0.01; 120 year: R² = 0.30, p < 0.05) than for the whole dataset.

3.4. Soil pH (H₂O)

Soil pH (H₂O) decreases significantly with increase in age, from neutral or 7.4 on average to 5.7 in the 120-year-old soil (Table 3). The pH values are slightly higher for the lower depth. The reference area has pH values of 6, slightly higher than that in the 120-year-old moraine soils. There is a significant inverse relationship between soil reaction and SOC concentration (R² = 0.83, p < 0.001) (Fig. 5). When the bivariate fit of the two soil properties was applied to the individual time groups, only the 65-year-old soil showed a significant decrease in pH with the increase in SOC concentration (R² = 0.32, p < 0.05) concentration.

3.5. Ammonium oxalate extractable Al, Fe and Si

There is a trend towards increase in Alox concentration with increase in time and the concentration of Alox is significantly higher in the 120-year-old moraine compared to that in the younger two (p < 0.01), and the increase in Alox concentration between the 8-year-old and 65-year-old moraines was not significant. The trend of increase of Feox with increase in time was weaker, with only the oldest soil differing significantly from the youngest (p < 0.05). There is a significant correlation between SOC and the amount of oxalate extractable Al (R² = 0.52, p < 0.001) and Fe (R² = 0.20, p < 0.001) (Fig. 6a and b) whereas extractable Si did not correlate with SOC concentration. Within individual timelines, strong correlation occurred between SOC concentration and extracted Al and Fe values only in the 120-year-old moraine (Alox: Fe:...
There is a significant difference among each other ($p<0.01$). There is a significant correlation between SOC concentration and Al/Fe ratio ($R^2 = 0.77, p < 0.001$) (Fig. 7) for the moraine soils. The correlation within individual time groups is significant for the 65- and 120-year-old soil groups ($R^2 = 0.32, p < 0.05$ and $R^2 = 0.59, p < 0.001$ respectively).

### 3.6. Soil pH (NaF)

The pH (NaF) in the moraine soils does not show a trend of increase with increase in time although there is a significant difference between the older two time groups and the youngest group ($p < 0.001$, Wilcoxon/Kruskal-Wallis). The reaction trend is stronger in the sub-soil layer (Table 4). The youngest soil has a higher pH (NaF), but pH (NaF) increases between the 65- and 120-year-old soils. There is a significant but weak correlation between pH (NaF) and $\text{Si}_{\text{ox}}$ concentration ($R^2 = 0.22, p < 0.01$). After splitting up the bivariate fit for each time group, fit is the strongest and significant only between pH (NaF) and $\text{Si}_{\text{ox}}$ concentration for the youngest soil ($R^2 = 0.41, p < 0.01$).

### 4. Discussion

#### 4.1. Changes of soil properties with time

The data presented indicate that the time (increasing age) and vegetation succession are the driving forces of soil formation. With the

### Table 3

Selected soil characteristics for 0–10 and 10–20 cm depths presented as average values with standard deviation in parenthesis.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age (years)</th>
<th>A-horizon (cm)</th>
<th>Bulk density (g cm$^{-3}$)</th>
<th>LOI (%)</th>
<th>SOC (%)</th>
<th>Total N (%)</th>
<th>C:N</th>
<th>pH (H$_2$O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>8</td>
<td>0.0 (0.0)</td>
<td>1.36 (0.16)</td>
<td>0.79 (0.26)</td>
<td>0.05 (0.01)</td>
<td>0.004 (0.001)</td>
<td>12 (2)</td>
<td>7.4 (0.2)</td>
</tr>
<tr>
<td>0–10</td>
<td>65</td>
<td>4.4 (3.2)</td>
<td>1.33 (0.17)</td>
<td>1.29 (0.60)</td>
<td>0.30 (0.22)</td>
<td>0.024 (0.016)</td>
<td>13 (6)</td>
<td>65 (0.2)</td>
</tr>
<tr>
<td>0–10</td>
<td>120</td>
<td>8.0 (2.4)</td>
<td>1.07 (0.15)</td>
<td>2.67 (1.13)</td>
<td>1.77 (1.10)</td>
<td>0.101 (0.064)</td>
<td>17 (3)</td>
<td>5.7 (0.2)</td>
</tr>
<tr>
<td>10–20</td>
<td>Ref. area</td>
<td>12.7 (0.6)</td>
<td>0.40 (0.04)</td>
<td>16.77 (1.75)</td>
<td>6.60 (0.49)</td>
<td>0.492 (0.057)</td>
<td>13 (1)</td>
<td>6.0 (0.1)</td>
</tr>
<tr>
<td>10–20</td>
<td>8</td>
<td>–</td>
<td>1.35 (0.20)</td>
<td>0.86 (0.20)</td>
<td>0.06 (0.02)</td>
<td>0.004 (0.001)</td>
<td>16 (4)</td>
<td>7.6 (0.2)</td>
</tr>
<tr>
<td>10–20</td>
<td>65</td>
<td>–</td>
<td>1.40 (0.19)</td>
<td>0.75 (0.20)</td>
<td>0.21 (0.26)</td>
<td>0.030 (0.023)</td>
<td>14 (1)</td>
<td>6.6 (0.3)</td>
</tr>
<tr>
<td>10–20</td>
<td>120</td>
<td>–</td>
<td>1.19 (0.10)</td>
<td>0.88 (0.10)</td>
<td>0.34 (0.16)</td>
<td>0.022 (0.010)</td>
<td>16 (2)</td>
<td>5.9 (0.2)</td>
</tr>
<tr>
<td>10–20</td>
<td>Ref. area</td>
<td>–</td>
<td>0.62 (0.05)</td>
<td>9.96 (1.77)</td>
<td>2.91 (0.78)</td>
<td>0.243 (0.071)</td>
<td>12 (0)</td>
<td>5.9 (0.1)</td>
</tr>
</tbody>
</table>

$n = 18$ for moraine soils and $n = 3$ for reference area except for: bulk density and LOI 10–20 cm where for 8 years $n = 6$, 65 years $n = 10$, 120 years $n = 6$; SOC 10–20 cm where for 65 years $n = 16$; Total N 0–10 cm where for 8 years $n = 3$, 65 years $n = 17$ and 10–20 cm where for 8 years $n = 6$, 65 years $n = 10$, 120 years $n = 6$; $C:N$ 0–10 cm where for 8 years $n = 6$, 65 years $n = 17$, and 10–20 cm where for 8 years $n = 6$, 65 years $n = 6$, 120 years $n = 17$. All values refer to the top 0–10 cm layer.
establishment of vegetation cover, the input of organic matter gradually changes the color of the topsoil from a dark gray to a blacker hue forming a horizon sequence in the moraines. Andisols typically have a dark colored A-horizon and the color of the horizons in the oldest soil is similar to that reported by Arnalds and Kimble (2001) for Andisols of deserts in Iceland. The color difference between the oldest and the younger two timelines indicates a more progressive soil formation in the 120-year-old soil, where the parent material is altered to a greater depth, and will eventually develop a weak B horizon (Bw). Such a Bw horizon is common in Andisols of Icelandic deserts and in more developed soils of well drained surfaces (Arnalds and Kimble, 2001; Arnalds et al., 1995) such as in the reference site.

Reduction in bulk density with increase in age is caused by the input of organic material (Crocker and Dickson, 1957; He and Tang, 2008), as shown by the increase in LOI (%) and SOC (%) with time, but also by the morphological changes of the moraine material. Fresh moraine material is typically poorly sorted. Wind and water erosion removes the finest grains either from the surface or translocate these deeper within the moraine profile (Romans et al., 1980), increasing the pore space in the surface layer. Additionally, freeze and thaw cycles uplift coarser material to the surface. These processes are the most active in the 0–10 cm layer. The high LOI (%) compared to the SOC (%) concentrations indicate that in addition to organic matter some inorganic volatile compounds were lost during the ignition.

An AC horizon sequence has developed in the moraines over 120 years, a simple sequence in comparison with those reported by other chronosequence studies of the Skaftafellsjökull 65-year-old moraine compared to non-vegetated barren lands (relic glacial moraines from the last ice age) in South Iceland (0.25–0.28%) (Arnalds et al., 2013). The 1.77% SOC from 120-year-old moraines in Skáfafell (0–10 cm) is more comparable with that of the surfaces of similar age for the Damma glacier with 1.5–2.4% SOC (0–4 cm) (Dümig et al., 2011). However, Egli et al. (2010) reported values ranging from 17.6% SOC in the A-horizon (0–3 cm) to 1.67% SOC in the C-horizon (3–13 cm). Furthermore, the different sampling methods make comparison between studies difficult as sampling at fixed depth intervals can cause mixing of horizons within samples, altering the SOC values for the same horizons. When the SOC concentration of the moraine is compared with that of the topsoil in the birch forest (Table 3), it is evident that the moraine soils have a large C sink capacity and comparable C:N ratio for the Damma glacier with 8.2–8.3% in freshly exposed moraines in front of Skáfafellsjökull, which is 1 unit higher than that for the 8-year-old surface in the present study. The high pH of the freshly exposed moraines indicates limited interaction between the atmosphere and the subglacial basal moraine (Gislason and Eugster, 1987). The data based on studies of the Skáfafellsá river, where it emerges from the Skátafellsjökull and the subglacial basal moraine (Gislason and Eugster, 1987). The lower limit of pH may be caused by the input of basaltic parent material, either volcanic deposits or reworked eolian volcanic material (Arnalds, 2008b; Gisladóttir et al., 2010, 2011), which rejuvenates the soil system and thus the pH. Icelandic Andisols exhibit a distinct trend towards lower pH with Iceland, feature ABwC horizon sequences, maintained by frequent ash deposition by eruptions and eolian reworking.

Concentration of SOC (%) increased with increase in time for this chronosequence. The SOC values for the 8-year-old moraine were close to zero (0.05%) or slightly less than 0.05% SOC reported by Egli et al. (2010) in 10-year-old moraines (0–9 cm depth) for the Morteratsch glacier, and 0.09–0.14% SOC in 15-year-old moraines (0–4 cm) reported by Dümig et al. (2011) for the Damma glacier, both in Switzerland. The 0.30% SOC in the 65-year-old moraines in Skáfafell is considerably lower than 0.69% SOC (0–4 cm, 65 years) for the Damma glacier and 0.60% SOC (0–12 cm, 60 years) for the Morteratsch glacier. Nevertheless, the SOC concentration in the Skáfafellsjökull 65-year-old moraine compared to non-vegetated barren lands (relic glacial moraines from the last ice age) in South Iceland (0.25–0.28%) (Arnalds et al., 2013). The 1.77% SOC from 120-year-old moraines in Skáfafell (0–10 cm) is more comparable with that of the surfaces of similar age for the Damma glacier with 1.5–2.4% SOC (0–4 cm) (Dümig et al., 2011). However, Egli et al. (2010) reported values ranging from 17.6% SOC in the A-horizon (0–3 cm) to 1.67% SOC in the C-horizon (3–13 cm). Furthermore, the different sampling methods make comparison between studies difficult as sampling at fixed depth intervals can cause mixing of horizons within samples, altering the SOC values for the same horizons. When the SOC concentration of the moraine is compared with that of the topsoil in the birch forest (Table 3), it is evident that the moraine soils have a large C sink capacity and comparable C:N ratio for the Damma glacier with 8.2–8.3% in freshly exposed moraines in front of Skáfafellsjökull, which is 1 unit higher than that for the 8-year-old surface in the present study. The high pH of the freshly exposed moraines indicates limited interaction between the atmosphere and the subglacial basal moraine (Gislason and Eugster, 1987). The data based on studies of the Skáfafellsá river, where it emerges from the Skátafellsjökull and the subglacial basal moraine (Gislason and Eugster, 1987). The lower limit of pH may be caused by the input of basaltic parent material, either volcanic deposits or reworked eolian volcanic material (Arnalds, 2008b; Gisladóttir et al., 2010, 2011), which rejuvenates the soil system and thus the pH. Icelandic Andisols exhibit a distinct trend towards lower pH with

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**Fig. 7. Bivariate fit of organic carbon (%) and Al:Si ratio in the top 10 cm. Best fit by using a logarithmic model where SOC (%) values were log transformed.**

### Table 4

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age (years)</th>
<th>pH</th>
<th>Al\textsubscript{ox} (%)</th>
<th>Fe\textsubscript{ox} (%)</th>
<th>Si\textsubscript{ox} (%)</th>
<th>Al:Si</th>
<th>Allophane (%)</th>
<th>Ferrhydrite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>8</td>
<td>8.9 (0.4)</td>
<td>0.35 (0.07)</td>
<td>1.31 (0.19)</td>
<td>0.26 (0.04)</td>
<td>1.3 (0.2)</td>
<td>1.5 (0.3)</td>
<td>2.2 (0.3)</td>
</tr>
<tr>
<td>0–10</td>
<td>65</td>
<td>8.0 (0.4)</td>
<td>0.40 (0.09)</td>
<td>1.47 (0.19)</td>
<td>0.24 (0.04)</td>
<td>1.6 (0.2)</td>
<td>1.5 (0.3)</td>
<td>2.5 (0.3)</td>
</tr>
<tr>
<td>0–10</td>
<td>120</td>
<td>8.3 (0.4)</td>
<td>0.55 (0.18)</td>
<td>1.51 (0.31)</td>
<td>0.25 (0.07)</td>
<td>2.2 (0.3)</td>
<td>2.1 (0.7)</td>
<td>2.6 (0.5)</td>
</tr>
<tr>
<td>0–10</td>
<td>Ref. area</td>
<td>9.2 (0.1)</td>
<td>1.90 (0.21)</td>
<td>3.01 (0.33)</td>
<td>0.63 (0.10)</td>
<td>3.1 (0.2)</td>
<td>8.1 (1.0)</td>
<td>5.1 (0.6)</td>
</tr>
<tr>
<td>10–20</td>
<td>8</td>
<td>9.1 (0.3)</td>
<td>0.33 (0.05)</td>
<td>1.26 (0.15)</td>
<td>0.25 (0.03)</td>
<td>1.3 (0.1)</td>
<td>1.4 (0.2)</td>
<td>2.2 (0.3)</td>
</tr>
<tr>
<td>10–20</td>
<td>65</td>
<td>8.3 (0.5)</td>
<td>0.36 (0.08)</td>
<td>1.51 (0.20)</td>
<td>0.25 (0.03)</td>
<td>1.4 (0.2)</td>
<td>1.5 (0.3)</td>
<td>2.6 (0.3)</td>
</tr>
<tr>
<td>10–20</td>
<td>120</td>
<td>8.5 (0.3)</td>
<td>0.40 (0.12)</td>
<td>1.41 (0.34)</td>
<td>0.23 (0.06)</td>
<td>1.7 (0.2)</td>
<td>1.5 (0.4)</td>
<td>2.4 (0.6)</td>
</tr>
<tr>
<td>10–20</td>
<td>Ref. area</td>
<td>9.5 (0.1)</td>
<td>2.11 (0.45)</td>
<td>3.27 (0.64)</td>
<td>0.78 (0.18)</td>
<td>2.7 (0.1)</td>
<td>8.5 (2.0)</td>
<td>5.6 (1.1)</td>
</tr>
</tbody>
</table>

\( n = 18 \) for moraine soils and \( n = 3 \) for reference area.
increase in SOC concentration (Arnalds, 2004; Gísladóttir et al., 2010). The weak correlation between pH (H$_2$O) and SOC concentration within each timeline indicates that it is the duration of weathering and vegetation succession that are the driving forces for reduced soil pH.

Conditions at Skáftafellsjökull, with abundant precipitation, basal meltwater and ground basaltic rocks of a wide range of grain sizes, provide an environment conducive to active chemical weathering. The present study shows a slow increase in the extracted values of Alox and Feox, in accord with those reported by Arnalds and Kimble (2001) for some Icelandic desert soils. The rate of increase is gradual, but poorly crystalline Al- and Fe-phases are already in the 8-year-old moraines present, 0.35% Alox and 1.31% Feox. The abundance of these elements leads to the formation of allophane and imogolite, the amorphous secondary minerals characteristic for volcanic soils. The calculated secondary mineral concentrations must be regarded with caution since the extracted Al and Fe in the raw moraine material may not necessarily originate from those forms. Dü¨mig et al. (2011) also reported an increase in non-crystalline Al-phases with increase in time from 15 to 137 years for a chronosequence in front of the Damma glacier. However, concentrations of Alox (0.02–0.08%, 15–140 years) and Feox (0.04–0.14%, 15–140 years) are lower for the Damma glacier (Dümig et al., 2011) than those for the Skáftafellsjökull glacier at Alox 0.35–0.55% and Feox 1.31–1.51% (8–120 years). On the other hand, the Alox and Feox values presented in this study are lower in the glacial moraines than 1.22% Alox and 2.08% Feox concentrations from barren areas in South Iceland (Arnalds et al., 2013).

High soil pH (NaF) is indicative of allophane and ferrihydrite and the observed increase between 65- and 120-year-old soils may represent an increase in the duration of weathering of the secondary minerals. The high pH values for the youngest soil also indicate other possible reasons. According to the Soil Survey Staff (2010), measurement of pH (NaF) is not applicable to soils with free carbonates. Icelandic soils are carbonate-free but perhaps the ground basalt rock in the moraine de-posit contains carbonates in the form of amygdules. Carbonates dissolve much faster than silicates, and would be rapidly dissolved and leached out of the soil under the proglacial conditions.

Poorly crystalline phases of Al and Fe can stabilize organic matter, an important factor of sequestering organic carbon in soils and one of the reasons of high SOC concentration in Andisols (Kleber et al., 2005). Kleber et al. (2005) concluded from the strong correlation between oxalate extracted Al and Fe and stable carbon concentration that the poorly crystalline Al- and Fe-phases were actively protecting organic matter in acid soils. This study shows a moderately strong correlation between extracted Al and Fe concentrations and SOC for the 120-year-old moraine only, possibly an indication of increased potential for stabilizing organic matter as andic properties evolving in the young moraine soils.

4.2. The development of Andisols on the proglacial moraines

The data indicate that the developing proglacial soils are still evolving and undergoing pedological transformation. The older moraines represent an AC horizon sequence but a fine-grained cambic (Bw) horizon has not yet formed in the moraines. In addition, low SOC concentrations and oxalate extractable Al and Fe values do not meet the criteria for volcanic soils in ST or WRB systems of soil classification, whereas soils under the birch forest would likely be classified as Cryands (ST) or Silanic Andosols (WRB).

How much time is needed to formation of mature Andisols from these glacial moraines? It is evident that the different soil constituents and properties develop at different rates. Soil pH (H$_2$O) is the only property that has reached some sort of a steady state (Fig. 8), other properties develop at much slower rate although occurring at different stages when emerging from under the glacier. The relatively mild and wet climatic conditions in Skáfellsjökull may favor chemical weathering (cf. Öskarsson et al., 2012). Dählgren et al. (1997) have suggested that andic soil properties may develop into Andisols in 200–300 years under humid weathering conditions. The present study indicate that the time needed for Andisols to develop is considerably more than 120 years, but exactly how much more time is needed is difficult to ascertain.

5. Conclusions

The proglacial soils are still in evolving compared to the well developed forest soils, which represent a climax ecosystem that will likely occupy the moraines in the future. There is a gradual increase in soil organic carbon and nitrogen concentrations over time. The increase in oxalate extracted Al- and Fe-phases occurs at a slower rate but already in the youngest moraine considerable concentrations of those elements are present. The input of organic material, morphological and physical changes in the parent material decrease the bulk density of the soil over time. Chemical weathering reduces soil pH rapidly throughout the chronosequence to levels below the reference area. In order to
further clarify the relationship between soil development and time, the study must incorporate a higher time resolution by increasing the number of time groups investigated.

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References


3 Soil carbon accretion along an age chronosequence formed by the retreat of the Skaftafellsjökull glacier, SE-Iceland
Soil carbon accretion along an age chronosequence formed by the retreat of the Skaftafellsjökull glacier, SE-Iceland

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A B S T R A C T
Climate warming has led to glacial retreat worldwide, where surfaces exposed to the atmosphere are subjected to weathering, vegetation colonization and new soil formation. On young soils developing along the recessional path left by the Skaftafellsjökull glacier, SE-Iceland, we investigated the accretion of soil organic carbon (SOC) and nitrogen (N), representing an age chronosequence of 120 years. In total, 54 sampling sites were distributed along three moraines deposited in 1890, 1945, and 2003. For comparison, soil samples were collected from nearby birch woodlands (Betula pubescens Ehrh.), representing soils in a mature ecosystem likely to establish on the moraines in the future. Results show that the average SOC and N concentrations increase with time and at faster rates over the latter part of the chronosequence period investigated (1945–1890). After 120 yrs, the soil contains 1.1 kg C m⁻² in the surface layer (0–10 cm), which is still about one third of the 3.2 kg C m⁻² in soil under the birch woodlands. The N stock estimated at 0.06 kg N m⁻² after 120 yrs is almost one fourth of that under the woodlands. The data suggest that landscape affects vegetation establishment and in turn, both landscape and vegetation affect soil development. Thus, concentrations of SOC, N and noncrystalline oxalate extractable Al and Fe are higher within depressions in the proglacial landscape. The comparison of SOC stock in the moraine soils with that under the birch forest shows that the young proglacial soils still have a large potential to accrete SOC within the developing pedosphere. With the observed accrual rate of 9.1 g C m⁻² yr⁻¹ in the top at 10 cm, it may take the moraine soils an additional period of 220 yrs to accrue SOC stocks comparable with those under the birch forest. Given the fact that all Icelandic glaciers are receding, assessing SOC accretion in new soil formation may be important to off-setting the greenhouse gas emissions.

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1. Introduction

The melting of glaciers exposes new surfaces where weathering and soil formation commence. These proglacial sites respond rapidly to climate change and usually have ample water draining through the deposits, which is important to chemical weathering and active vegetation colonization and succession, which accelerate soil formation processes (Gislason, 2008; He and Tang, 2008; Egli et al., 2010). Time and climate are the primary determinants of the relative degree of weathering in the pedogenic environment (Ugolini and Dahlgren, 2002), and both affect weathering rates and plant succession in glacier forefields. Effects of climate change on soil systems have enhanced scientific interest in proglacial sites for assessing the rates of soil formation (e.g., Alexander and Burt, 1996; Conen et al., 2007; Haugland and Haugland, 2008; He and Tang, 2008; Egli et al., 2010; Dümig et al., 2011). Glaciers in Iceland have been retreating from their maximum position at the end of the Little Ice Age (LIA), as demarcated by the terminal moraines deposited in 1850–1890 (Björnsson and Pállsson, 2008). The land in between the present day glaciers’ termini and the terminal moraines is herein referred to as proglacial areas.

Soil development is not simply a time-related factor but also influenced by vegetation and landscape, and these factors function on different scales (Burga et al., 2010). During the initial stages of plant succession, soil organic carbon (SOC) and nitrogen (N) concentrations in soils are closely related to the extent and species composition of vegetation cover and depend upon the magnitude of litter accumulation and OM input between plant species and growth forms (Crocker and Major, 1955; Dahlgren et al., 2004; Su et al., 2004; Rajaniemi and Allison, 2009). Similarly, abiotic factors such as landscape form, slope aspect, grain size distribution and moisture content affect vegetation establishment and can enhance soil development in their initial stages (Houle, 1997; Jumpponen et al., 1999; Egli et al., 2006; Burga et al., 2010). The concurrent yet incongruent effect of biotic and abiotic factors entails spatial variation in the developing soil properties.

Soils in Iceland are developed from volcanic ejecta and are generally classified as Andisols/Andosols (ST/WRB) (Arnalds and Öskarsson, 2009). These soils exhibit distinct properties such as high C sink capacity...
which is attributed to: 1) successive ash deposition and burial of the topsoil, 2) formation of stable bonds between organic matter (OM) and noncrystalline secondary minerals (e.g., active Al- and Fe-allophane, imogolite, ferrihydrite, Al/Fe–humus complexes), and 3) development of stable aggregates, encapsulating OM and protecting it against microbial attack (Dahlgren et al., 2004). Andisols are among the most fertile soils in the world and often accumulate large amounts of nutrients in the organic rich topsoil, e.g. N, which is the most important nutrient for plant growth and the maintenance of agricultural ecosystems.

Icelandic ecosystems have undergone large scale deterioration and subsequent soil erosion since the settlement of the island in 874 AD as a consequence of land use, volcanic eruptions and climate deterioration (Ólafsdóttir and Guðmundsson, 2002; Gísladóttir et al., 2010, 2011). Soils of the eroded and barren areas differ markedly from those of vegetated land with stark differences in SOC and N pools. Óskarsson et al. (2004) estimated the amount of SOC eroded since the settlement at 120–500 Tg (1 Tg = 10¹² g = 1 million Mg) and low soil N content is the major nutrient limiting the reestablishment of vegetation (Bradshaw, 1997; Magnússon, 1997). A comprehensive background data is needed to compare the added value of land restoration and the accompanied increase in SOC with sites where natural vegetation succession is active. In principle, a chronosequence represents conditions where time is the dominant factor of soil formation, but all other soil forming factors (i.e. parent material, climate, biota, and landscape) are similar (Jenny, 1941). A few chronosequence studies have been conducted in Iceland; in ecological restorations (Aradóttir et al., 2000; Arnalds et al., 2013), downy birch (Betula pubescens Ehrh.), in the regrowth of forests of different maturity stages (Kolka-Jónsson, 2011), in forest plantations (Snorrason et al., 2002), on grazing land (Gísladóttir et al., 2010, 2011), on lava fields (McPeek et al., 2007) and in the proglacial area of the Skafafellsjökull glacier (Persson, 1964; Gísladóttir et al., 2014).

The objective of this research is to study: 1) vegetation succession in the Skafafellsjökull glacier foreland, 2) the rates of natural accretion of SOC and N in the proglacial soils, and 3) the effects of vegetation and landscape in conjunction with time, on the developing soil properties.

2. Regional setting

The study site lies within the proglacial area of the glacier Skafafellsjökull (N64°00′, W16°55′), which extends south from the Vatnajökull ice cap to the lowlands (Fig. 1). The proglacial area lies at about 100 m above sea level (a.s.l.) and is covered by thick glacial moraines intersected with runoff channels of former and current rivers emerging from the glacier’s terminus. The moraine material comprises volcanic basalt and hyaloclastite, with those being the rock formations in the vicinity (jóhannesson and Sæmundsson, 2009). Tephra is a substantial constituent of the moraines originating from subglacial volcanoes, such as Grímsvötn (G), Katla (K) and Óraefajökull (Ö) central volcanoes (Larsen and Eiríksson, 2008) that have precipitated large amounts of tephra over Skafafellsjökull and the surroundings.

The climate is maritime with cool summers and mild winters (Einarsson, 1980). Mean annual temperature is 5.1 °C in Skafafell (Fig. 1) with mean temperature being 10.5 °C in July and 3.3 °C in January (1996–2007). Mean annual precipitation is around 1800 mm (values from Fagurhólsmýri, 1949–2007, Fig. 1). The glacier’s terminus has receded since the end of the LIA, where terminal moraines deposited in ~1890 mark the maximum extent of the glacier. The recession is intersected by a few periods of glacial advance as a response to changes in temperature (Sigurðsson et al., 2007). From 1890 to 2003 the terminus receded...
about 2 km and a lagoon has been forming in front of the glacier since ~2003.

The vegetation of the proglacial area primarily comprises mosses, dwarf shrubs and shrubs. Trees and shrubs (B. pubescens Ehrh. and Salix spp.) are the species that characterize climax ecosystems in Iceland, an example of which is found on the Skatalfellsheiði heathland west of the moraines (Fig. 1). Natural colonization of birch and willows is active on the sandur plains and moraines south of Vatnajökull where the woodlands in Skatalfellsheiði are an ideal source of seeds (Persson, 1964; Martineßdóttir et al., 2007). A mature ecosystem will eventually develop as vegetation succession continues on the Skatalfellsjökull moraines. Soil development is at an early stage and the proglacial soils have been classified as Cryands (ST) or Vitric Andosol/Regosol/Leptosol (WRB) (Vilmundardóttir et al., 2014). An AC horizon sequence has formed with the accumulation of OM and alteration of parent material on the oldest moraines.

The research area has been protected since 1967, when the Skatalfell National Park was established. The park was included in the Vatnajökull National Park in 2008, which currently covers an area of ~14 000 km². Prior to being included within the Skatalfell National Park, traditional farming was practiced in the area with sheep grazing and hay-making, but the farming conditions deteriorated during the LIA and ceased after the establishment of the National Park (Ives, 2007). Sheep grazing was abandoned entirely in 1987 when the area was fenced off for enhancing colonization of birch and willows on the heathland, glacial moraines and the sandur plains.

3. Materials and methods

3.1. Field setup

Sample collection and vegetation measurements were carried out in summer of 2010 and 2011. Sample sites in the proglacial area were distributed along three moraines with a known time of deposition: 2003, 1945 and 1890 (Hannessedóttir et al., 2014). The outline of the moraines was obtained as global positioning system (GPS) waypoints and six points were randomly selected for each of the moraines (Fig. 1). The selection was stratified to ensure that points from both sides of the proglacial area were chosen since a gradient in vegetation could be expected because of much richer vegetation in the forested Skatalfellsheiði heathland west of the moraines. If the site of a selected point showed a sign of disturbance, such as riverbeds or areas of intense coarse fragments, the site was abandoned and a new point was chosen. A 10 m transect was fixed parallel to the moraine ridge (glacier’s terminus) for each point. Soil samples were collected within three 0.25 m² quadrants per transect at 0–10 and 10–20 cm depths. Each of the three moraines was, therefore, sampled 18 times for each depth interval, giving a total of 54 sampling points on the moraines. Samples were also collected from nearby birch woodlands in Skatalfellsheiði (Fig. 1) where downy birch and Salix spp. are most abundant and grasses and herbs form dense undergrowth with ground moraine as substrate (Gudmundsson, 1998). The birch woodlands served as a reference area to compare the young soils with those in a mature ecosystem to which moraines may transform in the future.

3.2. Landscape and vegetation measurements

The landscape position and vegetation characteristics were documented for each quadrant. Landscape was classified using the geomorphic description and surface morphometry by Schoeneberger et al. (2002) — slope aspect (North/South), slope complexity (Simple/Complex), profile position (Summit/Shoulder/Backslope/Footslope/Toeslope) with an additional category for landform (Ridge/Slope/Depression). Vegetation was recorded using a Braun-Blanquet cover scale (Goldsmith and Harrison, 1976) where total vegetation cover, bare ground and cover of specific plant groups were estimated (Table 1) and the shrub height was measured. The dwarf shrubs species include species like Empetrum nigrum L., Calluna vulgaris (L.) Hull, Vaccinium alpinum L. and Salix herbacea L. and shrub species included B. pubescens (Ehrh.), Salix lanata L. and Salix phylicifolia L. (Table 1). Nomenclature followed is that described by Kristinsson (2010).

3.3. Soil sampling, preparation and analysis

Bulk density of the fine earth fraction was measured for both depths using small cubical cores of known volume. The volume of coarse fragments for the 0–10 cm depth was determined with the cavity method using insulation foam (Page-Dumroese et al., 1999; Brye et al., 2004) and reported by Stanich (2013). It is used here to calculate the SOC and N stocks in the glacier foreland. Stanich reported a non-significant difference in the total volume of coarse fragments throughout the chronosequence. Based on that and the fact that the average thickness of the A-horizon featured in the 120 yr-old and 65 yr-old moraines did not exceed 10 cm (Vilmundardóttir et al., 2014), an average value of the three timelines was used to evaluate the SOC and N stocks for the 10–20 cm depth. However, the calculations are only tentative.

Soil samples were analyzed at The University of Iceland and The Ohio State University, Columbus, Ohio, USA. Bulk density samples were dried, gently ground and sieved through a 2 mm sieve. The volume of coarse fragments (>2 mm) was determined by the water displacement method. The bulk density of the fine earth fraction (<2 mm) was calculated after subtracting the weight and volume of the coarse fraction from the weight and volume of the total sample. Bulk samples were air dried, gently ground and passed through a 2 mm sieve.

Concentrations of SOC and total N were determined by the dry combustion method at 900 °C using a Vario Max C–N elemental analyzer. Soils were estimated to be carbon-free and, therefore, the measured C was assumed to be the SOC. The C stock was estimated by:

\[ \text{SOC stock (kg C m}^{-2}\) = \( BD \times T \times \text{SOC} \% \times (100 - S/100) \times 10^{-2} \]  \( (1) \)

where \( BD \) is the bulk density (kg m\(^{-3}\)), \( SOC \% \) is the organic carbon concentration (\%), \( T \) is the thickness (m) and \( S \) is the content of coarse fragments (>2 mm) of the soil horizon (vol.%). The rate of change of C and N was determined by dividing the stocks by the time since exposure, assuming zero stock(s) in the unweathered moraines.

Concentration of coarse fragments \( (S) \) was estimated by:

\[ S(\%) = \frac{(\text{coarse fragments}>2 \text{ mm}) \times \text{total volume} \ (\text{m}^3) \times 100}{(2) \}

Total SOC and N stocks were subsequently determined by combining the stocks of both 0–10 and 10–20 cm depth intervals.

Soil pH was determined in water–soil suspension (1:1), and ammonium oxalate extraction was obtained in the dark by the shaking
method (Blakemore et al., 1987), with oxalate solution buffered at pH 3.0. The extracted Al and Fe were determined by inductively coupled plasma optical emission spectrometry (ICP-OES).

3.4. Data analyses

Comparison of vegetation and plant group cover between the three chronosequence age groups was done by comparing the groups pairwise, using the Wilcoxon non-parametric method (McDonald, 2009). The effects of landscape on vegetation establishment were analyzed for the whole moraine dataset \((n = 54)\) using the Wilcoxon/Kruskal–Wallis non-parametric test and then for each age group \((n = 18)\) using the Wilcoxon non-parametric method. The same analysis was used to determine the effects of landscape on soil properties (bulk density, SOC, N, pH \((\text{H}_2\text{O})\), \(\text{Al}_{\text{ox}}\) and \(\text{Fe}_{\text{ox}}\)), first for the moraine dataset and then for each individual age group. In a similar manner, the effects of vegetation on soil properties were analyzed using a bivariate fit. Statistical analysis was done in the JMP software (JMP, 2005).

4. Results

4.1. Landscape and vegetation along the chronosequence

4.1.1. Landscape

The proglacial area is heterogeneous, inclines slightly toward the south with small elevation difference from the terminal moraine toward...
the current terminal position (90–120 m a.s.l.). The topography of the older two moraines is affected by decades of weathering and cryoturbation, and large rocks are prominent on the surface. Small scale proglacial landforms are still evident in the youngest moraine, where features as annual moraines, crevasse fillings, and small scale eskers are evident in some places. Such forms consist largely of sand and have been eroded from the older moraines (Fig. 2).

4.1.2. Vegetation

Overall, vegetation is in early stages of colonization in the proglacial area. In the youngest moraine (8 years), mosses (Racomitrium spp.) and grasses (e.g. Festuca spp., Poa alpina L.) are the pioneer plants (Figs. 2 and 3a) but with a total ground cover of <10%. The vegetation cover progressively increases on the 65- and 120 yr-old moraines compared with that on the 8 yr-old moraine. The average plant cover after 65 yrs of exposure is 61.3% comprising mosses, dwarf shrubs (E. nigrum L., C. vulgaris (L.) Hull) and occasional willow shrubs (S. lanata L. and S. phyllicifolia L.) with an average height of 10 cm (Fig. 3b). The average plant cover on the 120 yr-old moraine is 66.7% but the increase is not significantly different from those of the 65 yr-old moraine. On the other hand, macrolichens predominate on ridges. The relationship between vegetation and landscape within each age group is less clearly defined, yet with similar trends as observed in the total dataset. Slope aspect and slope complexity, however, do not have much effect on vegetation establishment.

4.3. Soil organic carbon and nitrogen accretion in the proglacial area

The SOC concentration in soils increases with increase in the moraine age as has been reported by Vilmundardóttir et al. (2014). It can reach 1.77% on average in the 0–10 cm after 120 years of exposure (Table 4) but the increase in the subsoil is slower. There was no evidence of any buried soil, neither within the surface basalt till nor in the landscape dissected by the rivers. The moraine soils contain only one-fourth of the SOC concentration (0–10 cm) found in the reference area under birch woodlands (3.16 kg C m⁻²) in the topsoil (Table 4). The SOC stock is significantly denser in depressions than on ridges and slopes, predominantly comprising mosses and shrubs. On the other hand, macrolichens predominate on ridges. The relationship between vegetation and landscape within each age group is less clearly defined, yet with similar trends as observed in the total dataset. Slope aspect and slope complexity, however, do not have much effect on vegetation establishment.

Table 2

<table>
<thead>
<tr>
<th>Landform</th>
<th>Total vegetated</th>
<th>Biological crust</th>
<th>Macroleichens</th>
<th>Mosses</th>
<th>Grasses</th>
<th>Dwarf shrubs</th>
<th>Shrubs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yrs</td>
<td>865120</td>
<td>865120</td>
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<td>865120</td>
<td>865120</td>
<td>865120</td>
</tr>
<tr>
<td>8</td>
<td>0.001 – 0.1</td>
<td>0.247 – 0.3</td>
<td>0.124 – 0.6</td>
<td>0.055</td>
<td>0.022</td>
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</tr>
<tr>
<td>65</td>
<td>0.001 – 0.5</td>
<td>0.247 – 0.3</td>
<td>0.124 – 0.6</td>
<td>0.055</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.001 – 0.5</td>
<td>0.247 – 0.3</td>
<td>0.124 – 0.6</td>
<td>0.055</td>
<td>0.022</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nonparametric comparisons for each pair (p-value with level of significance as *) using the Wilcoxon/Kruskal–Wallis method. Signif. codes: 001 ‘***’; 005 ‘**’; 01 ‘*’; parameter not estimated ‘×’ due to absence of plant group or uneven distribution within landscape categories. Profile position: SU = summit, SH = shoulder, BS = backslope, FS = footslope, TS = toeslope.
lower in the 10–20 cm depth, and the difference in SOC stock among the two depths is the most profound for the soil formed on the oldest moraine and those under the birch woodlands.

Trends in the accretion pattern of N in the soil are generally the same as those for the SOC. The N stock in the topsoil increases with time (Fig. 4b); being ~0.004 kg N m⁻² in the 8 yr-old moraine, and accumulating 0.063 kg N m⁻² in the 120 yr-old moraine (Table 4).

The rate of accretion of N stock differs among two depths, being higher for the 0–10 than 10–20 cm depth, and the difference in SOC stock among 10 and 20 cm where for 8 yr s n = 6, 65 yrs n = 6 and 120 yrs n = 17.

**Table 4**

Soil constituents/properties and stocks of the moraine soils and the birch woodlands (reference area); average values (standard deviation in parenthesis).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Time (yrs)</th>
<th>C (%)b</th>
<th>kg C m⁻²</th>
<th>g C m⁻² yr⁻¹</th>
<th>N (%)b</th>
<th>kg N m⁻²</th>
<th>g N m⁻² yr⁻¹</th>
<th>Bulk density (g cm⁻³)b</th>
<th>&lt;2 mm (%vol.)b</th>
<th>pH (H₂O)b</th>
<th>Al₄₆₈ (2%)b</th>
<th>Fe₃₆₈ (5%)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>8</td>
<td>0.05</td>
<td>0.04</td>
<td>0.004</td>
<td>0.004</td>
<td>0.04</td>
<td>0.06</td>
<td>1.36 (0.16)</td>
<td>37.1 (12.6)</td>
<td>7.4 (0.2)</td>
<td>0.35 (0.07)</td>
<td>1.31 (0.19)</td>
</tr>
<tr>
<td>65</td>
<td>0.30</td>
<td>0.27</td>
<td>4.17</td>
<td>0.024 (0.016)</td>
<td>0.021</td>
<td>0.32</td>
<td>1.33 (0.17)</td>
<td>32.5 (15.5)</td>
<td>6.5 (0.2)</td>
<td>0.40 (0.09)</td>
<td>1.47 (0.19)</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.77</td>
<td>1.10</td>
<td>9.14</td>
<td>0.101 (0.064)</td>
<td>0.063</td>
<td>0.52</td>
<td>1.07 (0.15)</td>
<td>42.1 (18.5)</td>
<td>5.7 (0.2)</td>
<td>0.55 (0.18)</td>
<td>1.51 (0.31)</td>
<td></td>
</tr>
<tr>
<td>Birch woodlands</td>
<td>6.60</td>
<td>3.16</td>
<td>4.92</td>
<td>0.049 (0.053)</td>
<td>0.236</td>
<td>1.09</td>
<td>0.49 (0.04)</td>
<td>1.13 (0.139)</td>
<td>6.0 (0.1)</td>
<td>0.19 (0.21)</td>
<td>1.01 (0.33)</td>
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</tr>
<tr>
<td>10–20</td>
<td>8</td>
<td>0.06</td>
<td>0.05</td>
<td>0.004 (0.001)</td>
<td>0.003</td>
<td>0.39</td>
<td>1.35 (0.20)</td>
<td>7.6 (0.2)</td>
<td>0.33 (0.05)</td>
<td>1.26 (0.15)</td>
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<tr>
<td>65</td>
<td>0.21</td>
<td>0.18</td>
<td>2.83</td>
<td>0.030 (0.23)</td>
<td>0.027</td>
<td>0.41</td>
<td>1.40 (0.19)</td>
<td>6.6 (0.3)</td>
<td>0.36 (0.08)</td>
<td>1.51 (0.20)</td>
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<tr>
<td>120</td>
<td>0.34</td>
<td>0.25</td>
<td>2.12</td>
<td>0.022 (0.010)</td>
<td>0.016</td>
<td>0.14</td>
<td>1.19 (0.10)</td>
<td>5.9 (0.2)</td>
<td>0.40 (0.12)</td>
<td>1.41 (0.34)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birch woodlands</td>
<td>2.91</td>
<td>1.79</td>
<td>0.243</td>
<td>0.064 (0.125)</td>
<td>0.151</td>
<td>0.39</td>
<td>0.62 (0.05)</td>
<td>0.09 (0.1)</td>
<td>0.72 (0.09)</td>
<td>3.17 (0.37)</td>
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<td></td>
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<tr>
<td>0–20</td>
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<td>0.09</td>
<td>11.03</td>
<td>0.007</td>
<td>0.85</td>
<td>0</td>
<td>0.387</td>
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<tr>
<td>65</td>
<td>0.45</td>
<td>7.00</td>
<td>0.048</td>
<td>0.74</td>
<td>0</td>
<td>0.66</td>
<td>0</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>1.35</td>
<td>11.26</td>
<td>0.079</td>
<td>0.66</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Birch woodlands</td>
<td>4.95</td>
<td>1</td>
<td>0.287</td>
<td>0.387</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
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</tr>
</tbody>
</table>

n = 18 for moraine soils and n = 3 for reference area except for: SOC 10–20 cm where for 65 yrs n = 10; total N 0–10 cm where for 8 yrs n = 3, 65 yrs n = 17 and 10–20 cm where for 8 yrs n = 6, 65 yrs n = 6 and 120 yrs n = 17.

a Data published by Stanich (2013).
b Data published by Vilmundardóttir et al. (2014).

4.4. Effects of vegetation and landscape on soil formation

Among the vegetation parameters analyzed, total vegetation cover, mosses, macrolichens and dwarf shrubs show the strongest relations with the soil properties/constituents (Table 5). The concentration of SOC, N and oxalate extractable Al increases significantly with increase in vegetation cover. Similar trends are observed for increase in cover by mosses, macrolichens and dwarf shrubs. In contrast, the grass cover is negatively related to SOC and N concentrations. Bulk density and soil pH (H₂O) decline with increase in vegetation cover, cover of mosses, macrolichens and dwarf shrubs. Total vegetation and moss cover in some cases also show significant or near significant relationship with SOC and N concentrations, indicating the effect of vegetation/plant groups on soil development.

Profile position and landform again are the two parameters, which are significantly connected with several of the soil properties/constituents studied. Soils formed on backslope (BS) positions have significantly higher pH (H₂O) and lower SOC and N concentrations than those formed on other positions within a landscape. Similarly, soils developed on slopes have significantly higher pH (H₂O) and bulk density compared to those for the other landforms. Although not significantly different, soils developed on footslopes and toeslopes consistently contain more SOC and N concentrations along with Al₄₆₈ and Fe₃₆₈ than those evolved at other positions. Furthermore, soils formed on the 120 yr-old moraine contain significantly more oxalate extractable Fe in toeslopes and depressions.

![Fig. 4](image-url)
5. Discussion

5.1. Vegetation and landscape considerations

After 120 yrs since deglaciation, the vegetation cover of the Skáfadalur moraines is ~65%. It comprises mosses along with dwarf shrubs and occasional low growing shrubs rarely exceeding 50 cm in height and withstands an AC soil horizon sequence (Vilmundardóttir et al., 2014). Grasses characterize the younger moraines, indicating less stable environment where winds and water actively erode the fresh moraines. The shrub species seem to be active colonizers as well, establishing even in the youngest moraine. Mosses characterize the older moraines along with dwarf shrubs, indicating reduced eolian input and more stable environment but these plant groups have low tolerance to eolian deposition in comparison with grasses and shrubs (Vilmundardóttir et al., 2009).

In comparison with the published data from Alaska, China and Switzerland, the vegetation succession on the proglacial area in Skáfadalur occurs at seemingly slower rate. For example, Crocker and Dickson (1957) reported a spruce forest development on the moraines after 100–120 years of soil exposure. He and Tang (2008) described development of a coniferous forest over 150 years and Egli et al. (2010) reported establishment of Larici–Pinetum cembrae forests after only 77 years. These forest types and species do not exist in the Skáfadalur area. The relatively slow vegetation colonization and succession is probably a result of various environmental factors; frequent freezing and thawing cycles with concurrent cryoturbation, general species paucity in Iceland, strong winds, sheep grazing until the 1980s, and lack of soil moisture and available nutrients (e.g. Magnússon, 1997; Arnalds, 2008; Höðalisdóttir, 2010). Skáfadalur is still regarded as one of the sites in Iceland where plants are rapidly colonizing the moraines due to the proximity to the seed source in the woodlands in Skáfadalshreppi.

The data presented indicate the important effect of landscape on vegetation establishment where it is favored in depressions (and footslope/toeslope profile positions) within the moraine landscape due to some abiotic factors such as differences in soil moisture content, shelter, snow cover and incident radiation (Fowler, 1986). Some plant groups such as macrolichens did favor ridges above depressions. Landscape seemingly favors soil development similar to that of vegetation succession, and these two factors have synergistic effects in creating ‘hot spots’ or sites of relatively rapid soil development, where the accretion of SOC, N and oxalate extractable Al and Fe phases and therefore weathering occur at faster rates than those at other locations. Similarly, Egli et al. (2006) proposed a basis for spatial modeling by assessing the effects of landscape on soil properties. They documented that various landforms correlated well with soil evolution, where slope, exposure and landform determined the soil development. On a larger scale, Yoo et al. (2007) have pointed out and modeled higher chemical weathering rates at the base of hillslopes due to weathering of parent material in situ and of material eroded and transported from upslope. Erosional and depositional processes may also be at play in small scale landscape features as studied in the Skáfadalssjökull glacial foreland. It is difficult to distinguish between the effects of time vs. vegetation as soil forming factors because the time factor also affects successional stages of the colonizing vegetation. While examining the relationship between vegetation and soil within each time group, only a few parameters indicate significant relations. This relationship, as examined by analyzing the entire dataset, added important information on the effects of vegetation on soil development. However, the significance of mean values should be regarded with caution.

5.2. Soil organic carbon and nitrogen

When the SOC concentrations from the present study are compared with those of the findings of other studies in proglacial areas, the SOC concentration of 1.77% in the 0–10 cm layer after 120 years of soil formation is similar to the findings from the Damma glacier (Switzerland) with 1.52% and 1.89% SOC in the top at 0–4 cm after 120 yrs since glacial retreat (Dümig et al., 2011). The SOC concentration measured in the present study is slightly higher than that reported by He and Tang (2008) for the Halluogou glacier (China) where soils contained 1.4–1.5% SOC after 130 yrs of soil formation in E and Bhs horizons. Egli et al. (2010) reported the SOC concentration in soils of the Morteratsch glacier (Switzerland), showing a wide range of SOC after 120–128 yrs (0.62–17.6% SOC), depending on the horizon sampled. However, the specific protocol for soil sampling, e.g. whether sampling is done at fixed depth intervals or by horizons, must be considered when comparing the results of different studies as the difference in SOC values between specific horizons can be large. Further, the variation in SOC concentration increases with increase in time as is observed in soils of the 120 yr-old moraines. Such a trend of an increase in variation with time was also reported by Dümig et al. (2011) who concluded that site instability, such as drainage and debris flows, is the driving force affecting the variation. Sites of the present study were chosen carefully to eliminate those with recent disturbance. Thus local effects of landscape may cause the high variation observed, with frequently higher SOC concentrations in depressional positions.

The SOC stock at Skáfadalssjökull 120 years after glacial retreat was estimated at 1.10 kg C m$^{-2}$ (0–10 cm), corroborating with other estimations: ~1–5.5 kg C m$^{-2}$ after 100–150 yrs (Egli et al., 2010), 0.55 kg C m$^{-2}$ after 120 yrs (Dümig et al., 2011), 2.0 kg C m$^{-2}$ after 130 yrs (He and Tang, 2008), and 2.5 kg C m$^{-2}$ after 122 yrs from Glacier Bay in Alaska (Crocker and Major, 1955) but again the different sampling protocols must be regarded. The rate of accretion of SOC stock in the surface layer at Skáfadalssjökull ranges between 4.17–9.14 g C m$^{-2}$ yr$^{-1}$ which is also in accord with rates reported by Egli et al. (2001, 2010), He and Tang (2008) and Dümig et al. (2011).

The concentrations of N from Skáfadalssjökull (~0.1%) after 120 yrs are similar to those reported by He and Tang (2008) (0.1–0.2% of N in soils formed on 130 yr-old moraines), who also estimated the N stock (~0.3 kg m$^{-2}$), which is considerably higher than the values observed in the surface layer of the 120 yr-old soil in the studied site (0.06 kg N m$^{-2}$). The source of N in the soil was not investigated further but it is probably related to microbial activity established early on after deglaciation. In a study from a glacial chronosequence in the Peruvian Andes, Schmidt et al. (2008) reported the presence of cyanobacteria in the moraines already after 4–5 yrs since deglaciation and a great increase in soil N fixation rates long before the establishment of plant cover. For the same time, the increase in SOC along with the N-fixation in high arctic ecosystems has been established (Zielke et al., 2002, 2005). No data for N input via precipitation is available for this part of Iceland but studies from the south-west part indicate that it is very low (Eríksdóttir, 2008).

The initial ~0.05% SOC concentration on the 8yr-old moraines is considerably lower than the reported value of 0.25–0.28% SOC in barren lands (control treatments) in restoration experiment in S-Iceland reported by Arnalds et al. (2013). Indeed, the SOC concentration in the reclamation site had superseded those for the soils on the 65 yr-old moraines. Similar trends were observed for the accretion of N. The soils formed on the 120 yr-old moraines contained more than double the stocks of SOC and N than those of the reclaimed area. The SOC concentration in soils developed on lavas in S-Iceland under natural conditions showed that 0.21 kg C m$^{-2}$ had accreted on a lava field formed in 1783 AD (McPeek et al., 2007), which is still lower than that of 1.10 kg C m$^{-2}$ in soils formed on the 120 yr-old moraines. Preliminary results of a chronosequence study from restored birch forests (no fertilization) in S-Iceland reported SOC concentration of 8.8–11% in the surface horizon of a 60 yr-old forest, 5.6–8.0% SOC of 5–15 yr-old forest, and 4.5–6.2% in unforested, fully vegetated land (Kolka-Jónsson, 2011). These concentrations are similar to those under the birch woodlands in Skáfadalshreppi (reference area). The rate of SOC accretion of
9.14 g C m\(^{-2}\) yr\(^{-1}\) in the Skafatellsjökull foreland is considerably lower than that reported for the restored barren lands with rate of 60 g C m\(^{-2}\) yr\(^{-1}\) (Arnalds et al., 2013) and for the ~65 yr-old restored birch forests of 47 g C m\(^{-2}\) yr\(^{-1}\) (Kolka-Jónsson, 2011) and for the grazing lands of Krysvíkurheidi with the SOC accretion rate of 25–28 g C m\(^{-2}\) yr\(^{-1}\) (time period 1500–2006) (Gisladóttir et al., 2010). The rate of accretion by natural development in the proglacial area is therefore slower than that of fully vegetated ecosystems, such as grasslands and forests, under restoration. On the other hand, the rate of accretion in the proglacial area is higher than that of soils formed on lava flows (McPeek et al., 2007).

### 5.3. SOC and N accretion

The SOC and N stocks increase exponentially with increase in time, slower during the first decades and faster after the first 65 yrs since deglaciation. In contrast, several glacial chronosequence studies commonly report a power increase in SOC and N stocks; high rates during the first decades after deglaciation, followed by a regressive decline with increase in time and asymptotically approaching a steady state (Crockier and Dickson, 1957; Egli et al., 2001, 2010; He and Tang, 2008). A study from the Werenskiold glacier in Svalbard shows the same trend of increase (Kabala and Zapart, 2012).

### 5.4. Factors influencing SOC and N accrretion

The increase in SOC and N stocks in the studied area is governed by the deposition of tephra and charcoal, and vegetation succession (Arnalds et al., 2013). The incorporation of the SOC and N into the surface layer is also influenced by the temperature, rainfall, and freeze-thaw cycles (Kabala and Zapart, 2012). The SOC is also affected by the mineralogy and texture of the substrate, as well as by the microbial activity (Kabala and Zapart, 2012).

### 5.5. Conclusions

The SOC and N stocks in the studied area are significantly influenced by the vegetation type, landscape position, and soil properties. The highest SOC and N stocks are found in the proglacial area, followed by the bioturbated moraine, and then the summit area. The SOC and N stocks are also influenced by the age of the vegetation succession, with the oldest vegetation having the highest SOC and N stocks. The SOC and N stocks are also influenced by the climate, with higher SOC and N stocks in areas with higher rainfall and temperature.

### References

340 yrs since deglaciation, given that the SOC stocks under the birch woodlands have reached a steady state for well drained Andisols of Iceland. If calculated for the top 20 cm the additional time needed is 320 yrs. These projections do not account for the fact that Icelandic Andisols, especially within the volcanic zone, tend to form thicker solum which contains SOC throughout the entire profile because of the specific pedologic conditions of Andisols (Óskarsson et al., 2004). These projections are also based on the assumption that the rates of accretion do not slow down over time until the stock attains the concentration of 6%, which is the steady state level observed for most undisturbed Andisols (Nanzyo et al., 1993).

6. Conclusions

The data presented lead to the conclusion that time plays a fundamental role in soil forming process; nevertheless, vegetation succession alone and in conjunction with landscape is also an important factor of soil formation and C and N accretion. However, a different sampling protocol is needed to emphasize the role of these two factors and minimize the time effect. The modeling of SOC and N increase with time could be improved by including more moraines of different times of exposure within the chronosequence. The data of the present study can serve as a basis for modeling the regional C stock within the Skæftafellsjökull foreland, where time, vegetation and/or landscape are used as an indicator of the accrual rate of C and N stocks in soils developing over exposed moraines. Finally, the developing soils in the proglacial area of Skæftafellsjökull reveal the active C accrual processes which may continue for another 220 yrs (two centuries) and perhaps longer given the high volcanic activity within the region. The fact that all Icelandic glaciers are reducing in size makes this an important quality with respect to balancing national greenhouse gas emissions.

Acknowledgments


Kolka-Jónsson, P.V., 2011. Caribbōr (Kólhrákn): Carbon sequestration and soil development under mountain birch (Betula pubescens) in rehabilitated areas in southern Iceland. Unpublished Master’s Thesis, The Ohio State University, Columbus, Ohio, P.


Between ice and ocean; soil development along an age chronosequence formed by the retreating Breiðamerkurjökull glacier, SE-Iceland
Between ice and ocean; soil development along an age chronosequence formed by the retreating Breiðamerkurjökull glacier, SE-Iceland

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Vegetation succession

A B S T R A C T

As glaciers in Iceland retreat they expose new surfaces for plant succession and soil formation. In the foreland of Breiðamerkurjökull glacier, we used a high time resolution chronosequence to study vegetation succession; morphological, physical and chemical changes in soils; and the impact of avifauna on the vegetation and soils developing on the moraines. In total, 38 sampling sites were distributed along moraines deposited in 1890, 1930, 1945, 1960, 1982, 1994, 2004 and 2012, representing 8 age groups. On moraines, where the influence of seabirds was apparent, soils were collected from bird hummocks, one for each age group. Soil samples were also collected from nearby birch (Betula pubescens Ehrh.) woodlands, representing soils in a potentially future mature ecosystem. The results show that mosses and grasses dominated and characterized the vegetation on the moraines with the exception of the two youngest moraines that were non- or sparsely vegetated. An AC horizon sequence slowly formed yet the A horizon remained thin (~2.5 cm). Bulk density decreased with time since deglaciation, from 1.2 g cm−3 down to 0.8−1.0 g cm−3 in the oldest moraines. Similarly, soil pH (H2O) decreased with time, reaching a steady state at the value of 6 after 67 yrs. LOI (loss on ignition), SOC (soil organic carbon), and total N (nitrogen) concentrations along with pH (NaF) increased over the time span investigated. The increase in LOI, SOC and N concentrations occurred slowly during the first few decades, rates increased after 50 yrs since deglaciation but eolian input appeared to reduce the rates again in the 122 yr-old moraine. The highest SOC and N concentrations were reached in the 82 yr-old moraine (1.4% SOC, 0.07% N) and the highest NaF values of 9.3 after 67 yrs. The lack of shrubs and dwarf shrubs indicated that the long distance from seed sources retarded vegetation succession within the Breiðamerkurjökull moraines, which in turn affected the soil development on the moraines, although perhaps to a lesser degree than expected. The soil in the bird hummocks was characterized by dense root system and thick A (or O) horizons (~14 cm) generated by the dense growth of grasses and herbs, accompanied by considerably much higher SOC and N values (18% SOC, 1.1% N after 67 yrs) when compared to the surrounding moraine soils. Additionally, bulk density was much lower within the bird hummocks (0.26−0.75 g cm−3) and soil pH (H2O) was generally lower, ranging between 5.2 and 6.2 depending on moraine age. This study shows that the point-centered input by avifauna into the terrestrial ecosystem is an important factor in locally enhancing vegetation growth and the rates of soil formation increasing the heterogeneity within the moraine soils.

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1. Introduction

Chronosequences, an approach involving space-for-time substitution, have been widely used to study primary succession and soil formation. The concept of a chronosequence was systematized by Jenny (1941) in the context of soil development, where the soil as a whole, or a specific soil property, is a function of the soil forming factors: climate, available biota, topography, parent material and time, with time being the only truly independent factor. In a chronosequence, it is presupposed that time can be isolated as a factor in soil formation, but in reality the other factors may also change through time. Since the Little Ice Age (LIA), glaciers have been retreating due to a warming climate and the emerging glacial fore-fields have been regarded as ideal sites for studying primary plant succession and/or soil formation. Matthews (1992) did a comprehensive review on the various research from glacial fore-fields worldwide but one of the first studies linking the plant succession and soil development was done in Glacier Bay, Alaska, by Crocker and Major (1955). According to Ugolini and Dahlgren (2002), time and climate are the main determinants of the
relative degree of weathering of the soil environment but also affect the biota and plant succession. Increase in vegetation cover is probably the most obvious change occurring within glacier forelands, being initially slow and then the rate increases and a full cover is often attained within 30–50 yrs (Matthews, 1992). It is, however, highly dependent on local environmental factors, such as the nature of the substrate, the landscape and biological controls, such as patterns of immigration and species interaction. In general, vegetation stratification is developed over time, with time-dependent sequence of herbs, shrubs and trees for specific regions such as the Alps and Alaska (Burga et al., 2010; Crocker and Major, 1955), and cryptogams appear to precede phanerogams at higher latitudes and in mid- and high-alpine zones (Hodkinson et al., 2003; Persson, 1964; Stork, 1963). Animals also impact the plant suc- cession and soil development in various ways and add nutrients to the soil through dropping, often creating stark differences among sites of fertilization and the regular nutrient-poor surfaces (Bockheim and Haus, 2014; Tomassen et al., 2005).

The parent material is a fundamental determinant of the soil type formed in glacial moraines (Jenny, 1941). Iceland is a volcanic island and the moraine material is a mixture of ground volcanic rocks and glassy tephra, which covers outlets to glacial rivers to a significant extent due to relatively frequent events of tephra fall during sub-glacial eruptions. The windy environment redistributes tephra and finer particles deposited by rivers and glaciers, and this deposition rejuvenates the soil sys- tem through the addition of fresh parent material (Arnalds, 2008). Soils in Iceland are generally classified as Andisols/Andosols (STWRB) (Arnalds and Öskarsson, 2009), which feature distinct properties such as high C (C) sink capacity, low bulk density and poorly crystalline clay constituents with allophane being the most common. Icelandic soils have undergone large scale erosion and consequently the SOC and nitrogen (N) pools of eroded surfaces differ greatly from those under vegetated land (Gísladóttir et al., 2010; Öskarsson et al., 2004). To stabilize and improve the status of eroded areas, studies on revege- tation and restoration are being done in many regions of the country. Worldwide, soils contain ~1500 Pg organic carbon (OC) to 1 m depth, and comprise the largest terrestrial C pool (Schleeramann et al., 2014). However, human and natural processes have depleted the SOC pool af- fecting the net flux of greenhouse gases (GHGs) between the soil and the atmosphere (Arrouays et al., 2014). Currently there is a great inter- est in soil C as it offers an option to mitigate the increasing anthropogen- ic emissions and the ongoing climate change by being a potential sink for GHGs (Hartemink and McSweeney, 2014; IPCC, 2014). Many of the recent chronosequence studies have focused on this aspect, including the timeline from the Skæftafellsjökull fore-field, SE-Iceland for specific accumulation of SOC, governed by time and natural plant succession, proved to be less effective than restoration efforts of eroded areas despite a relatively rapid shrub land establishment (Arnalds et al., 2013; Vilmundardóttir et al., 2014; Vilmundardóttir et al., 2015). The Skæftafellsjökull proglacial area is in close proximity to birch (Betula pubescens Ehrh.) woodlands, which is the natural climax ecosystem in Iceland (Sigurðsson, 1977). However, there are many outlet glaciers in the country that are isolated from such seed sources but studies on soil development from these areas are lacking.

Many outlet glaciers of various sizes flow from the Vatnajökull ice- cap down to the lowlands of SE-Iceland (< 1 m a.s.l.). The pro- glacial areas have similar maritime climate (cool summers and mild winters) (Einarsson, 1984) but feature different geomorphic surroundings and drainage systems as well as vegetation composition. The vast Breiðamerkurjökull outlet glacier is a challenge to plant colonization in the moraines due to relatively long distance to seed sources. Nonethe- less, the sparsely vegetated moraines have attracted seabirds that fre- quently this area for roosting and nesting purposes. Breiðamerkurjökull’s history of advance and retreat is well known and it provides the settings of high time resolution chronosequence within the glacier foreland. By using data on soil development and vegetation succession within eight well dated glacial moraines, formed since the end of the LIA – 1890, and from isolated bird hummocks,1 the objectives were to investigate 1) vegetation succession within the pro-glacial area that is relatively isolated from seed sources, 2) soil formation on the glacial moraines in relation to time and vegetation, and 3) the impact of avifauna on the vegetation and developing soils. It was hypothesized that the vegeta- tion stratigraphy, developing on the moraines, would be different from the proglacial areas that are closer to seed sources, such as for Skæftafellsjökull, and it would result in lower rates of soil formation. The second hypothesis was that the presence of avifauna enhanced veg- etation growth and soil formation rates within restricted locations.

2. Material and methods

2.1. Study settings

The study site lies within the pro-glacial area of Breiðamerkurjökull glacier (N64°05′–64°02′, W16°18′–16°14′) (Fig. 1), which is the fourth largest outlet glacier in Iceland (Björnsson, 2009). The study area is confined between the remnants of the relic ice and the associ- ated landscapes left by the two medial moraines Máfabyggðarönd to the west and Esjufjallarönd and Jökulsárlón glacial lake to the east. Breiðamerkurjökull advanced when climate cooled during the LIA and reached its maximum extent in 1880–1890, creating the termi- nal moraines marking the LIA glacial maximum (Guðmundsson, 2014). South of the terminal moraines are the Breiðamerkurjökull glacie- r-fluvial plains in close proximity to the Atlantic Ocean. To the west, the sandur plains and the moraines are demarcated by the glacial river Fjállsá, and by Jökulsá to the east, originating from the pro-glacial lakes Fjállsárlón and Jökulsárlón. Despite being isolated by glaciers and often fierce glacial rivers, the area has been utilized by farmers for sheep grazing. Other land use is limited to tourism within the southern and eastern shores of Jökulsárlón.

The study area lies within 18–70 m a.s.l. in a relatively flat landscape with one small drop in relief where the glacier terminus was located in ~1960 and from there the land rises gradually to the present day term- inus. The climate is maritime with cool summers and mild winters (Einarsson, 1984), with a mean annual temperature of ~5 °C and in win- ter the temperature often hovers around zero (Table 1). Precipitation is abundant although likely less than measured at Kvísker and Hali, the weather stations in the shortest distance from Breiðamerkurjökull. Since 1890, the glacier front has receded although with static or readvancing periods, exposing various kinds of geomorphic features; e.g. thick ground moraines and a series of end moraines that have been well documented by the Icelandic Glaciation Society and by Sveinvar Guðmundsson (Guðmundsson, 2014). The moraines are com- posed of unsorted material derived from rock formations in the vicinity, which feature mostly volcanic basalt and hyaloclastite (Jóhannesson and Sæmundsson, 2009) although plutonic and geo-thermally altered rock types are also present. Tephra, fragmental materials produced in volcanic eruptions, is a substantial constituent of the moraines originating from sub-glacial volcanoes, such as Grímsvötn, Bárðarbunga, Katla and Óraefajökull central volcanoes (Óladóttir et al., 2011).

2.2. Field setup

Sample collection and vegetation measurements were carried out during summer of 2012 where sampling sites were restricted to end or ground moraines with a known/estimated time of deposition: 2012, 2004, 1994, 1982, 1960, 1945, 1930 and 1890, comprising 8 age groups. The outline of the moraines/glacial margin was identified as GPS waypoints, and five points were randomly selected for each of the moraines for measuring landscape, vegetation and for soil sampling.

1 Hummocks created by the accumulation of droppings where birds regularly perch and defecate.
Sampling sites are well drained and without signs of disturbance, such as dry riverbeds or flooded areas, otherwise they were omitted and the next point chosen instead. Sampling sites were restricted to the northern side of moraine ridges, excluded depressions/toe-slope positions (Schoenberger et al., 2002) to avoid sites of considerable sediment deposition, evident in the oldest moraine. Breiðamerkursandur is one of Iceland’s largest nesting grounds for the great skua (*Stercorarius skua*) (Lund-Hansen and Lange, 1991). Both the great skua and the Arctic skua (*Stercorarius parasiticus*) have had considerable impact on the soil environment and created ‘bird hummocks’ on the moraines, most often on the summits, and they were excluded from regular moraine soil sampling. To investigate the impact of avifauna on the soil environment, one sampling site was placed within such a hummock.

Birch and willows (*Salix* spp.) are the species that characterize climax ecosystems in Iceland and are already colonizing the moraines in front of Skaftafellsjökull and the outwash plain Skeiðarársandur (Marteinsdóttir et al., 2007; Vilmundardóttir et al., 2015). In theory, those species would therefore be the final stage of vegetation to develop on the Breiðamerkurjökull moraines. However, the study area is isolated from the nearest site of birch growing close to the farm Kvísker in ~11 km distance to the west (Fig. 1). Soil samples were collected within the birch woodlands at Stórihnaus at Kvísker to compare the young moraine soils with those of a mature ecosystem.

### Table 1

<table>
<thead>
<tr>
<th>Position</th>
<th>N 64°05′−64°02′</th>
<th>W 16°18′−16°14′</th>
</tr>
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<tr>
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</tr>
<tr>
<td>Climate</td>
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<tr>
<td>–July</td>
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</tr>
<tr>
<td>–January</td>
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<tr>
<td>Mean annual precipitation*</td>
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<tr>
<td>Kvísker</td>
<td>3500 mm 2250 mm</td>
<td></td>
</tr>
<tr>
<td>Hali</td>
<td>Basalt, hyaloocrasite, tephra</td>
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</tr>
<tr>
<td>Area</td>
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<td></td>
</tr>
</tbody>
</table>

* Based on unpublished data from IMO. Temperature and precipitation values are from the Fagurhólsmyri weather station, 1949−2007, and Hólar in Hornafjörður weather station, 1949–2011. Additional precipitation data are from Kvísker (1960−2011) and Hali (1999–2011) weather stations, which are located closer to the study site but no data on temperature is available. See Fig. 1 for locations of Fagurhólsmyri and Kvísker weather stations.

### 2.3. Field measurements and soil sampling

All measurements and sampling were performed within a 0.25 m² quadrant. Vegetation within the quadrant was recorded by using a slightly modified Braun-Blanquet cover scale (Goldsmith and Harrison, 1976), where the total cover and cover of specific plant groups were estimated (Table 2). In addition, general information on vegetation and species was documented for each moraine age group, names of plant species follow that by Kristinsson (2010). Soils were sampled at 0−5 cm and 5−15 cm depths. Bulk density of the fine earth fraction was measured for both depths using small cubical cores of known volume and applied perpendicular to the soil profile. The cores were of three sizes, 1.7 cm³ (n = 5), 7.9 cm³ (n = 3) and 19.5 cm³ (n = 2).
The following results are focused on the 0–5 cm depth unless stated otherwise. Soil bulk density was the highest in the youngest moraines and decreased from 1.24 g cm\(^{-3}\) on average down to 0.81 g cm\(^{-3}\) in the 67-yr-old moraine, after which the value maintained ~1.0 g cm\(^{-3}\) (Table 4). A Wilcoxon non-parametric test indicated a division in between moraines of 18 yrs and younger compared with those of 52 yrs and older. Soil bulk density values of the moraine were much higher than that in the 18 yr-old soil. Thereafter, adjacent age groups did not show a significant difference in SOC concentration and SOC in the 82 yr-old moraine, yet it was only 10% of the LOI in the birch woodlands (22.1%). The SOC concentration started close to zero (0.02%, Table 4) in the youngest moraine and increased to 3.1% in the 82 yr-old moraine, after which the average cover remained quite constant (36–57.5%). Grasses were already present in the 8 and 18 yr-old moraines where Poa flexuosa and Poa glauca were most apparent but Festuca vivipara featured throughout the chronosequence and had considerable cover in the oldest age groups. Biological crust increased with time and comprised a considerable part of the cover in the 67–112 yr-old moraines. Macro-lichens did not feature such a distinct increase with increase in time and their cover was the maximum on the 112 and 52 yr-old moraines. Dwarf shrubs, especially Empetrum nigrum, were also present on the moraines, particularly in the 30–82 yr-old moraines but their cover was patchy and rarely documented within plots. Shrubs were almost completely absent, a few small stands of Salix lanata (~15–20 cm tall) were observed close to the 18 yr-old moraine and a single sprout of birch (~30 cm tall) close to the Jökulsarlon by the sampling sites of the 30 yr-old moraine. Signs of grazing were negligible except for the moraines close to the glacier, especially after the 18 yr-old moraine, where evidence of grazing by barnacle goose (Branta leucopsis) was present.

### 3.2. Soil development

#### 3.2.1. Morphology of the moraine soils

Changes in texture were apparent already in the 8 yr-old moraine where silt-sized and finer grains had been translocated from the surface layer, leaving behind sandy material with a mantle of gravel on the surface and unsorted till underneath (Table 3). An A horizon was beginning to develop in the 30 and 52 yr-old moraines, which became more distinct thereafter although remaining thin, the development was primarily indicated by darkening in color with a hint of a granular structure in the oldest moraines. The oldest moraine featured more sandy horizons. The gley color was sometimes best fitted to describe the grayish color of the subsoil even though the soil was not waterlogged. The woodlands at Stórislauta featured two A horizons and a Bw horizon, a sequence typical for well drained Andisols (Fig. 3i–j). Tephra from the eruption in Grímsvötn in 2011 was evident in the forest undergrowth as 1 cm thick deposits. The origins of the tephra layers buried in the woodland soils are unknown but likely from Grímsvötn or Katla subglacial volcanoes (Óladóttir et al., 2011).

#### 3.2.2. Soil physical and chemical properties

The following results are focused on the 0–5 cm depth unless stated otherwise. Soil bulk density was the highest in the youngest moraines and decreased from 1.24 g cm\(^{-3}\) on average down to 0.81 g cm\(^{-3}\) in the 67-yr-old moraine, after which the value maintained ~1.0 g cm\(^{-3}\) (Table 4). A Wilcoxon non-parametric test indicated a division in between moraines of 18 yrs and younger compared with those of 52 yrs and older. Soil bulk density values of the moraine were much higher than that in the 18 yr-old soil. Thereafter, adjacent age groups did not show a significant difference in SOC concentration and the variation in concentration increased within age groups. The highest SOC concentration was attained in the 82 yr-old moraine, yet it was only 13% of that in soil under the birch woodlands. The magnitude of SOC increase in the lower depth was much slower than that for the top depth and barely detectable until after 52 yrs.

The N concentration was zero in the youngest three age groups but after 30 yrs N was detectable in the moraine soil. The N concentration reached 0.071% and it was the highest after 82 yrs, still only 16% of...
that in soil under the birch woodlands. The C:N ratio was higher in the younger moraines compared to the older ones but N was not detectable in the lower depth in the moraine soils.

Soil pH (H$_2$O) started as high as 8.3 and leveled off in 67 yrs, remaining at the value of 6 throughout the chronosequence. The woodland soil had a lower pH than that of the moraine soils which was 5.3. The lower depth featured pH values usually 0.5 unit higher than the top depth. Soil pH (NaF) increased from being around 8.0 to 9.3 in the 67 yr-old moraine, whilst the birch woodland soils had the highest NaF values of 10.1. The pH values were generally similar for the lower depth, except for the woodlands where the value reached 11.1.

3.2.3. The pattern of changes in soil characteristics with increase in time

All the measured soil properties showed changes with increase in time: bulk density and pH decreased whereas LOI, SOC, total N and pH in NaF increased with time since deglaciation (Table 4). These changes were generally less apparent in the subsoil except for soil pH (H$_2$O and NaF).

When fitting models to describe the trends of increase or decrease of the different soil properties, the best fit was most often through quartic polynomial models since the curves changed their path at the end of the chronosequence. This trend means that the increase in LOI, SOC, total N and pH (NaF) is ongoing more or less throughout the chronosequence, but instead of reaching its highest point in the oldest age group, a decrease was observed in the 122 yr-old moraine. The trend was just the opposite for soil bulk density. For LOI, SOC and total N, the variation also increased with increasing age, with an exception in the 122 yr-old moraine where it decreased again.

The relationships between the developing soil properties and vegetation cover showed that the age-dependent vegetation parameters correlated strongly with the soil parameters. This trend was apparent for the total vegetation cover and moss cover, where the cover was denser; the underlying soil had lower bulk density, higher LOI, SOC and N concentrations and lower pH (H$_2$O). The relationship between the vegetation parameters and soil pH (NaF) was not as clear but still showed an increase with increase in cover. The other vegetation parameters did not show any strong relationship with the soil characteristics.

3.3. The enriched soils under the bird hummocks

Bird hummocks, formed by the great skua and the Arctic skua, were on the tops of moraine ridges in particular but they also occurred on more level surfaces. The hummock vegetation differed from the surroundings as they were fully covered by vigorous grasses and herbs (Fig. 4). The vegetation formed zones of different species; grasses like F. vivipara and Agrostis stolonifera were dominant in the center along with the herbs Galium normanii, Rumex acetosilla and Thymus praecox, which often occurred on the margins of the grasses. Mosses and macro-lichens then encircled the grasses and herbs. The hummocks generally favored southerly directions and tephra from the eruption in Grímsvötn 2011, along with other types of eolian deposits, were evident in the sward layer of most of the hummocks investigated (Table 5). The hummocks occurred in all the moraine age groups studied, except for the two youngest moraines, although their size and prevalence were seemingly reduced in the younger moraines.

The grassy hummocks featured relatively thick A horizons incorporating many very fine roots compared to the other sampling sites on moraines of respective age (Fig. 4), and an O horizon was featured in the 67 yr-old moraine (Table 5). In the two oldest moraines, the structure of the A horizon was granular although of weak grade. The texture ranged between loamy sand to sand and it was apparent that the hummocks have trapped tephra and reworked aeolian material. Below the A horizon(s) the C horizon had the appearance of the glacial till.

Soil properties of the bird hummocks were different from those of the surrounding moraine soils. Bulk density was much lower compared to the moraine soils in the top depth, it maintained well below 1.0 and showed a trend towards decrease from younger to the older moraines (Table 6). Measuring bulk density was difficult due to the dense root system and some values must be regarded with caution. LOI values were much higher than in the moraine soils, as were also SOC and total N concentrations. These parameters were more comparable to what was measured in the soil under the birch woodlands. Soil pH (H$_2$O) was considerably lower than that in the moraine soils as was the pH (NaF). The highest LOI, SOC and N concentrations and the lowest bulk density and soil pH (H$_2$O and NaF) were observed in the 67 yr-old moraines.

4. Discussion

4.1. Vegetation considerations

Since the end of the LIA, from 1890 to 2000, the glacial recession in Iceland is estimated to have exposed 1285 km$^2$ Sigurðsson et al. (2013). Many of these deglaciated areas are now dynamic sites of...
plant succession and chemical weathering. Future predictions imply ongoing glacial recession where the rapidly thinning Breiðamerkurjökull outlet glacier will have retreated far inland by 2090 (Björnsson and Pálsson, 2008), increasing the area that is currently used for sheep grazing by local farmers. In the Breiðamerkurjökull foreland, mosses and grasses dominate and characterize the vegetation cover. This pattern
of vegetation succession is different from a chronosequence studied at Skáfafellsjökull, SE-Iceland, where dwarf shrubs and shrubs, along with mosses, characterized the moraines after 65–120 yrs (Vílmundardóttir et al., 2015), but those plant groups are rare to completely absent on the moraines of Breiðamerkurjökull. The difference could be explained somewhat by the contrasted distance to seed sources for these sites. Skáftafellsjökull lies beside the woodlands of Skáftafellsheiði, and the nearest source of birch to the study site at Breiðamerkurjökull could be close to Kvísker, around 11 km to the west, or towards east to Reynevillir – 12 km. The sparsely vegetated

<table>
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<th>Year</th>
<th>Depth (cm)</th>
<th>Permanent marking</th>
<th>Boundary (distinctness, topography)</th>
<th>Structure (grade, size, type)</th>
<th>Texture (moist)</th>
<th>Color (moist)</th>
<th>Consistency (moist)</th>
<th>Tephra layers</th>
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<td>0–5</td>
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</tr>
</tbody>
</table>

Profile description is from Schönenberger et al. (2002). Abbreviations: Roots, quantity — v1, very few; m1, moderately few; f1, few; 2, common; 3, many. Roots, size — v1, very fine; f, fine; m, medium; c, coarse. Boundary, distinctness — a, abrupt; c, clear. Boundary, topography — s, smooth; w, wavy. Structure, grade — 0, structureless; 1, weak; 2, moderate; 3, strong. Structure, size — v1, very fine; f, fine; m, medium. Texture — gr, granular; sbk, subangular blocky; sg, single grain; m, massive. Texture — s, sand; fs, fine sand; ls, loamy sand; sl, sandy loam; il, illitic. Consistency moist — lo, loose; fl, friable.

<table>
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<tr>
<th>Horizon (moraine)</th>
<th>Depth (cm)</th>
<th>Roots (quantity, size)</th>
<th>Boundary (distinctness, topography)</th>
<th>Structure (grade, size, type)</th>
<th>Texture (moist)</th>
<th>Color (moist)</th>
<th>Consistency (moist)</th>
<th>Tephra layers</th>
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<tr>
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<td>v1, vf</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>2.5/3</td>
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<td>0–4</td>
<td>v1, vf</td>
<td>c, w</td>
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<td>s</td>
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<td>v1, vf</td>
<td>a, w</td>
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<td>0–1</td>
<td>ml, f</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
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<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>GLEY 1.5/10 Y</td>
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</table>

Table 3

Soil morphology and profile description of selected profiles, one from each moraine investigated and one from the mature woodlands at Stórhúnaus.

<table>
<thead>
<tr>
<th>Horizon (moraine)</th>
<th>Depth (cm)</th>
<th>Roots (quantity, size)</th>
<th>Boundary (distinctness, topography)</th>
<th>Structure (grade, size, type)</th>
<th>Texture (moist)</th>
<th>Color (moist)</th>
<th>Consistency (moist)</th>
<th>Tephra layers</th>
</tr>
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<td>0–5</td>
<td>v1, vf</td>
<td>c, w</td>
<td>0, m</td>
<td>ls</td>
<td>SY 2.5/1</td>
<td>fr</td>
<td></td>
</tr>
<tr>
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<td>0–3</td>
<td>v1, vf</td>
<td>c, w</td>
<td>0, sg</td>
<td>s</td>
<td>SY 2.5/1</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>0–3</td>
<td>v1, vf</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>2.5/3</td>
<td>fr</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>0–4</td>
<td>v1, vf</td>
<td>c, w</td>
<td>0, m</td>
<td>s</td>
<td>SY 2.5/1</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>0–2</td>
<td>v1, vf</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>SY 2.5/1</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>1945</td>
<td>0–1</td>
<td>ml, f</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>GLEY 1.5 N</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>1930</td>
<td>0–1.5</td>
<td>v1, f</td>
<td>a, w</td>
<td>0, m</td>
<td>s</td>
<td>GLEY 1.5/10 Y</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>1890</td>
<td>0–2.5</td>
<td>v1, f</td>
<td>a, s</td>
<td>1, vf, gr</td>
<td>ls</td>
<td>SY 2.5/1</td>
<td>lo</td>
<td></td>
</tr>
</tbody>
</table>

Table 4

Selected soil characteristics for 0–5 and 5–15 cm depths presented as average values with standard deviation in parenthesis.
sandur plains south of the study site hardly contribute to a seed source for shrub or dwarf shrub dispersal. Further, the unstable surfaces of the outwash plains in SE-Iceland have shown to reduce seedling survival rates (Marteinsdóttir et al., 2010). There are several signs of eolian activity throughout the chronosequence at Breiðamerkurjökull; the retreating glacier constantly leaves behind finely ground material that is removed from the surface through wind and water erosion, deposited in vegetated surfaces or transported to water bodies. The glacier itself is covered by tephra deposits and plus recent events of tephra deposits, such as from Grímsvötn in 2011, this tephra is being reworked. The area was estimated by Arnalds (2010) to have a high deposition rate of 75–250 g m⁻² yr⁻¹ depending on topography and wind pattern.

Vilmundardóttir et al. (2015) reported that the successional stages in the Skafafellsjökull proglacial area also differ from what has been reported for other pro-glacial areas such as the Alps, Alaska and China, where forests are established within 70–150 yrs (Crocker and Dickson, 1957; Egli et al., 2010; He and Tang, 2008). In front of Skaftafellsjökull, there seemed to be a lag time in the initial plant establishment and soil development, possibly delaying the development of woodlands. However, after 120 yrs a shrub cover was forming in places closest to the seed source, a future indicator of woodlands, which is more comparable to a chronosequence from Norway at an elevation above tree line, showing that dwarf shrubs along with Salix spp. and Betula nana have established after 60 yrs (Matthews and Whittaker, 1987).

The development on the Breiðamerkurjökull moraines will likely experience an extended lag time until woodlands will develop on the Breiðamerkurjökull moraines, making the current status of the chronosequence more comparable to the development in glacial forefields in Svalbard, where vascular plants are slow to establish and represent only a small part of vegetation cover for the first 100 yrs (Hodkinson et al., 2003; Kabala and Zapart, 2012).

Plant groups can directly affect the underlying soil properties. Studies from Svalbard and the Andes have shown that cyanobacterial crust starts to form 2–4 yrs after deglaciation (Hodkinson et al., 2003; Schmidt et al., 2008), and it plays a major role in C and N inputs to the soil system. In a study from the Canadian Arctic, Stewart et al. (2011) reported that soil moisture influenced moss abundance and increasing moss abundance positively influenced N₂ fixation rates. Our study shows that biological crust starts to form in the 18 yr-old moraine and gradually increases its cover until reaching ~10% after 82 yrs. No

### Table 5

<table>
<thead>
<tr>
<th>Horizon (moraine)</th>
<th>Depth (cm)</th>
<th>Roots (quantity, size)</th>
<th>Boundary (distinctness, topography)</th>
<th>Structure (grade, size, type)</th>
<th>Texture*</th>
<th>Color (moist)</th>
<th>Consistence (moist)</th>
<th>Tephra layers</th>
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<td>1890 – 122 yrs</td>
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<td></td>
</tr>
<tr>
<td>A1</td>
<td>0–4</td>
<td>3, f</td>
<td>a, s</td>
<td>1, vf, gr</td>
<td>sl</td>
<td>10 YR 2/1</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
<td>A2</td>
<td>4–14</td>
<td>2, vf</td>
<td>a, s</td>
<td>1, vf, gr</td>
<td>ls</td>
<td>10 YR 2/2</td>
<td>lo</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>&gt;14</td>
<td></td>
<td></td>
<td></td>
<td>ne</td>
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<td>0–2.5</td>
<td>3, vf</td>
<td>c, s</td>
<td>1, vf, gr</td>
<td>ls</td>
<td>10 YR 3/2</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
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<td>2.5–9</td>
<td>3, vf</td>
<td>a, s</td>
<td>0, sg</td>
<td>sl</td>
<td>7.5 YR 2/3</td>
<td>lo</td>
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</tr>
<tr>
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<td>&gt;9</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>A</td>
<td>0–3</td>
<td>3, vf</td>
<td>c, w</td>
<td>0, sg</td>
<td>ls</td>
<td>7.5 YR 2/5</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
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<td>&gt;3</td>
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<td>A</td>
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<td>a, w</td>
<td>0, sg</td>
<td>sl</td>
<td>7.5 YR 2/5</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
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<td></td>
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</tr>
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<td>1930 – 30 yrs</td>
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<td>A</td>
<td>0–6</td>
<td>3, vf</td>
<td>c, w</td>
<td>0, sg</td>
<td>ls</td>
<td>10 YR 3/2</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
<td>C</td>
<td>&gt;6</td>
<td>2, vf</td>
<td>-</td>
<td></td>
<td>2.5Y 3/1</td>
<td>ne</td>
<td></td>
<td>lo</td>
</tr>
<tr>
<td>1914 – 18 yrs</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0–11</td>
<td>3, vf</td>
<td>c, w</td>
<td>0, sg</td>
<td>s</td>
<td>2.5Y 3/1</td>
<td>lo</td>
<td>Grímsvötn 2011 tephra</td>
</tr>
<tr>
<td>C</td>
<td>&gt;11</td>
<td>ne</td>
<td></td>
<td></td>
<td>ne</td>
<td>lo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Texture was estimated by feel on the fine earth fraction, gravel content not estimated.

Profile description terminology is from Schoonberger et al. (2002). Abbreviations: Roots, quantity – 2, common; 3, many. Roots, size – vf, very fine; f, fine. Boundary, distinctness – a, abrupt; c, clear. Boundary, topography – s, smooth; w, wavy. Structure, grade – 0, structureless; 1, weak. Structure, size – vf, very fine. Structure, type – gr, granular; sg, single grain. Texture – s, sand; ls, loamy sand; sl, sandy loam. Consistence moist – lo, loose.
relationship was observed between the proportional cover of biological crust, macro-lichens and the C and N concentration, there was, however, a significant positive relationship with the moss cover. Preliminary results show that N$_2$ fixing moss associated cyanobacterial communities are important in Icelandic ecosystems (Jónsdóttir, 2014; Russi Colmeneres et al., 2014). Plant groups can also indicate environmental conditions such as eolian deposition (Maun, 1998) where it can have a positive effect on the cover of grasses but negative on moss and lichen cover (Vilmundardóttir et al., 2009). The terminal moraines in the Breiðamerkurjökull foreland showed signs of past eolian deposition with the sandy texture (Table 3) and less stony surface compared to the younger moraines at Breiðamerkurjökull and the 120 yr-old moraines of Skáftafellssjökull. The eolian activity has probably receded after 1930 as indicated by the high proportions of mosses and macro-lichens in the 120 yr-old moraine at Breiðamerkurjökull.

### 4.2 Changes of soil properties with time

The data presented show that the soil development is occurring at a slower rate than that compared to the study from the Skáftafellsjökull moraines. There is a thin A horizon evident after 67 yrs and it remains thin throughout the chronosequence. No O horizons were present, indicating a slow input and/or relatively rapid breakdown of organic matter (OM). For both Breiðamerkurjökull and Skáftafellsjökull, the initial loss on ignition is too high to represent only OM being lost during the ignition process. This indicates that for soils developing in this kind of raw material, the LOI values of 0.6–0.8% represent something else than OM.

The unsorted glacial moraines start undergoing changes as soon as the surface is deglaciated, where wind and water erosion and downward translocation removes the finest grains from the surface and a layer of sandy gravel remains (Boulton and Dent, 1974; Romans et al., 1980; Vilmundardóttir et al., 2014). With the formation of an A horizon the portion of finer grains in the surface layer increases again.

The oldest moraine showed the most apparent signs of eolian activity, which could be related to the period when the glacier front was static/advancing between the period of 1904–1930 (Gumbundsson, 2014). Under such conditions, the glacial rivers shift their channels frequently and the proglacial landscape in between 1890 and 1930 shows a complex pattern of river channels. The shifting rivers create sources of fine grained material for eolian reworking and this may be reflected in the soil profiles of the oldest moraine.

The sudden change in the curves of the developing soil properties between the 82 and 122 yr-old moraines is probably relict many of the characteristics of Icelandic soils such as how deposition lowers the soil properties, high SOC and N concentrations, high SOC and N concentrations after 1930 as indicated by the high proportions of mosses and macro-lichens in the 120 yr-old moraine at Breiðamerkurjökull. The eolian activity has probably receded after 1930 as indicated by the high proportions of mosses and macro-lichens in the 120 yr-old moraine at Breiðamerkurjökull.

### Table 6

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Moraine age (yr)</th>
<th>Moraine (year)</th>
<th>Bulk density (g cm$^{-3}$)</th>
<th>LOI (%)</th>
<th>SOC (%)</th>
<th>Total N (%)</th>
<th>C:N</th>
<th>pH (H$_2$O)</th>
<th>pH (NaF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>1994</td>
<td>18</td>
<td>0.75</td>
<td>2.94</td>
<td>1.29</td>
<td>0.087</td>
<td>15</td>
<td>6.20</td>
<td>8.12</td>
</tr>
<tr>
<td>0-5</td>
<td>1982</td>
<td>30</td>
<td>0.46</td>
<td>8.00</td>
<td>3.80</td>
<td>0.339</td>
<td>11</td>
<td>5.31</td>
<td>7.74</td>
</tr>
<tr>
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<td>1950</td>
<td>52</td>
<td>0.50</td>
<td>23.76</td>
<td>11.79</td>
<td>0.829</td>
<td>14</td>
<td>5.69</td>
<td>7.88</td>
</tr>
<tr>
<td>0-5</td>
<td>1945</td>
<td>67</td>
<td>0.26</td>
<td>40.19</td>
<td>18.14</td>
<td>1.113</td>
<td>16</td>
<td>5.22</td>
<td>7.60</td>
</tr>
<tr>
<td>0-5</td>
<td>1930</td>
<td>82</td>
<td>0.57</td>
<td>17.04</td>
<td>9.07</td>
<td>0.594</td>
<td>15</td>
<td>5.55</td>
<td>7.93</td>
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<tr>
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<td>8.91</td>
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<tr>
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<td>6.43</td>
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<tr>
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<td>1982</td>
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<td>1.12</td>
<td>1.46</td>
<td>0.41</td>
<td>0.020</td>
<td>13</td>
<td>5.43</td>
<td>8.20</td>
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<td>5.21</td>
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</tr>
<tr>
<td>5-15</td>
<td>1945</td>
<td>67</td>
<td>0.39</td>
<td>25.28</td>
<td>12.92</td>
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<td>16</td>
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<tr>
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<tr>
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<td>2.07</td>
<td>0.136</td>
<td>15</td>
<td>6.13</td>
<td>7.71</td>
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</table>

Bulk density was measured once for each site but LOI, SOC, total N and pH were measured in duplicates.

The sudden change in the curves of the developing soil properties between the 82 and 122 yr-old moraines is probably relict many of the characteristics of Icelandic soils such as how deposition lowers the soil properties, high SOC and N concentrations, high SOC and N concentrations after 1930 as indicated by the high proportions of mosses and macro-lichens in the 120 yr-old moraine at Breiðamerkurjökull. The eolian activity has probably receded after 1930 as indicated by the high proportions of mosses and macro-lichens in the 120 yr-old moraine at Breiðamerkurjökull.

### 4.3 The enriched soils of the bird hummocks

The morphology, such as the thick A (or O) horizons and dense but fine root system, and the soil properties, high SOC and N concentrations, show that the bird hummocks are the hot spots for soil formation within the pro-glacial landscape, a result from the birds bringing nutrients from the sea to the terrestrial ecosystem (Bockheim and Haus, 2014). In contrast, the study from Skáftafellsjökull, which was devoid of bird hummocks and featured both less bird activity and different bird species, showed the most rapid soil development within depressions in the landscape (Vilmundardóttir et al., 2015). Although the age of the

<table>
<thead>
<tr>
<th>Moraine age (yr)</th>
<th>Moraine (year)</th>
<th>Bulk density (g cm$^{-3}$)</th>
<th>LOI (%)</th>
<th>SOC (%)</th>
<th>Total N (%)</th>
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<th>pH (H$_2$O)</th>
<th>pH (NaF)</th>
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</tr>
<tr>
<td>5-15</td>
<td>1960</td>
<td>52</td>
<td>0.96</td>
<td>1.42</td>
<td>0.49</td>
<td>0.028</td>
<td>5.21</td>
<td>7.97</td>
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<tr>
<td>5-15</td>
<td>1945</td>
<td>67</td>
<td>0.39</td>
<td>25.28</td>
<td>12.92</td>
<td>0.821</td>
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<td>7.70</td>
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<td>5-15</td>
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<td>0.78</td>
<td>5.23</td>
<td>2.38</td>
<td>0.180</td>
<td>5.48</td>
<td>8.36</td>
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<tr>
<td>5-15</td>
<td>1930</td>
<td>122</td>
<td>0.87</td>
<td>4.42</td>
<td>2.07</td>
<td>0.136</td>
<td>6.13</td>
<td>7.71</td>
</tr>
</tbody>
</table>
hummocks is considerably lower than the age of the moraines, as the birds probably avoid the immediate vicinity of the glacier and reflected by the lack of hummocks on the 18-yr-old moraines, there is some influence of time on the hummock soils. N concentrations were high already in the bird hummocks of the 18–30 yr-old moraines, which was not the case for SOC, suggesting that N input from birds in the otherwise nutrient-poor moraines is the trigger for plant establishment and OM input. The highest SOC and N concentrations were attained in the 67 yr-old moraine (18.1% SOC, 1.1% N), perhaps reflecting more level topography, less input of eolian material or longer distance from the main road, which runs close by the terminal moraine, and therefore a quieter environment favored by the birds compared to the 82 and 112 yr-old moraines. Verbeek and Boasson (1984) studied bird hummocks in the Pyrenees, France, and similarly reported significantly more N compared to the soils of their surroundings. As did Tomassen et al. (2005) for bird dropping sites in Irish bogs but those had significantly higher influxes of nutrients and showed more vegetation vigor than at reference sites without droppings. The impact of seabirds on vegetation establishment and soil formation is well established from the volcanic island, Surtsey, off the coast of S-Iceland, where the lesser black-backed gull (Larus fuscus) colonized the island in 1965, establishing a nesting colony on the young lava (Magnússon et al., 2009). After 23 yrs, the average SOC concentration within the bird colony was 1.84% and 0.15% N, creating a stark difference with low concentrations outside of the colony (0.05% SOC, 0.007% N). Seabirds are an important source of nutrients driving plant succession and soil formation with high C, N and P values in high latitudes (Croll et al., 2005; Maron et al., 2006; Michel et al., 2006), sometimes forming ornithogenic soils (Bockheim and Haus, 2014). At Breiðamerkurjökull, the effects of nutrient input seemed to be much localized to the areas with direct manure contact with the tree (Gersper and Holowaychuk, 1971; Rhoades, 1996). Ants and termites also change the soil properties in the vicinity of their nests and mounds by changing the physical and chemical properties, often raising the nutrient status (Donovan et al., 2001; Frouz and Jilková, 2008). The point-centered effects of these organisms, both flora and fauna, therefore increase the spatial variation of the soil itself and can maintain heterogeneity within ecosystems.

The elevated nutrient status also affects the soil pH (H2O), which is substantially lower than in the Breiðamerkurjökull moraine soils and is related to microbial activity producing acids that lower the pH (Michel et al., 2006). Grasses respond quickly to available nutrients as reflected by the abundance of grasses in the bird hummocks of the Breiðamerkurjökull fore-field and the dense root system under the hummocks was remarkably different to the root system present of the vegetation on the surrounding moraines. The grasses are an excellent sand trap, as was demonstrated by the thick soils formed in the bird hummocks. The captured eolian sediments reduce the OM concentration although the absolute content is not reduced (Vilmundardóttir et al., in preparation), usually producing A horizons instead of O horizons.

5. Conclusions

The data presented supports the two hypotheses proposed: the relative isolation from available seed sources affected the vegetation stratigraphy developing on the moraines as indicated by the absence of shrubs and rare occurrence of dwarf shrubs, and the point-centered nutrient inputs by bird droppings enhanced vegetation growth and soil formation. The soil development seemed somewhat slower as when compared with similar sites within the region of SE-Vatnajökull and was evident by the thin (1–2.5 cm) A horizon developing throughout the chronosequence. The highest LOI, SOC and total N concentrations (0–5 cm) were reached in the 82 yr-old moraines, 3.1%, 1.4% and 0.07%, respectively. The difference in LOI, SOC and N concentrations, however, was less than expected when compared to the Skafellsfjölluk study with its shrubland vegetation and even in international context. Therefore, the vegetation of the Breiðamerkurjökull foreland, dominated by mosses along with lichens, biological crust and grasses, was more effective at accumulating OM, SOC and N than hypothesized. Still, comparisons between studies are not straightforward due to the different sampling techniques. The effects of seabird droppings on the moraines created a stark difference in the vegetation and soils between sites of fertilization and the surrounding nutrient poor moraines, creating conditions for lush and grassy vegetation forming A (or O) horizons up to 14 cm thick, with SOC and N concentrations as high as 18% and 1.1% respectively in the 67 yr-old moraine. The effects, however, seemed to be restricted to the bird hummocks. Plant succession and soil formation is an active process within the glacier forelands and as all Icelandic glaciers are currently retreating, the accumulating OM and SOC as a result of natural processes could be an important quality in balancing national greenhouse gas emissions.

Acknowledgments

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References


5 A chronosequence approach to estimate regional soil organic carbon stocks within two glacial fore-fields in SE-Iceland

Abstract

Soil organic carbon (SOC) has received increased attention over the last decades because of its role as an option to mitigate the effects of increased anthropogenic greenhouse gas emissions. In Iceland, the loss of vegetation and soil due to land-use and natural processes has left large parts of the country as barren deserts. Land restoration actions have the primary goals to prevent further land degradation and restore lost ecosystems but the ancillary benefits of SOC accumulation with regards to the Kyoto Protocol are obvious. Natural vegetation succession is active in areas being exposed by glacial recession since the end of the Little Ice Age in ~1890. In this paper, we attempt to estimate the current regional SOC stocks on moraines in front of two glaciers in SE-Iceland, using surface age and SOC and vegetation cover data. RapidEye images were used to estimate the surface area of two vegetation classes with <50% cover and >50% cover. The regional SOC stock was calculated using soil data and the sum of the area of each cover class for each time zone. The rates of SOC accretion reached the maximum rates of 0.004−0.009 kg C m$^{-2}$ yr$^{-1}$ depending on the study site and moraine age. The regional SOC stocks for the two glacier fore-fields were estimated at 1605 Mg C (0–10 cm) for Skaftafellsjökull, and 1106 Mg C (0–5 cm) for Breiðamerkurjökull. The current annual increase in the moraine SOC stock was estimated to be 20.7 Mg C yr$^{-1}$ for Skaftafellsjökull and 19.7 Mg C yr$^{-1}$ for Breiðamerkurjökull.

Keywords: Glacial recession, land reclamation, soil organic carbon, SOC accretion, SOC stock, soil development, vegetation cover.
5.1 Introduction

Soil organic carbon (SOC) has received increased attention over the last decades because of its importance as an option to mitigate the human-induced increase of greenhouse gas (GHG) emissions to the atmosphere and the concurrent climate change via soil carbon sequestration (SCS) (Kennett 2002; Lal 2008; McBratney et al. 2014). Through the process of photosynthesis, where plants convert CO₂ from the atmosphere to produce organic matter (OM), their detritus is consequently incorporated in the underlying soils resulting in immobilization of carbon (C). The mechanisms for stabilizing SOC may be categorized as biochemical recalcitrance, chemical stabilization and physical protection. For example, SOC may be bound to clay minerals and organo-mineral compounds or by forming stable soil aggregates (Christensen 1996; Dahlgren et al. 2004). Under natural conditions, plants and soils thus sequester C from the atmosphere but human land-use has depleted the terrestrial carbon pool by disturbing and utilizing plants and soils (Lal 2004). According to the United Nations Framework Convention on Climate Change, the net change in C stocks and GHG emissions by sources and removals by sinks, resulting from direct human-induced land-use change and forestry activities, is considered as an option for countries to meet the commitments of the Kyoto Protocol (UNFCCC 2015). This includes, under article 3.4, any elected human-induced activities, which can be forest management, revegetation, cropland management and grazing land management.

In Iceland, the history of ecosystem decline and land degradation goes back to the Settlement in 874 AD and as a result from land-use, climate deterioration and volcanism, large parts of the country are now barren deserts (Arnalds et al. 2001; Ólafsdóttir and Guðmundsson 2002; Gísladóttir et al. 2010; Gísladóttir et al. 2011). Óskarsson et al. (2004) estimated the amount of SOC eroded since the Settlement at 120−500 Tg (1 Tg = 10¹² g = 1 million Mg). Since 1907, the Soil Conservation Service in Iceland (SCSI) has been combating soil erosion and sand encroachment, undertaking large scale revegetation actions, e.g. by using lyme-grass, seeding of grass species, applying mineral and organic fertilizers, protection from livestock grazing, planting of trees and seeding with the nootka lupine (Lupinus nootkatensis) (Aradóttir et al. 2013). As a result, these areas are accreting plant biomass and SOC (Aradóttir et al. 2000; Arnalds et al. 2000; Arnalds et al. 2013). Although the primary goals of the SCSI are to prevent land degradation and erosion, revegetate eroded areas, restore lost ecosystems and improve grazing lands, the ancillary benefits of SOC accumulation, with regards to the Kyoto Protocol, are obvious. In 2011, revegetation actions are estimated to have resulted in the net removal of CO₂ of 174 Gg and are projected to reach 274 Gg in 2030 (Borgþórsdóttir et al. 2014).

Glaciers cover ~10% of Iceland and since the end of the Little Ice Age (LIA) in ~1890 they have been steadily retreating. The area that has been deglaciated since 1890 until 2000 has been estimated to be 1285 km² (Sigurðsson et al. 2013). Models predict further reduction in glacial cover, and the largest ice-caps will have reduced in size with 15−40% of the glacial cover remaining by 2090 (Björnsson and Pálsson 2008). The emerging proglacial areas are now sites of active plant succession and soil formation (Persson 1964; Vilmundardóttir et al. 2015a; Vilmundardóttir et al. 2015b) and the moraine soils in front of Skjálfandijsjökull glacier are estimated to have accumulated 1.1 kg C m⁻² over a period of 120 years (Vilmundardóttir et al. 2015b). Since the processes of plant succession and soil development are governed by natural causes, these are not considered under the Kyoto Protocol. However, questions arise whether: 1) these proglacial areas are accreting SOC in
comparison with the sites of revegetation or forestry, and 2) do these areas contribute significantly to the country’s sources leading to the accumulation of C stocks with regards to the large areas emerging from glacial retreat.

During the initial stages of plant succession, SOC concentrations are closely related to the extent and species composition of vegetation cover and depend upon the magnitude of litter accumulation and OM input between plant species and growth forms (Crocker and Major 1955; Dahlgren et al. 2004; Su et al. 2004; Rajaniemi and Allison 2009). Based on a chronosequence study from Skaftafellsjökull, Vilmundardóttir et al. (2015b) reported that time and vegetation in conjunction with landscape were the primary drivers of soil formation and SOC accretion. The SOC stocks correlated with vegetation cover, and the latter itself reflected the impact of topography to some extent. Similarly, Egli et al. (2006) documented that various landforms correlated well with soil evolution, wherever the slope, exposure and landform determined the soil development.

The present study tests the hypothesis that the regional SOC stocks can be estimated within young proglacial landscapes on the basis of surface age, vegetation cover and plant communities. Therefore, the aim of this study was to estimate the SOC stock and rate of accretion for the Breiðamerkurjökull fore-field and the regional SOC stocks within the two forefields of Skaftafellsjökull and Breiðamerkurjökull, using the specific parameters of time since deglaciation, vegetation and plant group cover and SOC stocks. The study is based on previous work from Skaftafellsjökull (Stanich 2013; Vilmundardóttir et al. 2014; Vilmundardóttir et al. 2015b) and Breiðamerkurjökull (Vilmundardóttir et al. 2015a) to estimate the regional SOC stocks being formed within the two proglacial areas through the natural processes of plant succession and soil formation over the last 120 years.

5.2 Study area

The study sites are within the glacial fore-fields of two outlet glaciers extending from the Vatnajökull ice-cap down to the lowlands, Skaftafellsjökull and Breiðamerkurjökull (Fig. 5.1). Both glaciers advanced during the Little Ice Age (LIA) and reached their maximum extents in ~1890. Since then, both glaciers have receded although with some periods of re-advance (Guðmundsson 2014; Hannesdóttir et al. 2014b). The relatively small Skaftafellsjökull glacier has created a fore-field sheltered between mountain ridges while the vast Breiðamerkurjökull has exposed wide plains of thick moraines which are in close proximity to the Atlantic Ocean. Both sites have an oceanic climate with cool summers and mild winters (Einarsson 1984) with a mean annual temperature ~5°C, and in winter the temperatures often hover around zero (Table 5.1).
Both sites have similar parent material where the glacial moraines are mainly comprised of ground basaltic rock and hyaloclastite, including tephra that originates from sub-glacial volcanoes and has deposited on the glaciers or straight onto the fore-fields. Vegetation within the proglacial areas is primarily comprised of mosses; the Skaftafellsjökull moraines are characterized by dwarf shrubs and shrubs, whereas grasses characterize the moraines of Breiðamerkurjökull. The difference in vegetation stratigraphy is most likely the result of distance to seed sources (Vilmundardóttir et al. 2015a; Vilmundardóttir et al. 2015b). The developing soils on the well drained moraines have a thin A horizon, if present, with a large portion of the coarse material.
Table 5.1 General information about the study sites.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skaftafellsjökull / Breiðamerkurjökull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>N 64°02'–64°00' / N 64°05'–64°02'</td>
</tr>
<tr>
<td></td>
<td>W 16°57'–16°53' / W 16°18'–16°14'</td>
</tr>
<tr>
<td>Elevation range</td>
<td>70–120 m a.s.l. / 15–70 m a.s.l.</td>
</tr>
<tr>
<td></td>
<td>Skáftafell / Fagurhólsmýri / Hólar in Hornafjörður</td>
</tr>
<tr>
<td>Mean annual temperature*</td>
<td>5.1°C / 4.8°C / 4.7°C</td>
</tr>
<tr>
<td>July</td>
<td>10.5°C / 10.6°C / 10.5°C</td>
</tr>
<tr>
<td>January</td>
<td>3.3°C / 0.4°C / 0.3°C</td>
</tr>
<tr>
<td>Mean annual precipitation*</td>
<td>NA / 1800 mm / 1500 mm</td>
</tr>
<tr>
<td>Approximate area</td>
<td>7 km² / 11 km²</td>
</tr>
</tbody>
</table>

*Based on unpublished data from the IMO. Skáftafell weather station is the closest to the Skaftafellsjökull study site and records span the period from 1996–2007. Fagurhólsmýri weather station is midway between Skáftafellsjökull and Breiðamerkurjökull and the average values represent the period of 1949–2007. Hólar in Hornafjörður is the closest weather station to Breiðamerkurjökull to the east and values represent the period from 1949–2011. Additional precipitation data from Kvísker and Hali are also shown but those weather stations are located closer to Breiðamerkurjökull than Fagurhólsmýri and Hólar.

5.3 Methods

5.3.1 Field setup and sampling

Three moraines were sampled in summer 2010 and 2011 in the Skaftafellsjökull fore-field, representing the location of the terminus in 1890, 1945 and 2003. The outline of the moraines was identified as GPS waypoints and six points were randomly selected for each of the moraines. Sites with signs of disturbance were omitted and the next random point chosen instead. A 10 m transect was selected parallel to the moraine ridge for each point. Soil samples were collected on 0, 4 and 8 m distance for each transect within a 0.25 m² quadrant at 0–10 and 10–20 cm depths. Vegetation cover was measured using a Braun-Blanquet cover scale prior to sampling (Goldsmith and Harrison 1976). Soil samples from the Breiðamerkurjökull proglacial area were obtained during the summer 2012 on moraines exposed in 1890, 1930, 1945, 1960, 1982, 1994, 2004 and 2012. Five random GPS points were selected for sampling on the sites which met the same terms regarding disturbance as those for Skaftafellsjökull. Vegetation cover was measured within a 0.25 m² quadrant and soils were sampled at 0–5 and 5–15 cm depths for each site.

Bulk density of the fine earth fraction was measured at both depths using small cubical corers of known volume and obtained perpendicular to the soil profile. The corers were of three sizes, ranging from 1.4–19.5 cm³. The larger corers were preferred but the smaller ones were used in places where gravel content was high. Due to the small size of the corers, replicates for each bulk density sample were collected to obtain an average value of 5 replicates for the smallest, 3 for the medium sized and 2 for the largest corer. This sampling method was compared to the results reported by Stanich (2013), who sampled the same soils using the excavation method with insulation foam to determine bulk density and gravel volume using much larger samples (~1000 cm³). The methods resulted in very similar bulk density values but showed that the gravel content was greatly underestimated by the core method (Vilmundardóttir et al. 2015b).
5.3.2 Soil sample preparation and analysis

Soil samples were analyzed at the University of Iceland and the Ohio State University, Columbus, Ohio, USA. Bulk density samples were dried, gently ground and sieved through a 2 mm sieve. The volume of coarse fragments (>2 mm) was determined by the water displacement method. Bulk density of the fine earth fraction (<2 mm) was calculated after subtracting the weight and volume of the coarse fraction from the weight and volume of the total sample. Bulk samples were air dried, gently ground, passed through a 2 mm sieve, and stored pending analysis.

Concentrations of SOC in the Skaftafellsjökull soils were determined by the dry combustion method using a Vario Max C-N elementar analyzer. Samples were dried at 40°C, ground by hand and sieved through a 250 μm mesh. Samples from Breiðamerkurjökull moraines were ball milled and passed through a 150 μm sieve, then dried at 50°C prior to weighing and packing into tin containers. Concentrations of SOC were determined by a Flash 2000 Elemental Analyzer (Thermo-Scientific, Italy). Soils were estimated to be carbonate-free and the measured C assumed to be the SOC.

The C stock was estimated by using Eq. 1:

\[
\text{SOC stock (kg C m}^{-2}\text{)} = BD \times T \times \text{SOC}\% \times (100-S/100) \times 10^{-2}, \quad \text{(Eq. 1)}
\]

where, \(BD\) is the bulk density (kg m\(^{-3}\)), \(\text{SOC}\%\) is the organic carbon concentration (%), \(T\) is the thickness (m) and \(S\) is the content of coarse fragments (>2 mm) of the soil depth (vol. %). Data on concentration of coarse material reported by (Stanich 2013) were used herein to calculate SOC stocks in the glacier fore-fields. Concentration of coarse fragments (\(S\)) was estimated by using Eq. 2:

\[
S \text{ (%) = \left[ \frac{\text{coarse fragments >2 mm (m}^3\text{)}}{\text{total volume (m}^3\text{)}} \right] \times 100. \quad \text{(Eq. 2)}
\]

5.3.3 Vegetation cover assessment

Recent vegetation maps for the two study sites were not available. Therefore, other means for assessing regional vegetation cover were identified. The National Land Survey has been systematically collecting RapidEye images to cover the entire country. Images from the RapidEye satellite are composed of spectral bands designed for detecting vegetation cover with resolution of 5 m (orthorectified pixel size). The satellite’s sensors include five spectral bands. In addition to the blue, green and red (440–510, 520–590, 630–685 nm); it also has the ‘Red-Edge’ and Near-Infrared bands detecting radiation of 690–730 and 760–850 nm wavelengths, respectively (BlackBridge 2015). The use of the five spectral bands, including the Red-Edge band, has proven effective to classify vegetation cover and surface types (Schuster et al. 2012; Roslani et al. 2014). Cloudless images from this area are rare, but an image from 12 September 2012 was suitable for the image classification.

Since the field data only represented well drained and undisturbed ground or end moraines, subsets of the satellite images were created, omitting areas with former riverbeds, lakebeds or dead ice landscapes. For both glaciers, the terminal moraines from 1890 defined the southwardly extent of the areas to be classified. At Skaftafellsjökull, lateral moraines determined the western and eastern margins and the shores of the glacial lagoon that started forming in ~2000, determined the northern extent of the moraines included in the
classified area. At Breiðamerkurjökull, the eastern and western margins were determined by the dead-ice landscape formed by the median moraines of Mávabyggðarönd and Esjufjallarönd and by the shores of Jökulsárlón glacial lake to the east. The northern extent was confined to the terminus of Breiðamerkurjökull as located in 2012.

After trying out different ways of classifying the regions based on vegetation cover and/or plant groups and comparing them to the appropriate SOC stock values, a simple two class system using the vegetation cover only was chosen. In conjunction with time since deglaciation, those two indicators were used for assessing the regional SOC stock. The vegetation cover was subsequently classified into two groups: densely vegetated (cover >50%) and sparsely vegetated (cover <50%). The median values from the Braun-Blanquet cover scale were used to determine whether the vegetation cover percentage of sampling sites was above or below 50%. For Skaftafellsjökull, the average values of the three quadrants per transect were used to create one value, determining the cover class. Each sampling site has thus the attributes as a densely vegetated or a sparsely vegetated site.

Field measurements of vegetation cover and aerial images from Loftmyndir Inc. were used to create training samples for a supervised classification of each RapidEye image subset using the ArcGIS software. Each image subset, using all the five bands, was classified with the maximum likelihood classification method using the input signature file created with the training samples. The accuracy of the classification was determined using the field measures of vegetation cover, resulting in the overall accuracy of 78–82% accuracy for the Skaftafellsjökull and Breiðamerkurjökull fore-fields.

5.3.4 Estimating the carbon stocks of the glacier fore-fields

The glacier fore-fields were divided into time-zones to estimate the regional carbon stocks, and to which the SOC stock values from every moraine would apply. The two proglacial areas needed different approaches to define the time-zones due to the different resolution in the sampled chronosequences. The higher resolution in the Breiðamerkurjökull chronosequence allowed for drawing time-zone boundaries midway between each of the moraines sampled. At Skaftafellsjökull, boundaries were drawn representing the location of the glacier’s terminus ~1930 and 1980, representing the onset of new recession periods after having been advancing or static for some time (Guðmundsson 2014; Hannesdóttir et al. 2014a).

The areal extent of the two vegetation cover classes for each time-zone was calculated after converting the classified raster subset into shapefile, splitting the shapefile according to the defined time-zones and calculating the area of each polygon. The sum of the area of each vegetation cover class for each time zone was then used to calculate the regional carbon stock by using Eq. 3:

\[
\text{Regional SOC stock (Mg C ha)} = BD \times T \times A \times \text{SOC}\% \times (100-S/100), (\text{Eq. 3})
\]

where, \(BD\) is the bulk density (Mg m\(^{-3}\)), \(T\) is the thickness (m), \(A\) is the areal coverage (ha), \(\text{SOC}\) is the organic carbon concentration (%), and \(S\) is the content of coarse fragments (>2 mm) of the soil depth (vol. %).
5.4 Results

5.4.1 SOC stocks and rates of SOC accretion in the proglacial soils

The SOC stock increased with increase in time since deglaciation, although being less profound in the Breiðamerkurjökull area. In the oldest moraine of Breiðamerkurjökull representing 122 yrs since deglaciation, the SOC stock was estimated to be 0.50 kg C m\(^{-2}\), compared to 1.10 kg C m\(^{-2}\) for Skaftafellsjökull after 120 yrs since deglaciation (Table 5.2). The magnitude of SOC stock at Breiðamerkurjökull showed a slow initial increase, followed by an increase in rates after the first 50 years, reaching 4.5 g C m\(^{-2}\) yr\(^{-1}\) in the 67 and 82 yr-old moraines, and then decreasing again in the oldest moraine. The decrease in rates of SOC accretion at the end of the chronosequence is in contrast to the trend apparent for the Skaftafellsjökull area, which attained the maximum SOC accretion rate in the oldest moraine of 9.1 g C m\(^{-2}\) yr\(^{-1}\).

Table 5.2 SOC stocks and rate of SOC accretion for Skaftafellsjökull and Breiðamerkurjökull glacier fore-fields.

<table>
<thead>
<tr>
<th>Moraine</th>
<th>Depth (cm)</th>
<th>Moraine age (years)</th>
<th>Bulk density (g cm(^{-3}))(^{a,b})</th>
<th>SOC (%)(^{a,b})</th>
<th>&lt; 2 mm (vol.%)(^{c,d})</th>
<th>kg C m(^{-2}) (^{a})</th>
<th>g C m(^{-2}) yr(^{-1}) (^{a})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skaftafellsjökull</td>
<td>2003</td>
<td>0−10</td>
<td>1.36 (0.16)</td>
<td>0.05 (0.01)</td>
<td>37.1 (12.6)</td>
<td>0.04</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td>1945</td>
<td>0−10</td>
<td>1.33 (0.17)</td>
<td>0.30 (0.22)</td>
<td>32.5 (15.5)</td>
<td>0.27</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td>1890</td>
<td>0−10</td>
<td>1.07 (0.15)</td>
<td>1.77 (1.10)</td>
<td>42.2 (18.5)</td>
<td>1.10</td>
<td>9.14</td>
</tr>
<tr>
<td>Breiðamerkurjökull</td>
<td>2012</td>
<td>0−5</td>
<td>1.24 (0.08)</td>
<td>0.02 (0.00)</td>
<td>37.1</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>0−5</td>
<td>1.19 (0.06)</td>
<td>0.02 (0.01)</td>
<td>37.1</td>
<td>0.01</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>1994</td>
<td>0−5</td>
<td>1.22 (0.07)</td>
<td>0.11 (0.02)</td>
<td>37.1</td>
<td>0.04</td>
<td>2.26</td>
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<td></td>
<td>1982</td>
<td>0−5</td>
<td>0.94 (0.10)</td>
<td>0.26 (0.10)</td>
<td>37.1</td>
<td>0.07</td>
<td>2.49</td>
</tr>
<tr>
<td></td>
<td>1960</td>
<td>0−5</td>
<td>0.94 (0.13)</td>
<td>0.53 (0.29)</td>
<td>32.5</td>
<td>0.16</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>1945</td>
<td>0−5</td>
<td>0.81 (0.16)</td>
<td>1.14 (0.63)</td>
<td>32.5</td>
<td>0.30</td>
<td>4.48</td>
</tr>
<tr>
<td></td>
<td>1930</td>
<td>0−5</td>
<td>0.97 (0.14)</td>
<td>1.36 (0.62)</td>
<td>42.2</td>
<td>0.37</td>
<td>4.46</td>
</tr>
<tr>
<td></td>
<td>1890</td>
<td>0−5</td>
<td>1.01 (0.06)</td>
<td>1.01 (0.07)</td>
<td>3.5</td>
<td>0.50</td>
<td>4.05</td>
</tr>
</tbody>
</table>

\(^{a}\) Results from Skaftafellsjökull published by Vilmundardóttir et al. (2015b).
\(^{b}\) Results from Breiðamerkurjökull published by Vilmundardóttir et al. (2015a).
\(^{c}\) Results from Skaftafellsjökull published by Stanich (2013).
\(^{d}\) Concentrations of coarse fragments was not estimated in the Breiðamerkurjökull fore-field using the excavation method. Values from Skaftafellsjökull were used to calculate the SOC stock with the exception of the 1890 moraine, where the concentration of coarse fragments was estimated by using values from the cubical cores.

5.4.2 Regional SOC stocks

The SOC stocks (Mg ha\(^{-1}\), Mg = 1 metric ton) of densely vegetated surfaces (>50% cover) were 53–65% higher than those of the sparse vegetation cover (<50%). The total area of each glacial fore-field (undisturbed moraines only), for which the SOC stock was calculated, was 457 ha and 632 ha for Skaftafellsjökull and Breiðamerkurjökull, respectively (Fig. 5.2). Thereof, densely vegetated areal extent was estimated to be 233 ha (51%) and 360 ha (57%). The regional SOC stocks for the two fore-fields were estimated
at 1604.6 Mg C (0–10 cm) for the Skaftafellsjökull fore-field and 1105.9 Mg C (0–5 cm) for the Breiðamerkurjökull pro-glacial area (Table 5.3).

**Figure 5.2** The glacial moraines classified into densely vegetated (>50% cover, green) and sparsely vegetated surfaces (<50% cover, orange) including the defined time-zones.

**Table 5.3** Calculated SOC stocks according to moraine age, the two vegetation cover classes and aerial extent for the Skaftafellsjökull and Breiðamerkurjökull fore-fields.

<table>
<thead>
<tr>
<th>Moraine (year)</th>
<th>Depth (cm)</th>
<th>Moraine age (years)</th>
<th>SOC (Mg ha⁻¹)</th>
<th>Area (ha)</th>
<th>Regional SOC stock (Mg)</th>
<th>SOC (Mg ha⁻¹)</th>
<th>Area (ha)</th>
<th>Regional SOC stock (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skaftafellsjökull</strong></td>
<td></td>
<td></td>
<td>Dense vegetation cover &gt;50%</td>
<td>Sparse vegetation cover &lt;50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>0–10</td>
<td>8</td>
<td>0.72&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.1</td>
<td>0.1</td>
<td>0.42 (0.10)</td>
<td>63.3</td>
<td>26.6</td>
</tr>
<tr>
<td>1945</td>
<td>0–10</td>
<td>65</td>
<td>3.03 (1.94)</td>
<td>154.7</td>
<td>468.7</td>
<td>1.64 (0.57)</td>
<td>93.3</td>
<td>153.0</td>
</tr>
<tr>
<td>1890</td>
<td>0–10</td>
<td>120</td>
<td>11.66 (6.32)</td>
<td>78.2</td>
<td>911.8</td>
<td>7.53 (2.90)</td>
<td>5.9</td>
<td>44.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1380.6</td>
<td>Total</td>
<td>224.0</td>
<td></td>
</tr>
</tbody>
</table>

Combined for both cover classes: **1604.6 Mg C** (0–10 cm)

| Breiðamerkurjökull | | | | |
|-------------------|-----------|-------------|------------|------------|-------------------------|---------------|-----------|-------------------------|
| 2012 | 0–5 | 0 | 0.14<sup>a</sup> | 0 | 0.0 | 0.08 (0.02) | 39.1 | 3.1 |
| 2004 | 0–5 | 8 | 0.15<sup>a</sup> | 0.1 | 0.3 | 0.09 (0.02) | 66.7 | 6.0 |
| 1994 | 0–5 | 18 | 0.70<sup>a</sup> | 5.3 | 3.7 | 0.41 (0.08) | 46.0 | 18.9 |
| 1982 | 0–5 | 30 | 0.88 (0.13) | 33.4 | 29.4 | 0.54 (0.27) | 50.3 | 27.2 |
| 1960 | 0–5 | 52 | 1.81 (0.88) | 95.8 | 173.4 | 0.96 (−) | 39.9 | 38.3 |
| 1945 | 0–5 | 67 | 3.01 (1.51) | 94.5 | 284.4 | 1.75<sup>a</sup> | 13.4 | 23.5 |
| 1930 | 0–5 | 82 | 3.23 (1.92) | 107.6 | 347.5 | 1.88<sup>a</sup> | 13.0 | 24.4 |
| 1890 | 0–5 | 122 | 4.95 (0.56) | 22.9 | 113.4 | 2.89<sup>a</sup> | 4.3 | 12.4 |
| **Total** | | | | | 952.1 | Total | 153.8 | |

Combined for both cover classes: **1105.9 Mg C** (0–5 cm)

<sup>a</sup> Where SOC values for both vegetation cover classes were not available from the field dataset, they were estimated to be of similar proportions as featured by values where both vegetation cover classes for the same
moraine were available; the SOC stock was 58% higher on average, where surface was densely vegetated (>50%) compared to where vegetation cover was sparse (<50%).

5.5 Discussion

The studies from Skaftafellsjökull and Breiðamerkurjökull show that the rates of SOC accretion are low during the first decades after deglaciation but increased after the first 50 years. This trend is in contrast to studies of soil formation from other glaciated regions such as from the Swiss Alps (Egli et al. 2010), Glacier Bay in Alská (Crocker and Dickson 1957) and Svalbard (Kabala and Zapart 2012), where the reported rates were higher during the first decades and then decreased. At Skaftafellsjökull the rates of SOC accretion increased to 9 g m⁻² yr⁻¹, but the rates remained at 4−4.5 g m⁻² yr⁻¹ at Breiðamerkurjökull during the last decades. The different patterns of SOC increase observed in SE-Iceland indicate that the rates of soil formation are initially restricted by relatively slow vegetation succession within the fore-fields. It may be caused by various environmental factors, such as by frequent freezing and thawing cycles and concurrent cryoturbation, general species paucity in Iceland, past and present land-use, strong winds, lack of available nutrients and N-fixing plants (Magnússon 1997; Arnalds 2008; Þórhallsdóttir 2010).

The present study also attempted to apply a more intricate vegetation classification than reported herein to estimate the regional SOC stock based on cover percentage and plant composition. However, these approaches did not sufficiently reflect the SOC stocks of the moraine soils. These trends were attributed to the fact that the soil properties develop at a slower rate than the plant communities present within the proglacial landscapes in SE-Iceland, or that the stronger time factor was masking their effects on the rate of SOC accretion.

5.5.1 Comparison of the moraine soils to SOC accretion by land reclamation and forestry

Several reports on SOC accretion rates are available from sites of land reclamation treatments and forestry. Arnalds et al. (2000) reported a significant increase in SOC stock with increase in treatment age, with the average rate of increase of 0.06 kg C m⁻² yr⁻¹ (0–30 cm depth). The SOC stock within sites of exclusion from grazing only showed no relationship with time since exclusion. Arnalds et al. (2013) reported SOC accretion rates for different reclamation methods, and concluded that sites revegetated by seeding of grasses with fertilization result in the highest SOC accretion rates (0.055–0.065 kg C m⁻² yr⁻¹, 0–10 cm depth). Reclamation sites that received no fertilizer or seeds (lupine and/or trees) produced the lowest rates of SOC accretion (0.04 kg C m⁻² yr⁻¹, 0–10 cm depth). Würsch (2012) reported the SOC accretion rates of 0.022 kg C m⁻² yr⁻¹ (0–20 cm) in sites revegetated by the nootka lupine. These rates are substantially higher than those reported herein, where the accretion rates reached the highest average values of 0.009 and 0.005 kg C m⁻² yr⁻¹ in the Skaftafellsjökull (0–10 cm) and Breiðamerkurjökull (0–5 cm) moraines, respectively. It should be noted that comparisons between studies are not straight forward due to the differences in sampling depths used for calculating SOC stocks. During natural colonization of lime grass, Stefansdottir et al. (2014) estimated the rate of SOC accretion as 0.013 kg C m⁻² yr⁻¹ in 37 yr-old sand-dunes (0–75 cm depth) in the pristine volcanic island, Surtsey. The IPCC (2000) estimates the potential of restoring severely degraded land to be 0.03 kg C m⁻² yr⁻¹, which is similar or lower to what has been reported for the restored areas in Iceland (Arnalds et al. 2000; Arnalds et al. 2013), yet considerably higher.
than the SOC accretion within the glacier fore-fields. However, the present study excludes sites within the proglacial landscape that may feature higher rates of SOC accretion, such as dry streambeds and relic ponds, but aerial photographs indicate a more rapid vegetation succession in these features. These areas were not included in this study due to difficulties assessing the age of these surfaces and the different soil formation environment where water level is high.

In a restored birch forest, the SOC accretion rate was reported by Kolka-Jónsson (2011) as 0.012 kg C m\(^{-2}\) yr\(^{-1}\) in the top 0–5 cm layer. Within the 0–10 cm soil depth in planted larch forests of 14–53 years, Ritter (2007) reported a non-clear trend of increase in SOC stock with time or -0.018–+0.023 kg C m\(^{-2}\) yr\(^{-1}\), probably because larch was planted in an already vegetated land. The accretion rates within the two forest types are considerably lower than those reported from the reclamation sites. The proglacial areas have the lowest SOC accretion rates compared to revegetation and forestry, nevertheless the rates of increase present background values that are generated via natural plant succession without any human input. In contrast to the natural SOC accretion, revegetation efforts generally require inputs that involve CO\(_2\) emissions, depending on the method used. The most commonly used method in restoration is by seeding and fertilization where a mineral fertilizer is applied for the first years manly supplementing N, P and K (50–100 kg N and 27 kg P\(_2\)O\(_5\) ha\(^{-1}\) (Arnalds et al. 2000; Arnalds et al. 2013)).

The SCSI estimates the annual removal of CO\(_2\) from the atmosphere through land restoration (seeding and fertilizing, lupine, fertilizing) by soil formation to be 0.71 Mg C ha\(^{-1}\) yr\(^{-1}\) in the 0–30 cm soil depth (2.6 Mg CO\(_2\) ha\(^{-1}\) yr\(^{-1}\)) (Guðmundur Halldórsson, personal communications). In Hallsdóttir et al. (2010), the areal extent of land restoration between 1990–2008 was estimated to be 100 650 ha. This would lead to the annual accumulation of SOC stock of 71 462 Mg C yr\(^{-1}\). When calculating the annual accretion for each time zone in the proglacial areas, using the average accretion rates from Table 2 and then combined, the current annual increase in the moraine SOC stock is 20.7 Mg C yr\(^{-1}\) for Skaftafellsjökull in the top 10 cm layer and 19.7 Mg C yr\(^{-1}\) for Breiðamerkurjökull in the top 5 cm layer.

### 5.5.2 Regional application possibilities

This method of using chronosequences, vegetation cover and SOC measurements provides an insight to the active SOC accretion rate in the moraine soils within the proglacial areas. This is particularly important in the context that large areas have been deglaciated during the last century, and the deglaciation trend is not foreseen to end in the nearest future. From 1890 to 2000, the total decrease in glacial cover has been estimated as 1285 km\(^2\) or by >11% (Sigurðsson et al. 2013). The total area of the two study sites is 18 km\(^2\), which is only ~1% of the entire area that is estimated to have been deglaciated during the period of 1890–2000. The proglacial areas within Iceland probably differ greatly with regards to vegetation succession and SOC accretion rates, as is shown by the comparison between the two study sites. In order to estimate the SOC stock within other glacial fore-fields, additional field data are needed for assessing the SOC content of the soils. Large scale SOC stock estimates can be made possible by using information on glacial recession, remote sensing data suitable for vegetation classification and additional SOC data.
5.6 Conclusions

The slow rates of soil formation and SOC accretion made it difficult to use plant communities in conjunction with vegetation cover to estimate the regional SOC stocks. Using a simple cover classification of two classes proved the best way of estimating the underlying SOC stocks. A more intricate vegetation (or cover) classification could be made possible by ensuring the soil sampling scheme includes all the presupposed classes being used for the regional SOC stock estimate. The regional estimates of the SOC stocks were 1605 and 1106 Mg C for the Skaftafellsjökull (0–10 cm) and Breiðamerkurjökull (0–5 cm) proglacial areas, respectively. The current annual increase in the moraine SOC stock was 20.7 Mg C yr\(^{-1}\) for the 0–10 cm soil depth at Skaftafellsjökull and 19.7 Mg C yr\(^{-1}\) for the 0–5 cm depth at Breiðamerkurjökull. The maximum rates of increase were 0.004–0.009 kg C m\(^{-2}\) yr\(^{-1}\), depending on the study site, soil depth and moraine age. These rates were considerably lower in comparison with sites of land reclamation where seeding by grasses and fertilizing is applied, where the nootka lupine has been seeded and in forest plantations.

Acknowledgements

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References


Appendix A

Author contributions to the papers

Chapter 2. I collected field data along with three graduate students at the OSU, Guðrún Gísladóttir and more field assistants according to the setup of Þóra Ellen Þórhallsdóttir and Ólöf Birna Magnúsdóttir. I prepared soil samples and analyzed them both at the UI and OSU. I did the data analysis and wrote the manuscript. Co-authors, anonymous reviewer and journal editor provided valuable comments and suggestions on the manuscript.

Chapter 3. I collected field data along with three graduate students at the OSU, Guðrún Gísladóttir and more field assistants according to the setup of Þóra Ellen Þórhallsdóttir and Ólöf Birna Magnúsdóttir. I prepared soil samples and analyzed them both at the UI and OSU. I did the data analysis and wrote the manuscript. Co-authors, two anonymous reviewers and journal editor provided valuable comments and suggestions on the manuscript.

Chapter 4. I planned the study with Guðrún Gísladóttir, set up the sampling scheme and collected field data along with graduate students at the UI and Guðrún Gísladóttir. I prepared soil samples and analyzed them at the UI. I did the data analysis and wrote the manuscript. Co-authors, two anonymous reviewers and the journal editor provided valuable comments and suggestions on the manuscript.

Chapter 5. I planned the study with Guðrún Gísladóttir, based on the previous study setup from Skaftafellsjökull and Breiðamerkurjökull. I analyzed the data, carried out the GIS analysis and wrote the manuscript. Co-authors provided valuable comments on the manuscript.
Appendix B

Scientific publications outside of the PhD thesis


Good times during fieldwork at Skaftafellsjökull 2010: 2 m tall birch in the 120 yr-old moraine, Hvannadalshnúkur in Salix-sight; C-MASC for dr. Lal; sweating canoe carriers; canoe ride on the glacial lake; wiggling through a birch forest is great fun. Photos by Olga K. Vilmundardóttir, Nick Stanich, Melissa Herman and a helpful tourist.
At Breiðamerkurjökull: a lonely gullsteinbrjótur (Saxifraga azeioides) growing in 30 year old moraines; the local terrorist the great skua; the mighty Öræfajökull; my never ever complaining field assistants; wading one of the many glacial rivers; discovering the power of the great skua. Photos by Ólga K. Vilmundardóttir and Friðþór Sófus Sigurmundsson.