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A chronosequence approach to estimate the regional soil organic carbon stock on moraines of two glacial fore-fields in SE-Iceland

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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 areas as barren deserts. Land restoration actions have the primary goals to prevent land degradation and restore lost ecosystems but the ancillary benefits of SOC accumulation with regards to COP 21 are obvious. Natural vegetation succession is active in areas being exposed by glacial recession since the end of the Little Ice Age in ~1890. Here, we attempt to estimate the current regional SOC stock on undisturbed moraines in front of two glaciers in SE-Iceland, using surface age, soil properties and vegetation cover data. RapidEye images were used to estimate the surface area of two vegetation classes with <50% and >50% cover. 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 values of 0.004−0.009 kg C m^{-2} yr^{-1}. The regional SOC stock for the two glacier fore-fields was estimated at 1605 Mg C (0−10 cm) for Skaftafellsjökull (396 ha), and 1106 Mg C (0−5 cm) for Breiðamerkurjökull (632 ha). The current annual increase in the moraine SOC stocks was estimated at 20.7 Mg C yr^{-1} for Skaftafellsjökull and 19.7 Mg C yr^{-1} for Breiðamerkurjökull.

Key words: Glacial recession, land reclamation, proglacial areas, soil organic carbon, SOC accretion, SOC stock, soil development, vegetation cover.

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 C sequestration (SCS) (Kennett, 2002; Lal, 2008; McBratney et al., 2014). Plants convert CO_2 from the atmosphere to produce organic matter (OM), their detritus is consequently incorporated in the underlying soils resulting in immobilization of 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 sequester C from the atmosphere but anthropogenic land-use has depleted the terrestrial C pool by disturbing and utilizing plants and soils (Lal, 2004). According to the United Nations

Framework Convention on Climate Change (UNFCCC), the net change in C stocks and GHG emissions resulting from direct human-induced land-use change and forestry activities, is considered as an option for countries to meet the commitments of COP 21 (UNFCCC, 2015), which also recommended the “4 per Thousand” program of sequestering C in soils at the rate of 0.4% per year (Chambers et al., 2016; Lal, 2016). 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 erosion-induced SOC depletion since the Settlement at 120−500 Tg (1 Tg = 10^{12} 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 (*Leymus arenarius*), 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 are obvious with regards to COP 21 and the “4 per Thousand” initiative. In 2011, revegetation actions are estimated to have resulted in the net removal of CO_2 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 between 1890 and 2000 is estimated at 1285 km^2 (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 Skaftafellsjökull 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 COP 21 but can potentially be considered under the "4 per Thousand" initiative. However, questions arise regarding 1) the rates at which these proglacial areas are accreting SOC in comparison with the sites of revegetation or forestry, and 2) the significance of the C sink capacity of these areas emerging after glacial retreat from a national perspective.

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 that vary among 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 reflected the impact of topography to some extent. Similarly, Egli et al. (2006) documented that topography influenced soil evolution, with the slope gradient, slope aspect and landform determining 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, soil properties, vegetation cover and plant communities. The study builds upon the previous research from Skaftafellsjökull (Stanich, 2013; Vilmundardóttir et al., 2014; Vilmundardóttir et al., 2015b) and Breiðamerkurjökull (Vilmundardóttir et al., 2015a), where the development of soil properties and vegetation succession have been assessed and described. For the regional application, remote sensing data are used to classify vegetation cover and geomorphic features, as the estimate applies for undisturbed moraines only. These, in conjunction with the time since deglaciation, are used to estimate the regional SOC stocks accumulating within the two proglacial areas through the natural processes of plant succession and soil formation over the last 120 years.

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. 1). Both glaciers advanced during the *Little Ice Age* (LIA) and reached the 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 smaller 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 are at low elevations and have an oceanic climate with cool summers and mild winters (Einarsson, 1984). The mean annual temperature is ~5°C, and in winter the temperatures often hover around zero (Table 1).

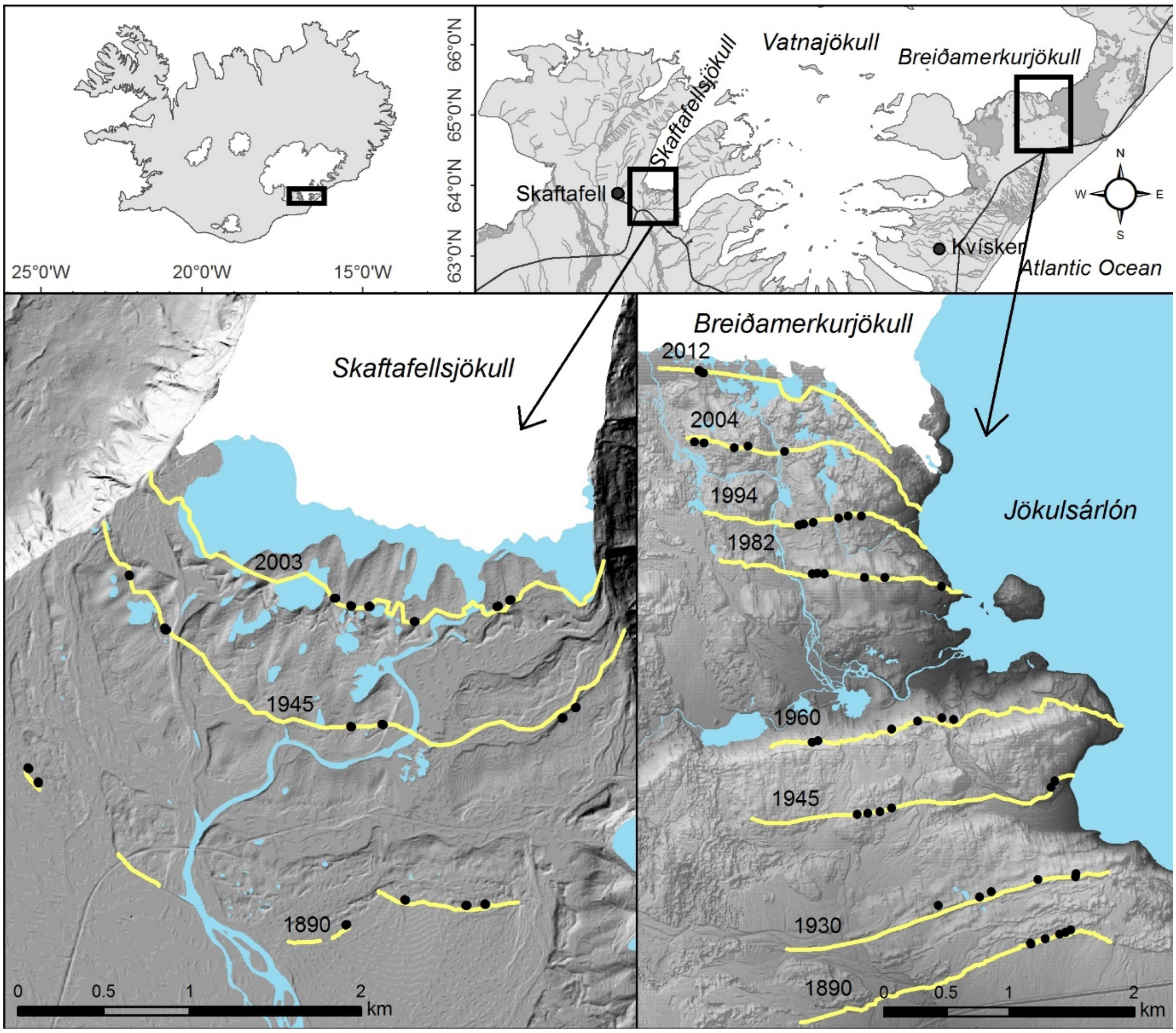


__Fig. 1.__ The study sites within the glacier fore-fields of Skaftafellsjökull and Breiðamerkurjökull. Lines mark the glacier position for a given year, redrawn from Hannesdóttir et al. (2014a) and Guðmundsson (2014), and circles mark the location of sampling sites/transects. The map background is a Lidar DEM from the Icelandic Meteorological Office (IMO), which was used for determining the extent of undisturbed moraines of the fore-fields. The position of the glaciers' termini is from 2012 for Skaftafellsjökull (drawn from RapidEye image) and 2013 for Breiðamerkurjökull (drawn from aerial photographs from Loftmyndir Inc. 2013). The locations of Skaftafell and Kvísker weather stations (Table 1) are shown on the larger inset map.

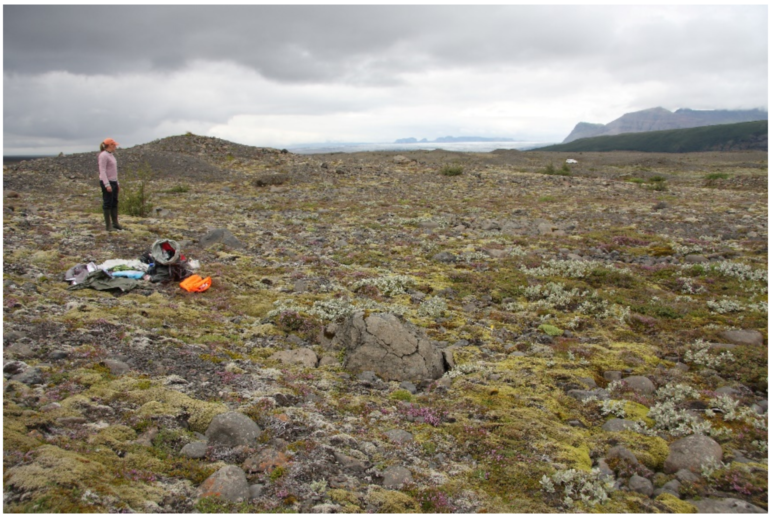
Table 1. General information about the study areas.

Parameter	Skaftafellsjökull	/	Breiðamerkurjökull
Position	N 64°02'−64°00' W 16°57'−16°53'		N 64°05'−64°02' W 16°18'−16°14'
Elevation range	70−120 m a.s.l.		15−70 m a.s.l.
	Skaftafell	Fagurhólsmýri	Hólar in Hornafjörður
Mean annual temperature*	5.1°C	4.8°C	4.7°C
July	10.5°C	10.6°C	10.5C
January	3.3°C	0.4°C	0.3°C
Mean annual precipitation*	NA	1800 mm	1500 mm

		Kvísker: 3500 mm Hali: 2250 mm
Approximate area	7 km^2	11 km^2

*Based on unpublished data from the IMO. Skaftafell weather station is the closest to the Skaftafellsjökull study site and records span the period from 1996−2007. Fagurhólsmýri weather station is midway between Skaftafellsjökull 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.

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 been deposited on the glaciers or straight onto the fore-fields. Vegetation within the proglacial areas is primarily comprised of mosses where the average cover ranged from 40−60% on the oldest moraines. At Skaftafellsjökull, dwarf shrub and shrub cover reached 25% on the oldest moraines (Fig. 2a) (Vilmundardóttir et al., 2015b). Shrubs and dwarf shrubs were rare or even absent at Breiðamerkurjökull but grasses were the vascular plant group with the largest cover percentage of 8% in the oldest moraine (Fig. 2b) (Vilmundardóttir et al., 2015a). The developing soils on the well drained moraines featured a thin A horizon, if at all present, developing on the parent material. The thickness of the A horizon was 8 cm on average in the oldest moraines of Skaftafellsjökull and was only 2−3 cm thick in the oldest moraines of Breiðamerkurjökull.


a)

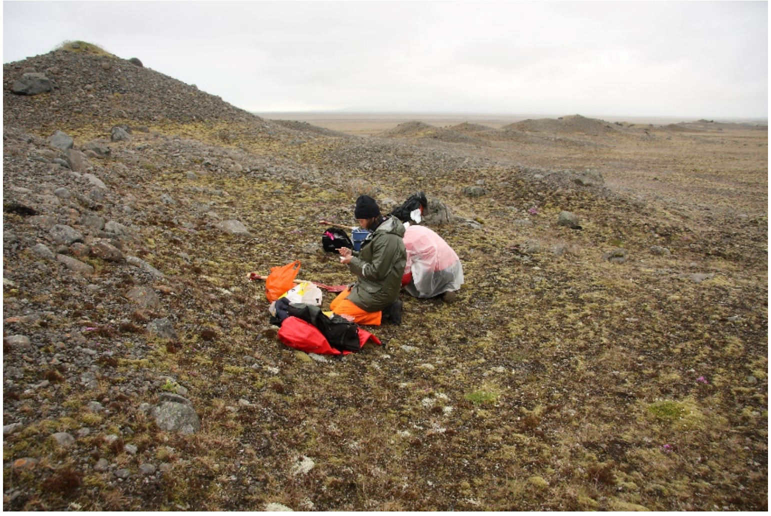

b)

__Fig. 2.__ Examples of sampling sites within the a) Skaftafellsjökull and b) Breiðamerkurjökull forefields, both moraines were formed in ~1890. Mosses had the highest average cover percentage of the plant groups investigated, 38% and 58% cover, respectively. The vascular plant groups with the highest cover percentage were dwarf shrubs that covered 20% at Skaftafellsjökull,and grasses that covered 8% at Breiðamerkurjökull.

Methods

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. The sites were located on ground- or end moraines devoid of natural or anthropogenic disturbances. Areas where the surface age could not be determined were avoided, such as sites of fluvial erosion/deposition and dry lakebeds or ponds. A 10 m transect was selected parallel to the moraine ridge for each point. Soil samples were collected at 0, 4 and 8 m distance for each transect within a 0.25 m^2 quadrant at 0−10 and 10−20 cm depth. 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 as those for Skaftafellsjökull. Vegetation cover was measured within a 0.25 m^2 quadrant and soils were sampled at 0−5 and 5−15 cm depth. The top depth incorporated the A horizon on the surface of the parent material. The lower depth was generally SOC poor, reaching the highest concentrations of 0.3% in the 10−20 cm in the 120 yr old moraine at Skaftafellsjökull and 0.2% in the 5−15 cm in the 122 yr old moraine at Breiðamerkurjökull (Vilmundardóttir et al., 2015a; Vilmundardóttir et al., 2015b).

Bulk density of the fine earth fraction was measured using small cubical cores of known volume and obtained perpendicular to the soil profile. The cores were of three sizes, ranging from 1.4−19.5 cm^3. The larger cores were preferred but the smaller ones were used in places where gravel content was high. Due to the small size of the cores, 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 core. This sampling method was compared with the results reported by Stanich (2013), who sampled the top depth of the same soils using the excavation method with insulation foam to determine bulk density and gravel volume using much larger samples (~1000 cm^3). The methods resulted in similar bulk density values (<2 mm) but showed that the content of coarse fractions was greatly underestimated by the core method

(Vilmundardóttir et al., 2015b). Therefore, the volume estimate of the coarse material determined by Stanich was used here to calculate the SOC stocks for the top depth.

Soil sample preparation and analysis

Soil samples were analyzed at the University of Iceland and the Carbon Management and Sequestration Centre of 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 was assumed to be SOC.

The C stock was estimated by using Eq. 1:

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

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 specific soil depth (vol. %). Data on concentration of coarse material reported by (Stanich, 2013) were used herein to calculate the SOC stocks in the glacier fore-fields. Since the volume estimate of the coarse fraction was only available for the top depth and SOC concentrations were generally very low for the lower depth (Vilmundardóttir et al., 2015a; Vilmundardóttir et al., 2015b), the regional SOC stock was calculated for the top depth only. Concentration of coarse fragments (S) was estimated by using Eq. 2:

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

The rates of SOC accretion were calculated in two ways: 1) by dividing the stocks by the surface age and 2) as split time rates where the difference in SOC stocks between the given moraines is divided with the respective time period.

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 (Lillesand et al., 2014). 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, only a simple two class system using the vegetation cover was chosen. The vegetation cover was 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 or a sparsely vegetated site. In conjunction with time since deglaciation, those two classes were used for assessing the regional SOC stock.

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.

Estimating the carbon stocks of the glacier fore-fields

The glacier fore-fields were divided into time-zones to estimate the regional C 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 C stock by using Eq. 3:

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

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

Results

SOC stocks and rates of SOC accretion in the proglacial soils

The SOC stocks generally 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 deglacition, 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 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}. Split time calculations indicate even higher rates of SOC accretion within the older moraines, reaching the highest rates of 15.1 g C m^{-2} yr^{-1} in the 120 yr old moraine at Skaftafellsjökull and 9.3 g C m^{-2} yr^{-1} between 1945−1960 at Breiðamerkurjökull (Table 2). Calculated rates of accretion at Skaftafellsjökull were somewhat higher during the earliest time period (2010−2003) compared to the second period (2003−1945). The reason for this is unclear but the SOC concentration is the lowest in the youngest moraine, the time split of the earliest period is much shorter compared to that for the other periods and it does not include the initial years after deglaciation.

Table 2. SOC stocks and rate of SOC accretion on undisturbed moraines within the Skaftafellsjökull and Breiðamerkurjökull glacier fore-fields. The rates of SOC accretion is reported in two ways: 1) by dividing the stocks by the surface age and 2) as split time rates where the difference in SOC stocks between the given moraines is divided with the respective time period.

Moraine (year)	Depth (cm)	Moraine age (years)	Bulk density (g cm^{-3})[a, b]	SOC (%)[a, b]	< 2 mm (vol.%)[c, d]	kg C m^{-2} [a]	g C m^{-2} yr^{-1} [a]	Split time	g C m^{-2} yr^{-1}
Skaftafellsjökull									
2003	0−10	8	1.36 (0.16)	0.05 (0.01)	37.1 (12.6)	0.04	5.09	2003−2010	5.0
1945	0−10	65	1.33 (0.17)	0.30 (0.22)	32.5 (15.5)	0.27	4.17	1945−2003	4.0
1890	0−10	120	1.07 (0.15)	1.77 (1.10)	42.2 (18.5)	1.10	9.14	1890−1945	15.1
Breiðamerkurjökull									
2012	0−5	0	1.24 (0.08)	0.02 (0.00)	37.1	0.01	−		
2004	0−5	8	1.19 (0.06)	0.02 (0.01)	37.1	0.01	1.12	2004−2012	0.0
1994	0−5	18	1.22 (0.07)	0.11 (0.02)	37.1	0.04	2.26	1994−2004	3.0
1982	0−5	30	0.94 (0.10)	0.26 (0.10)	37.1	0.07	2.49	1982−1994	2.5
1960	0−5	52	0.94 (0.13)	0.53 (0.29)	32.5	0.16	3.14	1960−1982	4.1
1945	0−5	67	0.81 (0.16)	1.14 (0.63)	32.5	0.30	4.48	1945−1960	9.3
1930	0−5	82	0.97 (0.14)	1.36 (0.62)	42.2	0.37	4.46	1930−1945	4.7
1890	0−5	122	1.01 (0.06)	1.01 (0.07)	3.5	0.50	4.05	1890−1930	3.3

[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 stocks with the exception of the 1890 moraine, where the concentration of coarse fragments was estimated by using values from the cubical cores.

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 stocks were calculated, was 396 ha and 632 ha for Skaftafellsjökull and Breiðamerkurjökull, respectively (Fig. 3). Thereof, densely vegetated areal extent was estimated to be 233 ha (59%) and 360 ha (57%). The regional SOC stocks for the two fore-fields were estimated at 1605 Mg C (0−10 cm) for the Skaftafellsjökull fore-field and 1106 Mg C (0−5 cm) for the Breiðamerkurjökull pro-glacial area (Table 3).

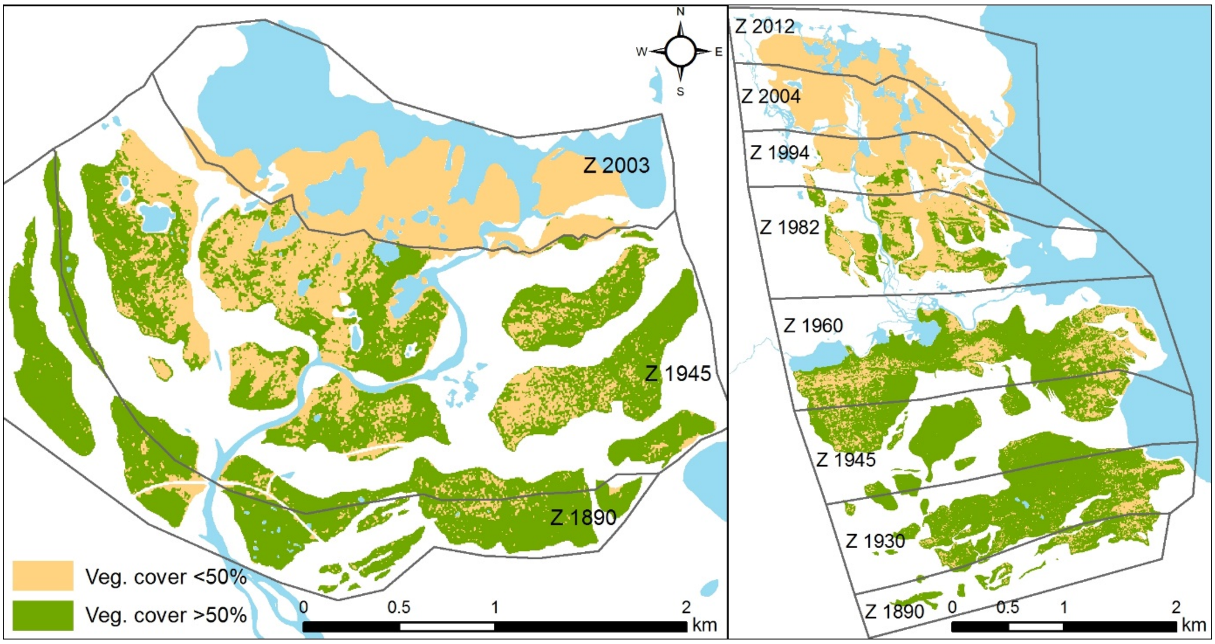


Fig. 3. *The undisturbed glacial moraines classified into densely vegetated (>50% cover, green) and sparsely vegetated surfaces (<50% cover, orange) including the defined time-zones.*

Table 3. Calculated SOC stocks according to moraine age, the two vegetation cover classes and aerial extent for the undisturbed moraines of the Skaftafellsjökull and Breiðamerkurjökull fore-fields.

Moraine (year)	Depth (cm)	Moraine age (years)	SOC (Mg ha^{-1})	Area (ha)	Regional SOC stock (Mg)	SOC (Mg ha^{-1})	Area (ha)	Regional SOC stock (Mg)
			Dense vegetation cover >50%			Sparse vegetation cover <50%		
Skaftafellsjökull								
2003	0−10	8	0.72[a]	0.1	0.1	0.42 (0.10)	63.3	26.6
1945	0−10	65	3.03 (1.94)	154.7	468.7	1.64 (0.57)	93.3	153.0
1890	0−10	120	11.66 (6.32)	78.2	911.8	7.53 (2.90)	5.9	44.4
				Total	1380.6		Total	224.0
Combined for both cover classes: **1604.6 Mg C** (0−10 cm)								
Breiðamerkurjökull								
2012	0−5	0	0.14[a]	0	0.0	0.08 (0.02)	39.1	3.1
2004	0−5	8	0.15[a]	0.1	0.3	0.09 (0.02)	66.7	6.0
1994	0−5	18	0.70[a]	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[a]	13.4	23.5
1930	0−5	82	3.23 (1.92)	107.6	347.5	1.88[a]	13.0	24.4
1890	0−5	122	4.95 (0.56)	22.9	113.4	2.89[a]	4.3	12.4
				Total	952.1		Total	153.8
Combined for both cover classes: **1105.9 Mg C** (0−5 cm)								

[a] 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%).

Discussion

The studies from Skaftafellsjökull and Breiðamerkurjökull show that the relative trends in the rates of SOC accretion are low during the first decades after deglaciation but increase 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 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 0.009 kg m^{-2} yr^{-1}, but the rates remained at 0.004−0.0045 kg 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 factors, e.g. the land use, which includes sheep grazing, frequent freezing and thawing cycles, concurrent cryoturbation and strong winds (Arnalds, 2008). A general species paucity in Iceland may also be a factor because the island was mostly covered with glaciers during the last glacial maximum and it is still a matter of debate whether any species survived in ice free areas (Rundgren and Ingólfsson, 1999; Norðdahl et al., 2008). The Atlantic Ocean itself is a great barrier to long distance seed dispersal (Þórhallsdóttir, 2010; Alsos et al., 2015) and there is a lack of available nutrients in the moraines and N-fixing plants, which is often the case within the sparsely vegetated areas in Iceland (Magnússon, 1997).

Andisols in general are capable of maintaining high SOC sequestration rates for centuries, due to their mineralogical properties, colloidal constituents and frequent burial events (Dahlgren et al., 2004). The volcanic soils of vegetated areas in Iceland are both capable of maintaining high SOC accretion rates for a long time and contain high SOC concentrations throughout the soil profile (Arnalds, 2004; Óskarsson et al., 2004). This is demonstrated within the birch (*Betula pubescens*) woodlands in Skaftafellsheiði where the SOC stock within the top 0–20 cm was estimated at 4.95 kg C m^{-2} (Vilmundardóttir et al., 2015b). The 1727 Öræfajökull tephra marker was identified at 23 cm depth within the soil profile and thickening rates from 1727 to 2011 were estimated at 0.8 mm yr^{-1}. By inferring from these data, rates of SOC accretion within the top 20 cm were estimated at 0.020 kg C m^{-2} yr^{-1}, which are similar to those reported by Gísladóttir et al. (2011) in Histosols in West Iceland for selected time periods since the settlement of the island in ~871. Gísladóttir and colleagues reported total average values of 0.016 kg C m^{-2} yr^{-1} from 665 BC to AD 2008. When the split time rates are considered, the rate of SOC accretion within the oldest moraine in Skaftafellsjökull reached 0.015 kg C m^{-2} yr^{-1}, a rate comparable to the accretion rates of the Histosols in West Iceland (Gísladóttir et al., 2011). This trend suggests that the rates of SOC accretion within the oldest moraines at Skaftafellsjökull may be drawing close to equilibrium and may stabilize at this level for a long period of time.

The present study also attempted to apply a more intricate vegetation classification than reported herein to estimate the regional SOC stocks 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.

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. The split time method, however, indicates that the rate of increase in the oldest moraine at Skaftafellsjökull is considerably higher and closer to these reported rates. However, comparisons among studies are not straight forward due to the differences in sampling depths used for calculating SOC stocks. During natural colonization of lyme 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 of Surtsey. The IPCC (2000) estimated the potential of restoring SOC on severely degraded lands at 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, as aerial photographs indicate a more rapid vegetation succession in these features. These areas were not included in this study due to difficulties in assessing the age of these surfaces and the different soil formation environment where water level is high. Therefore, additional research is needed to provide a complete picture on the regional SOC accretion within the glacier fore-fields.

In a restored birch forest, the SOC accretion rate was reported by Kolka-Jónsson (2011) at 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 (*Larix* spp.) 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. These comparisons show that the proglacial areas have the lowest SOC accretion rates compared to those for revegetation and forestry. Nevertheless the rates of increase within the proglacial areas present important 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 mainly supplementing N, P and K (50−100 kg N and 27 kg P_2O_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). Hallsdóttir et al. (2010) estimated the areal extent of land restoration between 1990−2008 at 100,650 ha. This estimate 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 combining these, the current annual increase in the moraine SOC stocks is 20.7 Mg C yr^{-1} for Skaftafellsjökull (top 10 cm layer, 396 ha), and 19.7 Mg C yr^{-1} for Breiðamerkurjökull (top 5 cm layer, 632 ha).

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 near future. From 1890 to 2000, the total decrease in glacial cover has been estimated at 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 as being deglaciated between 1890 and 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 stocks 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.

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, 396 ha) and Breiðamerkurjökull (0−5 cm, 632 ha) proglacial areas, respectively and the current annual increase in the moraine SOC stocks of the two areas was estimated at 20.7 Mg C yr^{-1} at Skaftafellsjökull and 19.7 Mg C yr^{-1} at Breiðamerkurjökull. The maximum rates of increase were 0.004−0.009 kg C m^{-2} yr^{-1}, depending on the study site 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. The split time rates indicate that the oldest moraine in Skaftafellsjökull may be close to reaching an equilibrium SOC accretion rate for the well drained Andisols in Iceland.

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