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ASSESSMENT OF SOIL ORGANIC CARBON STOCK VARIATION IN CROPLAND, RESTORED AND ERODED LANDS IN GUNNARSHOLT, ICELAND

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ABSTRACT

Soil organic carbon is an important component of soil organic matter that serves as a useful indicator of soil condition. It also explains the soils' potential to serve as sinks for inorganic carbon in climate change mitigation. Land restoration is a promising tool for carbon sequestration in soils. This study assessed the variation of soil organic carbon content among cropland, restored land and eroded land in Iceland. The cropland and restored land were both revegetated around 1976 and the site for the cropland converted in 2009. The study employed the loss-on-ignition method to estimate soil organic matter content. The soil organic carbon – loss-on-ignition relationship conversion factor was determined using regressions and used to calculate soil organic carbon. The results showed that soil organic carbon concentration was higher in the restored land than in the cropland and the eroded land, in the top 5 cm depth of soil. However, the highest soil organic carbon concentration was observed in the cropland compared to both the restored land and the eroded land for the 5-15 cm depth. For the top 15 cm depth, no significant difference was observed between the cropland and the restored land in soil organic carbon concentration. The total soil organic carbon stocks in the top 15 cm depth was highest in cropland compared to the restored land and the eroded land. The soil organic carbon contents for the eroded land were significantly lowest for both depths. The findings suggest that land restoration has great potential to improve soil organic carbon content.

Key words: soil organic carbon, land restoration, cropland, loss-on-ignition

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ABBREVIATIONS

ANOVA	Analysis of Variance
CL	Cropland
EPA	Environmental Protection Agency, Ghana
ER	Eroded land
FAO	Food and Agriculture Organization
GHGs	Greenhouse gases
IMO	Icelandic Meteorological Office
IPCC	Intergovernmental Panel on Climate Change
ITPS	Intergovernmental Technical Panel on Soils
LOI	Loss-on-ignition
MENR	Ministry for the Environment and Natural Resources, Iceland
RL	Restored land
SCSI	Soil Conservation Service of Iceland
SDG	Sustainable Development Goals
SE	Standard error
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nation Framework Convention on Climate Change

1. INTRODUCTION

Soil organic carbon (SOC) is an important component of soil organic matter (SOM) that serves as a useful indicator of soil condition (Stolbovoy et al. 2007). It also explains soils' potential to serve as sinks for inorganic carbon in climate change mitigation (FAO 2017). SOC is thus an essential parameter which can be utilised to estimate the level of degradation of land ecosystems. According to FAO (2017), five of the sustainable development goals (SDGs) can be accomplished if SOC levels are sustained or enhanced to optimal levels in the environment. The SDGs the FAO mentioned are SDG #2: 'zero hunger', SDG #3: 'good health and wellbeing', SDG #6: 'clean water and sanitation' SDG #13: 'climate action' and SDG #15: 'life on land'. Achieving zero hunger will require an increase in food production using soils with high organic carbon in a sustainable manner. Changes in rainfall patterns and temperature, droughts and floods as a result of climate change may affect crop production, which is likely to impact on the livelihoods of many people and particularly farmers in developing countries (Rosenzweig et al. 2001; Parry et al. 2004). Measures to maintain SOC are thus pertinent to attainment of the SDGs.

Vegetation cover is critical for soil condition (FAO & ITPS [Intergovernmental Technical Panel on Soils] 2015) and plays a key role in the amount of carbon stocks in the soil (O Arnalds et al. 2000). However, anthropogenic land degradation due to human's dependence on land resources has contributed substantially to vegetation loss and soil erosion (Lal 2004), with attendant loss in SOC (Lal 2003). Although it appears difficult to deal with due to the challenging needs of humans, restoration of degraded lands through revegetation seems to be a promising tool to reverse degradation and sequester carbon in vegetation and eventually in soils as organic carbon (Aradóttir et al. 2000; A Arnalds 2004). SOC losses from agricultural lands could be minimised and storage increased through sustainable agricultural measures such as conservation tillage, and erosion control (Lal 2004).

In Ghana, land degradation has attracted government attention because of the threat of desertification in the northern part of the country (EPA [Environmental Protection Agency] 2003). Numerous studies attributed the drivers of degradation to complex interrelationships between natural and anthropogenic factors such as climate change, rainfall variability, increasing agricultural activities/overcultivation, soil erosion, bushfires, population growth and poverty (EPA 2003; Braimoh & Vlek 2005; Yiran et al. 2012; Kleemann et al. 2017). The government's efforts to reverse degradation and restore degraded lands have led to initiation of projects such as the Ghana Environmental Management Project (EPA n.d.) and the Sustainable Land and Water Management Project (EPA n.d.). These projects' interventions include sustainable land management support to farmers to increase yield on their farms, tree growing on degraded community lands and forest reserves management (unpublished EPA internal reports). Successes have mostly been measured relying on indicators of immediate outputs such as number of activities implemented, number of trees planted, land area covered by interventions, number of beneficiaries or increase in crop yields (unpublished EPA internal reports). However, little attention is given to projects' long-term impact on soil health such as improvement in SOC levels through carbon sequestration. A knowledge gap, thus, exists on the benefits of such projects in Ghana for long-term ecosystem services restoration and climate change mitigation (FAO 2017). Knowledge of SOC stocks would give feedback on the overall goal of restoring the entire ecosystem of the area and how they are contributing to climate change mitigation. Further, positive feedback would provide an essence to continue with revegetation/reforestation activities or revise approaches to achieve maximum benefits in Ghana's northern savanna ecological zone. This study, conducted in Iceland, presented an opportunity for the author to build his capacity to conduct similar research back in Ghana to fill the knowledge gap identified above.

Though some SOC research has been conducted in Iceland, it appears much attention has been on managed forest ecosystems and identifying successes of SOC build-up in revegetated/reclaimed areas (e.g. O Arnalds et al. 2000; Snorrason et al. 2002). This study, however, focuses on the development of SOC as eroded land is revegetated and subsequently turned over to cropland. Thus, it provides important information on variations in SOC stocks in cropland, restored (revegetated) and eroded lands in Iceland. The present work may therefore be useful to Icelandic climate change policy, particularly on land use and management, as well as its international commitments on greenhouse gases (GHGs) inventory reporting under the United Nations Framework Convention on Climate Change (UNFCCC) (MENR [Ministry for the Environment and Natural Resources] 2018).

Globally, the study contributes to the general goal of combating climate change by adding knowledge on SOC variation for different land management practices. It may also aid understanding of optimal land management measures that promote soil quality and carbon sequestration in soils.

1.1 Aims and objectives

The overall aim of the study was to investigate SOC stocks variation between selected cropland, restored (revegetated) land and eroded land in Gunnarsholt, South Iceland, in order to understand the effects of different land management options on SOC.

The specific objectives were to:

1. Estimate SOC concentrations and stocks in the cropland, revegetated and eroded land.
2. Compare variations in the SOC concentrations and stocks for the three land types.
3. Make appropriate recommendation(s) for policy consideration on restoration measures and potential land use following land restoration.

1.2 Soil organic carbon and the global carbon cycle

SOC defines the overall quantity of organic carbon (C) in the soil regardless of its source or state of disintegration (Stolbovoy et al. 2007). SOC is a major component of SOM (Roper et al. 2019) and plays an important role in the global carbon cycle (FAO 2017). The quantity, in mass, of organic C stored in SOM defines SOC stocks (FAO & ITPS 2015). Organic C storage in soils is influenced by soil biochemical and biophysical processes (FAO 2017). Soil biota including plants and microorganisms convert carbon dioxide in the atmosphere into organic material, a process that leads to carbon sequestration, increase in SOC storage and consequent climate change mitigation (O Arnalds et al. 2000; FAO 2017). Soils are described as a major sink for carbon dioxide (in the form of organic C) and hold about double the amount of carbon in the atmosphere, (Batjes 2016). However, they can also be a major source of carbon dioxide emissions into the atmosphere (Lal 2004). For instance, global SOC estimates have decreased from around 1,500 Pg C (Eswaran et al. 1993; Batjes 1996) to about 1,400 Pg C (Batjes 2016) in the topmost 1 m of soil. This is an indication that some amount of SOC (about 100 Pg C) might have moved to other parts of the carbon cycle and some might have ended up in the atmosphere increasing carbon dioxide levels there. Hence, proper management measures are required to retain and sequester more carbon in soils (FAO 2017).

1.3 The UN Framework Convention on Climate Change and SOC estimates

The importance of SOC stock estimation, as part of the measures to reduce GHGs emission and mitigate climate change, is highly recognised in global agreements. For instance, Article #4 and Article #12 of the UNFCCC enjoin countries (parties to the convention) to report sources and sinks of greenhouse gases caused by human activities and as well present sustainable management measures of GHGs sources and sinks (UN 1992). The Kyoto Protocol, which required mainly industrialised countries to report on their GHGs emissions, gave backing to the Convention and defined the modalities for reporting, emphasizing reduction of sources and promotion of sinks (UN 1998). The Paris Agreement re-enforced previous agreements to reduce GHGs emissions by giving parties the opportunity to voluntarily reduce emissions through their own 'Nationally Determined Contributions' (UN 2015). Indeed, the Intergovernmental Panel on Climate Change (IPCC) guidelines presents specific details for SOC stock estimation in different land use types to enable national governments to present appropriate accounts in their reports (IPCC 2006). The crucial roles of SOC in soil health for agricultural lands' productivity and overall ecosystem services provision as well as human wellbeing are well expounded in FAO publications (FAO & ITPS 2015; FAO 2017).

Not surprisingly, interest in SOC research has been rising as part of the efforts to meet the goals of the UNFCC. Research has ranged from methods of SOC analysis (e.g. Konen et al. 2002; Stolbovoy et al. 2007; Abella & Zimmer 2007), global estimates in various types of ecosystems (e.g. Batjes 2016) and in land use and management categories (e.g. O Arnalds et al. 2000; Chiti et al. 2014; Vilmundardóttir et al. 2017). Although most of these studies have made some comparisons, the focus has mainly been on changes in forest management and land use (e.g. Tan et al. 2009; Chiti et al. 2014, 2016; Bruun et al. 2015), vegetation changes during reclamation (e.g. O Arnalds et al. 2000), or changes due to natural succession (e.g. Vilmundardóttir et al. 2017). For instance, Chiti et al. (2014) investigated the effects of prime forest conversion into tree plantations on SOC stocks. They found a prominent decrease in SOC stocks in the plantations, mainly within the 0–30 cm depth. Although Chiti et al. (2014) agreed that plantations could be used for land reclamation, especially in natural succession 'poor' areas, they noted that replacing prime forests with plantations encourages soil exploitation and hence reduction in SOC stocks. In another study, Chiti et al. (2016) compared tropical forests in three African countries, investigating effects of logging by comparing selectively logged and unlogged parts of forests. They found a higher reduction in SOC stocks in the logged areas than in the unlogged areas, with decreasing susceptibility of carbon losses as soil depth increased. Bruun et al. (2015) conducted similar research looking at conversion of natural forest into maize fields. Similar losses in SOC stocks were reported for the maize fields compared to the natural forests (Bruun et al. 2015).

1.4 Soil organic carbon investigation in Iceland

Icelandic research on SOC stocks has largely been influenced by the country's interest in reclamation of its degraded lands and its commitment to the UNFCCC, which informed Icelandic government implementation of the "carbon sequestration by reclamation program" (O Arnalds et al. 2000). Through this programme, O Arnalds et al. (2000) presented findings on SOC stocks rates in revegetated Icelandic deserts, sampling treated reclamation sites and adjoining untreated sites. Their results showed that the SOC content in untreated sites was generally lower than in the treated sites. They concluded that Icelandic soils were capable of sequestering organic C after revegetation and for long periods (>50 years). Similarly, O

Arnalds et al. (2013) considered SOC build-up in revegetated eroded desert soils and reported increases in SOC levels in the revegetated sites during the early years of restoration. Furthermore, Vilmundardóttir et al. (2017) compared SOC sequestration rates in two proglacial areas. They found, on average, about 59% higher SOC stocks in thick vegetal cover (> 50% cover) areas than thin vegetal cover (< 50% cover) areas. Other investigators such as Kolka-Jónsson (2011) and Hunziker (2011) have reported on carbon stocks in vegetation and soils of restored and natural forests.

However, most of these studies were limited in comparing SOC stock variations, especially in cropland and revegetated land, key different land use types defined in the IPCC (2006) guidelines, leaving a critical gap of research in the literature of SOC stocks. The current study therefore extends the SOC literature through comparison of cropland, restored land (revegetated and unforested), and eroded land.

2. METHODS

2.1 The study area

The study was carried out in the Gunnarsholt area of South Iceland (Fig. 1). Gunnarsholt is located near Mt Hekla, an active volcano, and near the town of Hella. The area experienced sand encroachment in the late 1800's and early part of the 1900's as a result of increased wind erosion and dust deposition from volcanic eruptions [Sigurjónsson, 1958, cited in (Strachan et al. 1998)]. Farmlands were affected by movement and deposition of desert sand causing farmers to abandon the place [Sigurjónsson, 1958, cited in (Strachan et al. 1998)]. The establishment of the Soil Conservation Service of Iceland (SCSI) with its headquarters at Gunnarsholt was a remarkable turning point in the history of the area, where previously degraded lands have now been restored through sustainable land management approaches (SCSI n.d.; Ágústsdóttir 2004).

Climatic data from 1958 to 2004 for the Hella weather station indicate a mean annual temperature of around 4°C, average annual precipitation about 1,230 mm and average annual wind speed as 4.5 ms^{-1} (IMO [Icelandic Meteorological Office] n.d.). Reported mean January and July temperatures are approximately – 1.4°C and 13°C, respectively (IMO n.d.).

The predominant soil types in the Gunnarsholt area are Andosols, which are soils of volcanic origin (Strachan et al. 1998; O Arnalds et al. 2013), with textures varying from sandy loam and loamy sand for the A and B horizons whilst the surfaces are mostly gravelly (O Arnalds et al. 2013). However, Strachan et al. (1998) found mainly silty loam and loam textures in soils of an experimental poplar plantation site near Gunnarsholt. The difference in soil texture classification might emanate from Boone et al.'s (1999) explanation that spatial variation in soil properties may be influenced by soil type such as forest or agricultural soils. The occurrence of frost-heave during winter helps keep the surface gravelly (O Arnalds et al. 2013). The carbon content of less fertile desert Andosols of Iceland is reported as below 10 g C kg^{-1}, but higher values, more than 30 to 80 g C kg^{-1}, are possible in fertile Andosols (O Arnalds & Kimble 2001).

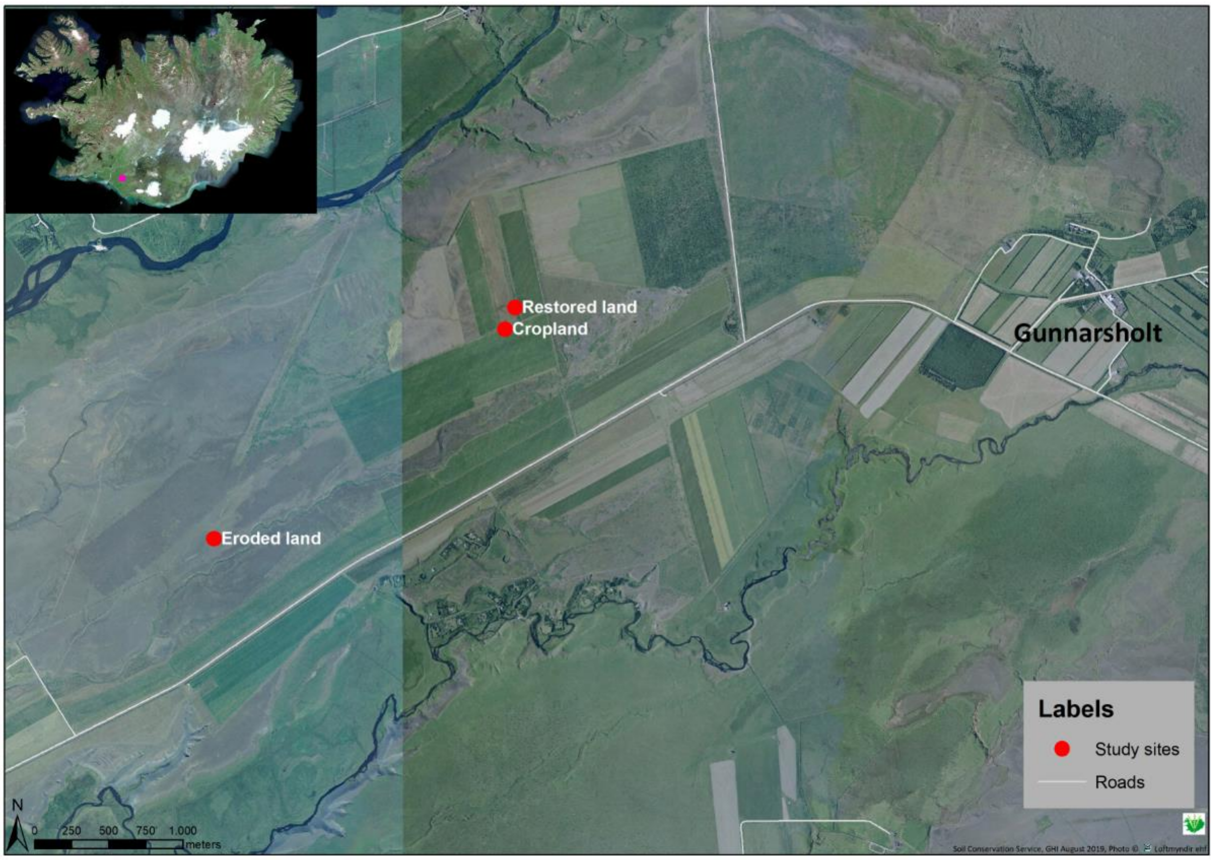

Figure 1. Map of the study area with the locations of the three experimental sites. Inset: Location of study area in Iceland, red dot shows the location of Gunnarsholt. (Source: Guðný H. Indriðadóttir, Soil Conservation Service of Iceland, 2019).

2.2 Study sites

In collaboration with the SCSI staff, three sampling sites, namely; (a) cropland (b) restored land and (c) eroded land, were identified in Gunnarsholt (see Fig. 2).

Historically, the whole area had been barren since the wind erosion period prior to 1700 (Sigurdsson 1982). In a personal communication with Sveinn Runólfsson, former director of the Soil Conservation Service of Iceland, on 10 August 2019, concerning the history of the cropland site, he stated that:

- The area was a gravelly glacial riverbed when the revegetation started in May 1976.
- The revegetation was carried out by a Piper Pawnee airplane which had the capacity of carrying 500 kg of fertilizer and grass seed.
- The grass seed consisted of 5 kg timothy (*Phleum pratensis*), 20 kg red fescue (Festuca rubra) and 5 kg annual ryegrass (*Lolium multiflorum*) and 400 kg 26-14 inorganic fertilizer. After distribution the field was cultivated using a light chain harrow to cover the grass seed and then rolled with an agricultural roller.
- A total of 33.2 tonnes of fertilizer and 2,520 kg of seed were applied.
- A year after the field was top dressed with 600 kg of 23-14-11 inorganic fertilizer and the grass later harvested for a grass cube factory in Gunnarsholt.
- The factory, established around 1962, produced and sold grass cubes as supplementary livestock feed for Icelandic farmers; a form of state intervention to minimize the impact of expensive livestock feed imported from Europe on the farmers. However,

during the 1980s livestock feed was becoming more subsidized in Europe, making imported feed inexpensive, and this led to the closure of the state-sponsored grass cube factory and cessation of grass harvesting in these fields in 1986 (Crofts 2011).
- Since then, the restored land has been developing into a heathland, part of which was converted to cropland in 2009.

According to Björgvin Þór Harðarson, farm owner, (7 August 2019, personal communication) the cropland has been under cropping since it was established in 2009. He indicated that the land has been used for cultivation of barley, except for 2018 when it was split for cultivation of rapeseed. Farm management practices adopted by the farmer included ploughing, application of shell sand, crop residue incorporation in soil, and application of inorganic fertilizer and manure. Detailed description of the farm management practices are presented in Table 1. At the time of sampling there was barley growing on this land.

Table 1. Farm management practices for the cropland since 2009. *NA stand for not applicable. **NK stands for not known. (Source: B. Þ. Harðarson, 7 August 2019, personal communication).

Practice	Last done (year)	Type/mode	Depth (cm)	Quantity (t ha^{-1})	Nutrients	Frequency
Ploughing	2018	Conventional	15-18	NA*	NA*	Every 3rd year
Shell sand	2011	Chisel ploughing	~ 10	2.00	NK**	Once
Crop residue incorporation	2018	Chisel and Conventional ploughing	~ 10 (15-18)	NA*	NK**	Every 1st year after ploughing and then during ploughing
Inorganic fertilizer	2019	Using seeder	3-4	~ 0.52	100N, 28P, 50K	Annually
Chicken manure	2019	Chisel ploughing	~ 10	~ 4.50	NPKS (%) (2.85, 0.51, 1.93, 0.3)	Once

The restored land is predominantly covered by grass and heath with sparse shrubs including willows and birch. No eroded spots were seen on it. Describing the history of the restored land, Sveinn Runólfsson, in a personal communication on 10 August 2019, stated that the restored land was revegetated using a similar procedure to that used on the cropland. According to him, revegetation of the restored land started in 1975 when the gravelly old glacial riverbed was first cultivated by a heavy disc harrow, and then a mixture of timothy (*Phleum pratensis)* and red fescue (*Festuca rubra*) grass seed was drilled into the seedbed and some 500 kg of 23-11-10 inorganic fertilizer was applied. He mentioned that the crop in the second year was used for the grass cube factory and in the following years it was harvested once every summer and the fertilizer application was around 600 g of 23-14-11 + Ca+Su per year. The field was not utilised for any other activity after the grass harvesting was discontinued due to the closure of the factory in 1986 (Crofts 2011; S Runólfsson, 10 August 2019, personal communication).

The eroded land has been barren for over three centuries and has never received any revegetation efforts (Sigurdsson 1982; S Runólfsson, 10 August 2019, personal communication). However, the few patches of grass (see Fig. 2), probably colonised it through natural vegetation succession and/or some seed has come from nearby revegetated sites (S Runólfsson, 10 August 2019, personal communication).

2.3 Study set up and soil sampling

The three sites were sampled on 24 and 25 June and 1 July 2019. For each site, a 58 m transect was randomly selected (see Fig. 2). Geographic Positioning System (GPS) coordinates were taken for the transect location. Soil samples were collected from 30 points at 2 m intervals along each transect, beginning at 0 m. For each transect, samples from 21 points taken at 0-5 cm depth were combined randomly in batches of 3's which produced seven composite samples.

For the remaining nine sampling points of each site, the initial plan was to take samples from 0-30 cm depth. During pre-sampling trials, it was noticed that the soil depth at the sites was shallower than expected. Therefore, the soil depth was measured for all the points. The average depths were 26, 23 and 17 cm for the cropland, restored land and eroded land, respectively. Based on the results of the depth measurement, samples for the nine points of each site were taken for the top 15 cm instead of the 0-30 cm depth. The samples from the nine points of each site were divided into 0-5 and 5-15 cm depths and randomly combined in batches of 3's to produce six composite samples (three each for the 0-5 and 5-15 cm depths). Thus, the total number of samples for each site was 13, resulting in 39 samples (i.e. 30 samples for 0-5 cm and nine samples for 5-15 cm) in total for the three sites.

A random combination of samples was predetermined with Microsoft Excel before going to the field. Samples for the cropland and restored land were taken with an auger which has an inner diameter of 4.8 cm. Samples for the eroded land were loose and could not be taken with the auger. Therefore, these samples were taken with 10 x 10 x 5 cm and 10 x 10 x 10 cm frames for the 0-5 and 5-15 cm depths, respectively.

Aboveground vegetation within sampling points in the restored land was carefully removed before taking the sample. Crops were also avoided in the cropland during sampling. The same samples were used for bulk density determination. It is important to note that the use of a single transect for sampling may not be very representative for the sites. However, this was applied bearing in mind the available time to complete this work. Methods such as that described in Stolbovoy et al. (2007) or that applied by Vilmundardóttir et al. (2017) may be useful for any future investigation similar to this current study.

2.4 Analytical methods

Various approaches to determining SOC concentrations exist in the literature. The potential of methods such as the Walkey-Black, dry combustion and loss-on-ignition (LOI) are well explained (Schumacher 2002; Zhang & Wang 2014; Roper et al. 2019). This study employed LOI, which is one of the most widely used methods for SOM and SOC analysis and is reported to be relatively inexpensive (Konen et al. 2002; Abella & Zimmer 2007; Roper et al. 2019).

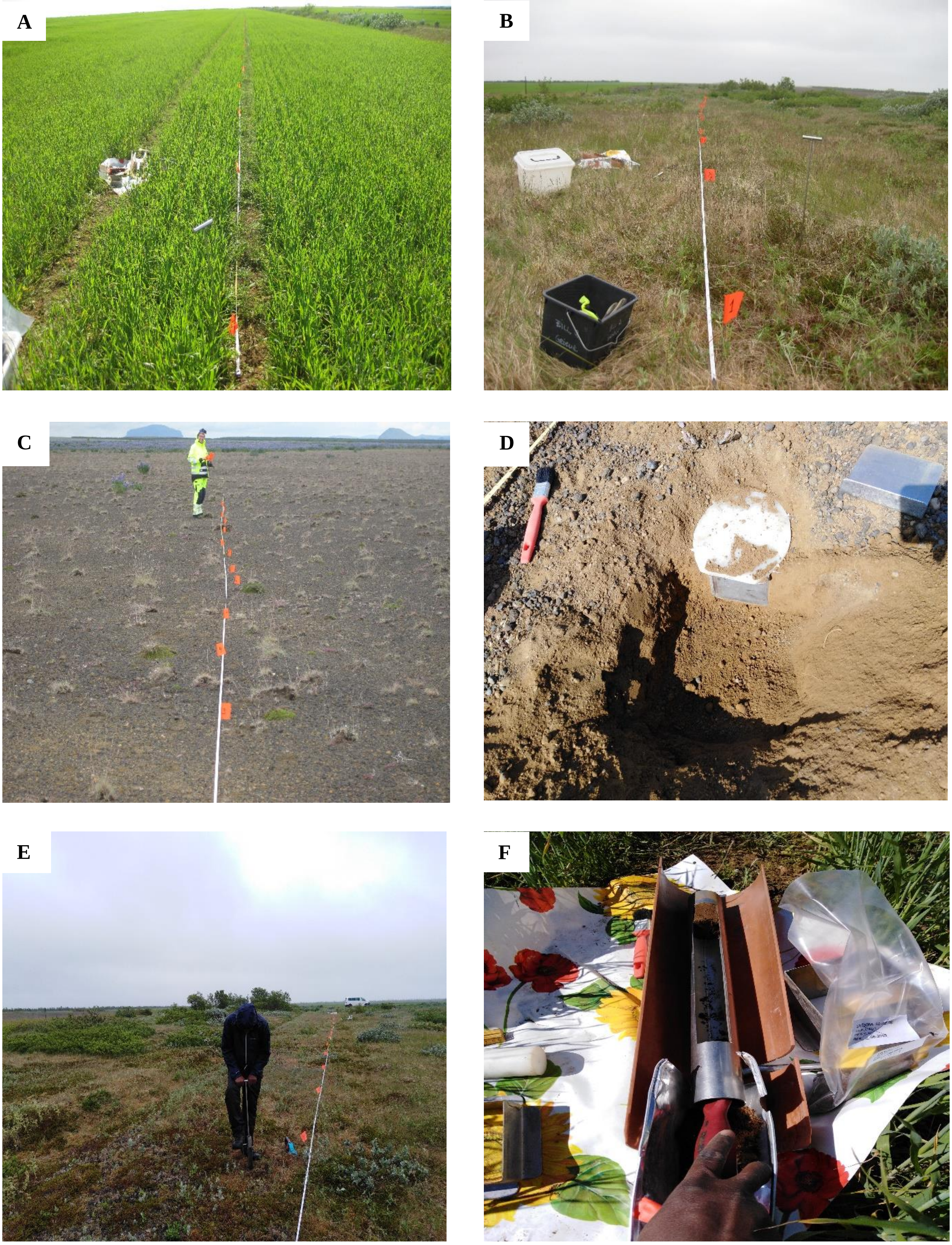

Figure 2. Field setup at the experimental sites and sample collection. **A** = cropland, **B** = restored land, **C** = eroded land, **D** = sample collection with frame on eroded land, **E** = sample collection with auger on restored land (Photo: Ö. Styrmisson, 25 June 2019) and **F** = taking out sample from auger.

2.4.1 Preparation of soil samples for analysis

All samples were initially dried in the oven at 40°C. The total weight of each sample was taken, and the sample sieved using a 2 mm sieve (see Fig. 3). The weight of the sieved soil (<2 mm), rock fragments (> 2 mm) and belowground vegetation (roots and buried litter >2 mm) were recorded. The soil sample was thoroughly mixed to ensure homogeneity and a subsample taken and stored for total carbon, dry matter and LOI analysis. The weights of the soil, coarse fragments and vegetation contents were used for bulk density calculation.

Figure 3. Weighing of soil samples before sieving. (Photo: W. Asare, 5 July 2019).

2.4.2 Analyses and calculations

Total carbon was determined through dry combustion using the 18 subsamples taken from 0-15 cm depth. The analysis was conducted with a vario MAX CN elemental analyser by Elementar Analysensysteme GmbH, Hanau, Germany. Each sample was analysed once. The total carbon was determined as carbon dioxide. Dry matter content was used to correct the total carbon results. The purpose of the total carbon analysis was to regress the results with LOI results in order to determine the conversion factor for LOI to SOC.

LOI was conducted for all samples in replicates of two. Approximately equal volumes (around 5 to 10 g) of the oven-dried at 40°C subsamples were placed in pre-weighed crucibles (15 mL in volume) and the weight taken using a high accuracy electronic balance (sensitivity = 0.1 mg) before drying at 105°C for 24 hours to obtain the dry weight. The samples were weighed hot from the oven. The weighing in and out of the oven, from 40°C to 105°C was done to obtain the dry matter content of the samples which is crucial for calculations of SOC stocks.

The samples were then transferred into a muffle furnace (Thermo Scientific, Thermolyne), and ignited at a temperature of 550°C for four hours, allowed to cool and returned to the oven for reheating at 105°C for about 2 hours. The reheating was carried out to remove any moisture absorbed by the samples during removal from the furnace because there was no desiccator to cool the samples before weighing. It was also to secure that the sample was weighed at the same condition before and after LOI. Each sample was then taken out of the oven and weighed in the hot state to give the weight after combustion. The LOI was estimated from the mass variation between the oven-dried weight and the combusted weight of the soil sample as shown in Equation (Eq.) 1 (Zhang & Wang 2014);

$$LOI\ (\%) = [(Wt_{oven\text{-}dry} - Wt_{comb}) / (Wt_{oven\text{-}dry})] \times 100 \qquad (1)$$

where, $Wt_{oven\text{-}dry}$ is the oven-dried weight of the soil sample at 105°C and Wt_{comb} is the weight of the soil sample after combustion at 550°C and reheating at 105°C.

Regression equations determined from the automated dry combustion (DC) method and LOI are widely used in the literature to estimate the relationship between DC and LOI (Konen et al. 2002; Pribyl 2010). In such equations the slope is a representation of the ratio of DC to LOI and usually assumed to be equivalent to the SOC:LOI ratio (Pribyl 2010). Based on this, the relationship between SOC and LOI is given by Eq. 2 (Pribyl 2010);

$$\mathrm{SOC} = \mathrm{Slope} \times \mathrm{LOI} \qquad (2)$$

where the slope is the conversion factor. The SOC amount can be estimated with Eq. 2 if the LOI amount is known. The data of the total carbon from DC and the LOI estimates were regressed to determine the appropriate SOC – LOI conversion factor for the sites of this study and this factor was applied to compute the SOC concentrations.

For bulk density estimation, the coarse fragments volume was determined through water displacement. The vegetation was oven-dried at 105°C and the weight measured after 24 hours. Where possible, the dried volume of the vegetation was also determined with the water displacement technique. Bulk density *(bd)* of each sample was then determined by deducting the volume of the rock fragments ($V_{RK>2mm}$) and vegetation ($V_{RT\ >2\mathrm{mm}}$) from the total volume (V_T) of the sample. The bulk density of the sample was then calculated by using Eq. 3;

$$bd = Wtsoil / (V_T - V_{RK>2mm} - V_{RT\ >2\mathrm{mm}}) \qquad (3)$$

where, *Wtsoil* is the dry weight of the soil sample at 105°C obtained from the dry matter content.

The SOC concentrations were estimated by multiplying the conversion factor of 45% determined from the regression (see *Section 3.1.2*) by the LOI results of each sample.

Because the rock fragment content was considered in the calculation of the bulk density (see Eq. 3), the Boone et al. (1999) equation was modified by taking out the rock fragment factor as shown in Eq. 4, and used to compute SOC stocks.

$$SOC_{stock} = c \times bd \times D \qquad (4)$$

where, SOC_{stock} represents SOC stock in kg C m^{-2}, *c* is the percent SOC mass concentration of the soil sample, *bd* represents the bulk density of the soil in kg m^{-3} and *D* denotes the volume of 1 m^2 sampled soil layer depth (m).

The respective bulk density of each sample was applied in calculating the SOC stock and the mean taken to represent the stock at each depth interval. The total SOC stocks per m^{-2} in the top 15 cm of soil in each site were calculated by adding the means for the 0-5 and 5-15 cm depths.

2.5 Statistical analysis

Statistical analysis employed IBM SPSS Statistics software. Descriptive statistics were computed. One-way Analysis of variance (ANOVA) and Tukey's test were performed to establish significant differences between the different sites as applied by Chiti et al. (2014). All graphs were done in Microsoft Excel. Significant differences were evaluated at the 95% confidence level ($p \leq 0.05$) and standard error (SE) reported at the same confidence level as 1.96×SE.

3. RESULTS

3.1 Regression Analysis

3.1.1 Total carbon and loss-on-ignition data

Descriptive statistics of the data used for regression analysis are shown in Table 2. The highest mean total carbon and mean LOI were observed in the cropland (CL) whilst the eroded land (ER) had the least for the 0-15 cm depth. However, in terms of range, the restored land (RL) had the widest, with the CL having the lowest for both total carbon and LOI for the same 0-15 cm depth. For the combined data, the respective means for both total carbon and LOI of all the samples (CL+RL+ER) were lower than in the CL and RL but higher than ER for the 0-15 cm depth. In contrast, the range for the CL+RL+ER was wider than the ranges for the individual sites.

Table 2. Results from total carbon (TC) analysis and their corresponding loss-on-ignition (LOI) values. Each sample is a composite of samples from three points. *Site: CL = cropland, RL = restored land and ER = eroded land. **TC values were corrected using dry matter content. ***0-15 cm depth is combination of results for samples from 0-5 and 5-15 cm depths.

Site*	**Depth (cm)**	**Number of samples**	**TC** (%)** Mean (Min – Max)	**LOI (%)** Mean (Min – Max)
CL	0-5	3	1.53 (1.49 – 1.57)	6.02 (5.83 – 6.13)
	5-15	3	1.53 (1.52 – 1.55)	5.85 (5.72 – 5.92)
	0-15* **	**6**	**1.53 (1.49 – 1.57)**	**5.94 (5.72 – 6.13)**
RL	0-5	3	2.23 (1.72 – 2.70)	6.93 (5.68 – 7.73)
	5-15	3	0.64 (0.53 – 0.76)	3.99 (3.82 – 4.07)
	0-15* **	**6**	**1.44 (0.53 – 2.70)**	**5.46 (3.82 – 7.73)**
ER	0-5	3	0.33 (0.27 – 0.39)	2.90 (2.66 – 3.06)
	5-15	3	0.22 (0.16 – 0.26)	2.95 (2.76 – 3.24)
	0-15* **	**6**	**0.28 (0.16 – 0.39)**	**2.93 (2.66 – 3.24)**
CL+RL+ER	**0-15*** **	**18**	**1.08 (0.16 – 2.70)**	**4.77 (2.66 – 7.73)**

3.1.2 Relationship between total carbon and loss-on-ignition

The regression results showed poor linear relationships between total carbon and LOI for CL and ER with insignificant p-values (Table 3), whereas for RL a significant linear relationship was observed (Fig. 4). However, when the data for all the three sites were combined (i.e. CL+RL+ER), a stronger relationship was observed between total carbon and LOI compared to the relationships of the individual sites (Fig 4). The slope (~ 45%) of the regression equation for the CL+RL+ER was applied for SOC calculation from the LOI results.

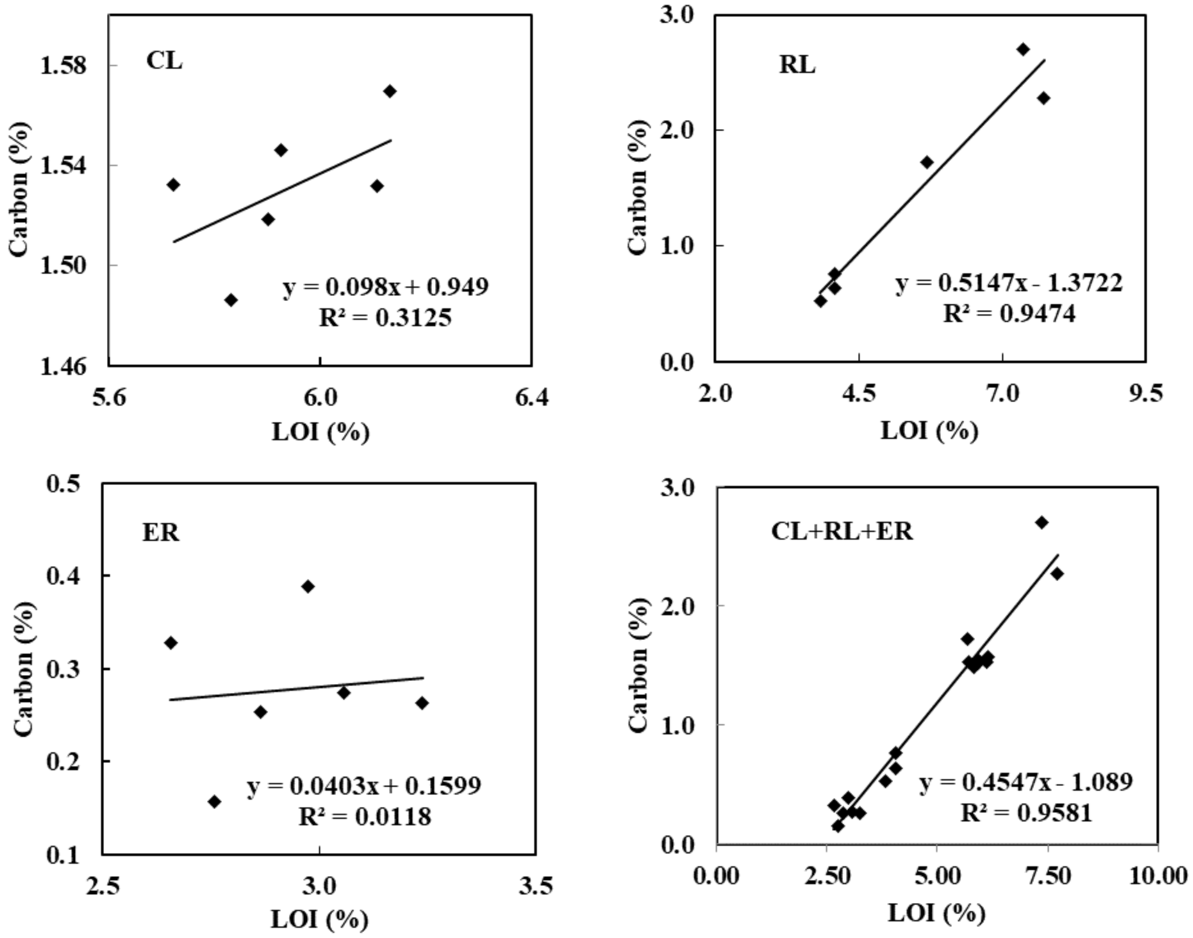

Figure 4. Relationship between total carbon and loss-on-ignition (LOI) for the cropland (CL), restored land (RL), eroded land (ER) and combined results for the three sites (CL+RL+ER).

Table 3. Summary of outputs for regression of soil organic carbon (SOC) and loss-on-ignition (LOI) relating to Figure 4. *Site: CL = cropland, RL = restored land and ER = eroded land. P-values are significant when $p \leq 0.05$.

Site*	Number of samples	Slope	Intercept	R^2	p
CL	6	0.098	0.949	0.3125	0.249
RL	6	0.5147	-1.3722	0.9474	0.001
ER	6	0.0403	0.1599	0.0118	0.837
CL+RL+ER	18	0.4547	-1.089	0.9581	0.000

3.2 Bulk density

Results of bulk densities for the different sites are presented in Table 4. An ANOVA test revealed a significant difference ($p < 0.000$) in mean bulk densities among the sites. In the 0-5 cm depth, the bulk density was significantly higher ($p < 0.000$) in ER than in CL and RL. However, there was no significant difference ($p = 0.067$) between CL and RL. For the 5-15 cm depth, bulk densities for the RL and ER were similar, but both RL and ER differed significantly ($p < 0.005$, $p < 0.003$, respectively) from CL. On average the bulk density for 0-15 cm depth was therefore highest in the ER while CL was the lowest (see Table 4).

Table 4. Summary of results for bulk densities, LOI, SOC concentration and stocks for the study sites. Each sample is a composite of samples from three points and standard errors (SE) calculated at 95% confidence level (mean ± 1.96 × SE). *Site: CL = cropland, RL = restored land and ER = eroded land. Different letters (next to values) within columns represent significant difference ($p \leq 0.05$) between sites for the corresponding depth. ** 0-15 cm depth: values are averages of means for %LOI and %SOC while SOC stocks are sum of means of the 0-5 and 5-15 cm.

Site*	Number of samples	Bulk density (g cm^{-3})	LOI (%)	SOC (%)	SOC (kg C m^{-2})
Depth: 0-5 cm					
CL	10	0.86 ± 0.03a	5.89 ± 0.12a	2.65 ± 0.06a	1.14 ± 0.03a
RL	10	0.78 ± 0.06a	6.93 ± 0.67b	3.12 ± 0.30b	1.20 ± 0.09a
ER	10	1.05 ± 0.05b	2.78 ± 0.16c	1.24 ± 0.07c	0.65 ± 0.05b
Depth: 5-15 cm					
CL	3	1.00 ± 0.03a	5.85 ± 0.13a	2.63 ± 0.06a	2.63 ± 0.06a
RL	3	1.15 ± 0.06b	3.99 ± 0.16b	1.79 ± 0.07b	2.06 ± 0.03b
ER	3	1.17 ± 0.03b	2.95 ± 0.29c	1.33 ± 0.13c	1.55 ± 0.11c
Depth: 0-15 cm**					
CL	13	0.93 ± 0.03	5.87 ± 0.13	2.64 ± 0.06	3.77
RL	13	0.97 ± 0.60	5.46 ± 0.42	2.46 ± 0.19	3.26
ER	13	1.11 ± 0.04	2.87 ± 0.23	1.66 ± 0.10	2.20

3.3 Comparison of soil organic carbon concentrations

The SOC concentrations generally varied among the sites (Table 4). In the 0-5 cm depth, the highest SOC content was found in RL, which was significantly different from CL and ER ($p = 0.004$, $p < 0.000$, respectively). All the three sites were significantly different from each other. However, for the 5-15 cm depth, SOC content was highest in CL compared to RL and ER. Again, there was a significant difference among all the three sites for the 5-15 cm depth. On average, SOC was slightly higher in CL than in RL from 0-15 cm depth (Table 4). Except for RL where a significant difference ($p = 0.001$) was noticed between 0-5 and 5-15 cm depths, the SOC amount at these depths for CL and ER were similar. However, the SOC content in ER for the 5-15 cm depth was slightly higher than at the 0-5 cm depth.

3.4 Comparison of soil organic carbon stocks

A summary of the computed results for SOC stocks (kg C m^{-2}) is presented in Table 4. Unlike the SOC where RL was significantly higher than CL, no significant difference ($p > 0.363$) was observed for SOC stocks between CL and RL at the 0-5 cm depth, although RL was slightly higher. Further, both RL and CL were significantly higher than ER at the 0-5 cm depth. For the 5-15 cm depth, SOC stocks varied significantly among the three sites, decreasing in amount from CL to ER. The total SOC stocks at 0-15 cm depth were thus highest in CL and least in ER.

4. DISCUSSION

4.1 Regression analysis

4.1.1 Total carbon and loss-on-ignition data

The trend of the total carbon data for the sites showed some discrepancies to that of their corresponding LOI values, albeit slightly. Although, the mean total carbon content for CL was constant for both 0-5 and 5-15 cm depths, there was a slight decrease in the LOI values from 0-5 cm to 5-15 cm depth. Similarly, in the ER, the total carbon content decreased in contrast with the LOI values which rather increased from the 0-5 cm to 5-15 cm depth, respectively. However, the total carbon values for RL decreased from 0-5 cm to 5-15 cm depth consistent with their corresponding LOI values. It is not clear what could have accounted for this discrepancy. However, it should be noted that unlike the LOI, where samples were analysed in replicates of two, the total carbon was only analysed once. The discrepancies in the trend of data variation observed for the sites probably influenced the outcome of the predictive equations resulting in poor relationships, especially for CL and ER. Also, the narrow differences noticed in the ranges for the data of the CL and ER may have contributed to the poor predictive equations for these sites. This assertion about the narrow range of influence is supported by the relatively strong predictive equations observed in RL and the combined data (CL+RL+ER), as discussed in the next section.

4.1.2 Relationship between total carbon and loss-on-ignition

Unlike De Vos et al. (2005) who found significant correlations (R^2 around 90 - 99%) between total organic carbon and LOI for different forest and mineral soils in Belgium and were able to develop different predictive equations for these soils, the results of this study showed a poor relationship, at least for the CL and ER. The reason for this might be attributable to the few numbers of samples (6 samples per site) for the total carbon and LOI analysis used in this study. Furthermore, the relatively narrow ranges observed in the total carbon and LOI data of the CL and ER possibly contributed, as a strong correlation was observed for the RL, which had relatively wide ranges for total carbon and LOI. De Vos et al.'s (2005) study had a huge number of samples (66 forest and 654 mineral soils) with wider ranges for total organic carbon and LOI.

Nevertheless, in this study, the combined data of all the sites (CL+RL+ER) showed a strong correlation with a slope of about 0.455, which is closer to the slopes ranging from 0.485 to 0.515 found by Áskelsdóttir & Guðmundsson (2009) for Geitasandur near Gunnarsholt. A critical review by Pribyl (2010) arguing against the commonly used "van Bemmelan factor" of 58% SOM as SOC revealed that several studies found different SOC – LOI conversion factors, supporting the variability of the factor for different soils, because the carbon content of soil is influenced by many factors such as soil depth, amount and composition of organic matter, clay content and vegetation cover. Considering the fact that the sites of this study were relatively close to each other (see Fig. 1) as well as the findings of Áskelsdóttir &

Guðmundsson (2009) and the arguments of Pribyl (2010) above, it appeared reasonable to apply the slope from the combined data to estimate SOC from LOI results.

4.2 Bulk density

The average bulk densities of the sites ranging from about 0.9 to 1.1 g cm^{-3} were similar to bulk densities (approximately 1.0 g cm^{-3} for 0-5 cm and 1.3 g cm^{-3} for 5-15 cm) reported for Andosols around the Gunnarsholt area (O Arnalds et al. 2013), but well above the range of 0.3 – 0.8 g cm^{-3} reported for typical Icelandic Andosols (O Arnalds 2008). The relatively high densities of the sites may be an indication that the soils are sandy loam (Brady & Weil 2014), consistent with the findings of O Arnalds et al. (2013). The increase in bulk densities with depth from the 0-5 to 5-15 cm in the CL and RL may be explained by high organic matter content, or possibly an influence of restoration for the surface layer. This assertion agrees with the interpretation of Ritter (2007) who found lower bulk densities in the 0-10 cm depth compared to 10-20 cm depth and suggested that the lower bulk densities might have resulted from high organic matter content or the effect of restoration on the soil with time.

4.3 Soil organic carbon concentrations

The SOC estimates reported here are within ranges reported for degraded soils (< 2%) and undisturbed soils (between 2 and 8%) in Iceland for the 0-5 cm depth of soil layer (Óskarsson et al. 2004). SOC concentrations in the 0-5 cm depth of soil were significantly higher in RL than in the CL and ER in this study. However, the SOC concentration for the RL was higher compared to SOC values (range: 2.5-2.8%) reported for 50-year-old revegetated sites (grasslands) near Mt Hekla (Hunziker et al. 2019). The significant decrease of SOC observed from 0-5 to 5-15 cm depths in the RL was also similar to results reported by Óskarsson et al. (2004) for both disturbed and undisturbed soils in Iceland. Ritter (2007) found in east Iceland SOC concentrations around 5% and 3% for 0-10 and 10-20 cm depths, respectively, for heath land, which was compared with reforested sites of native Downy birch (*B. pubescens* Ehrh.) and Siberian larch (*L. sibirica* Ledeb.). Similarly, Hunziker et al. (2019) found higher SOC concentrations in 0-5 cm depth than in 5-10 cm depth for grassland sites where the SOC concentration decreased from 2.5 to 2.0%, respectively. The substantial decrease in SOC concentrations from the surface to subsurface layer might probably be due to higher organic matter content (due to the presence of vegetation) in the surface layer than in the subsurface layer.

An interesting finding was the significantly higher SOC concentration in CL than that in RL at the 5-15 cm depth. However, this was most likely due to the incorporation of crop residue, which is the practice in the CL, which may have buried organic matter deeper into the soil, redistributing carbon among soil layers, as suggested by Ferro et al. (2014). It is also possible that the annual input of inorganic fertilizer by the farmer increased carbon sequestration in the CL and perhaps increased SOM, resulting in increased SOC, although most of it was probably removed by harvesting. Another likelihood for the higher SOC content in the CL may have been the influence of the barley, which is reported to have a deep root system with the potential of extending about a meter deep, and a large volume occurring in the top 10 cm depth of soil (Matuszek 2017). Also, application of chicken manure in 2019 is likely to have caused some increase in carbon stocks in CL. The total application of chicken manure was approximately 4.50 ton/ha (Table 1). The dry matter content of chicken manure used in Gunnarsholt is around 60% (Jóhannsson et al. 2017) which gives 2.70 tons dry matter/ ha or 0.27 kg/m^2. As a certain part of dry matter is ash, organic matter will be lower than this and the carbon content still lower as organic matter includes other materials besides carbon. Compared to the total carbon stock in CL (0-15) of 3.77 kg/m^2, it is unlikely that the chicken manure had had a considerable impact on carbon stocks in CL. Previous studies have reported increased SOC concentrations for croplands through crop residue retention, fertilisation and manure application (Manna et al. 2005; Chivenge et al. 2007; Dalal et al. 2011).

The significantly lower SOC concentrations observed for both the 0-5 and 5-15 cm depths in the ER compared to CL and RL were not unexpected as similar results have been found for eroded lands in Iceland (see O Arnalds et al. 2013). In contrast, Hunziker et al. (2019) found far higher SOC concentrations approximately 1.7 and 3% for 0-5 and 5-10 cm depths, respectively, for eroded land than this study, and their values were higher compared to some of the revegetated and afforestation sites they studied. However, the slightly higher SOC concentrations in the 5-15 cm than in the 0-5 cm depth were consistent with results reported by Hunziker et al. (2019), where higher SOC concentrations were reported for the subsurface layer (5-10 cm) than in the surface layer (0-5 cm) for barren land. Evidently, the observed difference between the ER and the managed lands (CL and RL) supports suggestions that land use and management practices such as revegetation (O Arnalds et al. 2000) and conservation agricultural practices (Lal 2004) have great potential to improve SOC concentrations.

Comparing the RL (which is about 44 years) in this study to the study of Hunziker et al. (2019) on reforested and natural forest sites showed that the RL had a relatively higher SOC content than reforested sites with birch (15 and 20 years: having around 2.1 and 2.9% median values respectively), whilst the RL value was slightly lower compared to the 25 year old birch (around 3.4% median value) at the 0-5 cm depth. Furthermore, the SOC contents for RL were far lower compared to 50-year old reforested birch (8.1% median value) and old natural birch (6.3%) sites in Hunziker et al. (2019). The high levels of SOC contents in the older birch sites of Hunziker et al. (2019) than in their younger birch sites as well as the RL in this study suggests that the potential of restored lands to sequester carbon depends on time and the type of vegetation. Hence land restoration should be viewed as a long-term intervention for carbon sequestration and eventual climate change mitigation.

4.4 Soil organic carbon stocks

In this study, the SOC stocks found at the 0-5 cm depth appeared similar to results reported in the literature for Icelandic soils. Hunziker et al. (2019) found about 0.7 kg C m^{-2} for severely eroded land and around 1 kg C m^{-2} for grassland sites at the 0-5 cm depth. The results in this study for the top 15 cm depth are somewhat similar to SOC stocks (ranging between 2 and 4 kg C m^{-2}) found by Aradóttir et al. (2000) for the top 20 cm depth in over 20-50 years revegetated lands (through grass seeding and fertilisation) near Gunnarsholt. Ritter (2007) found approximately 2 kg C m^{-2} at 0-10 cm depth and about 1.7 kg C m^{-2} at 10-20 cm depth for a heath land in east Iceland.

The SOC stocks presented in this study for CL and RL, which have undergone restoration, are clearly different from the eroded land which has never received any revegetation efforts. Assuming that CL and RL were both at the same state like ER before revegetation (as suggested by the history of the sites), and that they would have had similar SOC stocks as ER, the current study found significantly higher SOC stocks of more than 1 kg C m^{-2} in CL and RL than in ER in the top 15 cm depth of soil. This finding agrees with the conclusions of previous studies (see Aradóttir et al. 2000; O Arnalds et al. 2000, 2013) that land restoration has the potential to increase carbon sequestration in soils. The unexpected finding of CL having more SOC stocks in the 0-15 cm layer than RL will require further investigation to confirm suggestions that farm management practices like crop residue incorporation, inorganic fertilizer and manure application might have contributed to increase organic carbon content and ploughing helped redistribute this organic carbon to the subsurface depth.

The SOC stocks in the younger birch sites of Hunziker et al. (2019) were lower than in the RL of this study for the 0-5 cm depth. In contrast, the SOC stocks were approximately 1 kg C m^{-2} higher for the reforested birch (50-year old) and old natural birch sites than in the RL of this study for the 0-5 cm depth. Although Hunziker et al. (2019) suggested that lesser SOC stocks for the younger birch sites might imply that C sequestration increases with age as is evident in the older birch sites, it appears, from this comparison, that reforestation will probably retain more C in soils than land management through revegetation without forest and conservation agriculture. Albeit, it probably takes a long time (> 50 years) (O Arnalds et al. 2000) to see this potential. Thus, the carbon sequestration rate of the sites in the present study should be of interest for future studies as that could further explain the sequestration potential of the different sites.

4.5 Sources of uncertainty in results

It is important to point out that the results of this study are only an estimation of the possible SOC concentrations and stocks due to the low number of samples used and the methodology adopted in sampling and analysing SOC content. As earlier stated, the single transect approach adopted in the sampling may not be very representative of the true distribution of SOC in the sites and this may have skewed the results. Also, the LOI method has largely been described by many researchers (see Nelson & Sommers 1996; Pribyl 2010) as being less accurate compared to other methods like the dry combustion method, because it (LOI) only estimates organic matter based on weight loss through combustion. In the process of heating at high temperature, inorganic components including chemically bound water, clay compounds and carbonates in the soil break down and increase weight loss leading to possible overestimation of organic matter (Nelson & Sommers 1996). Furthermore, the likelihood of incomplete combustion of organic matter has also been reported as a source of underestimation of organic matter in applying the LOI (Pribyl 2010), whereas Heiri et al. (2001) reported several factors, including duration of heating, sample size and sample position inside the furnace, that tend to influence the quality of LOI results.

Nonetheless, the findings of this study showed a clear difference between degraded lands (ER) and managed lands (CL and RL) and demonstrated that restoration of degraded lands holds promise for sequestering C in soils, which could help improve soil quality but also mitigate GHGs in the atmosphere. The lack of a significant difference between the SOC content of CL and RL in the 0-15 cm depth suggests that croplands could be used sustainably to provide required food and at the same time maintain or improve SOC levels to minimise GHGs.

4.6 Policy implications

The findings may have important implications for Icelandic SOC research. In particular, the high SOC content in the CL should be of interest to Iceland. SOC research in croplands seems to be limited in Iceland, hence the CL result presents an opportunity for the country to revise C sequestration policy in order to harness the C storage potential of croplands, especially that its land area under cultivation for cereal crops is reportedly increasing (Reykdal et al. 2014).

Equally, the results present an interesting opportunity to make a case for SOC research in similar sites in Ghana, where land restoration is approached through reforestation, natural regeneration and conservation agriculture, among others. It will be fascinating to see if results from such a study will follow a similar pattern, especially because of the different climatic conditions of the two countries. With the knowledge and skills acquired through this study, especially in applying the LOI method, the researcher is equipped to conduct SOC research in Ghana. Although the LOI method has been described as less accurate (Nelson & Sommers 1996), it could be very useful in analysing huge numbers of samples, particularly in a developing country like Ghana where funding may be a constraint to research. In such situations, LOI results could be regressed with results of only a few samples analysed through dry combustion in order to minimise funding challenges.

5. CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to assess the variation in SOC concentrations and stocks among cropland, restored land and eroded land in Iceland. SOC concentration was higher in RL than in CL and ER, at the 0-5 cm soil depth. Interestingly, higher SOC concentration was found in CL than in RL for the 5-15 cm depth. No significant difference was observed between the SOC content of CL and RL at the 0-15 cm depth (average of 0-5 and 5-15 cm depths). The total SOC stocks at 0-15 cm depth was highest in CL and least in ER, though the CL was only slightly higher than the RL. The observed differences between the managed lands (CL and RL) and the ER suggest that land restoration and conservation agricultural practices have great potential to improve SOC concentrations. The unexpected findings in the CL will require further investigation to confirm suggestions that farm management practices like crop residue incorporation, inorganic fertilizer and manure application and/or barley root system might have contributed to the increased SOC content and that ploughing helped redistribute this SOC down to the subsurface. The carbon sequestration rate of the sites should also be of interest for future studies since this could explain the sequestration potential of the different sites.

Based on the findings of this study, it is recommended that: (1) Land restoration through revegetation and reforestation as a land management approach should be encouraged as it also has the potential of increasing SOC content, and (2) where restored land is to be converted for cropping, farm management practices such as crop residue retention/incorporation, fertilization and manure application should be encouraged to help increase or maintain the SOC levels.

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