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# Carbon sequestration and reclamation of severely degraded soils in Iceland

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## SUMMARY

Iceland has extensive deserts and barren patches in spite of it’s humid environment. The soils of the deserts are sandy Andisols, with limited sources of macro-nutrients and low water holding capacity. Andisols have a general tendency to immobilize carbon, and undisturbed, fully vegetated Andisols in Iceland often contain >40 kg C $m^{-2}$, often to more than 1.5 m depth. The difference between soils of barren areas, with <1 kg C $m^{-2}$ and undisturbed Andisols indicates that reclamation of degraded sites may have high potential for carbon sequestration.

The objective of this research was to develop methods to determine carbon sequestration rates in soils in relation to reclamation of degraded land in Iceland and to verify sequestration rates for reclamation activities. Carbon was determined in soils of 33 reclamation areas of different age throughout Iceland. At many sites, adjacent non-reclaimed areas were also sampled for comparison.

The results show that reclamation of Icelandic deserts results in an average sequestration rate in soils of 0.6 t C $ha^{-1}$ $yr^{-1}$, which is maintained >50 yrs. This number does not include sequestration in aboveground or belowground biomass, (0.01–0.5 t $ha^{-1}$ $yr^{-1}$), which is reported in a concurrent paper (Aradóttir *et al.*, 2000).

Soil carbon sequestration rates were highly variable. In some areas, sequestration rates slowed when plant succession was restrained ecological thresholds. It is important to determine these thresholds and find economic means to overcome them to promote carbon sequestration over longer periods. Results suggest that sequestration of carbon to mitigate greenhouse gas emissions can be monitored and verified in Iceland.

Key words: Andisols, carbon sequestration, climate change, deserts, reclamation, restoration.

## YFIRLIT

### *Binding kolefnis í jarðvegi á uppgræðslusvæðum á Íslandi*

Í greininni er fjallað um niðurstöður rannsókna á bindingu kolefnis á uppgræðslusvæðum. Verkefnið er unnið í tengslum við sérstakt átak ríkistjórnarinnar til að auka bindingu kolefnis með skógrækt og landgræðslu til að vega á móti losun gróðurhúsalofttegunda. Gerð hefur verið grein fyrir fyrstu niðurstöðum rannsókna á bindingu með skógrækt á öðrum vettvangi (Arnór Snorrason o.fl., 2000), en auk þess er gerð grein fyrir bindingu kolefnis í gróðri á landgræðslusvæðum í þessu sama hefti Búvísinda (Ása L. Aradóttir o.fl., 2000).

Mun meira er bundið af kolefni í jarðvegi (>1500–2300 Gt C) en öðrum hlutum lífkerfisins að heimshöfunum undanskildum. Um 750 Gt C eru í andrúmsloftinu, en 500–560 Gt C í gróðri, þar af um 360 Gt

C í skógi (sjá IPCC, 2000). Því er nú bæði litið til jarðvegs og gróðurs sem hugsanlegra valkosta til að binda kolefni úr andrúmsloftinu. Binding í jarðvegi er ekki síst góður kostur þar sem um leið er aukin framleiðni og virkni vistkerfa þar sem vistkerfi eru endurheimt á auðnum og hnignuðum svæðum.

Íslenskur jarðvegur telst til svonefndrar eldfjallajarðar (Andosol eða Andisol), en slíkur jarðvegur hefur tilhneigingu til að binda kolefni í jarðvegi umfram annan jarðveg þurrlendis (sjá t.d. Wada, 1985; Shoji o.fl., 1993). Mikið af kolefni er bundið í íslenskum jarðvegi, oft >40 kg/m$^2$ í þurrlendisjarðvegi, en >90 kg/m$^2$ í jarðvegi votlendis. Jarðvegur auðnanna telst einnig til þessarar jarðvegsgerðar, en þar er lítið af kolefni. Þegar gróður festir rætur í auðnunum taka lífræn efni að safnast fyrir í jarðveginum, jafnframt því sem hann verður smám saman frjósamari. Því er hugsanlegt að binda umtalsvert kolefni í jarðvegi við landgræðslu á Íslandi. Það er mjög mikilsvert að komast að því hve hraðfara þessi binding er, ef hún á að verða viðurkennd mótvægisleið vegna losunar gróðurhúsalofttegunda.

Markmið rannsóknanna var að þróa aðferðir til kanna bindingu kolefnis í jarðvegi við landgræðslu og ákvarða hve mikil binding hefur orðið við hið sérstaka átak ríkisstjórnarinnar til að binda kolefni með landgræðslu og skógrækt.

Kolefni var kannað í jarðvegi á 62 stöðum á 33 landgræðslusvæðum á landinu (1. mynd, 2. tafla). Jarðvegssýnum var yfirleitt safnað með jarðvegsbor (2 og 5 cm í þvermál) og þau voru tekin úr ákveðnum dýptarbilum á hverjum stað: 0–10, 10–20 og 20–30 cm. Hvert sýni var samsett úr fimm kjörnum, og þrjú slík sýni voru tekin á hverjum stað. Þar sem mikið grjót kom í veg fyrir notkun jarðvegsbors voru sýni tekin úr jarðvegssniðum. Sýnin voru tekin úr jarðvegi á misgömlum landgræðslusvæðum, en einnig voru sýni tekin til samanburðar í jaðri svæðanna þar sem engin landgræðsla hafði átt sér stað. Grjót (>2 mm) var ákvarðað í hverju sýni sem og rúmþyngd og kolefni fínefna (<2 mm). Allar dýptir voru lagðar saman og þessar stærðir eru síðan notaðar til að ákvarða kolefnismagn jarðvegsins í kg C/m$^2$.

Bindihraði var bæði kannaður með aðhvarfsjöfnum (3. mynd) og með því að bera saman landgræðslusvæði og svæði þar sem engin landgræðsla hefur átt sér stað. Binding þar sem sáð er í sendnar auðnir er að meðaltali um 0,6 t C/ha á ári. Þessi binding er sambærileg eða meiri en binding sem verður við að breyta ræktarlandi í graslendi víða annars staðar (sjá Sampson og Scholes, 2000; IPCC, 2000), en er bæði örari og varir í lengri tíma en víða annars staðar við á landgræðslu á röskuðum svæðum (IPCC, 2000).

Rannsóknirnar sýna ljóslega að á sumum svæðum hægir mjög á bindingunni þegar náttúruleg gróðurframvinda er hæg eða stöðvast. Því er mikilvægt að finna hagkvæmar leiðir til þess að yfirvinna þröskulda sem stöðva framvindu vistkerfanna þar sem það gerist.

Með því að nota meðalbindihraða og tölulegar upplýsingar frá hverju svæði fyrir sig má fá glögga mynd af bindingu á landgræðslusvæðum á Íslandi, en slíkra upplýsinga er krafist í tengslum við loftslagssamning Sameinuðu þjóðanna (FCCC).

## INTRODUCTION

Efforts to sequester carbon by restoring severely degraded lands are among major actions taken by the Icelandic government in relation to the implementation of the Framework Convention for Climate Change (FCCC). Efforts are made to sequester carbon both in soils and aboveground biomass. This program is termed the "*Carbon Sequestration by Reclamation Program*" (*CSR-Program*).

An important part of the CSR-Program is to verify the carbon sequestration accompanying ecosystem restoration activities. A special project was established at the initial stages of the CSR-Program to develop methods for measuring sequestration. This project contained four components: sequestration in trees and by forestation, sequestration in biomass other than trees, sequestration in soils, and measurements of carbon fluxes. Here we report carbon sequestration in soils undergoing revegetation/restoration efforts in Icelandic deserts. Aradóttir *et al.* (2000) reported results for sequestration by rangeland vegetation. Sequestration by reforestation was discussed by Snorrason *et al.* (2000).

The terms "revegetation" and "reclamation" will be used interchangeably to refer to treatments aimed at restoring ecological processes on degraded lands.

## SOILS AND CARBON SEQUESTRATION

### *Carbon levels in soils*

Soils are among the most important organic carbon reservoirs exceeded only by fossil fuels and oceans. Organic carbon storage in soils has been estimated as 1500–2300 Gt C, which compares to 760 Gt C in the atmosphere and 500–560 Gt C in biomass (Schlesinger, 1991; Lal *et al.*, 1997; Bolin and Sukumar, 2000; IPCC, 2000; Jobbágy and Jackson, 2000). Forest vegetation stores about 360 Gt C (see Bolin and Sukumar, 2000; IPCC, 2000). Agricultural practices and land degradation are believed to have caused massive depletion in soil organic carbon (ICPP, 2000), but these quantities are uncertain and are very dependent on the time frame of reference (e.g., 100 years or 5000 years).

The relatively high levels of organic carbon in soils have prompted interest in managing soils to increase carbon sequestration to mitigate effects of greenhouse gas emissions. The possibilities of sequestering carbon by special activities that enrich carbon in soils have been extensively investigated (see e.g., Lal *et al.*, 1997, 1998a). However, verification is difficult, especially if measurements are made only over short time periods. Heterogeneity of soils and the difficulty in determining bulk density are additional challenges for quantifying and monitoring soil organic carbon over large areas. Other approaches, such as modeling gas fluxes (e.g., Valentini *et al.*, 2000) and radiocarbon dating of organic matter (e.g., Trumbore, 2000) are promising approaches which can be used in conjunction with conventional methods.

The possibilities of managing land use to promote carbon levels of soils of agricultural lands has been more thoroughly investigated than have those in rangelands. Degraded rangelands are of special interest because of their geographically extensive area and because of added benefit of restoring other ecosystem goods and services (e.g., A. Arnalds, 2000; Lal *et al.*, 1999; see also Sampson and Scholes, 2000). It is important to ensure that carbon sequestration in soils and biomass can be adequately verified, if such efforts are included as a method to mitigate greenhouse gas emissions.

Extensive databases have been constructed for organic carbon in soils in several countries, including the United States (Lal *et al.*, 1998b), Canada (Lacelle, 1997; Tarnocai, 1997), Indonesia (Reich *et al.*, 1997) and Albania (Zdruli *et al.*, 1997). Soil maps, soil classification, and geographical information systems (GIS) have been used to combine spatial data with laboratory analysis of the soils.

Organic carbon content of soil orders (major types of soils) have been reported by Eswaran *et al.* (1993). Although their distribution is limited (about 1.7 million km$^2$), Histosols (organic soils) store the greatest quantities of soil carbon, both in terms of density (205 kg C m$^{-2}$) and global quantity (357 Gt C). The assessment by Eswaran *et al.* indicates that Andisols, soils that form in volcanic ejecta, have highest organic carbon density when Histosols are excluded (31 kg C m$^{-2}$), while organic carbon density of other soil orders are commonly near 10 kg C m$^{-2}$ (Eswaran *et al.*, 1993). The carbon levels Eswaran *et al.* (1993) reported for Andisols may be underestimated judging from discussion provided by Jobbágy and Jackson (2000) and because Andisols commonly store more carbon at depths than other dryland soils (see e.g., Shoji *et al.*, 1993). The high levels of carbon reported for Andisols are attributed to the tendency of such soils to immobilize organic molecules (see e.g., Wada, 1985; Shoji *et al.*, 1993).

### *Icelandic soils*

Iceland is a volcanic island dominated by Andisols or andic intergrades of other soil orders (O. Arnalds, 1999ab; Arnalds *et al.*, 2000). Permafrost is nearly absent, but soils rich in organic matter are common. Detailed examination of well-developed soil profiles show carbon densities of 40 kg C m$^{-2}$ (brown allophanic Andisols; Arnalds *et al.*, 1995) to >90 kg C m$^{-2}$ (wetland soils, Andisols and Histosols, see Arnalds *et al.*, 2000). A preliminary assessment estimated

**Table 1**. Selected soil characteristics of Icelandic deserts (see Arnalds and Kimble, 2000, for more detailed information).
*1. tafla. Nokkur einkenni íslensks jarðvegs á auðnum; annars vegar jarðvegur á melum (M) og hins vegar sendinn jarðvegur.*

| Type | Depth<br>m | C<br>% | pH | Clay<br>% | CEC<br>meq/100 g | 15 bar $H_2O$<br>% |
|---|---|---|---|---|---|---|
| M (Virtric Andisol)[a)] | 0.2–0.5 | 0.5–1.5 | 6.5–7 | 5–15 | 5–15 | 5–15 |
| S, SH, SM (Sandy Andisol)[a)] | 0.1–2 | 0.1–1.0 | 6.5–7 | 1–5 | 2–10 | 1–10 |

a) See Arnalds *et al.*, 2000.

the carbon content of Icelandic soils at about 2550 million t C (O. Arnalds, 1999b). This estimate contains large uncertainties due to map scale and limited soil inventories. A lower number (2149 million t C) was recently reported to the FCCC (unpublished document).

Deserts now cover about 40 000 km$^2$ in Iceland. Soils of these deserts have been described by Arnalds and Kimble (2000). They are primarily Andisols, rich in volcanic glass, but with relatively low allophane clay and organic C (0.08–0.5 kg C m$^{-2}$) content. Present-day surfaces currently covered with barren patches or more continuous deserts were often previously covered with fertile allophanic soils and full vegetation cover. Erosion has since removed the brown Andisol mantle and/or sand encroachment has taken place (O. Arnalds, 1998, 1999a, 2000; Arnalds *et al.*, 1997). The desertified ecosystems are the subject of revegetation and restoration efforts by the government and Non Governmental Organizations (see A. Arnalds 1999, 2000).

The extent of Icelandic deserts was surveyed during a national assessment of soil erosion (Arnalds *et al.*, 1997). Desert surfaces were classified into several geomorphological landunits, which were subsequently used for surface characterization during the *CSR-Program*. The following surface types occur in the research presented here (Tables 1 and 2):

- *Melur (M and A)*. Old till surfaces (typical melur, M in Table 2) or more recent glaciofluvial flood plains (A). The surface is gravelly, as frost-heave lifts stones to the surface. The till surfaces have typically previously been covered with fine textured allophanic Andisols, but man-induced erosion has since removed this mantle, exposing the old till surface (about 10 000 yrs old). The floodplains are more gravelly and usually quite packed (high bulk density of the <2 mm fraction).
- *Sandar (S)*. Sand-fields, mainly consisting of volcanic glass originating from glacial rivers or volcanic ash deposition. These surfaces are often unstable, subjected to intense wind erosion, infertile, and subjected to periodic draught due to low water holding capacity (Table 1).
- *Sendnir melar* (*SM*, sandy gravel). The sandy gravel surfaces are melar where eolian sand (2 to >20 cm thick) has been deposited on to the gravelly surface. Frost-heave lifts up coarse fragments to maintain the gravelly surface over sandy materials.
- *Sendin hraun (SH;* sandy lava surfaces). These surfaces occur where sand has been deposited into Holocene lava surfaces by eolian processes, glaciofluvial floods and/or volcanic ash deposition.

## MATERIALS AND METHODS

### *Sites and locations*

A total of 62 **locations** at 33 reclamation **sites** (Figure 1) were sampled during the summers of 1998 and 1999. At several sites, multiple locations were sampled, e.g., revegetation treatments of different ages or untreated locations at the site. Where possible, we sampled paired locations where no reclamation efforts had been

**Table 2**. Description of sampling sites.
*2. tafla. Yfirlit um sýnatökustaði.*

| South Iceland | | | | | | North Iceland | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Site | kg C m$^{-2}$ | Age | Surface type[a] | Treatment[a] | No. | Site | kg C m$^{-2}$ | Age | Surface type | Treatment |
| 3 | Kálfafell | 1.32 | 30 | A | E | 23 | Hólssandur-0 | 0.95 | 0 | SM | O |
| 4 | Steinasandur | 2.70 | 28 | A | G | 24 | Hólssandur | 2.19 | 38 | SM | G |
| 5 | Breiðamerkursandur | 0.99 | 43 | A | E | 25 | Ærlækjarsel-0 | 0.04 | 0 | S | O |
| 6 | Ásakvíslar | 3.87 | 30 | SH | G | 26 | Ærlækjarsel | 0.90 | 38 | S | G |
| 7 | Ásakvíslar | 1.42 | 30 | SH | E | 27 | Ássandur | 1.01 | 28 | A | G |
| 8 | Atlaey | 2.36 | 1 | SM | G | 28 | Bakkahlaup | 0.63 | 28 | SM | G |
| 9 | Atlaey-0 | 0.92 | 0 | SM | O | 29 | Vatnsbæjargirðing | 0.92 | 38 | S | G |
| 10 | Bakkavöllur | 0.57 | 42 | S | G | 30 | Vatnsbæjargirðing | 2.46 | 45 | S | E |
| 11 | Vakalág | 1.74 | 38 | SM | E | 32 | Gautlönd | 1.00 | 8 | SM | G |
| 12 | Rauðuskriður | 0.22 | 64 | A | E | 34 | Baldursheimur-0 | 0.47 | 0 | SM | O |
| 13 | Gunnarsholt, lúp. | 1.47 | 28 | SM | G | 33 | Baldursheimur | 0.99 | 8 | SM | G |
| 14 | Langibakki | 2.95 | 26 | SM | G | 35 | Grænavatn | 0.44 | 8 | SM | G |
| 15 | Sandatún, lúp. | 2.94 | 48 | SM | G | 36 | Grænavatn-0 | 0.28 | 0 | SM | O |
| 16 | Vestur-hraun | 2.36 | 23 | SH | G | 37 | Garður | 2.06 | 20 | SH | G |
| 18 | Svínhagamelar | 0.18 | 0 | S | O | 38 | Garður-0 | 0.15 | 0 | SH | O |
| 19 | Selsund | 0.53 | 0 | SH | O | 39 | Heiðasporðsgirðing | 0.91 | 30 | SH | G |
| 20 | Sandá | 0.82 | 23 | SM | G | 40 | Hólasandur, lúp. | 0.24 | 7 | SM | G |
| 21 | Krísuvík | 1.69 | 4 | SM | G | 41 | Hólasandur-0 | 0.39 | 0 | SM | O |
| 22 | Sandskeið | 1.26 | 20 | M | G | 42 | Hólasandur, uppgr. | 3.84 | 25 | SM | G |
| 43 | Leirdalur 94 | 0.32 | 5 | S | G | 56 | Árskógar 97 | 0.09 | 2 | S | G |
| 45 | Leirdalur 98 | 0.11 | 1 | S | G | 57 | Árskógar-0 | 0.07 | 0 | S | O |
| 46 | Leirdalur-0 | 0.13 | 0 | S | O | 58 | Kvensöðull 94 | 0.36 | 5 | S | L |
| 47 | Sauðafell | 3.39 | 40 | S | G | 59 | Kvensöðull 98 | 0.16 | 1 | S | L |
| 48 | Skógey 86 | 0.43 | 13 | S | G | 66 | Kvensöðull-0 | 0.08 | 0 | S | O |
| 49 | Skógey 87 | 1.28 | 11 | S | G | 60 | Vatnsbæjargirð.60 | 0.50 | 39 | S | G |
| 50 | Skógey 90 | 0.58 | 9 | S | G | 61 | Vatnsbæjargirð.85 | 0.59 | 14 | S | G |
| 51 | Skógey 96 | 0.31 | 3 | S | G | 62 | Vatnsbæjargirð.94 | 0.26 | 5 | S | G |
| 52 | Stelpa | 0.27 | 26 | S | L | 63 | Ærlækjarsel 93 | 0.21 | 6 | S | G |
| 53 | Hólar-0 | 1.28 | 0 | M | O | 64 | Ærlækjarsel 97 | 0.11 | 2 | S | G |
| 54 | Hólar 88 | 2.05 | 11 | M | G | 65 | Ærlækjarsel-0 | 0.07 | 0 | S | O |
| 55 | Hólar 97 | 1.62 | 2 | M | G | | | | | | |

a) See text for explanation.

undertaken for comparison. A brief description of each site is given in Table 2.

## *Reclamation treatments*

Revegetation and restoration efforts are done by various methods in Iceland. Following is a brief description of the treatments in the study (see also Aradóttir *et al*., 2000).

**Seeding and fertilization** is the most commonly used method. Usually the areas are seeded by introduced grasses such as *Festuca rubra* and *Deschampsia beringensis*, and fertilized two years with about 100 kg N ha$^{-1}$, supplemented by phosphorus and potassium. Farmers often use organic fertilizers and old hay for revegetation purposes, which is also included in this treatment, together with Lupine legume seeding (G indicating treatment in Table 2).

**Lymegrass** (*Leymus arenarius*) fertilized with about 100 kg N ha$^{-1}$ is used for stabilizing active eolian sand (L in Table 2).

When desert areas are excluded from grazing, vegetation cover often develops as a result of secondary succession. The rate of succession is quite variable and site dependent. This treatment is termed **exclusion** (E in Table 2).

### *Sampling*

Sampling density was based on variability tests reported by Arnalds *et al.* (1999, 2000). At each location three samples were obtained for carbon analysis. Each sample was a composite of five cores. The cores were obtained with 2 and 5 cm diameter samplers, depending on site characteristics, and each core was split into three depths: 0–10 cm, 10–20 cm, and 20–30 cm. Where gravel prevented coring, a pit was dug with a shovel, and samples were collected from within the respective 10 cm depth increments. It should be noted that the soils are very shallow and deeper sampling adds very limited amount of carbon to the total content (<1% addition to the carbon stored at the location) with the exception of the lymegrass locations (Ólafur Arnalds, unpublished data).

### *Sample treatment and analysis*

Each sample was air-dried and passed through a 2 mm sieve. The mass and volume of the coarse fraction (>2 mm) and the mass (dry weight) of the fine fraction were quantified. The fine fraction was dried at 60°C and analyzed for carbon concentration by dry combustion with a Leco-CR12 carbon analyzer (Nelson and Sommers, 1982).

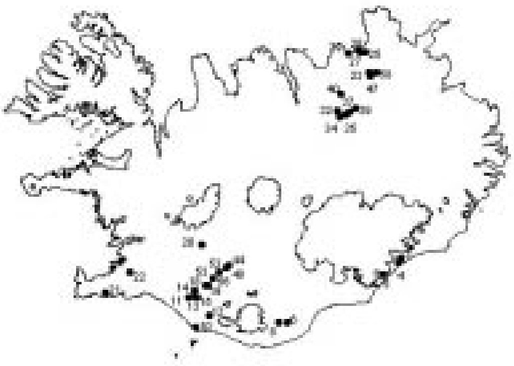

**Figure 1**. Samplings sites. Each site can have several sampling locations. Numbers refer to sampling locations (Table 2), but only one location number is shown for each site in the figure.
*1. mynd. Sýnatökustaðir. Tölur gefa til kynna númer í 2. töflu.*

All depth intervals were combined for one value reported as kg C m$^{-2}$. Coarse fragments (>2 mm) were excluded from the calculations and the carbon mass of the fine fraction (<2mm) was adjusted for bulk density of that fraction. Bulk density was determined by a core method in sandy areas but "compliant cavity" method at the gravelly sites (see Soil Survey Staff, 1996).

Data analysis included two approaches. The first involves a regression of carbon content and treatment age, using the slope of the regression line as an estimate of annual carbon sequestration. The second method compared paired revegetated versus untreated control sites. Regressions were based on raw rather than averaged data points using the SPSS statistical package (V. 10.0).

## RESULTS

### *A general "regression fit" method*

Carbon storage at each site (kg C m$^{-2}$) as a function reclamation treatment age (yrs) for all locations is shown in Figure 2. A regression for all locations and reclamation treatments resulted in average sequestration rate of 0.027 kg C m$^{-2}$ yr$^{-1}$ ($C=0.59+0.027\times Age$; $r^2=0.20$, $P<0.001$, $n=160$).

The data were analyzed by reclamation treatment (Table 2) and geographical location (North and South Iceland), and run separately for the most common substrate types (Figure 3). The treatment groups in Figure 3 include general seeding and fertilizing (denoted G in Table 2, including organic fertilizers), untreated locations (O) and others, such as exclusion from grazing (E). The lymegrass treatments were excluded as such sites are subjected to substantial eolian deposition resulting in burial of accumulated carbon. The data was examined for the sandy sites separately (S+SM+SH surfaces), which were by far the most common substrates in the dataset. Three sites, Atlaey, Sauðafell, and Krísuvík, have the occurrence of scattered old soil remnants rich in organic carbon and they are omitted from the regression analysis. The data for the Vatnsbæjargirðing were characterized by extreme values, both low and high, (locations 29, 30, and 60–62 in Table 2). The reason is quite variable treatment within that site, with continuous fertilization in places (for lymegrass seed-harvesting) and eolian sedimentation and lack of fertilizers in other places. This site was therefore excluded from regression analysis.

The North Iceland locations in Figure 3 show sequestration rates of 0.052 kg C $m^{-2}$ $yr^{-1}$ (C=0.31+Age×0.052; $r^2$=0.49, P<0.001, n=55), while the South Iceland data indicate rate of 0.063 (C=0.44+Age×0.063; $r^2$=0.68, P<0.001, n=16).

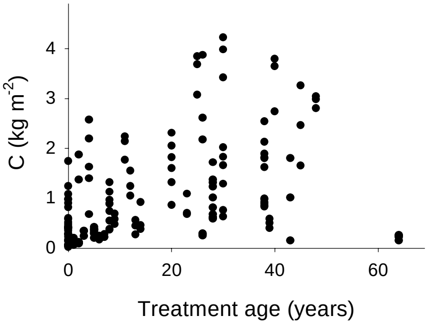

**Figure 2**. Soil carbon density as a function of reclamation treatment age (including only protection from grazing). All locations.
*2. mynd. Kolefnissöfnun í jarðvegi, allir sýnatökustaðir, allar landgræðslumeðferðir, þar með talin svæði sem hafa verið friðuð fyrir beit án annarra aðgerða.*

The data for sites and locations which have been excluded from grazing (E as treatment in Table 2) showed no relationship with age. The data show some sites with very low carbon densities (<0.5 kg C $m^{-2}$) at sites protected from grazing for over 60 years, while other are quite high after shorter periods (>2.5 kg C $m^{-2}$, 45 yrs).

The calculations of C were adjusted for coarse fragments (CF). The CF content was quite variable from place to place, even within plots at the same location. CF variability was most pronounced on gravelly surfaces such as the floodplains (A) and lag gravel surfaces (M), but was minimal in the sandy and tephra (S, SM, and SH) surfaces. Low or no increases in carbon density was observed on gravelly areas (A and M treatments in Table 2). The use of general sequestration factors is not recommended for such sites for the time being. The carbon pool has to be well documented at the beginning of revegetation efforts and with periodic measurements (e.g., 10 yr intervals).

## *Paired comparisons*

The data include a total number of 27 pairs representing untreated degraded land (age 0 in Table 2) and reclaimed land of various age.

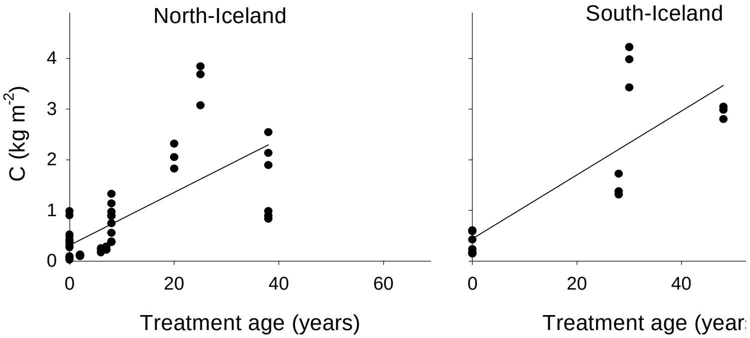

**Figure 3**. Soil organic carbon (kg C $m^{-2}$) in fertilized and untreated (G+O) locations on sandy areas (S+SM+SH-surfaces) plotted against treatment age. Separate regression plots for North and South Iceland. See Table 2 for treatments and soil surface types.
*3. mynd. Kolefnisinnihald á landgræðslusvæðum (sáð og áborið land). Tengslagreining eftir landshlutum.*

Some of the pairs are from the same sites (different treatment ages), utilizing the same untreated land for baseline (age=zero). The Atlaey site is excluded from this analysis for reasons explained earlier.

Average sequestration rates estimated from paired comparisons were similar to those obtained regression (0.062 kg C $m^{-2}$ $yr^{-1}$; SE= 0.0076). Some of the sites have treatments which are younger than 5 years. Excluding treatments younger than 5 years gives about the same sequestration rate (0.063 kg C $m^{-2}$ $yr^{-1}$). Somewhat higher rate was found for 8 pairs from South Iceland than the average (0.073 kg C $m^{-2}$ $yr^{-1}$).

## DISCUSSION

### *Rate of sequestration*

Verification of carbon sequestration in soils is difficult because of the heterogeneity of soils. Our data indicates that both detailed analysis of long-term plots and pairing of data gives similar results which are a reasonably accurate account of carbon sequestration in Icelandic desert soils.

The IPCC report (Sampson and Scholes, 2000) indicates a very broad range of carbon sequestration rates associated with restoration of degraded land (0.1–7 t C $ha^{-1}$ $yr^{-1}$). The rate of carbon sequestration associated with reclamation of degraded Icelandic soils (0.6 t C $ha^{-1}$ $yr^{-1}$ or 0.06 kg C $m^{-2}$ $yr^{-1}$) fall within this range and can be considered relatively high. For example, Izaurralde *et al.* (1998) reported maximum theoretic rates for Canadian prairie soils of about 0.15 t C $ha^{-1}$ $yr^{-1}$. In the IPCC report (2000), an average rate of carbon gain of 0.25 t C $ha^{-1}$ $yr^{-1}$ is proposed for restoration of severely degraded land, primarily based on estimates by Lal and Bruce (1999).

The time interval for carbon sequestration cited for restoration of severely degraded lands by the IPCC (2000) is short, (4–25 years), but others, such as Lal and Bruce (1999) have indicated longer sequestration periods. We infer from the data that >60 yr sequestration periods can be reached in soils in Iceland when reclamation efforts are successful.

The IPCC (2000) uses existing literature to report sequestration rates for degraded grasslands separately from restoration of degraded lands. The report's values for reduction of grassland degradation ("reduce degradation") range between 0.22 and 1.3 t C $ha^{-1}$ $yr^{-1}$ over 20–110 yr periods. These values are comparable to those obtained for reclamation of barren areas in Iceland (0.6 t C $ha^{-1}$ $yr^{-1}$ in soils; 0.01–0.5 t C $ha^{-1}$ $yr^{-1}$ in biomass, see Aradóttir *et al.*, 2000 for biomass).

The data were not sufficient at this point to develop elaborate models for sequestration, such as multi-compartment models suggested by Izaurralde *et al.* (1998) and Liski *et al.* (1998), but we have already identified some of the major factors involved, such as the substrate, treatment, and region of the country.

### *Implications for sequestration in Iceland*

The Icelandic data show that sequestration rates are highly variable. Of particular importance are sites where vegetation succession has halted due to some natural thresholds that prevent further vegetation development. This has resulted in very slow sequestration rates at these sites. It is a priority to find economic means of overcoming these successional thresholds in plant community development, both to ensure successful restoration and to promote continued sequestration. Alternative methods for quantifying carbon sequestration have to be developed for sites with active eolian processes (wind erosion). These sites, when seeded with lymegrass, can potentially sequester more carbon than we are reporting for other treatments in this paper, as roots and organic matter are continuously being buried under eolian sediments.

The data demonstrate clearly that significant amounts of carbon can be sequestered by reclamation of degraded land in Iceland. This activity could both fall under "restoration of severely degraded lands" and "grazing lands management" (by set-aside and human intervention by seeding and grazing) as these activities are outlined by the IPCC report (2000).

If carbon sequestration by reclamation of degraded areas is promoted as a FCCC activity to reduce atmospheric carbon levels, such activities need to be clearly verifiable. The general rate obtained in this study (0.6 t C $ha^{-1}$ $yr^{-1}$) in addition to data gathered at several locations at each site for CF, BD, and carbon, are used to calculate more site specific rates for each carbon sequestration activity area. Combined with detailed data for the size of the area being treated (in ha, areas often several hundred ha), relatively reliable numbers can be obtained for carbon sequestration associated with reclamation of degraded areas in Iceland. This calls for sampling of areas being used as “FCCC sites”. The cost of verification needs therefore to be considered in relation to these activities. The cost of sequestration research and verification has been of the order of 10% of the total costs of binding the carbon under the CSR-Program, which is indicative of general verification costs associated with these activities (CSR-Program internal report).

It is of importance that encouragement of reclamation activities in relation to greenhouse gas emission mitigation does not only result in carbon sequestration, it can halt ongoing degradation processes that potentially emit carbon from the systems. Preliminary data show that Icelandic deserts may be loosing more carbon than is being taken up (Hlynur Óskarsson, unpublished data; CSR-Program research).

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