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Carbon accumulation in vegetation and soils by reclamation of degraded areas

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SUMMARY

A study was compiled to quantify organic carbon stock in reclaimed ecosystems in Iceland. The objective of this paper is to report the carbon mass in vegetation of such systems and to assess its contribution to total carbon sequestration. Organic carbon stock was measured in three components, i.e. in aboveground and belowground biomass, and soil on land with different conditions and under different reclamation methods. The study shows that reclamation of degraded land results in organic carbon sequestration and that a part of the sequestration is in the biomass. The annual rate of sequestration in aboveground biomass ranged from 0.01 to 0.5 t C ha^{-1}, the amount depending on the reclamation method used and site conditions. More comprehensive dataset on carbon sequestration under diverse conditions is, however, needed to use as basis for modelling of organic carbon sequestration. These results show that reclamation measures designed to restore the ecological potential of degraded land can have the additional advantage of carbon sequestration.

Key words: above- and belowground biomass, biomass components, carbon sequestration, carbon stock, degraded land, Iceland, rehabilitation, revegetation.

YFIRLIT

Kolefnisuppsöfnun í gróðri og jarðvegi á uppgræðslusvæðum

Binding kolefnis á uppgræðslusvæðum hefur verið rannsökuð hér á landi í tengslum við sérstakt átak ríkisstjórnarinnar til að vega á móti losun gróðurhúsalofttegunda með aukinni skógrækt og landgræðslu. Í þessari grein er fjallað um niðurstöður mælinga sem gerðar voru sumarið og haustið 1999 á kolefnisuppsöfnun í gróðri á uppgræðslusvæðum. Kolefnisforði í gróðri (ofan- og neðanjarðar) og jarðvegi var mældur á tíu landgræðslusvæðum, þar sem var að finna misgamlar uppgræðslur við mismunandi aðstæður hvað varðar úrkomu, hæð yfir sjó og landgerð. Mismunandi uppgræðsluaðferðirnar hafa verið notaðar á þessum svæðum, þ.e. melsáningar með áburðargjöf, aðrar grassáningar með áburðargjöf, lúpínusáningar og uppgræðsla með búfjáráburði og tilbúnum áburði. Niðurstöðurnar sýndu að kolefni binst bæði í gróðri og jarðvegi við uppgræðslu gróðurlítilla svæða. Árleg binding í gróðri ofanjarðar var á bilinu 0,01–0,5 tonn kolefnis á ha og fór bindihraðinn bæði eftir uppgræðsluaðferðum og umhverfisaðstæðum. Kolefnisbinding í grassáningum var hraðari á Suðurlandi en Norðurlandi, en gögnin leyfðu ekki frekari samanburð á milli landgræðslusvæða né mismunandi uppgræðsluaðferða. Nauðsynlegt er að afla sambærilegra gagna fyrir uppgræðsluaðgerðir af mismunandi aldri á fleiri svæðum til að fá gleggri mynd af þeim þáttum sem hafa áhrif á bindihraðann. Slíkar upplýsingar má nota til að þróa líkön sem hægt væri að nýta við áætlanagerð og eftirlit vegna bindiaðgerða.

INTRODUCTION

Reclamation of eroded land generally involves increases in plant cover that result in accumulation of carbon stocks in biomass and soils. Degraded land has the potential to be a substantial carbon sink because of low initial carbon levels. However, many factors affect the succession and soil development of degraded land, such as limited availability of propagules and physical and chemical properties of soils that hamper plant establishment and growth (del Moral and Bliss, 1993; Magnússon, 1994; Whisenant, 1999). Carbon gains by rehabilitation of eroded and desertified soils have been estimated to be of the order of 0.1 to 0.4 t C ha^{-1} yr^{-1} (Sampson and Scholes, 2000). To our knowledge, direct studies of carbon sequestration in relation to reclamation of severely degraded lands are limited and site specific. However, sequestration potential and rates have been inferred from information on carbon levels, and assessment of the condition of the land (e.g. Ash *et al.*, 1996; Li and Zhao, 1998; Sampson and Scholes, 2000).

Iceland has a history of severe ecosystem degradation (Arnalds, 1987) and large-scale soil erosion (Arnalds *et al.*, 1997; Arnalds, 1999). Organized measures to halt the soil erosion and restore the damaged ecosystems started at the turn of the 20th century (Runólfsson, 1987; Arnalds, 2000). Some of the most extensively used activities are outlined below.

In the beginning the main emphasis was on stabilizing drifting sand. The native grass *Leymus arenarius* was seeded for this purpose and in some areas extensive barriers of stones and timber were constructed (Magnússon, 1997). The *Leymus* is still the most important species used to stabilize active eolian surfaces in Iceland. The *Leymus* stands are fertilized at establishment and at later stages if needed for maintaining or increasing plant cover and/or facilitating seed production.

Large-scale revegetation and range improvement by seeding other grass species and fertilization became common in the 1940s and 50s (Magnússon, 1997). Several native and exotic species and varieties have been used, but currently the exotics *Deschampsia beringensis* and *Festuca rubra* (var. Leik) are most widely used, and the natives *D. caespitosa* and *F. richardsonii* to a lesser extent. Annual grasses, such as *Lolium multiflorum*, are also used occasionally to reduce frost heaving and promote colonization of indigenous vegetation.

Cultivation of an introduced Nootka lupin, *Lupinus nootkatensis*, for reclamation started in the mid 1980s. The lupin can be very productive and forms dense patches that can expand by 1–2 meters a year on level ground. However, its ability to outcompete some of the native vegetation limits its potential uses (Magnússon, 1999).

Since the 1990s, sheep farmers and other land users have participated in a soil conservation programme aimed at increasing vegetative cover of eroded areas and improving the land for grazing (Arnalds, 2000). Activities under this programme include the spreading of manure and other organic fertilizers on sparsely vegetated land and applying low levels (25–50 kg N ha^{-1}) of NPK fertilizer annually or less frequently.

Other activities have been used to a lesser extent, such as planting and seeding of native *Betula pubescens*, *Salix* shrubs and the legumes *Lathyrus japonicus* and *Trifolium repens*.

An effort to sequester carbon by reclamation activities on severely degraded and eroded lands is one of the actions taken by the Icelandic government to implement the Framework

Convention for Climate Change (FCCC). A research programme, to assess potential carbon sequestration rates and develop methods to verify carbon sequestration in actual reclamation programs, is conducted as a part of that effort (see concurrent paper by Arnalds *et al.*, 2000b). Before that, no direct studies on carbon sequestration of reclaimed areas had been carried out, and potential sequestration rates have been inferred from limited data on soil carbon and biomass of revegetated sites (Jónsson and Óskarsson, 1996). In the current research programme, carbon stocks in different parts of the ecosystem, i.e. the soils and above- and belowground biomass, are measured at sites treated with different reclamation methods and under different conditions.

The objective of this paper is to report carbon stocks in vegetation of degraded land that is being reclaimed, and assess its contribution to total carbon sequestration by reclamation activities.

MATERIALS AND METHODS

Site description

Ten sites representing five different regions in Iceland were studied (Figure 1). Nine of these sites have been subject to reclamation treatments by the Soil Conservation Service and a local farmer is doing reclamation work at one site. The sites represented a range of environmental conditions (two coastal and one inland region at low elevation and two inland regions at higher elevation), precipitation regimes and commonly used reclamation methods (Table 1). The reclamation methods or treatments included (1) sown grasses and fertilizer applications (GF), (2) sown *Leymus arenarius* and fertilization (LF), (3) sown *Lupinus nootkatensis* (Lu), and (4) organic and inorganic fertilizer applications (FeG) (Table 1). These methods are described in the introduction. All sites were protected from livestock grazing except the FeG site (number 7).

Field sampling

At each site, landscape elements with identical treatment and treatment age were delineated, divided into three parts and a 10×10 m plot randomly located within each. The GF sites in Gunnarsholt and Ássandur, a part of a study on vegetation succession (Járngerður Grétarsdóttir, in preparation), had five plots in each landscape element. One or more plots were also located within untreated landscape elements to serve as controls. It was, however, difficult to find controls that had not been affected by the reclamation activities, either directly (e.g. fertilizer drift) or indirectly (e.g. protection from grazing, seed rain and litter deposition from treated areas). GPS (global position system) coordinates were recorded for the plots, and each corner was marked by small posts.

Five 0.5×0.5 m subplots were placed within each 10×10 m plot, using randomly generated X- and Y-coordinates. Aboveground biomass of the subplots was harvested by cutting at the soil surface. A 0.25×0.25 m subsample, from one corner of the subplot was collected separately, refrigerated and stored for later separation into different vegetation components. A soil core (30 cm deep) was taken from the centre of each subplot. All five soil cores from each 10×10 m plot were then pooled for analysis of soil organic carbon. At Ássandur and Gunnarsholt samples were taken to only 10 and 20 cm depths, respectively. A separate soil core (3 cm in diameter and 30 cm deep) was ob-

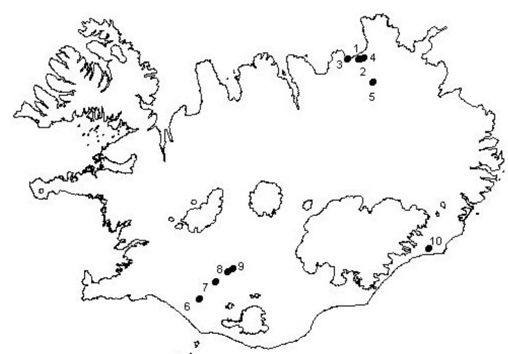

Figure 1. Map of Iceland showing the location of the study sites. Numbers refer to sites in Table 1.
1. mynd. Kort sem sýnir staðsetningu rannsóknasvæðanna. Númerin visa til svæða í 1. töflu.

Table 1. Description of the study sites arranged after regions. Substrate and reclamation method (treatment) codes are given below. Precipitation for each site is based on data from the nearest weather station (based on data from the Icelandic Meteorological Office). Age represents the time (in years) since initiation of reclamation treatment; age=0 represents 'controls' which were not seeded or fertilized.

1. tafla. Uppgræðslusvæðin sem rannsóknirnar fóru fram á, raðað eftir landssvæðum. Skýringar á landgerðum og uppgræðsluaðferðum eru gefnar undir töflunni. Úrkomutölur eru fyrir næstu veðurstöð (byggt á upplýsingum frá Veðurstofu Íslands). Aldur vísar til árafjölda síðan uppgræðsluaðgerðir hófust; aldur=0 vísar til viðmiðunarsvæða sem ekki hefur verið sáð í né þau áborin.

	Coordinates	Altitude m (a.s.l.)	Precipitation mm	Substrate	Reclamation treatment	Age
A. – North East Iceland; lowland			570			
1. Ássandur (east), Kelduhverfi	66°03'N 16°31'W	ca 25		Á	GF	0, 24, 39
2. Ássandur (west), Kelduhverfi	66°04'N 16°37'W	ca 25		S	GF	0, 39
3. Vatnsbæjargirðing, Kelduhverfi	66°06'N 16°52'W	5–10		S	LF	0, 5, 14, 39
4. Ærlækjasel, Kelduhverfi	66°06'N 16°30'W	5–10		S	Lu	0, 2, 6
B. – North East Icleand; highland edge						
5. Kvennsöðull and Sauðafell	65°53'N 16°21'W	350	360	S	LF	0, 1, 5, 39
C. – South Iceland; lowland						
6. Gunnarsholt, Rangárvellir	63°51'N 20°18'W	ca 50	870	SM	GF	0, 23, 24, 39, 46
7. Hólar, Heklusveit	63°59'N 19°57'W	ca 150	940	SM	FeG	0, 2, 10
D. – South Iceland; highland edge			960			
8. Árskógar, Landmannaafréttur	64°05'N 19°43'W	240–260		S	LF	0, 2
9. Leirdalur and Stelpa, Landmannaafréttur	64°08'N 19°32'W	300–320		S	LF	0, 1, 5, 26
E. – South East Iceland; lowland						
10. Skógey	64°20'N 15°18'W	2–5	1450	S/(Á)	GF	0, 3, 9, 12, 13

Substrate types (see description in Arnalds *et al.*, 2000b):
- Á = Glaciofluvial flood-planes.
- S = Sand-fields.
- SH = Sandy lava surfaces.
- SM = Sandy gravel surfaces.

Reclamation methods:
- GF = Sown grasses and fertilization.
- LF = Sown *Leymus arenarius* and fertilization.
- Lu = Sown *Lupinus nootkatensis*.
- FeG = Organic and inorganic fertilization.

All sites except FeG were protected from livestock grazing.

tained from one subplot for determination of root biomass at all sites except Ássandur and Gunnarsholt. Sampling of the Ássandur and Gunnarsholt plots took place in early August 1999. All other plots were sampled between 20 August and 7 October 1999.

Sample processing and data analysis

Aboveground biomass was dried at 70°C for minimum two days and weighed. The 0.25×0.25 m subsamples from each subplot were separated into grass, forb, shrub, moss, standing dead and litter, and cryptogamic crust components. Preliminary analysis indicated that no significant differences in the aboveground biomass of various plant components ($P>0.3$ for grasses; $P>0.6$ for all other groups) between a $0.06 m^2$ subplot and a $0.25\ m^2$ subplot (Kristín Svavarsdóttir, unpublished data). Therefore, the proportion of different vegetation components in the subsample was used to calculate the biomass of each component in the whole sample.

A total of 186 samples representing these different vegetation components from various treatments and regions were analysed for organic carbon content by dry combustion (Nelson and Sommers, 1982) using Leco-CR12 carbon analyser. The carbon content of each group was stable but distinctive, except for mosses and cryptogamic crust where eolian deposition and other soil contamination may have lowered it (Ása L. Aradóttir and Kristín Svavarsdóttir, in preparation). Biomass of each component were multiplied by the carbon concentrations of plant components and those were then summed across all components to estimate the total carbon mass in the sample.

Preparation and analysis of soil samples and and calculation of soil organic carbon were conducted as described by Arnalds *et al.* (2000b). Roots were extracted from soil samples by washing on a 2 mm mesh sieve and separated by hand into three diameter classes (<1, 1–2, and >2 mm), dried at 105°C for 24 hours and weighed. All root samples of each diameter class and site combination were bulked and carbon concentration analyzed. The carbon concentration varied with diameter class, with lower values in small diameter classes, probably due to fine soil particles adhering to the root surface. The carbon concentrations were used with biomass data for each soil core sample to calculate total carbon stock in roots to 30 cm soil depth (Þorbergur Hjalti Jónsson, in preparation).

Biomass and organic carbon mass from the five subplots of each 10×10 m plot were summed and converted to tonne per hectare ($t\ ha^{-1}$). Mean carbon mass ($t\ C\ ha^{-1}$) in plants (aboveground and belowground to 30 cm) and soils (to 30 cm) were calculated and graphically displayed for detecting patterns. Throughout the paper, means are presented ±1 standard error.

Rates of carbon sequestration in aboveground biomass were estimated by regressing carbon mass against treatment age for each region within a reclamation method (Sokal and Rohlf, 1981) using SPSS version 10.0.5. The slope of the regression line corresponds to the sequestration rate.

RESULTS

Aboveground biomass

Aboveground biomass ranged from 0 to 20 $t\ ha^{-1}$ (Table 2). In all regions, biomass of untreated land was $\leq 0.8\ t\ ha^{-1}$. Aboveground biomass differed among reclamation treatments and regions, with biomass tending to increase with age. The greatest biomass occurred in GF treatments applied in South Iceland (C) and Southeast Iceland (E), the oldest E site only 13 years old compared with 46 years in C (Table 2). The plant groups comprising the biomass differed depending on the reclamation methods, with the GF and FeG treatments containing more diversity than the LF and Lu treatments (Table 2). Grasses, litter and forbs occurred in all four reclamation methods. With the exception of the oldest LF site at higher elevation in North Iceland (B) shrubs occurred only in old GF sites (Table 2). Mosses and cryptogamic crust were also predominantly found at GF sites, although moss was a considerable component at the FeG site in South Iceland. Forbs were an important

Table 2. Mean aboveground biomass (t ha^{-1}) of the vegetation components by reclamation methods and regions. Total biomass (t ha^{-1}) mean and standard error (SE) are also given. Untreated controls are designated as age=0. Litter values include standing dead biomass. See Table 1 for explanation of reclamation methods and region codes.

2. tafla. Lífmassi ofanjarðar (t ha^{-1}) fyrir mismunandi gróðurflokka, raðað eftir uppgræðsluaðferðum og landssvæðum. Einnig er sýndur heildarlífmassi ofanjarðar (meðaltal og staðalskekkja, SE). Viðmiðunarsvæði sem ekki hafa verið grædd upp eru sýnd sem 0 ára. Áfast dautt efni er talið með sinu. Skýringar á uppgræðsluaðferðum og merkingum landssvæða eru gefnar í 1. töflu.

Reclamation treatment	Region	Age (yr)	Grasses	Litter	Herbs	Crust	Moss	Shrubs	Total biomass	SE
GF	A	0[a)]	0.01	0.01	0.01	0	0.004	0.01	0.1	0.01
	A	0[b)]	0.003	0.01	0.02	0	0	0	0.1	0.02
	A	24	0.01	0.2	0.001	0	0.3	0.6	1.1	0.20
	A	39[a)]	0.01	0.3	0.01	0	0.1	1.0	1.5	0.59
	A	39[b)]	0.1	0.1	0.03	0	0.002	0	0.3	0.03
	C	0	0.2	0.03	0.2	0	0.3	0	0.8	0.29
	C	21	3.7	4.0	0.01	0.1	11.8	0	19.3	7.27
	C	23	0.4	2.5	0.01	0.9	4.1	0.003	8.1	0.84
	C	24	0.4	2.7	0.2	1.0	4.6	0.3	10.2	0.96
	C	39	0.1	0.4	0.02	2.9	11.4	2.1	16.8	1.72
	C	46	0.7	1.9	0.03	0.08	15.6	0.8	19.2	2.40
	E	0	0	0	0	0	0	0	0	-
	E	3	0.6	0.4	0.02	0	0	0	1.3	0.13
	E	9	0.2	1.1	0.02	16.7	0	0	18.1	4.26
	E	12	0.1	1.1	0.0003	9.2	0	0	10.4	3.67
	E	13	0.2	0.5	0.005	0	19.1	0	20.0	4.34
LF	A	0	0	0	0	0	0	0	0	-
	A	5	0.2	0.03	0	0	0	0	0.2	0.05
	A	14	2.6	4.1	0.01	0	0	0	6.6	0.95
	A	39	1.6	1.5	0	0	0	0	3.1	0.48
	B	0	0	0	0	0	0	0	0	-
	B	1	0.1	0.02	0	0	0	0	0.1	0.02
	B	5	0.7	0.5	0	0	0	0	1.2	0.33
	B	39	0.4	1.2	0.04	0	0.1	0.1	1.9	0.59
	D	0	0	0	0.002	0	0	0	0.01	-
	D	1	0.5	0.03	0.003	0	0	0	0.5	0.12
	D	2	1.2	0.5	0.1	0	0	0	1.8	0.49
	D	5	1.6	2.6	0.04	0	0.1	0	4.3	1.15
	D	26	1.6	1.6	0	0	0	0	3.3	0.20
Lu	A	0	0.005	0.0005	0.02	0	0	0	0.05	-
	A	2	0.02	0.02	0.2	0	0	0	0.2	0.08
	A	5	0.1	3.7	2.4	0	0	0	6.2	1.20
	A	6	0.1	4.1	2.4	0	0.01	0	6.6	2.07
FeG	C	0	0.02	0.03	0.1	0	0.01	0	0.3	0.03
	C	2	0.6	0.7	0.8	0.1	1.4	0	3.5	0.73
	C	10	1.2	1.1	0.6	0	4.6	0	8.4	1.06

a) Site 1, Ássandur, east.
b) Site 2, Ássandur, west.

component in the Lu treatment, in which the live and litter biomass consisted mainly of the sown *Lupinus nootkatensis* (Ása L. Aradóttir and Kristín Svavarsdóttir, unpublished data).

Plant carbon mass

Carbon stock in above- and belowground biomass varied greatly between reclamation methods (Figures 2 and 3). Direct comparison between the methods could, however, not be carried out because number of sites and years since reclamation started varied between the methods. Two methods, sown *Lupinus nootkatensis* (Lu) and organic and inorganic fertilizers (FeG) were limited to one region each and the oldest plots at these sites were much younger than for the other two methods. However, the data showed the general pattern of increasing carbon stock in vegetation with age of the reclamation measures.

Carbon stock in aboveground biomass at GF sites ranged from 0.02±0.005 t C ha^{-1} at a control site in North Iceland to 7.9±1.78 t C ha^{-1} in a 21 year old site in South Iceland (Figure 2A). The carbon stock increased with time but the pattern differed between regions. Carbon in the vegetation was very low in North Iceland with only 1 t C ha^{-1} at the oldest reclamation site, 39 years old. All sites receiving the GF treatment were lowland sites and separate regression analyses on the three regions indicate that the carbon sequestration rate in the aboveground biomass was highest in Southeast Iceland with 0.3 t C ha^{-1} yr^{-1} (C=–0.52+0.34 yrs; P<0.01, r^2=0.49) and lowest in North Iceland with a rate of 0.01 t

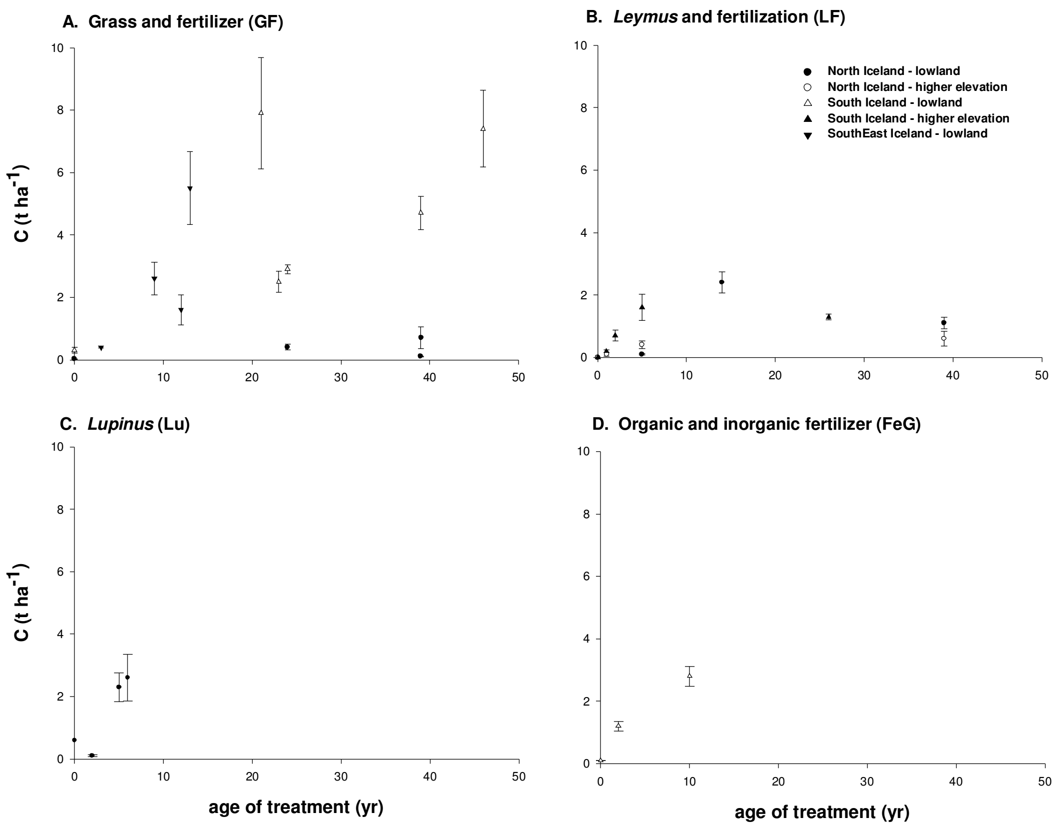

Figure 2. Carbon stock (t ha^{-1}) in aboveground biomass versus age of treatment for different reclamation methods and regions. Each of the four reclamation methods is shown in a separate graph: A. sown grasses and fertilized (GF); B. *Leymus arenarius* sown and fertilized (LF); C. *Lupinus nootkatensis* sown (Lu); and D. organic and inorganic fertilizer (FeG).

2. mynd. Kolefnisforði (t ha^{-1}) í ofanjarðarhlutum gróðurs eftir aldri uppgræðsluaðgerðanna og landssvæðum, Myndirnar sýna niðurstöður fyrir mismunandi uppgræðsluaðferðir: A. grassáning og áburðargjöf (GF); B. melgresissáning og áburðargjöf (LF); C. lúpínusáning (Lu); og D. uppgræðsla bithaga með búfjáráburði og tilbúnum áburði(FeG).

C ha^{-1} yr^{-1} (C=0.05+0.01 yrs; $P<0.05$, $r^2=0.18$). The carbon stock in North Iceland ranged from 0.02 to 0.7 t C ha^{-1}, while it was much higher in Southeast Iceland reaching 5.5 t C ha^{-1} after only 13 years. The relationship between carbon stock and time in South Iceland was intermediate with annual sequestration rates of 0.1 t C ha^{-1} (C= 0.58+0.13 yrs; $P<0.001$, $r^2=0.45$), and carbon stock ranging from 0.3 to 7.9 t C ha^{-1}. Data for carbon stock in belowground biomass of the same treatment were unavailable for regions A and C. In Southeast Iceland, there was a considerable variation of carbon stock in roots within treatment age (Figure 3A) suggesting that conditions can vary greatly in the same region. The ratio of aboveground to belowground carbon stock was close to one at the Southeast sites (E) with the exception of the 13-years-old site that had ten times more carbon in the aboveground biomass (Table 3), due to a large moss component (Table 2).

Above- and belowground carbon stock at LF sites was lower than at GF sites (Figures 2B and 3B). Only one site (14 years old lowland

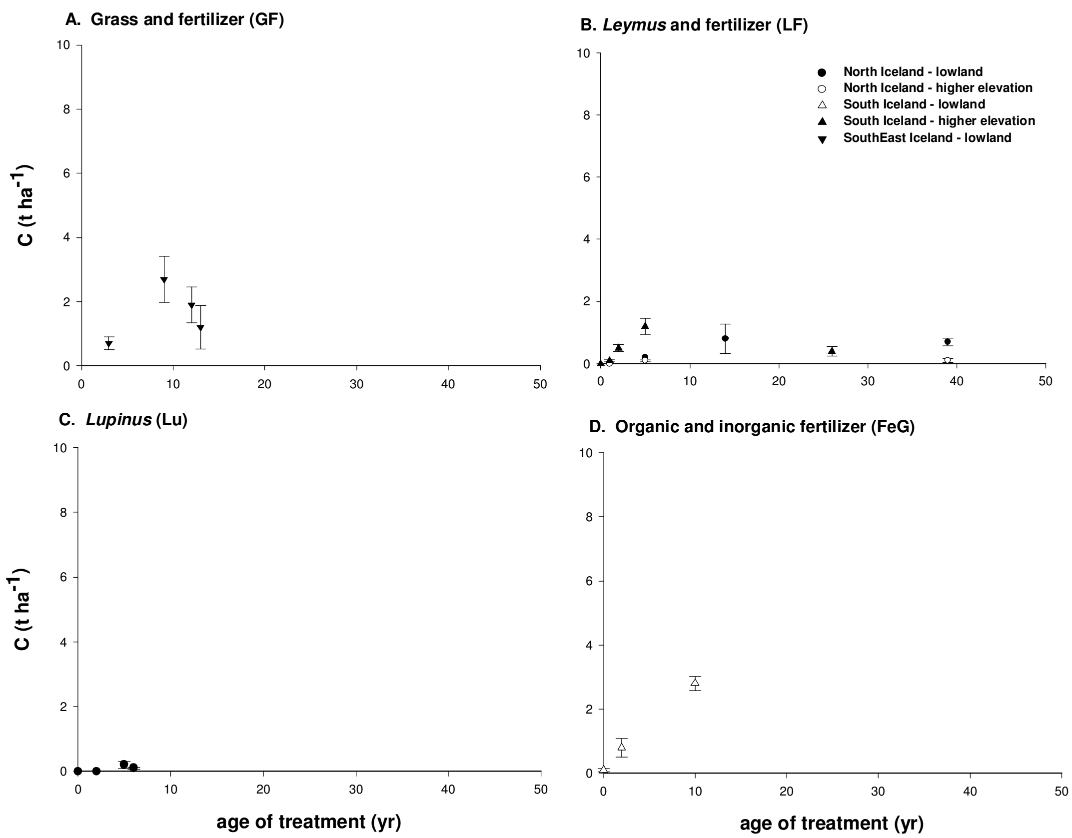

Figure 3. Carbon stock (t ha^{-1}) in belowground biomass versus age of treatment for different reclamation methods and regions. Each of the four reclamation methods is shown in a separate graph: A. sown grasses and fertilized (GF); B. *Leymus arenarius* sown and fertilized (LF); C. *Lupinus nootkatensis* sown (Lu); and D. organic and inorganic fertilizer (FeG).

3. mynd. Kolefnisforði (t ha^{-1}) í rótum eftir aldri uppgræðsluaðgerðanna og landssvæðum, Myndirnar sýna niðurstöður fyrir mismunandi uppgræðsluaðferðir: A. grassáning og áburðargjöf (GF); B. melgresissáning og áburðargjöf (LF); C. lúpínusáning (Lu); og D. uppgræðsla bithaga með búfjáráburði og tilbúnum áburði (FeG).

Table 3. Mean and standard error (SE) of the ratio of carbon stock in aboveground and belowground biomass (a/b ratio) and in aboveground biomass and soil (a/s ratio) after reclamation methods and regions. For the a/b ratio, number of samples (n) is shown. Where n<3, there was no measurable root biomass in one or more samples. For the a/s ratio, n was equal to 3 with the exceptions of FeG-C age 0 and 2, where n=2 and n=1, respectively.

3. tafla. Hlutfall kolefnisforða í ofan- og neðanjarðarhlutum gróðurs (a/b) og kolefnisforða í ofanjarðarhlutum gróðus og í jarðvegi (a/s). Sýndur er fjöldi reita (n) sem notaðir voru til að reikna a/b-hlutfallið. Þar sem n<3 var ekki mælanlegur rótamassi í einu eða fleiri sýnum. Í öllum tilvikum var n=3 fyrir a/s hlutfallið, nema í FeG uppgræðslum, þar sem n=2 í tveggja ára og n=1 í viðmiðunarreit (0 ára).

Reclamation treatment	Region	Age	a/b ratio	SE	n	a/s ratio	SE
GF	A[a)]	0	-	-	-	0.04	0.012
		24	-	-	-	0.2	0.03
		39[c)]	-	-	-	1.0	0.65
		39[d)]	-	-	-	0.04	0.005
	C[b)]	0	-	-	-	0.03	0.021
		21	-	-	-	0.3	0.06
		23	-	-	-	0.09	0.026
		24	-	-	-	0.1	0.004
		39	-	-	-	0.2	0.03
		46	-	-	-	0.3	0.07
	E	3	0.7	0.19	3	0.1	0.02
		9	1.4	0.77	3	0.5	0.09
		12	1.1	0.45	3	0.1	0.03
		13	10.1	5.25	3	1.5	0.63
LF	A	5	0.2		1	0.1	-
		14	5.4	2.49	3	0.5	0.16
		39	1.8	0.30	3	0.23	0.04
	B	1	11.6		1	0.07	0.043
		5	16.9	9.38	3	0.1	0.02
		39	7.1	3.60	3	0.02	0.009
	D	1	15.3	13.22	3	0.2	0.02
		2	1.6	0.42	3	0.7	0.23
		5	1.3	0.40	3	0.5	0.11
		26	3.6	0.82	3	0.5	0.05
Lu	A	2	32.5		1	0.08	0.031
		5	7.2	0.8	2	0.8	0.22
		6	38.4	18.02	3	1.2	0.34
FeG	C	0	1.3	0.48	2	0.01	0.005
		2	2.0	1.08	2	0.08	0.003
		10	1.0	0.09	3	0.1	0.02

a) No root samples were collected for this treatment-region combination, and soils were only sampled to 10 cm depth.
b) No root samples were collected for this treatment-region combination, and soils were only sampled to 20 cm depth.
c) Site 1, Ássandur west.
d) Site 2, Ássandur east.

site in North Iceland) reached 2 t C ha^{-1} of carbon stock in the aboveground biomass. At higher elevation LF sites, maximum carbon stock was 0.6±0.23 and 1.6±0.42 t C ha^{-1} for North and South Iceland, respectively. Significant linear relationships between aboveground or belowground carbon stock and time since reclamation measures started were not detected at the three different LF sites. The ratio of carbon stock in aboveground to belowground biomass was relatively high (Table 3) with up to 17 times more carbon stored in aboveground biomass than in root biomass.

Data from sown *Lupinus nootkatensis* sites (Lu) were limited to only one region (a lowland site in North Iceland) and the oldest plots were only six years old. These limited data indicated that the Lu method had the highest carbon sequestration rate, 0.5 t C ha^{-1} yr^{-1} (C=–0.37+0.50 yrs; $P<0.01$, $r^2=0.62$). The carbon stock increased from 0.6 to 2.6±0.75 t C ha^{-1} over a six years period (Figure 2C). Belowground carbon was, however, very low at all sites with maximum of 0.2 t C ha^{-1} at the five years old site (Figure 3C). Thus, the ratio of carbon stock in above- to belowground biomass was very high with almost 40 times more carbon accumulated in aboveground than in belowground biomass (Table 3).

The pattern of the above- and belowground carbon in the FeG method was similar to the GF and Lu methods (Figures 2D and 3D), i.e. carbon stock was primarily aboveground and increased with age. This reclamation method was only sampled in South Iceland (site C), and the carbon stock ranged from 0.1±0.01 to 2.8±0.32 t C ha^{-1} at the 10 years old site. The relationship between time and carbon in the aboveground biomass was strong and indicated relatively high sequestration rate, 0.3 t C ha^{-1} yr^{-1} (C=0.36+0.25 yrs; $P<0.001$, $r^2=0.89$). The ratio of above- and belowground carbon was nearer the ratio of 3–12 years old GF sites in Southeast Iceland (data were missing for other GF regions) than for the LF and Lu sites (Table 3).

Soil carbon mass

Carbon stock in the soil also varied between reclamation methods and among regions (Figure 4). However, as a general rule, more carbon was present in the soil than in the biomass (note that the scale is four times larger in the figure for soils than in the biomass figures). The soil proportion of the total carbon stock in the system was ranked in decreasing order from FeG>LF>Lu>GF (87, 74, 63 and 61%, respectively; sites A and C for the GF method not included). The ratio of carbon stock in aboveground vegetation and soils is shown in Table 3. There appeared to be a weak trend for the ratio to increase with time within reclamation method and a region. Therefore, although the carbon pool was largest in the soil, the carbon stock in aboveground biomass appeared to increase relatively more over time than the carbon stock in the soil. The Lu reclamation method differed from the other methods in storing relatively larger proportion of the carbon stock in the aboveground biomass (Table 3).

DISCUSSION

Our data show that reclamation of degraded areas in Iceland resulted in carbon sequestration in above- and belowground biomass and in soils. In most cases, carbon stock was larger in the aboveground biomass than in roots (Table 3), and there was an indication of differences between reclamation methods. The amount of carbon stored in the biomass and sequestration rates varied considerably depending on the regions and conditions at the sites. The aboveground carbon sequestration rate observed in this study ranged from 0.01 to 0.5 t C ha^{-1} yr^{-1} depending on reclamation method and region. This represents both lower and higher rates than the 0.1–0.4 t C ha^{-1} yr^{-1} given by Sampson and Scholes (2000) for carbon sequestration on a badly degraded land. However, we calculated sequestration rates for aboveground biomass only. When organic carbon in soils is also included (see Arnalds *et al.*, 2000b and Figure 4) the total sequestration rates are considerable higher.

Preliminary studies on carbon storage of reclaimed land in Iceland gave sequestration rates of 0.3–0.6 tonn ha^{-1} yr^{-1} in aboveground biomass (Arnalds *et al.*, 2000a), the upper range of rates reported here. Their data were for two reclamation methods comparable with those we studied (GF and Lu), but each from only one location. A site with two GF methods of different age in South Iceland showed sequestration rate of 0.3 and 0.6 t C ha^{-1} yr^{-1} for 45 and 17 years old sites, respectively (Arnalds *et al.*, 2000a). This GF site was included in the current study, where it gave a considerably lower sequestration rate of 0.1 t C ha^{-1} yr^{-1}. This difference can largely be explained by inclusion of additional plots, 23, 24 and 39 years old, that had much lower carbon stocks than the plots included in the previous study (Figure 2A). The additional plots in our study involved sowing of annual grasses whereas those studied by Arnalds *et al.* (2000a) consisted of more persistent perennial grasses. The design of the current study, with replicated plots of different ages, allowed for the regression approach rather than comparison of pairs as used by Arnalds *et al.* (2000a). The paired comparison is especially limited when suitable controls are lacking, that often

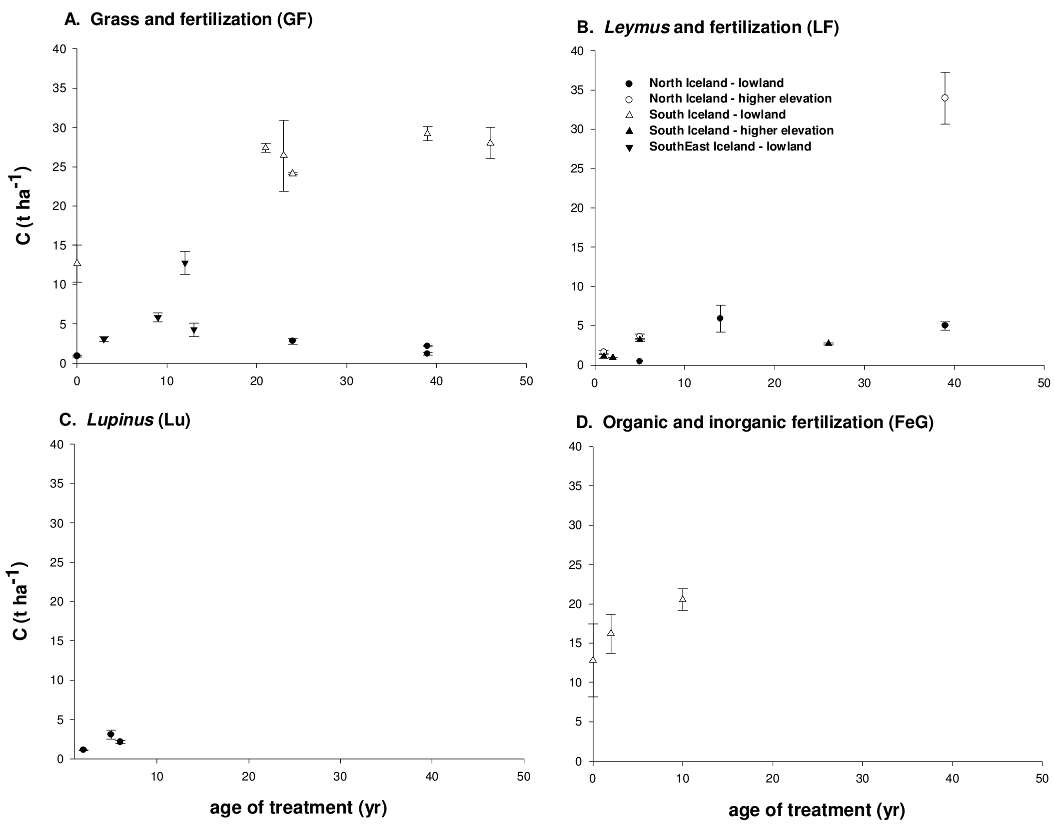

Figure 4. Carbon stock (t ha^{-1}) in soils versus age of treatment for different reclamation methods and regions. Each of the four reclamation methods is shown in a separate graph: A. sown grasses and fertilized (GF); B. *Leymus arenarius* sown and fertilized (LF); C. *Lupinus nootkatensis* sown (Lu); and D. organic and inorganic fertilizer (FeG). Note that the y-axis scale here is different from Figures 2 and 3.

4. mynd. Kolefnisforði (t ha^{-1}) í jarðvegi eftir aldri uppgræðsluaðgerðanna og landssvæðum. Myndirnar sýna niðurstöður fyrir mismunandi uppgræðsluaðferðir: A. grassáning og áburðargjöf (GF); B. melgresissáning og áburðargjöf (LF); C. lúpínusáning (Lu); og D. uppgræðsla bithaga með búfjáráburði og tilbúnum áburði(FeG). Vakin er athygli á að mælikvarði y-ássins er annar en á 2. og 3. mynd.

is the case when studying reclaimed sites not initially established for research purposes. Arnalds *et al.* (2000a) reported one 20 years old Lu site in Southwest Iceland with the same sequestration rate in aboveground vegetation (0.5 t C ha^{-1} yr^{-1}) as our Lu site in North Iceland, that had 2, 5 and 6 years old treatments.

Our sites represent a range of conditions including a threefold difference in annual precipitation, elevations ranging from 2 m to 350 m a.s.l., contrasting substrate types and levels of eolian deposition (Table 1). Sites sown with grasses and fertilized (GF) clearly showed faster carbon accumulation in the south and southeast of Iceland than in the north. Annual precipitation is highest in southeast (E) and lowest in the north (A), following the same order as carbon sequestration rate in the aboveground biomass. Other factors, such as temperature are also likely to contribute to the observed pattern, as mean temperature is lower and the growing season shorter in the north than south. This is consistent with the higher sequestration in soils in South Iceland compared to North Iceland reported by Arnalds *et al.* (2000b) and the increases in soil organic carbon with precipitation on a global scale (Jobbágy and Jackson, 2000). Differences within a region were also observed in the North Iceland lowlands. Aboveground carbon stocks at site 2 (GF) was only 0.1±0.01 t C ha^{-1} at a 39 years old treatment resulting in annual sequestration rate of 0.003 t C ha^{-1}. By comparison, aboveground carbon stocks at site 1 was 0.4± 0.09 and 0.7±0.35 at 24 and 39 years old treatments, respectively (Figure 2A). The conditions seem to be more stressful at site 2, despite only short distance between them, possibly due to differences in eolian deposition. At site 2, there was difficulty establishing sown grasses (Stefán Sigfússon, personal communication) and there has been less invasion of other species into the area than at site 1 (Járngerður Grétarsdóttir, in preparation).

There was not a significant linear relationship between carbon stock and age in sites where *Leymus arenarius* was sown. In South Iceland, however, the carbon accumulation was faster in the first years after the reclamation started than at later stages (Figure 2B), indicating a possible non-linear relationship. All sites with a *Leymus* treatment had active sand surfaces with sand sedimentation that can create sand dunes and ridges up to 2–3 m high. Biomass and soils buried under sand sedimentation may have a long residence time and contribute significantly to carbon sequestration by reclamation activities. However, constant changes of the soil surface in *Leymus* sites with active sand movement, including both erosion and burial of biomass and soil, call for other methods than used here to quantify carbon storage and sequestration (cf. Arnalds *et al.*, 2000b).

Even though we observed differences in sequestration rates between reclamation methods, the data do not allow for a direct statistical comparison between the methods due to confounding between treatments and sites. The two reclamation methods that gave the highest sequestration rates (Lu and FeG) were limited to one site each and short time period (6 and 10 years for Lu and FeG, respectively). Furthermore, different reclamation methods are generally applied under different conditions, e.g. the *Leymus* is often used on active sand dunes but the GF methods is rather used on more stable sandy sites and on gravel surfaces.

In the current study, the largest pool of carbon was in the soil (Figures 2 and 3, Table 3), but biomass, especially the aboveground component, also contributed considerably to the total carbon stock. This emphasises the need for an ecosystem approach in assessment of carbon sequestration (Arnalds *et al.*, 2000ab; Sampson and Scholes, 2000). Our study showed that the importance of aboveground biomass in the total carbon stock may differ between reclamation methods. The aboveground carbon stock at the Lu sites was, for instance, much higher than in roots and that soil organic carbon was relatively small at these sites. Jónsson and Óskarsson (1996) predicted that carbon sequestration rate in soil under *Lupinus nootkatensis* would peak approximately five years after establishment at almost 4 t ha^{-1} yr^{-1}, but our data showed much slower sequestration in young *Lupinus* stands. Over time, the carbon stock of aboveground biomass increased more than carbon stock in soil. This was particularly evident at sites with considerable shrub and/or moss biomass (Table 2 and 3). Shrubs were a measurable component in GF plots >24 years old and the 39 yr old *Leymus* treatment at site 6. The importance of shrubs lies in the longer residence time of the woody biomass compared to forbs and litter (Sampson and Scholes, 2000), and the effect of patches in the lanscape on resource accumulation and establishment of other species (Magnússon, 1994; Ludwig and Tongway, 1996; Tongway and Ludwig, 1996; Archer *et al.*, 2000). Where *Salix* and *Betula* shrubs were present, their distribution was patchy, with isolated individuals or small clusters of plants, resulting in great within-plot heterogeneity in aboveground biomass. The structure of our data did not permit examination of the belowground heterogeneity, but the effects of patchy vegetation on accumulation of soil carbon has been reported in other systems (e.g. Kelly *et al.*, 1996; Tongway and Ludwig, 1996, Archer *et al.*, 2000). Further studies are needed on the role of the shrub component in biomass accumulation, carbon sequestration and successional dynamics of areas under reclamation.

In South- and Southeast-Iceland, mosses and cryptogamic crust were an important proportion of the biomass at GF and FeG sites, but to a lesser extent in North-Iceland (Table 2). Climate, especially precipitation, has been shown to be an important controlling factor in population dynamics and growth of the moss *Hylocomium splendens* in a boreal forest in Norway (Økland, 1995, 1997), and that other bryophytes behaved in a similar fashion (Økland, 1995). The decompositon rates of mosses are slow compared to vascular plants (Oechel and Van Cleve, 1986 – and references cited therein). If the residence time of carbon stored in mosses is longer than for some of the other vegetation components, the mosses might be an important factor in carbon sequestration in some parts of Iceland. The mosses are also important in many natural ecosystems in Iceland, but more studies on the dynamics of the moss fields are needed.

The results presented here and by Arnalds *et al.* (2000b) suggest that differences in carbon sequestration rates between sites depend on many factors, such as precipitation, substrate and the reclamation method. This underscores the need to study more thoroughly the effect of different conditions and reclamation methods on carbon sequestration in biomass and soils. The creation of a database in relation to carbon sequestration verification is an important step in the development and testing of models that can predict rates of carbon sequestration given different scenarios. These models would be used in conjunction with strategic sampling to monitor the sequestration of carbon by specific activities (cf. Arnalds *et al.*, 2000b).

Reclamation of degraded land can promote sustainable development and ecosystem health through reduced erosion, increased biological productivity, and water and soil quality. Sequestration of carbon in biomass and soils that can serve to mitigate the greenhouse effect presents an additional benefit from reclamation activities (Lal *et al.*, 1998). Biodiversity is another factor that can be affected by reclamation activities (Sampson and Scholes, 2000). Indeed, we found a trend towards increased number of vascular plant species with treatment age (Ása L. Aradóttir and Kristín Svavarsdóttir, unpublished data), but the species diversity varied greatly between sites and reclamation methods. However, it is also conceivable that reclamation activities could have a negative effect on biodiversity if they are narrowly focused on limited ecosystem services such as carbon sequestration and involve monocultures of exotic species that can invade natural systems and prevent establishment of native species on reclaimed sites. Therefore it is important to ensure that reclamation activities aimed at carbon sequestration are balanced with other conservation objectives and are in accordance with other UN conventions, such as the Convention to Combat Desertification (CCD) and the Convention on Biological Diversity.

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