

## Research Article

# Soil Carbon Accumulation and CO<sub>2</sub> Flux in Experimental Restoration Plots, Southern Iceland: Comparing Soil Treatment Strategies

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Experimental plots were established on severely eroded land surfaces in Iceland in 1999 to study the rates and limits of soil carbon sequestration during restoration and succession. The carbon content in the upper 10 cm of soils increased substantially during the initial eight years in all plots for which the treatments included both fertilizer and seeding with grasses, concomitant with the increase in vegetative cover. In the following five years, however, the soil carbon accumulation rates declined to negligible for most treatments and the carbon content in soils mainly remained relatively constant. We suggest that burial of vegetated surfaces by aeolian drift and nutrient limitation inhibited productivity and carbon sequestration in most plots. Only plots seeded with lupine demonstrated continued long-term soil carbon accumulation and soil CO<sub>2</sub> flux rates significantly higher than background levels. This demonstrates that lupine was the sole treatment that resulted in vegetation capable of sustained growth independent of nutrient availability and resistant to disruption by aeolian processes.

## 1. Introduction

Interest in the carbon cycle and the various sources and sinks of rapidly exchangeable carbon often focuses on above-ground biomass of specific biomes, most typically tropical to temperate forests. But this approach ignores the much greater mass of carbon stored in soils globally, estimated at over 2300 Gt C [1]. In terrestrial ecosystems, the largest reservoirs are quite predictably found in tropical ecosystems, due to their high productivity, with 20% of the global soil organic carbon (SOC) reservoir in tropical evergreen forests [1]. However, high latitude settings also store considerable SOC, with the 144 Gt estimated in tundra soils amounting to 6% of the global SOC pool, a mass nearly equal to that estimated for boreal forest or deciduous temperate forest soils [1]. This may, however, be an underestimate as a recent study increased the numbers for high latitude soils by almost an order of magnitude [2]. A better understanding of the size

of the high latitude SOC pool and the rates of exchange with the atmosphere is required to enhance our ability to model anticipated changes in global climate.

The near-Arctic latitude of Iceland presents an excellent location for studies of SOC dynamics, both as examples of extreme soil degradation due to anthropogenically driven ecosystem change and for the potential of these high latitude soils to sequester atmospheric carbon through ecosystem restoration. The general history of ecosystem degradation in Iceland is relatively well known. Prior to settlement in 874 AD, Iceland was much more extensively vegetated than it is today. As much as 65% of the land surface was covered by vegetation at the time of settlement, compared to 28% today [3–8]. A combination of deforestation and overgrazing of vulnerable ecosystems produced a landscape susceptible to extensive erosion, the mechanics of which have been investigated in some detail [9–11]. Long-term erosion ultimately led to desertification of large areas of the country, with ca. 40%

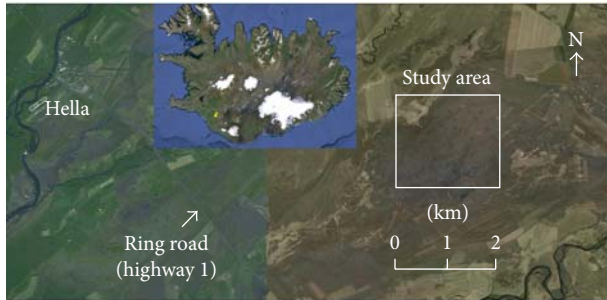


FIGURE 1: Location of the study area in southwestern Iceland (yellow pin on inset map). Image adapted from Google Earth. Small rectangles in study area outline are 1-hectare experimental plots.

of the total surface subjected to considerable to severe erosion [12]. Interest in soil preservation and restoration in Iceland is long-standing, dating to the very early twentieth century and continuing to the present [13–17]. In recent decades, scientists have recognized that land restoration in Iceland also offers the opportunity for sequestration of considerable amounts of atmospheric carbon as the desert soils that resulted from ecosystem degradation typically contain several orders of magnitude less carbon than the soils of fully vegetated ecosystems [18–21]. The study presented here is a continuation of the soil restoration experimental project in southern Iceland described by Aradottir et al. [22] and Arnalds et al. [20]. The project examined both the success of various soil treatments in promoting ecological restoration of severely degraded soils and the consequent rates of carbon sequestration. This study is a comparison to the previously published results to determine if the SOC sequestration trends for various treatments were maintained after the initial study period.

## 2. Methods

**2.1. Study Location.** The Soil Conservation Service of Iceland established the Geitasundur Restoration Research Area in 1999 on a portion of the Geitasundur desert in South Iceland (Figure 1). The project area forms a roughly rectangular expanse ca. 3 km  $\times$  1.2 km, located 8 km east of Hella (69°49'30.73"N, 20°13'55.04"W). The soils in this area are classified as Vitric Andosols consisting primarily of basaltic to andesitic glass and basaltic rock fragments [10]. The soil surface in the project area is unstable due to erosion by wind, water [23], and cryoturbation [8], the last of which is in part responsible for maintaining a gravel load on the soil surface. South Iceland experiences a maritime climate that is affected by the Irminger Current, a branch of the North Atlantic Current that provides a rainy climate with cool and short summers [24]; mean temperatures vary from  $-2^{\circ}\text{C}$  in January to  $11^{\circ}\text{C}$  in July and annual precipitation averages 1260 mm (1971–2000 average for the station at Hella; [22]).

**2.2. Experimental Design.** The experiment comprised 40 plots, each 1 ha, with 10 treatments replicated four times. These ranged from untreated (control) to various combinations of treatments with nitrogen and phosphate-based

fertilizer, seeding with various grasses and/or lupine (*Lupinus nootkatensis*), birch (*Betula pubescens*), and willows (*Salix phylicifolia*, *S. lanata*); see [22] for details. Plots seeded with grasses and planted with birch and willows were fertilized at the time of seeding and again in 2001, 2003, and 2005. Active wind deposition of sediment compromised the results from many of the plots in the southern portion of the study area [20], and these plots were dropped from data collection in the present study. The present study was limited to 10 plots in the northern part of this project area focusing on four of the treatments: control (C)—two plots; fertilizer and seeded grass (G)—three plots; fertilizer, seeded grass and birch and willows planted in clusters (GBW)—three plots; seeded lupine (L)—two plots. Soils in all ten plots had been sampled previously in 2003, 2005, and 2007.

The surface cover of the one-hectare experimental plots was visually estimated within 10 m by 10 m subplots that were randomly selected for sampling (see below). The control plots were characterized by a rocky lag of gravel to cobble-sized clasts that covered ca. 30% of the surface (Figure 2(a)). The surface was sparsely vegetated, with grass tufts and mounds of moss campion (*Silene acaulis*), typically surrounded by haloes of fine-grained aeolian sediment, covering from 2% to a local maximum of 15% of the surface (Figure 2(b)). The fertilizer-grass (G) plots varied in vegetative cover, varying locally (in subplots) from a low of 40% to a high of ca. 70% (exclusive of biological soil crust, or BSC). Grass tufts are widely scattered, and nongrasses are typically more abundant, such as black crowberry (*Empetrum nigrum*), moss campion, and less frequent wildflowers and willows (Figures 2(c)–2(f)). Coverage by biological soil crust (BSC) also varied, ranging from 10% to as much as ca. 40% (Figure 2(f)). Locally, the surface was often buried by a fine-grained aeolian veneer. Similarly, the cover of gravel, exposed as a lag between the floral mounds, varied greatly. The grass-birch-willow (GBW) plots typically had 40–50% vegetation cover (excluding BSC), most of which is moss and crowberry, and 30–40% BSC cover (Figures 3(a) and 3(b)). Birches were up to 110 cm tall and willows up to 20 cm tall. Aeolian blowouts formed low spots that exposed large patches of gravel lag. Plots seeded with lupine (L) exhibited a distribution that clearly reflected wind-control of the seeding, with the lupine typically absent from the upwind margins of the plots, increasing in density toward the center and extending well beyond the downwind plot boundaries; hence density of the lupines varied across the plots. Dense clusters of lupine form raised tufts of multiple-stemmed plants that cover ca. 50% of the plot surface (Figures 3(c) and 3(d)).

**2.3. Data Collection.** The data collection was conducted in June 2012. Within each 1 ha experimental plot, we randomly selected five nonadjoining 10 m by 10 m subplots from a hypothetical grid of 100 subplots for sampling. Sample points were selected at the four corners and in the center of each subplot. At each sample point, we removed a 20 cm long, 3 cm diameter soil core, from which we extracted and separated the A (0–5 cm) and B (5–10 cm) segments for analysis of SOC. At each sample point, we also measured the soil  $\text{CO}_2$  flux with



FIGURE 2: Views of control and grass-seeded plots. (a) Typical control plot exhibiting a gravelly surface with isolated tufts of grasses. (b) Detail of (a). Gravel-free haloes of sand surrounding grass tufts are aeolian deposits. (c) Typical view of grass-seeded plot. Surface is ca. 70% vegetated, with 50% grass and 20% nongrass (mostly crowberry). (d) Contrast between rocky, sparsely vegetated untreated surface (C) and the more heavily vegetated grass-seeded surface (G). The baffling effect of the vegetation is evidenced by the significant accumulation of aeolian sediment veneer; mc = moss campion, cb = crowberry. (e) Detail of grass-seeded plot illustrating variety of native plants succeeding initial grass seeding and aeolian sediment veneer; mc = moss campion, cb = crowberry. (f) Detail of grass-seeded plot illustrating BSC covering entire surface that is not vegetation or rock.

a Li-Cor LI-8100A soil gas chamber system equipped with a 20 cm diameter collection chamber and soil moisture and temperature probes. The collection chamber was set on a soil collar with variable vertical offset.  $\text{CO}_2$  concentrations were measured continuously for 90 seconds following a 45-second purge cycle, and the soil  $\text{CO}_2$  flux was calculated from a linear regression line in units of  $\mu\text{mol CO}_2 \text{ sec}^{-1} \text{ m}^{-2}$ .

In the laboratory, the carbon content was measured from the soil core samples. Each sample was sterilized with dry heat, homogenized, and sieved with a 2 mm screen to remove larger rocks and root fragments, and the <2 mm fraction

pulverized. From each processed sample, 0.1 to 0.125 g was drawn for analysis with a Leco TruSpec CN by combustion in a pure  $\text{O}_2$  atmosphere at  $950^\circ\text{C}$ . The weight percent carbon ( $\text{C}_{\text{soil}}\%$ ) was calculated from the composition of the evolved gases as measured by an infrared cell. In summary, the data collected at each of the 10 plots included 50 measurements of  $\text{C}_{\text{soil}}\%$  (25 A samples, 25 B samples) and 25 soil  $\text{CO}_2$  flux measurements.

**2.4. Data Analysis.** The mean, standard deviation (SD), and standard error for each treatment were calculated for the A

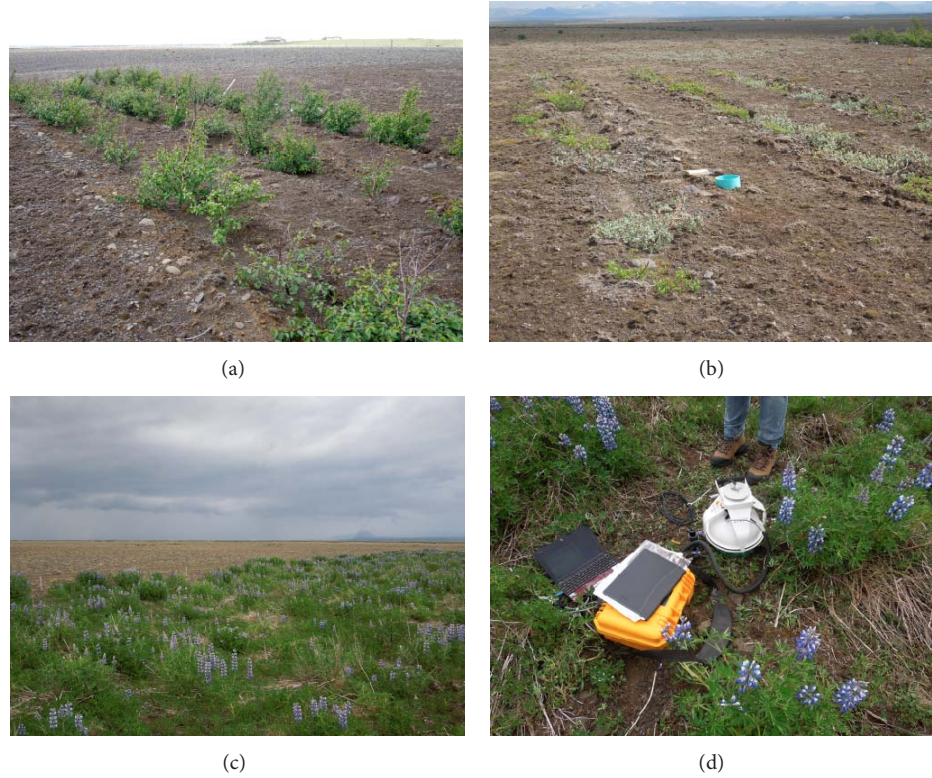


FIGURE 3: Views of grass-birch-willow and lupine-treated plots. (a) Rows of birch planted in plowed furrows surrounded by sparsely vegetated land surface originally seeded with grasses, but now largely covered by other native species (mainly crowberry) and BSC. (b) Willow and birch rows surrounded by BSC and other nongrasses. Soil collar is 20 cm in diameter. (c) Lupine-seeded plot presents highest biomass of all treatments. (d) Detail of area in (c) illustrates patchy distribution of lupine clusters with intervening open ground. Li-Cor soil gas analyzer system shown.

and B layers for each treatment from the arithmetic average of all samples for the treatment type. Therefore,  $N = 50$  for C and L (two plots each), and  $N = 75$  for G and GBW (three plots each). The carbon stocks for each treatment type were calculated for the upper 10 cm of soil (from the average of the A and B layers) in  $\text{kg m}^{-2}$  assuming a bulk density of  $1.02 \text{ g cm}^{-3}$  and active soil volume of 89% [20]. Because the sampling in 2012 did not include all of the plots studied by Arnalds et al. [20], the change in SOC since 2007 was calculated by comparing data for individual plots from this study with the raw data collected from the previous study for the same plots (Arnalds, pers. comm.). The significance of the difference for each plot was evaluated by one-way ANOVA. Analyses were completed utilizing the SigmaStat software package produced by Systat Software Inc. Correlations between  $C_{\text{soil}}\%$  and soil  $\text{CO}_2$  flux were evaluated by Pearson's product-moment regression, performed with Microsoft Excel. Results are presented herein as statistically significant where the probability of the null hypothesis  $p < 0.05$ .

### 3. Results

**3.1. Soil Organic Carbon Content.** The mean carbon content of the soils in all four treatment areas is less than 1.0%

TABLE 1: Summary results of soil carbon analysis and soil  $\text{CO}_2$  flux measurements.  $N = 50$  for control and lupine;  $N = 75$  for grass and GBW (grass-birch-willow). Mean shown  $\pm$  standard error. SD = standard deviation. Soil carbon stock calculated as  $\text{kg m}^{-2}$  elemental carbon.  $\text{CO}_{2\text{soil}}$  measurement in  $\mu\text{mol m}^{-2} \text{sec}^{-1}$ .

Treatment		A $C_{\text{soil}}\%$	B $C_{\text{soil}}\%$	Soil C stock	$\text{CO}_{2\text{soil}}$
Control	Mean	$0.35 \pm 0.02$	0.36	$0.43 \pm 0.02$	$0.59 \pm 0.06$
	SD	0.11		0.14	0.58
	Range	0.13–0.58		0.20–1.06	0.01–2.65
Grass	Mean	$0.48 \pm 0.02$	0.38	$0.33 \pm 0.01$	$0.52 \pm 0.04$
	SD	0.18		0.11	0.33
	Range	0.28–1.11		0.02–0.62	0–1.67
GBW	Mean	$0.64 \pm 0.03$	0.52	$0.5 \pm 0.02$	$0.49 \pm 0.06$
	SD	0.24		0.18	0.48
	Range	0.34–1.32		0.25–1.21	0–3.73
Lupine	Mean	$0.67 \pm 0.03$	0.61	$0.65 \pm 0.03$	$2.9 \pm 0.23$
	SD	0.23		0.21	1.61
	Range	0.18–1.23		0.26–1.22	0.28–7.06

(Table 1, Figure 4). The control plots exhibit the lowest carbon content of the treatments but differ from the other treatments in that the B layer (5 to 10 cm soil depth) has a slightly higher carbon content than the A layer (0 to 5 cm soil depth).

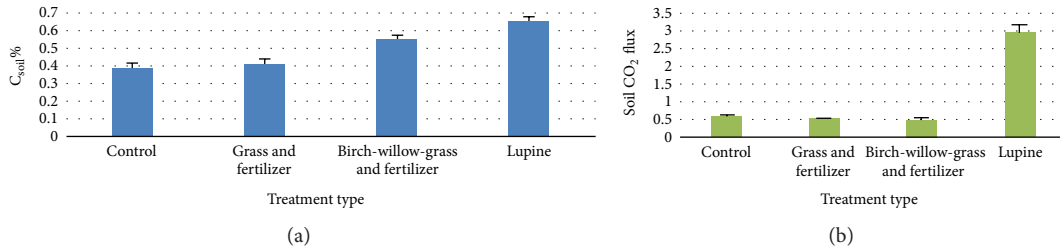


FIGURE 4: Summary results. (a) Mean soil carbon content for all samples (A and B layers combined shown plus one standard error) for all four treatments:  $N = 50$  for control and lupine plots;  $N = 75$  for grass and grass-birch-willow treated plots. (b) Mean soil  $CO_2$  flux (in  $\mu\text{mol m}^{-2} \text{sec}^{-1}$ ). Sample size as in (a) (shown plus one standard error).

The carbon stock for the control plots is estimated at  $0.36 \text{ kg m}^{-2}$ . Plots treated with fertilizer and seeded with grasses demonstrated slightly higher carbon levels compared to the control plots, but the difference is statistically indistinguishable ( $p = 0.22$ ). The A layer in these plots displays a significantly ( $p < 0.05$ ) higher carbon content than the corresponding layer in the control plots, while the B layer is much lower. The carbon stock for these plots is nearly identical to the control plots at  $0.38 \text{ kg m}^{-2}$ . Plots seeded with grass-birch-willow display statistically significant higher levels of soil carbon than the control and grass-seeded plots, with higher levels in the A layer than in the B layer. Both A and B layer  $C_{soil}$  means are higher for this treatment than for fertilizer-grass plots. The carbon stocks for this treatment are estimated at  $0.52 \text{ kg m}^{-2}$ . The highest soil carbon levels were observed in samples from plots seeded with lupine, where the carbon contents of the A layer and B layer were nearly equal. The A layer  $C_{soil}$  is nearly identical to that of the grass-birch-willow plots, while the lupine B layer  $C_{soil}$  is significantly higher than that of the grass-birch-willow plots. The carbon stock for these plots is the highest of all treatments at  $0.61 \text{ kg m}^{-2}$ .

**3.2. Soil  $CO_2$  Flux.** Most of the treatment plots yielded similar rates of soil  $CO_2$  production (Table 1, Figure 4). The control, fertilizer-grass, and grass-birch-willow treatments all produced low mean  $CO_{2soil}$  flux rates of 0.5 to  $0.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ . The lupine-treated plots yielded much higher  $CO_2$  flux rates than the other treatments (mean  $CO_{2soil} = 2.90 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). The lupine plots also display the widest range of values and highest standard deviation among the treatments compared to the other treatments; next highest standard deviation was observed in the control plots. The lupine-treated plots are also distinctive in being the only plots displaying a statistically significant positive correlation between  $C_{soil}\%$  (A and B layers) and soil  $CO_2$  flux with  $r^2 > 0.1$  (Figure 5). All other treatments yield negative slope to almost no slope and  $r^2 < 0.1$ .

## 4. Discussion

**4.1. Previous Work.** The work by Aradottir et al. [22] focused on the vegetative patterns in the experimental plots, particularly the increase in vegetative cover, and found that all plots that had been seeded with grasses as part of the treatment

showed rapid increases in cover for the first few years. After 2003, however, these plots showed a gradual decline in vegetative cover. The plots seeded with lupine exhibited a substantially lower vegetative cover than those treated with grasses, but the lupine-treated plots also displayed a continuing increase in cover. Similarly, the increase of SOC in the top 5 cm of the soil profile was greatest in those plots containing grasses. Below 5 cm, the lupine plots produced a SOC increase comparable to that of the grasses. Additionally, they found that fertilization alone promoted formation of BSCs and ecological succession by fostering colonization by native species.

The study by Arnalds et al. [20] focused on the trends in carbon storage and other soil properties for these same plots, collecting and analyzing the carbon and nitrogen content for all treatment areas in 2005 and again in 2007. They found that most treatment plans produced increased SOC in 2005, compared to the control plots, but as found by Aradottir et al. [22], the greatest increases in the upper 5 cm of the soil were in those plots in which seeding with grasses was part of the treatment. All treatments other than the control (untreated) produced SOC increases below 5 cm, but the increases were smaller than in the top 5 cm. When resampled in 2007, several treatments showed significant gains in SOC in the top 5 cm compared to 2005 values, in particular, the plots with lupine and those with combinations of grasses and trees.

**4.2. Comparison to Prior Results.** Arnalds et al. [20] presented the results of analyses of the soils in the experimental plots, including carbon content, conducted in 2003, 2005, and 2007 (Table 6 in [20]). The 2003 results included only the control and fertilizer-grass treatment plots whereas the results for 2005 and 2007 include also the grass-birch-willow and lupine treatments. Table 2 and Figure 6 present summaries of the results from 2005 and 2007 compared to those of the present study for individual plots and for treatment types.

The control plots exhibited stability in both of the A and B layers across the study period of 2003 through 2007 [20]. The mean  $C_{soil}$  of the A and B layers measured in the control plots in 2012 is significantly higher compared to that measured in 2005 and 2007. The fertilizer-grass treatment demonstrated a marked increase of  $C_{soil}$  in comparison to the control plots when first measured in 2003, and  $C_{soil}$  continued to increase when measured in 2005, and again in 2007.

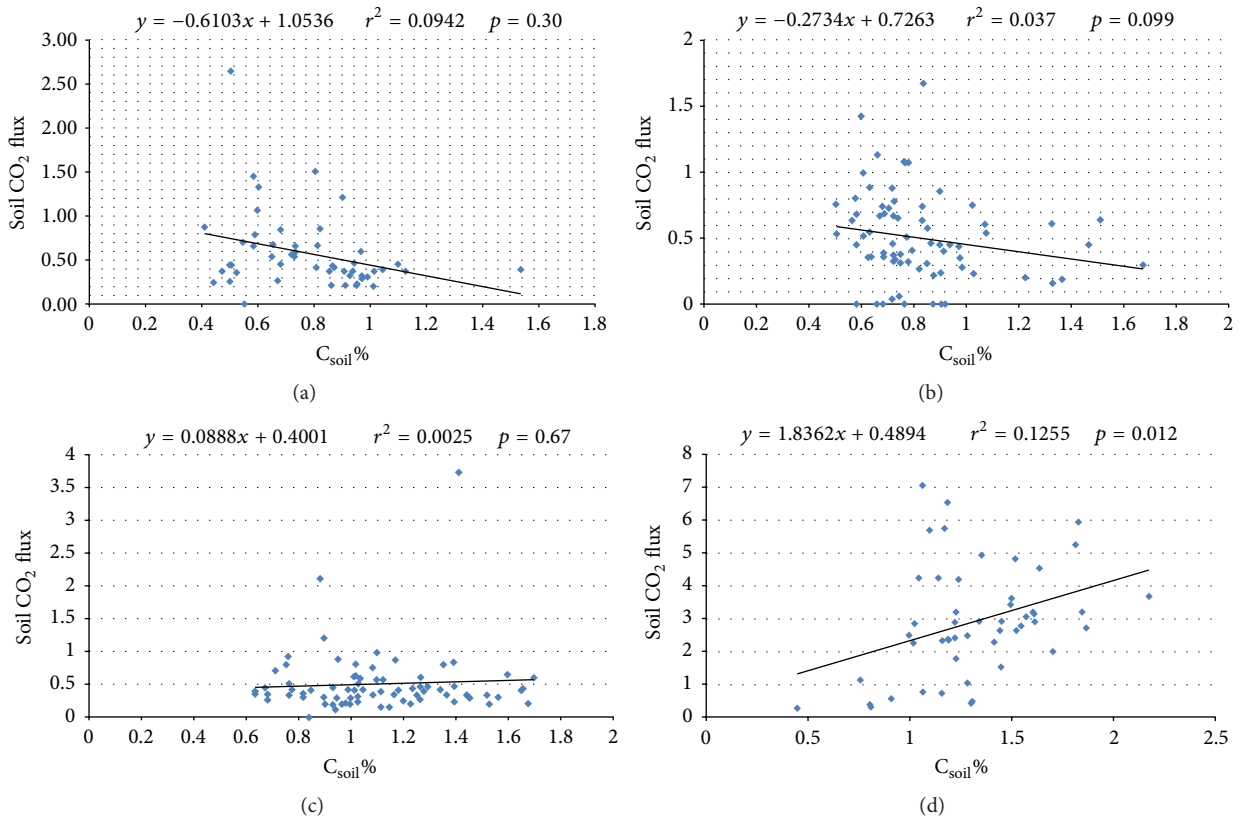


FIGURE 5: Scatter plots of soil carbon versus soil CO<sub>2</sub> flux for individual samples shown for all four treatments, with slope and  $r^2$  of regression line: (a) = control; (b) = fertilizer/grass; (c) = grass, birch, and willow; (d) = lupine.

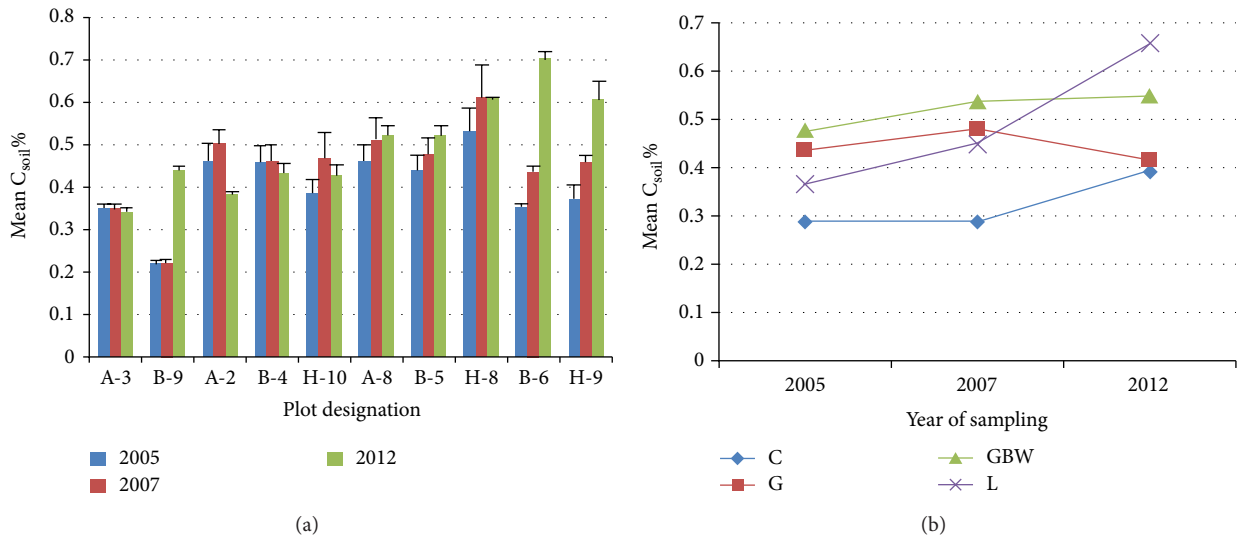


FIGURE 6: Comparison of 2012 results with 2005 and 2007. (a) Mean C<sub>soil</sub> for individual plots (0–10 cm mean plus 1 SE) for each sample year. Control = A-3, B-9; fertilizer-grass = A-2, B-4, H-10; grass-birch-willow = A-8, B-5, H-8; lupine = B-6, H-9. (b) Mean for plots averaged by treatment. C = control, G = fertilizer-grass; GBW = grass-birch-willow; L = lupine.

TABLE 2: Results for soil carbon analysis from this study compared with results for individual plots sampled in 2007 (study by Arnalds et al. 2013 [20]). The significance (probability  $p$ ) of the difference is evaluated by one-way ANOVA.

Plot number	A layer				B layer				Treatment
	2007	2012	Change	$p$	2007	2012	Change	$p$	
A-3	0.322	0.319	–	1.0	0.384	0.364	–	0.387	Control
B-9	0.217	0.436	+	<0.001	0.225	0.443	+	<0.001	Control
A-2	0.539	0.389	–	<0.001	0.467	0.378	–	<0.001	Grass
B-4	0.536	0.516	–	0.8	0.392	0.354	–	0.582	Grass
H-10	0.617	0.428	–	0.013	0.322	0.425	+	0.148	Grass
A-8	0.593	0.611	+	0.8	0.434	0.435	+	0.988	GBW
B-5	0.574	0.572	–	0.98	0.386	0.473	+	0.295	GBW
H-8	0.725	0.613	–	0.006	0.496	0.602	+	0.132	GBW
B-6	0.459	0.702	+	0.002	0.417	0.704	+	0.004	Lupine
H-9	0.469	0.611	+	0.187	0.452	0.605	+	0.057	Lupine

In contrast to the results for the control plots, the 2012 fertilizer-grass measurements show a significant decrease in the A and B layers in most plots compared to the values from 2007.

The grass-birch-willow treated plots had the highest  $C_{\text{soil}}$  of all treatments when first measured in 2005; the A layer  $C_{\text{soil}}$  was twice that of the control plots, and  $C_{\text{soil}}$  continued to increase in both A and B layers when measured in 2007. The 2012 measurements demonstrate a continued increase, although the increase is not statistically significant. Considered separately, the A layer  $C_{\text{soil}}$  for 2012 is indistinguishable from 2007, while the B layer for 2012 exhibited a significant increase compared to 2007.

The largest observed change in  $C_{\text{soil}}$  between 2007 and 2012 is in the lupine-seeded plots. In 2005 and 2007, these plots exhibited  $C_{\text{soil}}$  values higher than control plots, but with A layer  $C_{\text{soil}}$  values substantially lower than fertilizer-grass or grass-birch-willow treated plots. However, the B layer  $C_{\text{soil}}$  in the lupine-seeded plots was comparable to the other treatments in both 2005 and 2007 measurements. The 2012 measurements demonstrated large and statistically significant increases in  $C_{\text{soil}}$  in both the A and B layers compared to 2007.

**4.3. Interpretation of Individual Plots.** There are differences in temporal trends between plots that received identical treatment, as seen in Figure 6 and Table 2, which bear examination. First, the control plot changes from 2007 to 2012 exhibit a trend of increasing  $C_{\text{soil}}$  that primarily reflects changes in plot B-9, as plot A-3 was almost unchanged. Field observations indicate that the macrovegetative cover in plots A-3 and B-9 was not noticeably different at the time of sampling. These plots presented mainly a gravelly deflation surface with isolated grass tufts surrounded by aeolian haloes and small patches of BSC. Thus, we consider the results for plot B-9 as anomalous. Although the 2012 sampling scheme was designed for randomization, we speculate that the 25 sample points within plot B-9 may have included a disproportionate number of sites covered by vegetation or BSC.

The three fertilizer-grass plots yielded similarly contrasting results when compared to the trends established earlier in the study of Arnalds et al. [20]. Plot B-4, which exhibited almost no change in  $C_{\text{soil}}$  from 2005 to 2007, remained unchanged in 2012. In contrast,  $C_{\text{soil}}$  increased in both A-2 and H-10 from 2005 to 2007, but it decreased in 2012. We note, however, that, in H-10, the decrease in the A layer was partially offset by an increase in the B layer. The grass-seeded plots, in general, display only partial vegetative cover, much of which consists of nongrasses, such as crowberry and moss campion. Comparison of Figure 2A from Arnalds et al. [20] with Figures 2(c) and 2(d) herein demonstrates a substantial decrease in surface coverage by grass, although we lack a quantitative measure of this decrease. We note that the common native species have root systems that are less densely clustered and thus may be less effective at storing carbon in the soil than the grasses, which form systems of many closely packed roots in the upper soil layer. Moss campion, for example, forms hemispherical clusters of stems emanating from single, woody root [25]. Similarly, crowberry typically grows initially from one primary root, although it develops adventitious roots from procumbent stems as it grows [26]. Additionally, we observed that aeolian drift is extensive on some grass-seeded plots, forming haloes up to 5 cm thick around islands of vascular vegetation. Burial of the vegetated surface causes a decrease in the A layer  $C_{\text{soil}}$  but potentially an increase in the B layer which stores the organic matter of the buried A layer. As noted by previous workers [20, 27, 28], the relationship between the stability of the land surface and soil carbon storage includes both loss through erosion and gains by aeolian burial. Burial of the original surface by several centimeters of aeolian sediment in plot H-10 adequately explains both the decrease of  $C_{\text{soil}}$  in the A layer and the increase in the B layer. A similar explanation may apply to the trend for plot H-8, one of the grass-birch-willow plots; the other two of these (A-8 and B-5) were relatively unchanged from 2007 to 2012, but H-8 displayed a decrease in the A layer with a concomitant increase in the B layer.

As noted above, the lupine plots are the only treatment in which the increase in  $C_{\text{soil}}$  observed in the earlier study [20] continued through 2012. The data presented in that

study indicate a carbon accumulation rate of approximately  $0.04 \text{ kg m}^{-2} \text{ y}^{-1}$  from 2005 to 2007. Comparison to the data presented herein demonstrates maintenance of this accumulation rate from 2007 to 2012.

**4.4. Soil  $\text{CO}_2$  Flux.** As described above, most of the treatments yielded  $\text{CO}_{2\text{soil}}$  flux values nearly an order of magnitude lower than the lupine plots. The primary sources of  $\text{CO}_{2\text{soil}}$  are aerobic decomposition of organic matter and root respiration, but in soils with particularly low organic contents, such as these, the former source will be negligible. Hence, the  $\text{CO}_{2\text{soil}}$  values we observed record almost entirely respiration from the roots systems of the aboveground vegetation. Qualitative observation indicates that the aboveground biomass of the lupine-seeded plots far exceeds that of the other plots, potentially by an order of magnitude; hence, total root mass in the lupine plots also greatly exceeds that of other plots. Therefore, it is not surprising that the resultant root respiration volume is much higher in the lupine-treated plots than in any other treatment plots.

As noted above, the lupine-treated plots are the only treatment in which we find a positive correlation between  $C_{\text{soil}}$  and  $\text{CO}_{2\text{soil}}$  flux. At a qualitative level, this appears to be a function of the aboveground vegetative cover. Lupine plots, with the highest biomass, are most effective at incorporating SOM and also have the largest and most active root systems. Interestingly, the control and grass-seeded plots both demonstrate weak negative correlations between  $C_{\text{soil}}$  and  $\text{CO}_{2\text{soil}}$ . We speculate that in the grass-seeded plots this relationship might result from the common occurrence of BSC in these plots; BSC may contribute to SOM if crusts are buried by very thin aeolian veneers, thus contributing to soil carbon sequestration, but BSC produces no root systems that respire  $\text{CO}_2$ . Grass-birch-willow plots exhibit no correlation between  $C_{\text{soil}}$  and  $\text{CO}_{2\text{soil}}$ . Due to the very low proportion of the plot area occupied by the birch and willow clusters, most sample points will not be sufficiently close to the root systems of the trees to record root respiration.

**4.5. Implications for Restoration.** From the outset, the experimental plots at Geitasandur serve the dual purposes of (1) investigating the efficacy of various restoration treatments in stabilizing and restoring to a vegetated state the severely eroded Andisols of southern Iceland and (2) comparing the efficiency of these treatments in promoting soil carbon sequestration. The work of Aradottir et al. [22] noted that treatments that included seeding with grasses produced the most rapid increases in vegetative cover. The authors also demonstrated the significance of fertilization as part of the soil treatment in promoting growth of vascular plants, bryophytes, and BSC. As we noted above, however, their data indicated the increasing spread of vegetation in most plots only through the first three to four years, following which vegetative cover declined; the sole treatment to demonstrate continued growth was seeding with lupine. We found that substantial areas of the soil surface, up to a maximum of 40%, in the fertilizer-grass and grass-birch-willow plots were covered by BSC when examined in 2012. As the BSC

helps stabilize the soil surface by providing resistance to aeolian deflation, the treatments that included fertilization can nonetheless be considered successful in reducing erosion potential.

The study of Arnalds et al. [20] focused more on the soil characteristics of the Geitasandur experimental plots, in particular, on the rates of carbon sequestration. As with the later study [22], the authors found that the most rapid changes in the initial years following fertilization and seeding occurred in those plots in which the treatment included fertilizer and seeding with grasses, regardless of other treatments applied. The subsequent declines in both vegetative cover and  $C_{\text{soil}}$  seen in this study highlight the importance of nutrient availability for restoration in Iceland.

Arnalds et al. [20] speculated that reclaimed land could sequester soil carbon at a continued rate of up to  $0.06 \text{ kg m}^{-2} \text{ y}^{-1}$  for decades, or even centuries, but only if full vegetation cover is maintained. The present study confirms that the rate of carbon storage declines or halts completely without this cover. This poses the question of how much maintenance (refertilization and/or reseeded) is required to continue this rate of carbon sequestration. The answer to this question depends on numerous factors, such as the stability of the soil surface (resistance to erosive forces from wind and water), as well as other factors including soil conditions (e.g., water holding capacity), rainfall, and various other environmental factors (see discussion in [29]). Previous long-term studies of vegetation and carbon changes as a result of experimental reclamation treatments in other areas of Iceland have demonstrated sustained and substantial increases in both biomass and soil carbon on decadal scales in areas where environmental factors are more favorable [18].

In the present study, we find that the most robust vegetation, the largest increase in SOC, and the highest soil  $\text{CO}_2$  flux are all found in the lupine-seeded plots. As stated above, these plots were the only ones found to continue sequestering carbon at a high rate 12 years after initial seeding. This finding has significant implications for land reclamation planning in Iceland. Arctic lupine (*L. nootkatensis*) was first introduced to Iceland in the late nineteenth century, initially for experimental trials, but imported more formally for large-scale afforestation studies in the mid-twentieth century [30]. The species has several properties that make it well-suited for reclaiming the badly eroded, sandy soils of Iceland, including the fact that it is largely self-fertilizing and a prolific seed-producer. Thus, it spreads and continues to grow with little or no maintenance. Despite its clear potential for afforestation, however, lupine has negative ecological and societal impacts; as a shade-intolerant, it quickly outgrows and tends to crowd out much of the low-growing native heath shrubbery, reducing local floral diversity [31–33]. Moreover, the alkaloid content of the foliage makes it inappropriate as a major component of the grazing fodder [34]. As a nitrogen-fixing species, however, lupine may prove useful in promoting succession of native species with appropriate management [30–32, 35].



## 5. Conclusions

The experimental plots at Geitasandur that were established in 1999 to study land reclamation and carbon sequestration were resampled in 2012 and the results compared with earlier studies [20, 22]. Most of the plots that were untreated (control), fertilized, and seeded with grasses or treated with fertilizer, seeded with grasses, and planted with birch and willow exhibited no further increase in soil carbon from the values last measured in 2007. This contrasts with the earlier results that demonstrated rapid increase in soil carbon in all plots receiving fertilizer and grass, with or without trees. Nutrient limitation and degradation of the soil surface due to aeolian processes likely contributed to the decline in soil carbon sequestration. Some plots demonstrated declines in soil carbon in the upper 5 cm of the soil profile but increases in the underlying 5 cm. We interpret this pattern as resulting from preservation of carbon by burial of the vegetated surface by aeolian drift. The only plots that displayed significant and consistent increase in soil carbon content were those seeded with lupine. These plots also exhibited substantially higher aboveground biomass and root respiration, as measured by soil CO<sub>2</sub> flux. These results suggest that lupine may have utility in reclamation and stabilization of eroded land surfaces and in promoting carbon sequestration, but other ecological factors, such as ecological diversity, require serious consideration.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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