ASSESSMENT OF THE IMPACT OF DIFFERENT REVEGETATION METHODS ON SOIL CARBON STOCKS IN ICELAND

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ABSTRACT

Soils have more capacity to store high amounts of carbon than vegetation in the terrestrial carbon pools. The objective of the study was to assess the impact of time, reclamation methods and spatial variation on carbon concentration in soils on reclamation sites in Iceland. A total of 60 reclamation sites were studied. At each site, samples were collected from 10 m x 10 m plots in which five sub plots of 0.5 m x 0.5 m area were selected randomly for the above- and below-ground biomass and soil sampling. The reclamation methods included in this study were: a) sowing of Alaska lupine (*Lupinus nootkatensis*), b) sowing of a mixture of grass species and c) fertilization. For comparison, soils from control plots were sampled and analysed. The results showed that the method and the spatial variation of reclamation sites have a very highly significant effect on carbon concentration. However, the time length since reclamation started was found to have no statistically significant effect. Fertilizing the plots for reclamation did give a significantly higher carbon concentration compared to control plots. This was not the case when the plots were sown with lupine or grass species. For an efficient operation of all the methods, it is important to study the soil physical and chemical properties and the nutrient demand of the different methods of reclamation. This helps to apply the right method of reclamation in the appropriate soil type and to increase the productivity of the method.

1. INTRODUCTION

1.1 Background

The main causes of ecosystem disturbance in Iceland include the natural factors of harsh climate, in which high climatic fluctuation aggravate the condition while reducing the resistance ability of vegetation, weak soil structure, and volcanic eruptions. The human factors causing ecosystem disturbance are unsustainable land use, mainly grazing and extensive woodland clearance (Arnalds, 2002, 2004; Runolfsson & Arnalds, 2004). These ecosystem disturbances result in severely degraded vegetation, high reduction in biological diversity, loss of land fertility, change in hydrologic patterns, and microclimate (Runolfsson & Arnalds, 2004). Hence a large amount of soil and organic carbon, the foundation of land fertility, have been lost as a result of the loss of vegetation and soil erosion, which is the effect and at the same time cause of land degradation (Runolfsson & Arnalds, 2004; Trumper, Ravilious & Dickson, 2008).

To tackle the problem of greenhouse gas emission and to maintain the health of the global climate, reduction of carbon emission has a fundamental role (Arnalds, 2002, 2004; Marland, Garten, Post & West, 2004). However, this reduction in carbon emission alone may not be an effective course of action. It should include returning the carbon to its permanent storage, the soils, through improving the vegetation cover of the degraded land, which in turn has a direct effect on the soil fertility and productivity (Arnalds, 2002, 2004).

A comprehensive programme that gives the Icelandic Soil Conservation Service (ISCS) an operational framework for the period 2003–2014 was set by the Icelandic government. This framework was to mitigate land degradation and desertification, revegetation of eroded land, and attaining sustainable land use (Runolfsson & Arnalds, 2004). The programme includes carbon sequestration as one component of its activities and co-operating and working with different parts of the community and governmental and nongovernmental organizations as the main tools for its achievement (Arnalds, 2002, 2004; Runolfsson & Arnalds, 2004).

Reclamation of degraded land, as in the case of Iceland, has the full potential to cause accumulation of significant amounts of carbon and this can play a major role as a tool in combating climate change and improving food security through reversing the degradation trend (Aradottir, Svavarsdottir, Jonsson & Gudbergsson 2000; Arnalds, 2002, 2004).

1.2 Justification

The advancing sand drift which caused devastating effects on valuable farmlands initiated the establishment of the Icelandic Soil Conservation Service with the aim of combating soil erosion and land degradation in 1907 (Agustsdottir, 2004; Arnalds *et al.,* 2001). The activities of ISCS in the first 70 years primarily focused on stopping the catastrophic wind erosion of pastures and rangelands, which later shifted to revegetation of vast areas of eroded land (Agustsdottir, 2004). Varieties of methods have been employed for restoration including seeding with various species, fertilization and exclusion of rangelands from animal grazing (Arnalds, Gudbergsson & Gudmundsson*,* 2000).

In Iceland, reclamation of severely degraded areas is mainly done through fertilization of land, with or without seeding of various species, and protection from grazing (Agustsdottir, 2004). The native grass, lime grass (*Leymus arenarius)*, is used for reclamation of areas with an unstable surface, such as sand dunes and erosion fronts (Greipsson & Davy, 1994, 1996; Aradottir *et al*., 2000). To reclaim degraded land with a relatively stable surface spreading of mineral fertilizer, with or without seeding of grass species, is used. These methods became common starting in the 1940s and 1950s (Agustsdottir, 2004). Furthermore, a perennial nitrogen fixating plant, Nootka lupine, (*Lupinus nootkatensis*), has also been used to reclaim degraded lands (Magnusson B., Magnusson, S.H. & Sigurdsson, 2001). This Nootka lupine is a non-native plant which was introduced for reclamation starting in the mid-1980s (Aradottir *et al*., 2000). As it is light-demanding, fast growing and adapted to an open environment, its main habitat is the areas where natural disturbance is frequent, such as sand and gravel along the coastline and mountain slopes, the vast eroded areas, volcanic sands and floodplain areas of Iceland (Magnusson, 2006). Therefore, Nootka lupine is a very effective plant for land reclamation in which responses to soil fertility can be detected within a short period of reclamation time (Aradottir *et al.,* 2000; Magnusson *et al.,* 2001).

New national and international environmental standards such as the Framework Convention for Climate Change (FCCC) have resulted in new restoration objectives such as carbon sequestration (Aradottir, 2003). To meet this demand, the Icelandic government has initiated an effort to sequester carbon in soil and vegetation and assess potential carbon sequestration rates and develop validation methods for carbon sequestration in the reclamation programs (Aradottir *et al.,* 2000). Hence carbon stocks in the different parts of the ecosystem, including above and below-ground biomass, and soils have been measured in different reclamation sites (Aradottir *et al.,* 2000; Arnalds *et al.,* 2000).

Among the carbon reservoirs in an ecosystem, soils are the most important pools next to fossil fuels and oceans (Arnalds *et al.,* 2000). Soils also have more capacity to store high amounts of carbon than vegetation in the terrestrial ecosystem which, therefore, needs more attention to study and compile information on their functions and dynamics in regulating the carbon balance in the terrestrial ecosystem (Post & Kwon, 2000). Even though researchers are working on issues related to carbon stocks and sequestration in Iceland, studies on soil conditions are scarce and more investigation is needed in relation to the effect of revegetation and reclamation and their long term impact on carbon accumulation (Ritter, 2007), Generally, understanding soil carbon concentration calls for studies concerning different issues such as use of different reclamation methods and their impact. Hence this study was initiated to assess the impact of the types of reclamation; fertilization, grass sowing and Nootka lupine (*Lupinus nootkatensis*) sowing on soil carbon within a given time frame. Additionally, this will help to understand the pattern of soil carbon concentration along the soil depth and the impact of the species in the long term on soil fertility, in addition to controlling soil erosion.

1.3 Objectives

The general objective of the study was to assess the impact of time and type of reclamation on carbon concentration in soils in different climatic zones of Iceland. Specifically this study aimed to:

- Assess the effect of time of reclamation on the concentration of carbon in soil
- Assess the effect of method of reclamation on the concentration of carbon in soil
- Assess the concentration of organic carbon at different soil depths
- Assess the impact of geographical variation on the concentration of carbon in soil

1.4 Research questions

- ▶ Does the method of reclamation have a significant effect on soil carbon concentration?
- ▶ Is there a significant difference in the C-concentration across different depths in the soil?
- ▶ How does time affect the C-concentration at the different depths in the soil?
- ▶ Is there any difference in the concentration of soil carbon as time of reclamation increases?
- ▶ Do all the reclamation methods have the same trend with regard to changes in soil carbon concentration with time?
- ▶ Is there a significant difference in the C-concentration within the different methods?
- ▶ Is there a significant difference in the C-concentration between the reclamation areas and control plots?
- ▶ Does the difference in geographical variation affect the carbon concentration significantly?

2. METHODS AND MATERIALS

2.1 Description of study sites

The study area was land reclamation sites in Iceland. The geographic location of Iceland is in the North Atlantic Ocean between 63°23' and 65°32'N latitude and 13°29' and 24°32'W longitude. In 2007 the Icelandic Soil Conservation Service developed a network for monitoring carbon sequestration in land reclamation areas established in 1990 or later. Permanent 10 x 10 m plots are established at 1 km intervals in all the reclamation areas. Plots are also established in non-treated eroded areas, control plots, within 30 m from reclamation sites. These plots are used for reference to establish the base line of carbon concentration in soils and vegetation prior to reclamation. The Icelandic Soil Conservation Service started collecting samples within this network in 2007. Hence soils from a total of 60 sites (sites listed in appendix 1), of which 11 were control plots, were sampled and analysed (Fig. 1). The sampling points are distributed along the volcanically active ridge of Iceland, the Mid-Atlantic Ridge, stretching from south-west to the north-eastern part (Jakobsdottir, Gudmundsson & Stefansson, 2000). In addition to these points, there were points analysed in southern Iceland.

2.2 Sampling

2.2.1 Field data collection

This study was carried out using data collected in 2007 from areas reclaimed using three different methods and from control plots (Fig. 1). The areas were under treatment for the range of 0 to 19 years from the time the reclamation started. The reclamation methods include:

- Sowing a mixture of grass species: were seeded and fertilized for two years at the rate of about 100 kg N ha^{-1}, supplemented by phosphorus and potassium (Arnalds *et al.,* 2000). In case of poor performance of the grasses, after three years, sometimes application of fertilizer was continued for one or more years.
- Sowing of Nootka lupine: lupine was sown in areas where there is high degradation. Lupine sowing is done without application of fertilizer because lupine is a nitrogen fixating legume (Magnusson *et al.,* 2001).
- Fertilization: was applied to degraded lands at an average rate of 325 kg ha^{-1}. This is in order to facilitate and speed up natural succession. In this method there is no application of any plant seeds.

Control plots adjacent to the reclamation areas were also sampled for soil carbon analysis. The average carbon content in the control plots was then compared to the three different treatments for comparing the change in carbon content from the degraded to the reclaimed state.

Permanent 10 m x 10 m plots that had been set up for the carbon sequestration monitoring program by the ISCS were used for sampling (Fig. 2a). From each 100 m^2 plot five 0.5 m x 0.5 m sub-plots were selected randomly for the above- and below-ground biomass and soil sampling (Fig. 2b).

For analysis of soil carbon, composite soil samples (MacDicken, 1997) were taken from three different depths of the soils (0–10, 10–20, 20–30 cm). An auger and cake pans were used to take soil samples from each point. Cake pans were used in areas where there were loose sandy

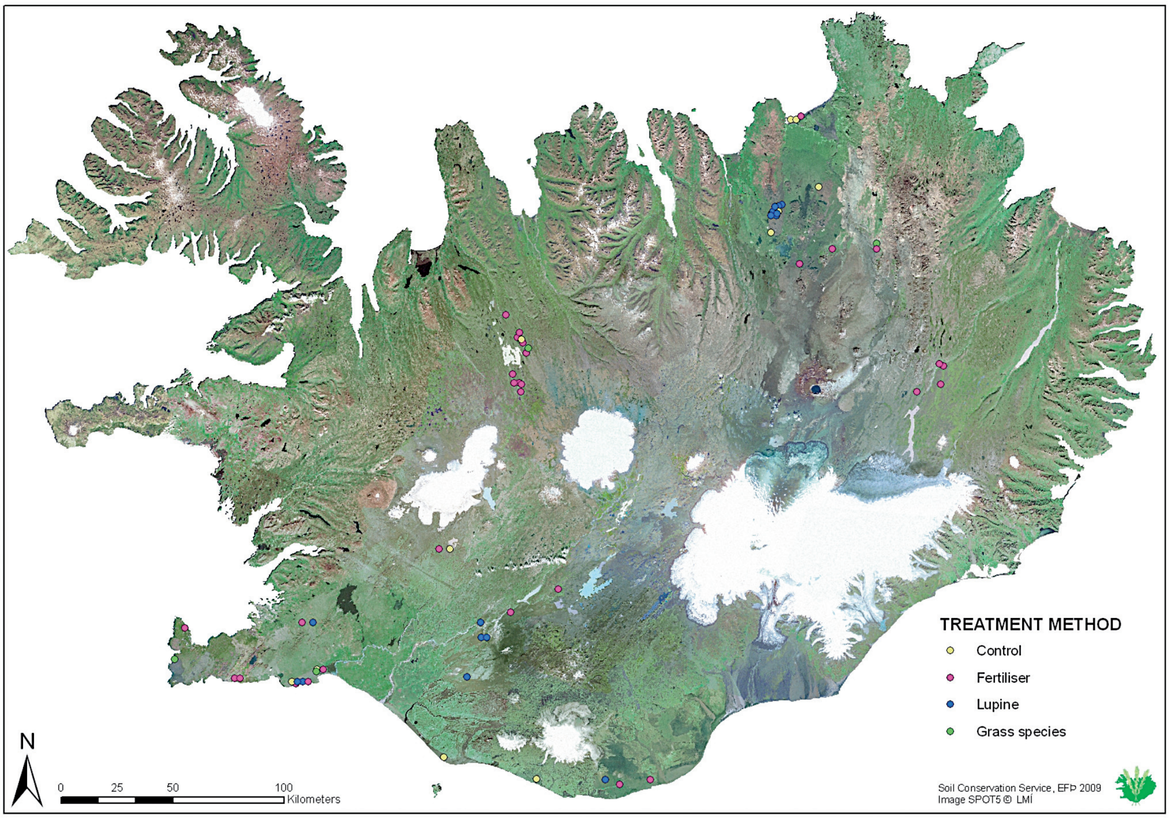


Fig. 1. *Map of the study area with the sampling points. The treatment methods and controls are indicated with dots of different colours.*

soils without aggregation (Fig. 3a) while the auger was used in areas (Fig. 3b) where the soils were relatively fine and formed aggregates. While sampling using the auger, cake pans were also used (Fig. 3c) at the same time to sample the top 0–10 cm depth in order to avoid the error that can be created during sampling with the auger. A tape measure was used to identify the different sampling depths of the soils from the auger (Fig. 3d).

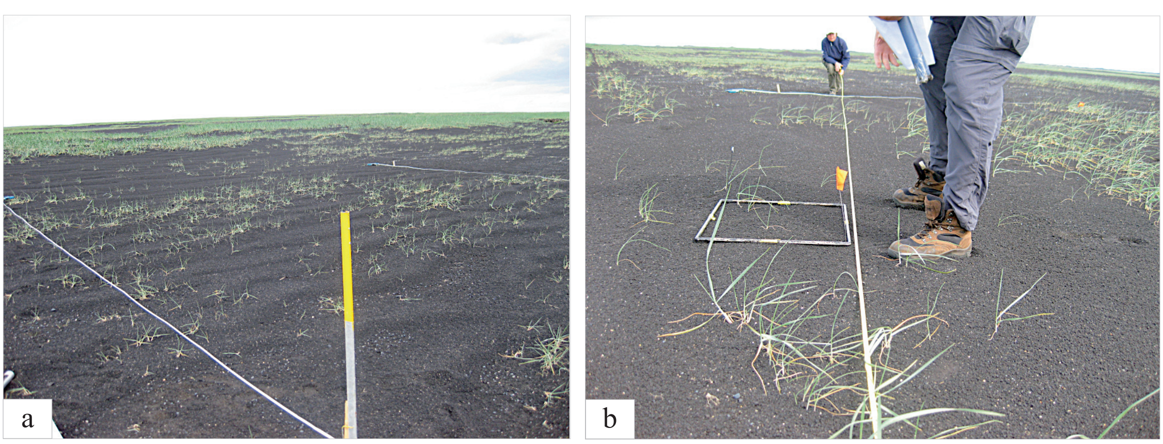


Fig. 2*. A plot of 100 m² marked with poles for permanent monitoring. (a) Meter tape stretched over the plot to locate random sub-plots. (b) Sub-plots of 0.5 x 0.5 m² randomly selected for above- and below-ground sampling. (Photo: Tigist Araya).*

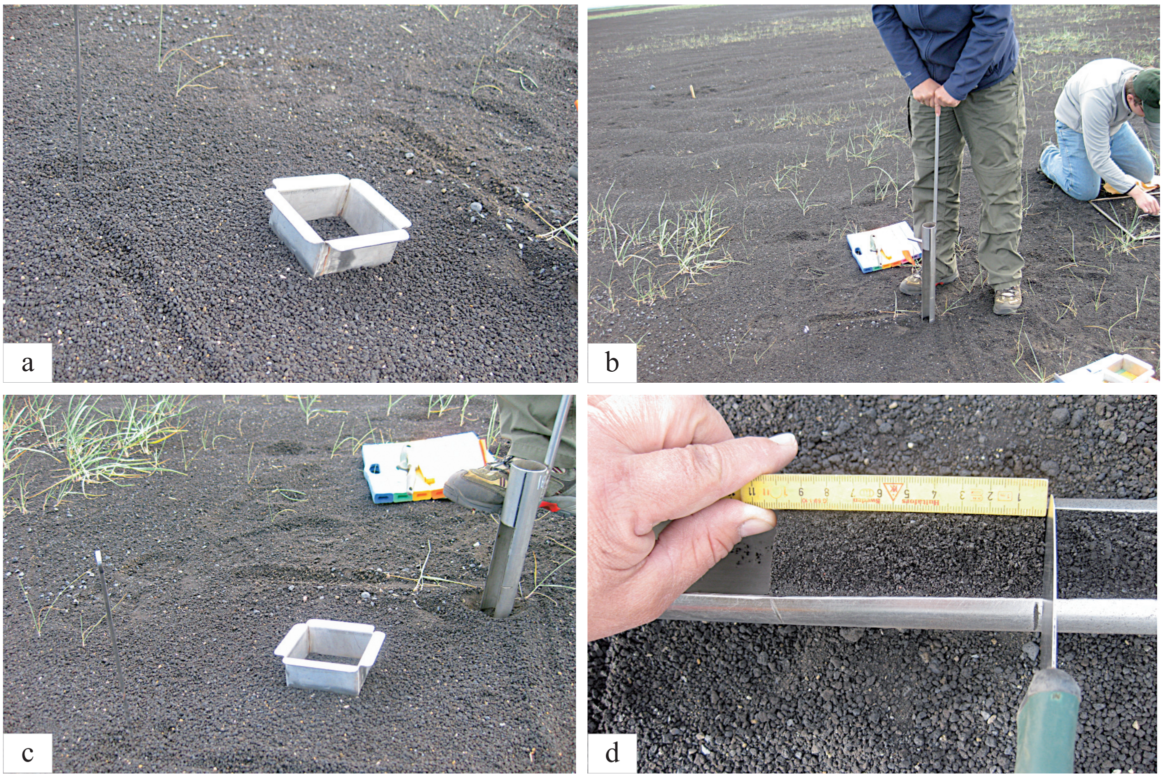


Fig. 3. Soil sample collection from monitoring plots. (a) Sampling using cake pan, (b) sampling using auger in areas where the soil aggregation was relatively high and impossible to sample using cake pan, (c) soil sampling using both auger and cake pan method, and (d) sorting the soils of different depths while sampling using auger. (Photo: Tigist Araya).

2.2.2 Secondary data gathering

In addition to the data which were used from field measurement and laboratory tests, a literature review was also undertaken as a source of the secondary data. Hence the secondary data source was gathered to get information about the application of the different treatment methods and the amount of fertilizer applied.

2.2.3 Data analysis

Data analysis included different methods. To assess the impact of different factors on the carbon concentration, the reclamation time, 0–19 years, and the three sampling depths were considered for all the reclamation methods. JMP statistical software (version 8.0.1) and Microsoft Excel 2007 software were used to analyse the data.

The effect of method of reclamation on the average carbon concentration and carbon in the top 10 cm was tested using one way ANOVA. The means of all the methods were compared to test the statistical difference between pairs of methods using the Tukey-Kramer HSD (honestly significant difference) test. The Tukey-Kramer HSD test shows whether the difference in means exceeds the least significant difference for all pairs of treatments. In this test positive values show significant difference between the pairs and negative values show that there is no significant difference in the amount of carbon between the pair of methods (SAS Institute Inc., 2008). The concentration trend of soil carbon at the different depths (0–10, 10–20 and 20–30 cm) was also examined against the different treatments of reclamation using the Tukey-Kramer HSD test. Leverage plots were used to display the significance test in carbon sequestration due to the vegetation cover, the course fragment content of the soil, the spatial location and age of reclamation. A leverage plot is a graphical display of an effect's significance test (SAS Institute Inc., 2008). Parameter estimates and stepwise analysis methods of JMP statistical software (version 8.0.1) were used to prioritize the impact of the different factors affecting the soil carbon concentration.

The independent effect of the methods was analysed using Microsoft Excel 2007 software which shows a regression of carbon content and treatment age, using the slope of the regression line as an indication of carbon storage.

For each sampling point the Geographic Positioning System (GPS) reading was recorded. A map of the sampling points was produced based on the GPS readings (Fig. 1). ArcGIS software was used to map the points and assess the even distribution of the different reclamation methods along the sampling sites.

3. RESULTS

3.1 Method of reclamation

The mean carbon concentration values of the control plots (mean = 0.24%), lupine sowing (mean = 0.46%) and grass sowing (mean = 0.65%) methods were found to be smaller than the grand mean (0.98%) (Fig. 4 and Table 1). However, the mean value of fertilization treatment was found to be higher (mean = 1.56%) than the grand mean.

The analysis of average carbon concentration, due to reclamation treatments, illustrated that the method of reclamation has a highly significant effect ($p<0.001$) on carbon concentration (Fig. 5). This significant difference was mainly contributed by the fertilization method of

Table 1. *Mean values for reclamation methods.*

Level	Least Sq Mean	Std Error	Mean
Control	0.24	0.35	0.24
Fertilizer	1.56	0.21	1.56
Grass species	0.65	0.57	0.65
Lupine	0.46	0.3	0.46

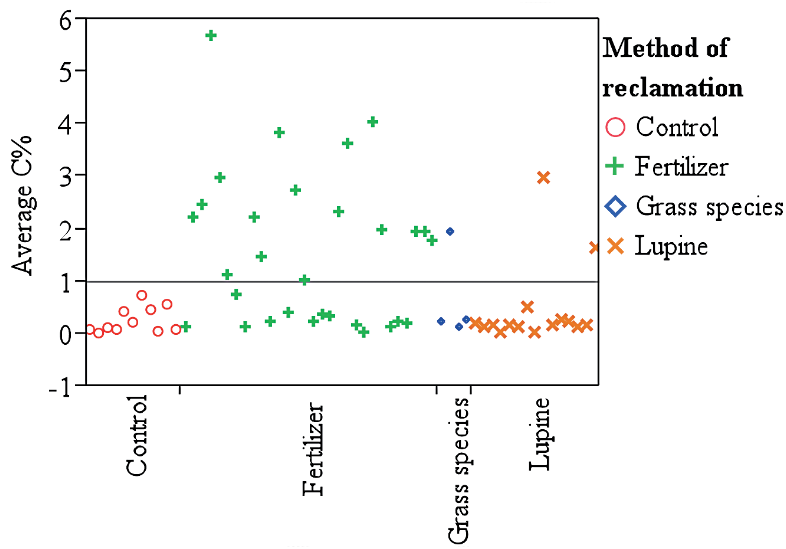


***Fig. 4**. Average carbon (%) versus method of reclamation; the grey horizontal line is the grand mean (0.982%).*

reclamation (Table 2). Among all the methods of reclamation, fertilization treatment resulted in a concentration of a higher amount of carbon ($p<0.001$). The lupine sowing and grass sowing methods, however, did not differ significantly in carbon concentration from the control (Table 2). Hence, the level of carbon content was found to be high in the fertilization methods of reclamation, followed by grass sowing, and the lowest was found in the lupine sowing method.

The comparison was also carried out for the treatments alone without the control plots to determine whether carbon concentration differs among reclamation methods. In this comparison

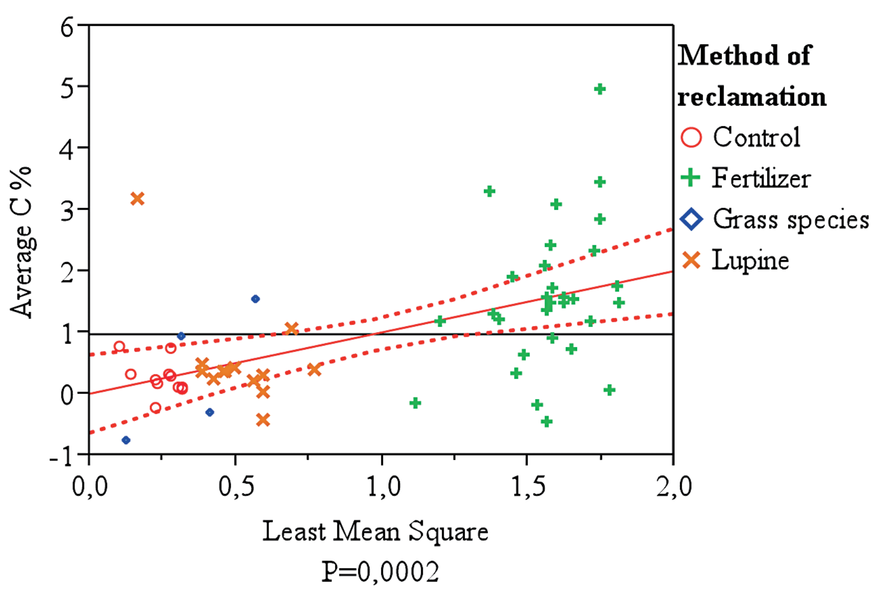


***Fig. 5**. Average carbon concentration versus method; the black horizontal line is the grand mean (0.982%), the solid pink line is the fitted line and the pink dotted line is the 0.05 significance curve.*

Table 2. *Parameter estimates of the methods of reclamation.*

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.73	0.19	3.81	0.0003*
Method of reclamation [Control]	-0.49	0.31	-1.57	0.12
Method of reclamation [Fertilizer]	0.83	0.24	3.45	0.0011*
Method of reclamation [Grass species]	-0.08	0.45	-0.18	0.86

Table 3. *Analysis of variance of methods of reclamation without control plots, * indicates significant effect of method of reclamation in carbon concentration.*

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Method of reclamation	2	13.1	6.6	4.1	0.0225*
Error	46	73.3	1.6		
Corrected Total	48	86.4			

Table 4. *Analysis of variance of the effect of method of reclamation on carbon content of 0–10 cm soil depth, * indicates significant effect of method of reclamation on carbon concentration.*

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Method of reclamation	3	33.2	11.1	4.0	0.0126*
Error	56	156.7	2.8		
Corrected Total	59	189.9			

also the method showed a significant effect ($p<0.05$) (Table 3) due to the fertilizer method of treatment. However, there was statistically no difference between the grass sowing and lupine reclamation methods (Fig. 6).

The relationship was also tested for the soil carbon in the top 10 cm (0–10 cm) depth. This comparison was done in order to assess the carbon in the topsoil which is the main plant residue accumulation zone and where high carbon can be accumulated. In this soil depth (0–10 cm) under different reclamation treatments, the reclamation method still showed a significant between treatment effect ($p<0.05$) on carbon concentration (Table 4 and Fig. 7).

Based on the comparisons for all pairs using the Tukey-Kramer HSD, among the treatment methods, the impact of fertilizer treatment was significantly different compared to the control plots and lupine sowing (Table 5). The grass and lupine sowing methods are also not

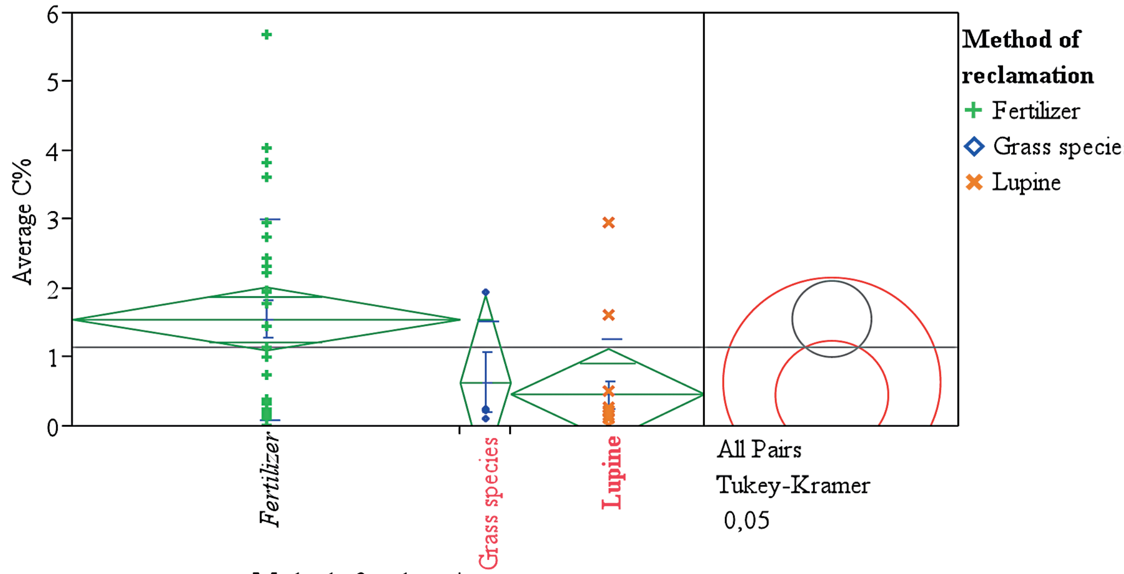


Fig. 6. Scatter plot with mean diamonds for average C (%) versus method; the red circles indicate no significant difference due to grass species and lupine sowing methods, the grey circle indicates a significant difference in fertilizer, the blue bars represent mean error bars, the line at the centre of the diamonds is the group mean and the grey horizontal line is the grand mean.

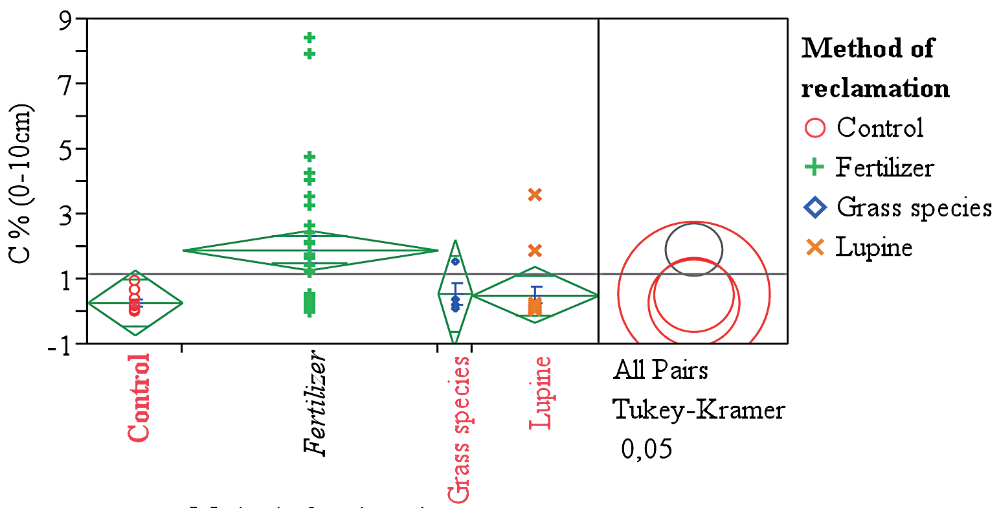


***Fig.** 7. Scatter plot with mean diamonds for amount of carbon in 0–10 cm soil depth versus method; the red circles indicate no significant effect between grass and lupine sowing methods compared to control plots, the grey circle indicates a significant difference in fertilizer, the blue bars represent mean error bars, the line at the centre of the diamonds is the group mean and the grey horizontal line is the grand mean.*

Table 5. *A Least Significant Difference (LSD) threshold matrix. The values in the table are comparisons of the difference in mean values of pairs of treatments with the least significant difference using the Tukey-Kramer HSD (honestly significant difference). Positive values indicate significant difference while negative values are indications of no significant difference.*

Abs(Dif)-LSD	Fertilizer	Grass species	Lupine	Control
Fertilizer	-0.79	-0.71	0.14	0.25
Grass species	-0.71	-2.15	-1.53	-1.37
Lupine	0.14	-1.53	-1.11	-0.98
Control	0.25	-1.37	-0.98	-1.30

significantly different from each other. Similarly, the impact of fertilization and grass sowing methods were not significantly different. On the other hand, the fertilization method resulted in a significant effect on carbon concentration as compared with the control plots but the carbon concentrations in grass and lupine treatments were not significantly different from the carbon in the control plots (Table 5).

3.2 Length of time of reclamation

Carbon stock was plotted (Fig. 8) against the time since reclamation to illustrate the relationship. The distributions of the carbon measurements do not show any pattern against the effect of time (Fig. 8). The carbon distributions also show that time of reclamation had no significant contribution (p = 0.28) for the carbon concentration for all the reclamation methods.

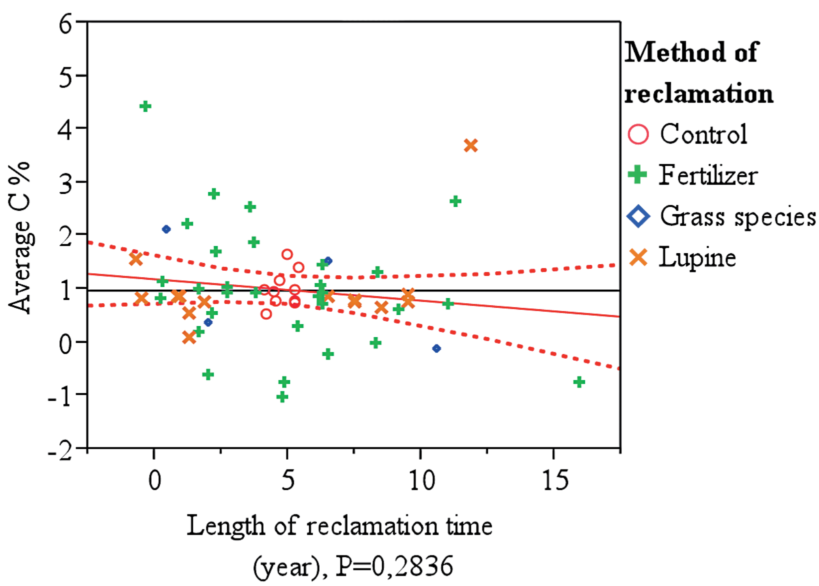
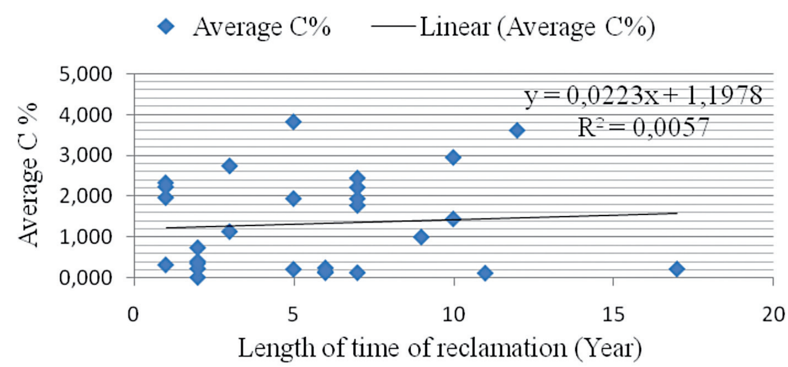
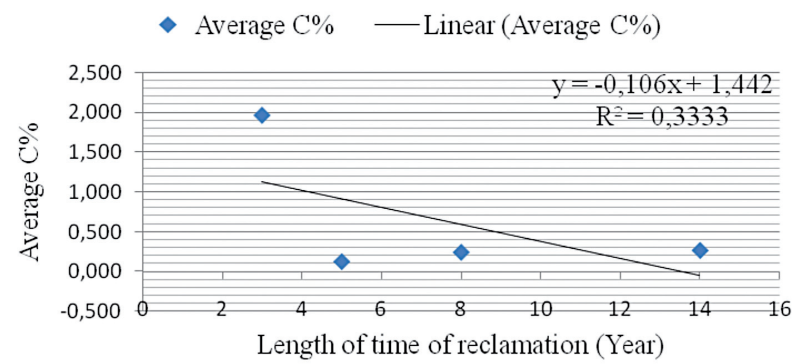


Fig. 8*. Average carbon change versus time length of reclamation (yr); the black horizontal line is the grand mean (0.982), the solid pink line gives the fit and the pink dotted line is the 0.05 significance curve.*

a)



b)



c)

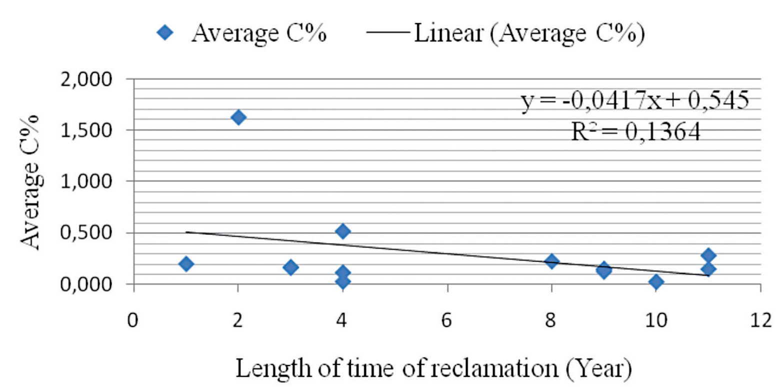


Fig. 9. *Regression analysis on effect of time of reclamation on carbon concentration for the different methods; (a) fertilization method of reclamation, (b) grass sowing and (c) lupine sowing.*

The impact of time on each reclamation type was also assessed separately. The length of time had no significant effect on carbon storage in the overall situation. Besides, in analysis of the individual methods, even though the regression line for fertilizer treatment had a positive slope (0.022) it was very close to zero (Fig. 9a), thus indicating that the carbon concentration was not correlated to the time of reclamation (R^2 = 0.006). The other treatments, grass and lupine plantation methods, had slightly negative slopes on the regression line (-0.11 and -0.042, respectively) which was also very close to zero, indicating there was no relationship (R^2 = 0.3 for grass sowing and 0.14 for Lupine sowing) between the treatment methods and the length of time (Fig. 9b and c).

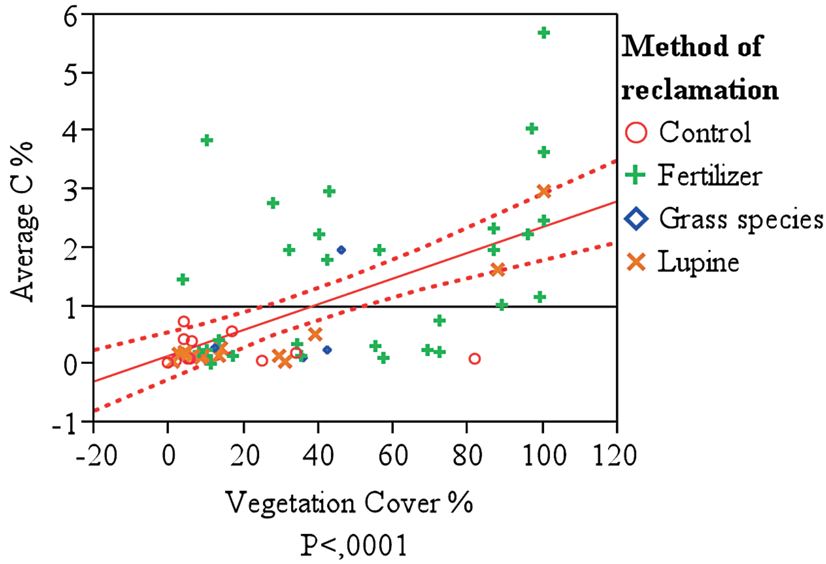


Fig. 10. *Average carbon concentration due to vegetation cover change; the black horizontal line is the grand mean (0.982), the solid pink line gives the fit and the pink dotted line is the 0.05 significance curve.*

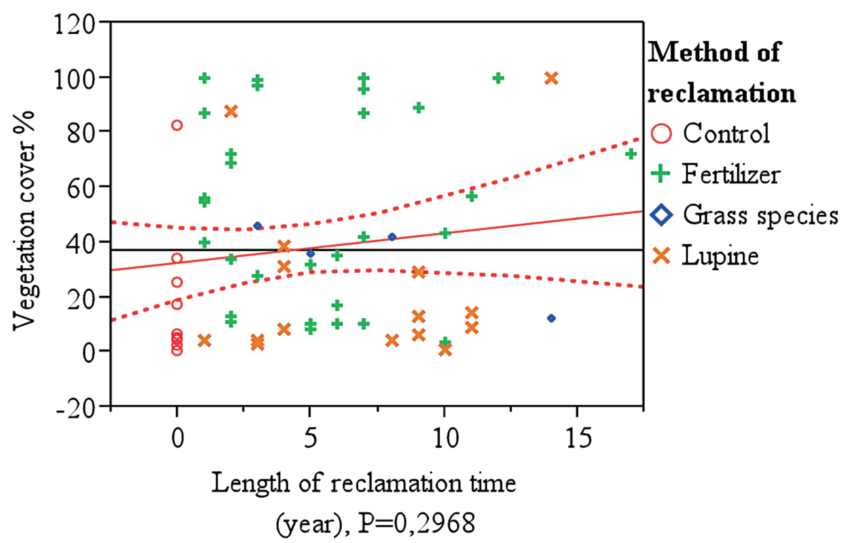


Fig. 11. *Vegetation cover change versus length of time reclamation; the black horizontal line is the grand mean (0.982), the solid pink line gives the fit and the pink dotted line is the 0.05 significance curve.*

Table 6. *Stepwise analysis of factors.*

Parameter	**Estimate**	**nDF**	**SS**	**"F Ratio"**	**"Prob>F"**
Intercept	1.0	1.0	0.0	0.0	1.0
Method of reclamation [Control & Lupine & Grass species-Fertilizer]	-0.6	1.0	20.0	15.6	0.00022*
Method of reclamation [Control-Lupine & Grass species]	0.0	1.0	0.5	0.4	0.5
Method of reclamation [Lupine- Grass species]	0.0	2.0	0.6	0.2	0.8
Length of reclamation time (year)	0.0	1.0	0.0	0.0	1.0

To understand the effect of time on vegetation cover, vegetation cover was plotted against time of reclamation. In general vegetation cover has a direct relation to carbon concentration. This relation was also manifested in this study by the fact that the vegetation cover had a very highly significant effect ($p<0.0001$) on carbon stocks in the tested plots (Fig. 10).

However, this time versus cover analysis for the method of reclamation showed that the change in vegetation cover had no relation to the time length of reclamation. Hence the analysis indicated that the time had no significant effect ($p = 0.297$) in changing the amount of vegetation cover in all the reclamation methods (Fig. 11). Hence, all the reclamation methods analysed were found to be less sensitive to the length of time of treatment.

In general the stepwise analysis of the factors (Table 6) indicated that the impact of the reclamation time did not significantly affect the concentration of carbon stored in the soils. In addition, the reclamation methods with grass and lupine were not found to be significantly different in their carbon stocks.

3.3 Carbon concentration along soil depth

The depth of concentration of carbon in the soil was assessed for the different reclamation methods separately. In areas reclaimed with the fertilization method of treatment the carbon amount decreased from the top down to 30 cm but the differences were not statistically significant (Fig. 12a). In areas sown with lupine the amount of carbon was almost uniform at all the depth categories (Fig. 12b). However, in the areas seeded with grass (Fig. 12c), there was a fluctuation in the carbon stocks and the depth of concentration did not show a uniform trend of change.

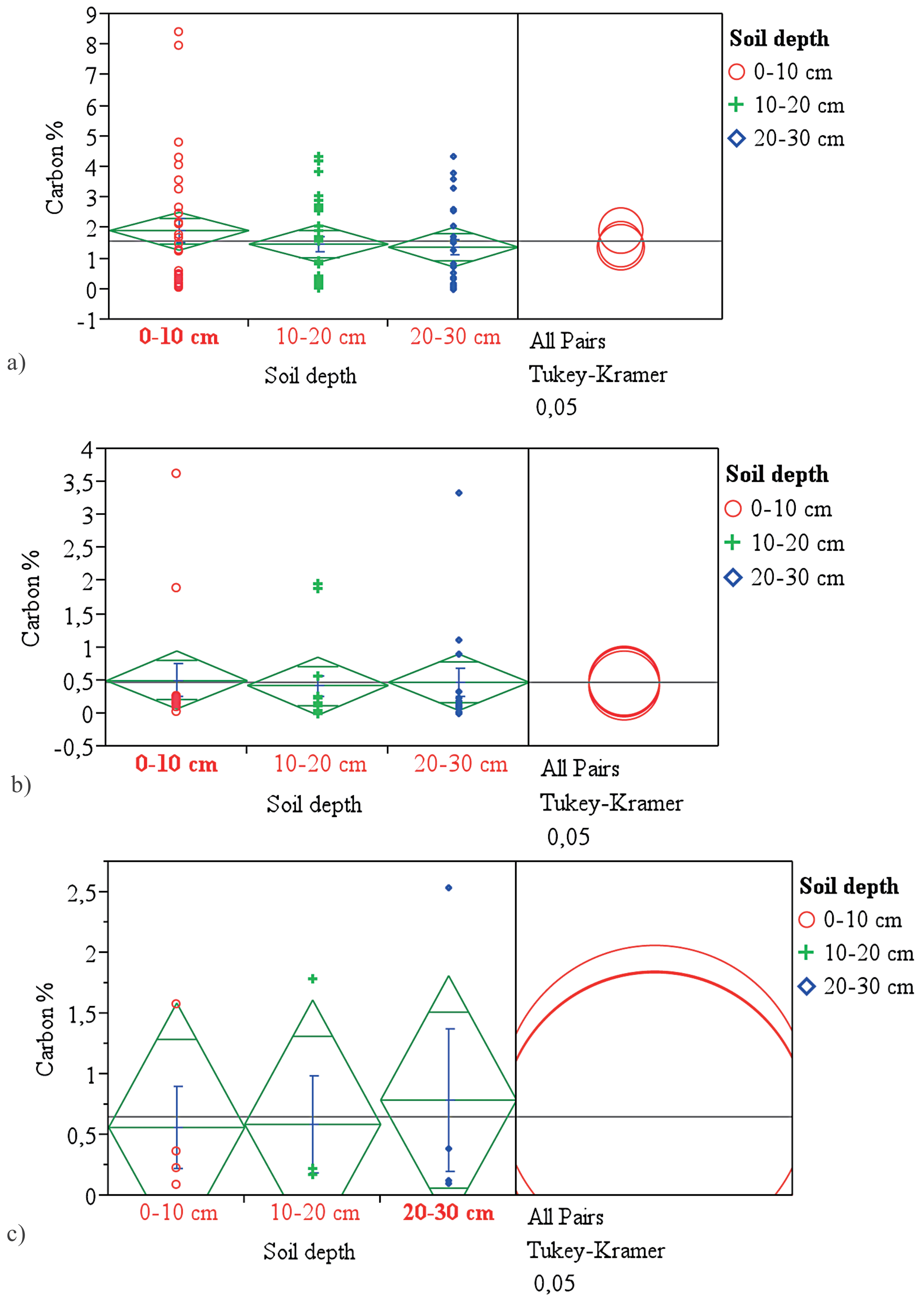


Fig. 12. *Carbon concentration along soil depth; (a) fertilization method, (b) lupine sowing and (c) grass species sowing. The red circles indicate no significant difference in amount of carbon at all the depths, the blue bars represent the mean error, the line at the centre of the diamonds is the group mean and the grey horizontal line is the grand mean.*

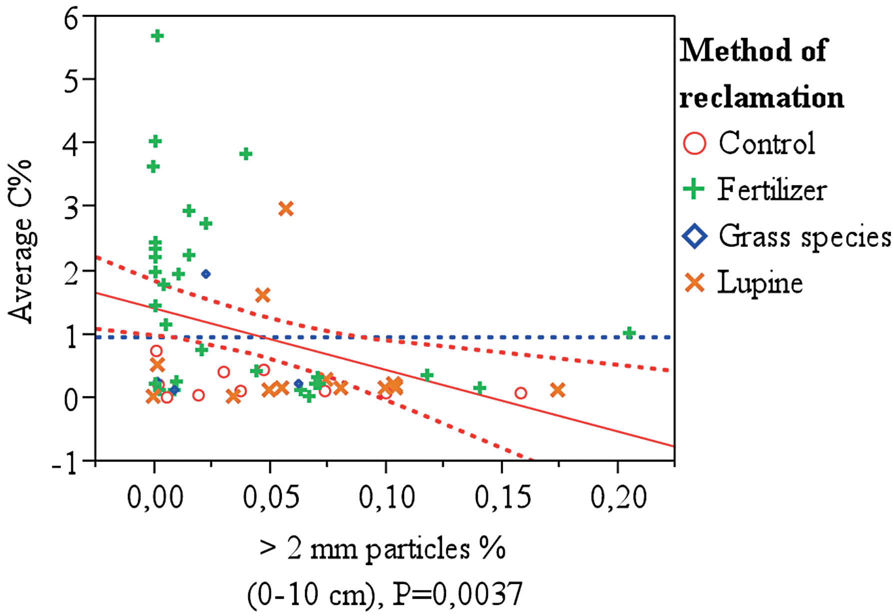


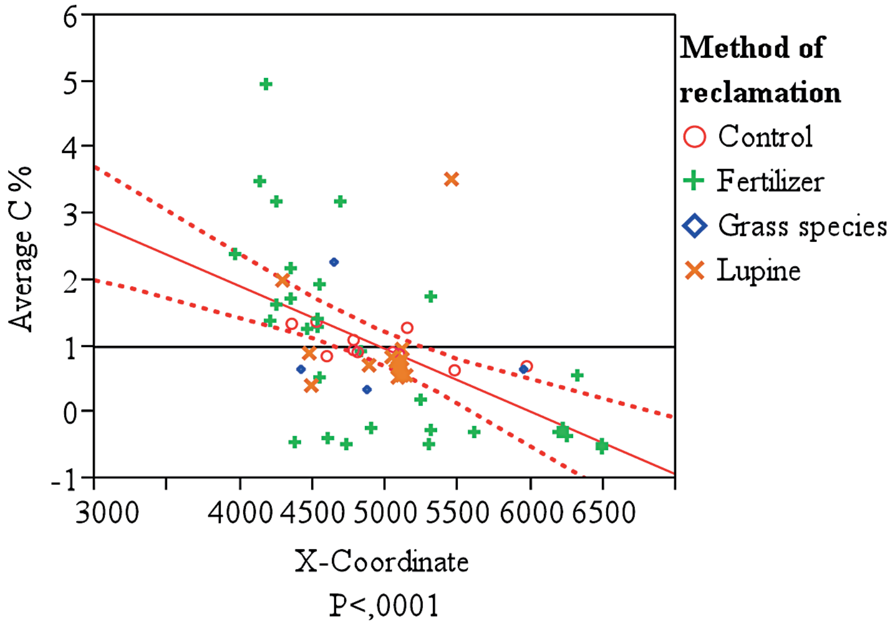
Fig. 13. *Average carbon content in soils with coarse particle size >2 mm; the blue dotted horizontal line is the grand mean (0.982), the solid pink line gives the fit and the pink dotted line is the 0.05 significance curve.*

On the other hand, the soil texture showed a significant effect in the concentration of carbon. As the amount of particles >2 mm was reduced the amount of carbon in the soil increased significantly ($p<0.01$) (Fig. 13). This was true at all the soil depths.

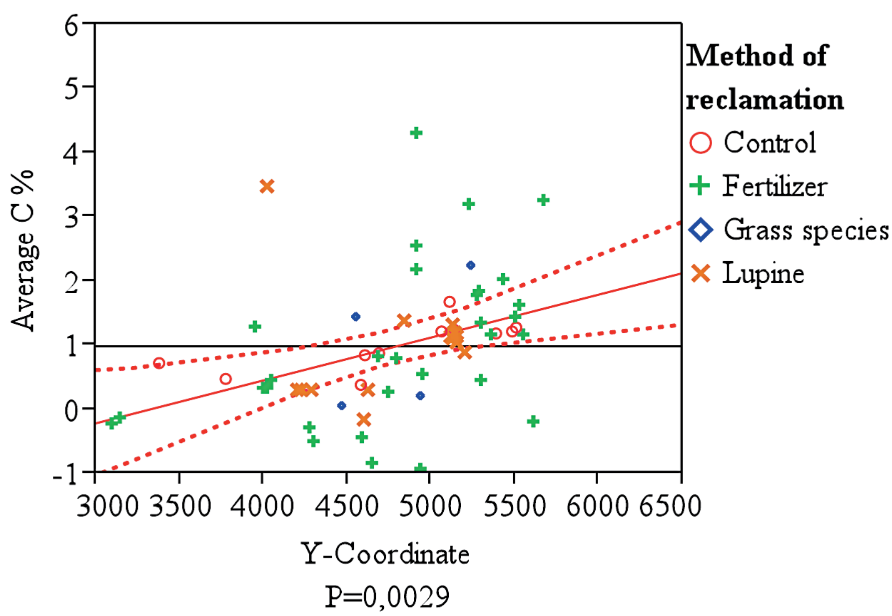
3.4 Effect of geographical variation on carbon concentration

The map of the reclamation sites shows that the studied sites for different reclamation methods were primarily distributed along an axis stretching from the south-west to the north- east (Fig. 1). Hence, to assess the impact of spatial variation on carbon stocks the X and Y co-ordinates were plotted against the concentration of carbon in all the reclamation sites. As indicated in Fig. 14a, the concentration of carbon in the western part was significantly higher than in the eastern part ($p<0.0001$). Fig. 14b also shows that the carbon concentration in the northern part was significantly higher than in the southern part ($p<0.01$).

This effect of geographical location (area of treatment), especially the east-west direction effect, was also found to be comparable to that of the treatment method (Table 7) where both had a highly significant effect on the carbon concentration ($p<0.0001$).



a)



b)

Fig. 14. *Effect of geographic distribution, represented as GPS values, on carbon concentration; the black horizontal line is the grand mean (0.982%), the solid pink line gives the fit line and the pink dotted line is the 0.05 significance curve. (a) In the x coordinate the lower value (3000) indicates the west direction and the higher value (6500) east. (b) In the Y coordinate the lower value (3000) indicates the south and the higher value (6500) north.*

Table 7. *Parameter estimates of method and sites of reclamation.*

Parameter	Estimate	SS	"F Ratio"	"Prob>F"
Intercept	1.0	0.0	0.0	1.0
Method of reclamation [Control & Lupine & Grass species-Fertilizer]	-0.6	20.0	15.6	0.00022*
Method of reclamation [Control-Lupine & Grass species]	0.0	0.5	0.4	0.5
Method of reclamation [Lupine-Grass species]	0.0	0.6	0.2	0.8
Length of reclamation time (year)	0.0	0.0	0.0	1.0

4. DISCUSSION

4.1 General discussion

This study showed that reclamation can increase carbon concentration in the soil. However, this is dependent upon many different factors. This was also demonstrated clearly by Arnalds *et al*. (2000), who showed that significant amounts of carbon can be sequestered by reclamation of degraded land in Iceland.

The main factors found to influence carbon content in the soil were the spatial location and the method of reclamation, especially the fertilization method. The data used to analyse the effect of the different factors on soil carbon concentration were enough to substantiate these statements and results. However, the number of samples for the grass sowing method of reclamation was not adequate as there were very few plots considered in this study. Therefore, in order to see the exact effect of this reclamation method and to be sure about the results given in this study, it is important to take several more factors into consideration. In addition, the analysis used in this study focused more or less on the impact of individual factors separately. The combined effect and the interaction of the different factors in affecting the carbon concentration were not undertaken. Hence a multivariate analysis should be undertaken to identify the impact of the different factors and their interaction.

4.2 Method of reclamation

A significant effect of carbon concentration was observed as a result of the method of reclamation applied. This significant effect was mainly due to the fertilization method of reclamation. However, a paired comparison illustrated that the difference between sowing grass and fertilization method was not significant. This was perhaps due to the overlap in the method of treatment. In the grass sowing reclamation method, in addition to grass sowing, the areas are fertilized for about two years (Arnalds, 2000). This indicates that the similarity can be a result of this fertilizer inclusion in the reclamation time in both methods. The higher carbon concentration in areas treated by fertilization only, compared to grass seeding, may indicate that the former areas were in a better condition than the areas sown with grass seed. However, it must be considered that only five plots treated with grass seeding were included in this study. One must therefore interpret such data with extreme care.

Sowing of lupine did not have a significant effect on carbon concentration as compared to the control plots. According to Aradottir *et al*. (2000), the soil organic carbon was small at the lupine sites, and moreover the above-ground carbon stock was found to be much higher than in the roots. In addition the vegetation cover of Nootka lupine plants was less than the vegetative cover of the fertilized areas (Fig. 11). This was due to the gradual development over a number of years from small plants in the vegetative stage in the years of germination (Björnsson, 2007). The data also showed that the plant coverage in lupine plots was highly variable. In most plots it was very low. As the distribution of the lupine was very patchy in the establishment phase, sampling on a fixed grid may not be the best method for assessing carbon accumulation in the soil in such plots.

To use all the methods effectively, continuous nutrient supply is important and required for sequestration of carbon to take place. This is because concentration of nitrogen in the soil organic matter is concurrent with sequestration of carbon, and other nutrients such as sulphur and phosphorus are probably accumulated in the organic matter as well (Björnsson, 2007). Besides, for full exploitation of the potential of Nootka lupine for carbon sequestration in eroded areas, it is important to have a good supply of sulphur and phosphorus (Björnsson, 2007).

In the vegetation cover versus average carbon analysis, even though the vegetation cover showed a highly significant difference in the carbon concentration, some points were observed to have a high vegetation cover but low average carbon (Fig. 10). This is a very rare condition. However, it might be explained by the age of reclamation. Most of these areas were reclaimed by fertilization. After such treatment vegetation cover increases quickly, whereas root establishment and carbon storage in soil may be a slower process.

4.3 Effect of time

The study revealed that the age of treatment had no significant effect ($p = 0.28$) in carbon concentration in all the treatment methods. Aradottir *et al*. (2000) found that on areas reclaimed with lime grass, the increase in soil carbon concentration was faster in the first years after the reclamation started than at later stages. This indicated a possible non-linear relationship. However, the fertilization method of reclamation showed a very weak positive regression line, while the grass and lupine sowing methods showed a very weak negative relation (Fig. 9). According to Arnalds *et al.* (1999), variability in the carbon stored on desert soils was observed between areas where they only found a significant correlation when studying one specific method in one specific area. This indicates that the impact of the time and treatment methods was highly affected by their environmental factors. Hence it is important to study the impact of age in an area's specific base in order to see the specific contribution of the method of reclamation.

4.4 Effect of soil depth

No significant effect of depth on carbon concentration was found. For the fertilized plots there was a trend for a decreasing carbon concentration value from the top down to 30 cm depth of the soil. This result can be expected in areas where the plants have shallow rooting depths as in the case of grass sowing. In areas reclaimed by sowing grass the carbon concentration fluctuated and the average carbon in the lowest depth (20–30 cm) was higher than on upper depths (0–10 and 10–20 cm). This probably could be related to the history of the soils of the areas where this treatment was applied. The soils where the grasses were sown had a relatively fine texture (Fig. 13) which could probably mean older soils. Hence in such old soils the amount of carbon in the lower depths can be higher than in the topsoil due to translocation of materials from the top down (Phillips, 2007). Besides, because of the heterogeneity of soils verification of carbon sequestration in soils is very difficult (Arnalds *et al.,* 2000). Hence, it is important to undertake soil classification, which is a useful tool to help account for carbon levels in soils. Here it must also be considered that these results were based on very few plots.

The lupine and grass sowing treatment methods had no significant difference on carbon concentration as compared with the control plots. A probable reason could be that some of the control plots were found in relatively old soils (Fig. 1) which have a higher organic carbon content. The texture of the soil can be an indication of age of the soils. As indicated in Fig. 13 soils with a low amount of course fractions (particles >2 mm) were found to have a significantly higher amount of average carbon content than those with a high amount of particles >2 mm ($p<0.01$). This was true in all the depth ranges of the soil; as the coarse fractions decreased, the amount of carbon increased. Hence, this presence of relatively older soils can mask the effect of the treatments in the lupine sowing and grass sowing reclamation areas as compared to the control plots. It must also be kept in mind that vegetation coverage was very low in most of the lupine and grass sowing treatments; therefore it is not surprising that very little build-up of carbon in the top layer could be observed. It is also possible that due to the depth division of the soil carbon samples in 0–10, 10–20 and 20–30 cm depth intervals building up of carbon close to the surface was not detected due to the diluting effect of soil that had not been affected by this process.

4.5 Effect of geographical variation

The reclamation areas are concentrated mainly along the volcanically active ridge of Iceland (Jakobsdottir *et al.,* 2000). Because the degradation is high and the land is sensitive to erosion the reclamation work is most important in this area. Most of the plots studied in this research fell within this area. However, in addition to these plots, there were plots analysed in the southern and in the northern parts of the country (Fig. 1). Hence, this study considered a wide variety of spatial factors that can affect the methods and carbon storage potential of the soils. Accordingly, the effect of spatial variation was found to be very highly significant. In this spatial variation the east-west spatial variation seemed to be stronger ($p<0.0001$) than the north-south spatial variation ($p<0.01$). To establish a link between the methods and location, the distribution of the methods along the sampling sites were assessed through mapping. The distribution map, therefore, illustrated that all the methods were applied in all the sampling locations except that the lupine was not found in the central part of Iceland. However this absence of lupine in the central part did not create any difference in the results obtained because the lupine sites were located in the long stretch from the south-west and southern part to the north-east part, which could give the main result. However, with a relatively limited number of plots, as in this study, uneven geographic distribution may have a large effect on the result. For instance, seven out of fifteen studied lupine plots were located on Holasandur in North-East Iceland. Special conditions in that particular area might therefore have contributed very significantly to those particular data. The potential cause of the variation in the carbon storage in the different locations is the climatic condition. The annual precipitation is lowest in the north and the mean temperature is lower in the north than south, which resulted in shorter growing season (Aradottir *et al.,* 2000).

The distribution of the sampling points has shown a significant effect in the soil carbon concentration. This is an important observation when we consider the large area effect of the reclamation activity. However, it is also important to study the impact of the methods in a specific locality. This helps to show the extent of the carbon concentration difference due to the different methods within a specific area. This also reduces the impact of different locations so that the methods can be evaluated relatively purely by their contribution of the minimum external factors applied.

5. CONCLUSION

The reclamation methods evidenced a considerable contribution to the carbon storage in reclamation sites in Iceland. However the time of reclamation, and the grass sowing and lupine sowing methods had no effect on the amount of carbon storage. The main factors contributing to a significant amount of carbon were the spatial variation and the fertilization method of reclamation. Hence from this result it is vital to note that there is a need to know more about the soil types where the reclamation methods are applied in order to know the effects on the different soil types. Otherwise a study will not be grounded on any base information about the main component of the issue, soil, to know the exact outputs. It is, furthermore, also important to know the chemical properties of the soils, other than the carbon content, to determine the interaction with the fertilizer applied and the demand of the plant species. On the other hand it is important to study the current level of fertilizer use and the demand of the reclamation species. This helps to know the deficiency of the land in order to be able to supplement treatments with the nutrients which are suitable to both the land and the reclamation method (species of reclamation) and improve the application rate. Additionally, it is important to seek for alternative reclamation species for those which do not show any significant effect on carbon storage.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my special thanks to Hafdis Hanna Ægisdottir and Sigridur Dalmannsdottir, managers of the Land Restoration Training Programme, for their hospitality and all their help during my stay in Iceland. I am grateful to my supervisors Gudmundur Halldorsson, Anna Maria Agustsdottir at ISCS and Brian Slater, professor at the Ohio State University, Columbus, Ohio, USA, for their invaluable and constructive guidance and follow-up during my study. I thank Gudmundur Halldorsson and Johann Thorsson for sharing unpublished results for use in this work. I would also like to express my appreciation to Johann Thorsson for his help and explanations in the field work and for his advice during data analysis. My gratitude goes to Elin Fjola Thorarinsdottir for helping me in the preparation of maps. This research is sponsored by the Iceland Government via the Land Restoration Training Programme.

REFERENCES

Agustsdottir, A.M. (2004). Revegetation of eroded land and possibilities of carbon sequestration in Iceland. *Nutrient Cycling in Agro Ecosystems*, *70*, 241–247.

Aradottir, A.L. (2003). Restoration challenges and strategies in Iceland. *Briefing papers of the first SCAPE workshop in Alicante (ES)*, 14–16 June 2003, 61–65.

Aradottir, A.L., Svavarsdottir, K., Jonsson, Th.H. & Gudbergsson, G. (2000). Carbon accumulation in vegetation and soils by reclamation of degraded areas. *Icelandic Agricultural Sciences*, *13*, 99–113.

Arnalds, A. (2002). Carbon sequestration – A powerful incentive in combating land degradation and desertification. *12th ISCO Conference, 26–31 May 2002*. Beijing: 12th ISCO Confernce.

Arnalds, A. (2004). Carbon sequestration and the restoration of land health: An example from Iceland. *Journal of Climate Change*, *65*, 333–346.

Arnalds, O., Aradottir, A.L., Snorrasson, A., Gudbergsson, G., Jonsson, Th.H. & Agustsdottir, A.M. (1999). *Organic Carbon Sequestration by Restoration of Severely Degraded Areas in Iceland Preliminary Results*. Rala Report 197.

Arnalds, O., Gudbergsson, G. & Gudmundsson, J. (2000). Carbon sequestration and reclamation of severely degraded soils in Iceland. *Icelandic Agricultural Sciences*, *13*, 87–97.

Arnalds, O., Thorarinsdottir, E.F., Metusalemsson, S., Jonsson, A., Gretarsson, E. & Arnason, A. (2001). *Soil erosion in Iceland*. Reykjavik: Soil Conservation Service, Agriculture Research Institute.

Björnsson, H. (2007). Fertilization of Nootka lupin (*Lupinus nootkatensis*) for biomass production and carbon sequestration. *Icelandic Agricultural Sciences*, *20*, 81–92.

FAO. (2004). *Carbon Sequestration in Dryland Soils*. *World Soil Resources Report 102*. ISBN 92-5-105230-1.

Greipsson, S. & Davy, A.J. (1994). *Leymus arenarius*. Characteristics and uses of a dune-building grass. *Icelandic Agricultural Sciences*, *8*, 41–50.

Greipsson, S. & Davy, A.J. (1996). Sand accretion and salinity as constraints on the establishment of *Leymus arenarius* for land reclamation in Iceland. *Annals of Botany*, *78*, 611–618.

Jakobsdottir, S.S., Gudmundsson, G.B. & Stefansson, R. (2000). Seismicity in Iceland 1991–2000 monitored by the SIL seismic system, *Jökull*, *No. 51*. 87–94.

MacDicken, K.G. (1997). *A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects*. Arlington, VA, USA: Winrock International Institute for Agricultural Development, Forest Carbon Monitoring Program.

Magnusson, B., Magnusson, S.H. & Sigurdsson, B.D. (2001). *Vegetation Succession in Areas Colonized by the Introduced Nootka lupine (Lupinus nootkatensis) in Iceland*. *Rala Report 207*. (In Icelandic with extended English summary)

Magnusson, B. (2006). NOBANIS – Invasive Alien Species Fact Sheet – *Lupinus nootkatensis*. Online Database of the North European and Baltic Network on Invasive Alien Species – NOBANIS. Retrieved 19 July, 2009, from www.nobanis.org.

Marland, G., Garten, C.T.Jr., Post, W.M. & West, T.O. (2004). Studies on enhancing carbon sequestration in soils. *Energy*, *29*, 1643–1650.

Phillips, J.D. (2007). Development of texture contrast soils by a combination of bioturbation and translocation. *Catena*, *70*, 92–104.

Post, W.M. & Kwon, K.C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, *6*, 317–328.

Ritter, E. (2007). Carbon, nitrogen and phosphorus in volcanic soils following afforestation with native birch (*Betula pubescens*) and introduced larch (*Larix sibirica*) in Iceland. *Plant Soil*, *295*, 239–251.

Runolfsson, S. & Arnalds, A. (2004). *Landcare at the Top of the World – Conservation Strategies in Iceland*. *13th International Soil Conservation Organisation Conference, Brisbane*, Paper No. 256, 1–4.

SAS Institute Inc. (2008). *JMP® Statistics and Graphics Guide* (pp 111–147). Cary, North Carolina: SAS Institute, Inc.

Trumper, K., Ravilious, C. & Dickson, B. (2008). *Carbon in Drylands: Desertification, Climate Change and Carbon Finance*. *A UNEP-UNDP-UNCCD Technical Note for Discussion at CRIC 7*, Istanbul, Turkey, 03–14 November. Cambridge, UK: UNEP-WCWC.

APPENDIX

Plot no.	X	Y	Yr of measurement	Yr of establishment	Reclamation time (yr)	C% (0–10 cm)	C% (10–20 cm)	C% (20–30 cm)	Average C%	Method of reclamation	% > 2 mm particles (0–10 cm)	% > 2 mm particles (10–20 cm)	% > 2 mm particles (20–30 cm)	Vegetation Cover %
200	3189	3840	2007	1993	14	0.2	0.2	0.4	0.3	Grass sp.	0.1	2.1	1.0	12
203	3824	3785	2007	2002	5	0.1	0.2	0.1	0.1	Grass sp.	0.9	0.1	0.3	36
204	3809	4005	2007	2005	2	1.9	1.9	1.1	1.6	Lupine	4.7	2.9	4.1	88
211	4589	3940	2007	2004	3	0.1	0.2	0.2	0.2	Lupine	9.9	5.9	17.5	2.6
214	4704	5120	2007	2000	7	2.7	2.7	-	1.8	Fertilizer	0.4	0.2	-	42
218	5889	5840	2007	1998	9	0.2	0.1	0.1	0.1	Lupine	4.9	4.5	5.9	13
219	5894	5850	2007		0	0.1	0.1	0.0	0.1	Control	7.4	8.1	4.1	5
223	3734	3730	2007	2002	5	0.4	1.7	3.8	2.0	Fertilizer	1.1	0.5	0.2	32
227	4734	5080	2007	2000	7	2.5	1.7	1.6	1.9	Fertilizer	-	-	-	87
228	4744	5275	2007	0	0	1.0	0.5	0.2	0.6	Control	-	-	-	17
230	5859	5830	2007	1999	8	0.2	0.2	0.2	0.2	Lupine	10.3	11.3	9.4	4.2
231	5864	5840	2007	1996	11	0.3	0.3	0.3	0.3	Lupine	7.4	3.9	4.3	14
232	5869	5850	2007	1996	11	0.3	0.1	0.1	0.2	Lupine	10.4	17.2	19.8	9
234	5974	6260	2007	0	0	0.0	0.0	0.0	0.0	Control	2.0	1.5	0.6	25
235	6074	5960	2007	0	0	0.7	0.6	-	0.4	Control	4.8	5.5	-	4.2
237	6334	5680	2007	2002	5	0.3	0.2	0.2	0.2	Fertilizer	7.0	2.0	3.2	8
240	3789	3740	2007	2001	6	0.1	0.1	0.6	0.3	Fertilizer	1.0	0.1	0.8	10
242	4499	3760	2007	1993	14	3.6	2.0	3.3	3.0	Lupine	5.7	10.3	1.6	100
243	4694	4050	2007	2000	7	0.1	0.1	0.1	0.1	Fertilizer	6.3	8.3	9.4	10
244	4724	5285	2007	2006	1	1.7	1.7	2.6	2.0	Fertilizer	0.0	0.1	0.2	56
245	4674	5385	2007	2004	3	8.0	4.2		4.1	Fertilizer	0.1	1.0	-	97
249	5994	6275	2007	2005	2	0.0	0.0	0.0	0.0	Fertilizer	6.7	19.9	9.5	11
255	3714	3740	2007	0	0	0.4	0.5	1.2	0.7	Control	0.1	0.1	0.0	4
256	3759	4005	2007	2001	6	0.2	0.1	0.1	0.2	Fertilizer	14.1	15.5	18.9	17
260	3829	3795	2007	0	0	0.2	0.1	0.2	0.2	Control	0.3	0.1	0.1	34
261	4424	4335	2007	0	0	0.2	0.6	0.5	0.4	Control	3.1	0.9	0.6	6.4
263	4739	5040	2007	1995	12	4.8	2.8	3.3	3.6	Fertilizer	0.0	0.0	0.0	100
264	4774	5235	2007	2004	3	1.6	1.8	2.5	2.0	Grass sp.	2.2	0.0	0.0	46
268	6134	5680	2007	2006	1	1.8	2.7	2.6	2.3	Fertilizer	0.0	0.0	0.0	87
269	6514	5040	2007	2006	1	0.3	0.3	0.4	0.3	Fertilizer	7.1	1.4	0.0	55

Plot no.	X	Y	Yr of measurement	Yr of establishment	Reclamation time (yr)	C% (0–10 cm)	C% (10–20 cm)	C% (20–30 cm)	Average C%	Method of reclamation	% > 2 mm particles (0–10 cm)	% > 2 mm particles (10–20 cm)	% > 2 mm particles (20–30 cm)	Vegetation Cover %
270	6614	5165	2007	2005	2	0.6	0.3	0.2	0.4	Fertilizer	11.8	21.6	28.1	34
271	6634	5155	2007	2005	2	0.4	0.2	0.1	0.2	Fertilizer	7.2	25.0	-	69
275	4709	5080	2007	1998	9	1.5	0.8	0.7	1.0	Fertilizer	20.5	9.2	7.1	89
276	4764	5215	2007	2004	3	3.3	2.9	2.1	2.8	Fertilizer	2.2	2.2	1.6	28
277	4909	4155	2007	2005	2	0.5	0.4	0.3	0.4	Fertilizer	4.4	4.2	5.6	13
285	3459	3755	2007	2002	5	4.1	3.8	3.6	3.8	Fertilizer	3.9	3.1	0.8	10.2
287	3764	3740	2007	2003	4	0.0	0.0	0.0	0.0	Lupine	0.0	0.0	0.0	31
288	3854	3795	2007	1990	17	0.4	0.1	0.1	0.2	Fertilizer	0.1	0.0	-	72
289	4374	4335	2007	1997	10	1.2	1.6	1.5	1.5	Fertilizer	0.1	0.0	0.0	3.4
292	4734	5305	2007	2000	7	2.2	1.9	2.6	2.2	Fertilizer	0.0	0.0	0.0	96
294	5184	3280	2007	1996	11	0.2	0.1	0.1	0.1	Fertilizer	0.2	3.2	14.0	57
297	5859	5755	2007	0	0	0.1	0.1	0.0	0.1	Control	10.0	11.5	9.4	6
298	5949	6260	2007	0	0	0.1	0.1	0.1	0.1	Control	3.7	8.1	4.7	82
299	5989	5615	2007	2005	2	0.5	0.9	0.8	0.7	Fertilizer	2.1	0.5	1.7	72
300	6334	5705	2007	1999	8	0.4	0.2	0.1	0.2	Grass sp.	6.2	9.4	10.1	42
301	6619	5075	2007	2004	3	1.3	0.9	1.3	1.1	Fertilizer	0.5	3.0	0.1	99
303	3234	3980	2007	1997	10	4.3	3.1	1.5	3.0	Fertilizer	1.5	3.2	3.0	43
304	3484	3755	2007	2006	1	8.4	4.4	4.3	5.7	Fertilizer	0.1	0.0	0.1	100
307	3739	3740	2007	2003	4	0.1	0.6	0.9	0.5	Lupine	0.1	0.3	0.0	38.75
310	4559	4005	2007	2003	4	0.1	0.1	0.1	0.1	Lupine	17.4	15.1	13.8	8.2
311	4564	3940	2007	2004	3	0.1	0.2	0.2	0.2	Lupine	10.4	9.9	8.0	4.2
312	4744	5075	2007	2000	7	3.6	2.1	1.7	2.5	Fertilizer	0.0	0.0	0.0	100
317	5879	5870	2007	1997	10	0.1	0.0	0.0	0.0	Lupine	3.4	0.9	1.3	1
318	5884	5830	2007	1998	9	0.2	0.2	0.1	0.2	Lupine	5.5	3.2	2.9	6.2
323	4394	3400	2007	0	0	0.0	0.0	0.0	0.0	Control	0.6	0.4	0.1	0
325	4809	3305	2007	0	0	0.1	0.0	0.0	0.1	Control	15.9	13.2	13.8	2
326	4749	5260	2007	2006	1	2.1	2.6	2.0	2.2	Fertilizer	1.5	1.0	2.5	40
329	5319	3300	2007	2001	6	0.1	0.2	0.1	0.1	Fertilizer	0.9	1.0	0.3	35
331	5894	5875	2007	1998	9	0.2	0.1	0.1	0.1	Lupine	8.1	4.9	6.7	29.2
332	5909	5880	2007	2006	1	0.2	0.2	0.1	0.2	Lupine	10.4	9.5	5.1	4.2