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ASSESSMENT OF SOIL CARBON IN RECLAIMED LAND IN SOUTH-WEST ICELAND

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ABSTRACT

Reclamation of degraded land using revegetation is one way of sequestering carbon into the soils. In this study an assessment was done to estimate the status of soil carbon amounts after revegetation with trees and grass in South-West Iceland (Hafnarmelar). Natural woodland and eroded plots were part of the assessed plots as controls, making four plots in all. Soil samples were collected from all the plots and were analysed for bulk density, soil texture and carbon content. Total % carbon (C) was analysed using a vario MAX CN analyser (measured % C) and Loss on Ignition (LOI; calculated % C). The results showed that natural woodland, tree, grass and eroded plots had 9.32%, 4.91%, 1.12% and 0.76% C, respectively, with the natural woodland different from the tree plot ($p = 0.0001$) and the tree plot different from the grass plot ($p = 0.0001$). The grass and eroded plots did not differ ($p = 0.0566$). Notably, the grass plot had carbon below the minimum expected levels of 1.5% in Icelandic Andosol under vegetation. The natural woodland and the tree plot had a finer soil texture than the grass and eroded plot. Results suggest that where land has been properly restored or kept in its natural condition, soil properties improve significantly, especially when trees are part of the restored vegetation. Therefore more restoration efforts are encouraged. The results also showed that LOI is a good but not very accurate estimator of soil organic carbon unless equations are developed with respect to the known carbon content of a particular soil type.

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1. INTRODUCTION

Land degradation is one of the major problems affecting the physical, chemical and biological stability of the soil. Different authors have provided different figures on land degradation depending on the areas of focus. The general trend is that land degradation is increasing (UNEP 2007). Land degradation destroys natural systems, affects many people and attracts regional and international actions. The causes of land degradation are both natural and human induced; especially the latter causes more disruptive effects to the natural balance of ecosystems (Morgan 1979). Human causes include poor irrigation, lack of crop rotations, overgrazing, frequent use of machinery, deforestation and poor soil and water conservation. The natural calamities causing land degradation include floods, droughts, landslides, and volcanic eruptions (UNEP 2007). Often, these natural causes are influenced by human interference with nature (Buringh 1984)**.**

Land degradation through vegetation removal results in soil erosion and loss of valuable nutrients from the soil. Carbon loss is a good example. The trend shows soil carbon being lost from soils into the atmosphere through unsustainable land use (Walker & Desanker 2004). Bai et al. (2008) estimated that over 950 million tonnes of soil carbon were lost from 1981 to 2003, affecting about 1.5 billion people globally. This carbon loss was from 35 million km^2 of degraded land. Deforestation was a major factor causing carbon loss through erosion (Eswaran et al. 1993). Recent concerns about climate change in relation to land degradation have resulted in increased emphasis on studies on the quantities, occurrences and behaviour of carbon.

Carbon as an element occurs naturally and soils are the major active carbon pool. In the form of carbon dioxide, it can be captured from the atmosphere by plants with energy from the sun in the process of photosynthesis (Taiz & Zeiger 2006). When carbon from the soil finds its way into the atmosphere it combines with oxygen to form carbon dioxide. Carbon dioxide has greenhouse gas effects. In contrast, carbon sequestered in the soil has many advantages. Carbon provides structure and energy to living organisms and according to Brady & Weil (1999), soil organic carbon influences plant growth by providing energy and triggering mineralization. Organic carbon compounds help cement soil particles and thus improve soil structure. This makes soil more resistant to erosion. An increase in soil organic matter and total soil carbon facilitates biodiversity in soils through inflow of soil fauna and flora to take advantage of released nutrients. This enhances the natural control of pests and diseases. Generally, organic matter provides conditions that improve the properties and functioning of the soil and its associated abiotic and biotic components. Scarcity of soil organic carbon means lost biological activity, poor soil aeration, poor infiltration, poor drainage, pests and disease prevalence, and toxic accumulation (Brady & Weil 1999).

Approaches to reduce carbon loss from land differ depending on the objectives. These objectives could be agricultural food productivity, soil erosion control, mitigation of climate change, natural resource management and biodiversity. A number of institutions have specific provisions to reverse land degradation, climate change and desertification. The United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD) and the United Nations Framework Convention for Climate Change (UNFCCC) aim at reducing land degradation and climate change. Sustainable and better management of existing agricultural soils and restoration of carbon in degraded soils are estimated to increase carbon sinks of about 445-882 tonnes per year globally (IPCC 1996).

In Europe, croplands are the major source of carbon loss into the atmosphere due to land use changes (Smith 2004). Current remedies for this include afforestation, organic agriculture, improved crop rotations, irrigation, and no or reduced tillage (Smith 2004). In Iceland, unsustainable land use has caused degradation since the settlement over 1000 years ago (Crofts 2011). Overgrazing and wood harvesting were the dominant causes of erosion, leaving bare unstable soils. A full 40% of the area of Iceland is considered to be desert and unstable (Arnalds et al. 2001). The vulnerability of soils to degradation forces differs depending on the soil's level of stability.

1.1 Soils of Iceland

There are four major classes of soils in Iceland namely; Andosols, Vitrisols, Histosols and Cryosols/Leptosols/Calcisols (Arnalds 2015). Iceland is dominated by Andosols which have andic or vitric characteristics, i.e. with allophanes or volcanic glass, respectively (Molloy 1998; FAO n.d.). Allophane is a non-crystalline clay with a tendency to adsorb carbon and other nutrients (Brady & Weil 1999; Arnalds 2015). Andosols have good water holding capacity, high carbon accumulation, and usually low bulk density (0.7 g/cm^3) (Arnalds 2004). They are further grouped into three classes, i.e. Brown Andosols, Gleyic Andosols and Histic Andosols. Brown Andosols are soils in vegetated environments. They are usually well drained, light soils (bulk density of less than 0.8 $g\ cm^{-3}$) with less than 12% carbon in dry areas. Gleyic Andosols occur in wetland areas. They have less than 12% carbon in the surface horizon. Histic Andosols contain 12-20% carbon in the first 30 cm depth. They are usually waterlogged but some occur in dry areas with birch and other vegetation types. They are common in West and North Iceland. In West Iceland, Histic Andosols occur in dry areas. Histosols have carbon content greater than 20% in the first 30 cm depth. They are common in the far west and far north of the country. Vitrisols occur in desert areas. They have 0.2-1% carbon content in surface layers. They have little water retention due to coarse soil texture (Arnalds 2004).

1.2 Soil carbon loss and land restoration in Iceland

Iceland has lost millions of tons of organic matter and soil carbon since settlement due to land degradation (Oskarsson et al. 2004). Iceland has up to 45,000 km^2 of degraded land in need of restoration (Arnalds et al. 2001). This degradation has prompted systematic land restoration.

The Icelandic Government through the Soil Conservation Service of Iceland (SCSI) restores degraded areas to achieve carbon sequestration, stop erosion and improve land ecosystem condition (Arnalds et al. 2000). Intensive and systematic approaches to this started in 1907. Some of the methods include seeding grass mixtures, planting/seeding trees and applying fertilizers. The aim is to bring back the lost chemical, physical and biological conditions of the land and soil. In Iceland, land restoration is done partly to implement and contribute to the provisions in the United Nations Framework Convention for Climate Change (UNFCCC) (Arnalds et al. 2000).

One of the SCSI's major approaches to achieving land restoration has been the project called 'Farmers Heal the Land' (FHL), a project which started in 1994. The project targets completely bare land, slightly bare land, and lightly or not grazed farmland. This project is an improved setup after its predecessor, the *Neighbourhood Project,* which focused narrowly on restoration of small portions of land around homesteads. FHL aims at placing more focus on the roles farmers play in land restoration and emphasising restoration activities as being 'owned' by farmers (Crofts 2011). The numbers of participating farmers have been rising from 370 in 1994 to around 574 currently (SCSI 2014). Sheep farmers are the dominant participants. However, the project is open to all owners and custodians of degraded land (S. Askelsdottir, 10 September 2015, Soil Conservation Service of Iceland, Hvanneyri, personal communication). There is almost uniform distribution of participating farmers throughout Iceland. In the FHL project, the SCSI covers 85% of the costs for seed and inorganic fertilizer to be used in the restoration of degraded areas. Extension staffs from the SCSI provide advice to the participating farmers. Farmers contribute labour and 15% of the fertilizer costs. The project is seen as yielding good land reclamation results in terms of ha restored and has also enhanced the mutual relationship between farmers and the SCSI as an institution (Berglund et al. 2013).

According to Arnalds et al. (2000), the reclamation of severely degraded soil in Iceland can result in sequestration of 0.6 tonnes (t) of carbon per ha (hectare) per year. The Icelandic carbon sequestration rates thus fall within the Intergovernmental Panel on Climate Change (IPCC) carbon sequestration rates of 0.1-0.7 t C per ha per year (Arnalds et al. 2000). Aradottir et al. (2000) reported sequestration rates ranging from 0.01-0.5 t C per ha per year for the above- ground and underground vegetative matter. In assessing the carbon accumulation in restored unstable sandy desert, Arnalds et al. (2013) observed that soil carbon increased from 0.3% to 0.7% in some grass reclaimed plots. However, the average annual accumulation was 0.4-0.63 t C per ha during the first stages of restoration. The accumulation was significant in areas treated with grass seeding and inorganic fertilizer and not in untreated degraded areas (control). The untreated (control) plots had no carbon increase. This finding corresponds to that of Bjarnadottir et al. (2009), where they reported use of birch and other trees in carbon sequestration in Iceland as successful. The ability of Icelandic soils to accumulate carbon after revegetation provides a favourable environment for carbon sequestration. By 2001 close to 130 km^2 were restored (Agustsdottir 2004).

The continued assessment of carbon in soils is desirable in Iceland and Europe as a whole (Sigurdsson & Snorrason 2000). In Iceland, research has been done to assess the impact of land restoration on carbon sequestration in some parts of the country but little is known about carbon amounts in land reclaimed under the FHL project. This research has been intended to generate evidence based information on carbon accumulation on FHL reclaimed land. Four treatments have been examined, namely: reclamation with trees, reclamation with grass, natural woodland as control, and eroded area as another control. In this paper, these four land uses will be referred to as 'treatment' or just 'plots'.

1.3 Research objectives

The goal of the research was to assess the impact of land reclamation under the FHL project on soil carbon accumulation. Specifically, the project intended to achieve the following objectives:

1. To assess the difference in soil carbon content between reclaimed and non-reclaimed land
2. To compare the effect of grass and tree reclamation respectively on soil carbon content

3. To compare carbon content between non-degraded (natural woodland) and degraded areas
4. To acquire skills and gain knowledge on soil carbon analysis

1.4 Relevance of the research to Malawi

The research was conducted in Iceland with the intention to learn and adapt its processes and findings to the situation in my home country, Malawi. In Malawi, rapid population growth is exerting pressure on natural resources resulting in land degradation. In 1992 soil loss through water erosion in Malawi was estimated at 20 tonnes per ha per year (World Bank 1992). Considerable amounts of soil nutrient loss have been estimated equivalent to U$2 billion per year (Chigowo 2007). Walker & Desanker (2004) observed that soil carbon loss is on the increase in Malawi, mainly in agricultural land. Even in fallow land, soil carbon content was decreasing because of short resting periods. They attributed limited crop yields in Malawi to loss of carbon and nitrogen from soils. Low crop yield has serious consequences such as famine and economic frictions in the country. Consequently, Walker and Desanker (2004) advised quick responses in order to halt the extreme loss of carbon from soils.

Malawi government has been promoting approaches that aim at sequestering carbon in soil and vegetation and minimising carbon loss. The current initiatives focus on Climate-Smart Agriculture (CSA). CSA has three principles; increased agricultural productivity, enhanced environmental and community resilience, and carbon sequestration (FAO 2013). Major activities for achieving these principles include afforestation, agroforestry, conservation agriculture and crop diversification. These initiatives are expected to create reduction of CO_2 in the atmosphere and a win-win situation for communities and the environment (carbon sequestration). These approaches require knowledge and skills on the occurrence and assessment of soil carbon. Currently there is a knowledge gap on soil carbon issues in Malawi (Namangale 2015). The overall objective with this study was to fill this gap.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted in South-West Iceland in the Hafnarmelar area (Fig. 1). The mean annual temperature in 1998-2014 was 5.3°C, with a mean January temperature of 0.9°C and mean July temperature of 11.4°C (Icelandic Meteorological Office, unpublished data). The data also showed a mean annual precipitation of about 1100 mm. According to the soil map of Iceland (Arnalds 2015), the common soil types are Histic Andosols, Gleyic Andosols and Brown Andosols. Two farms in the area, participating in the Soil Conservation Service of Iceland FHL's project, were selected as the study site. This site was chosen because it had a variety of management and reclamation examples. The study site was characterised by 1) islands of natural birch woodland, 2) land revegetated with trees and grass, 3) land revegetated with grass and 4) some highly degraded land; hereafter these will be referred to as natural woodland, tree plot, grass plot and eroded plot, respectively.

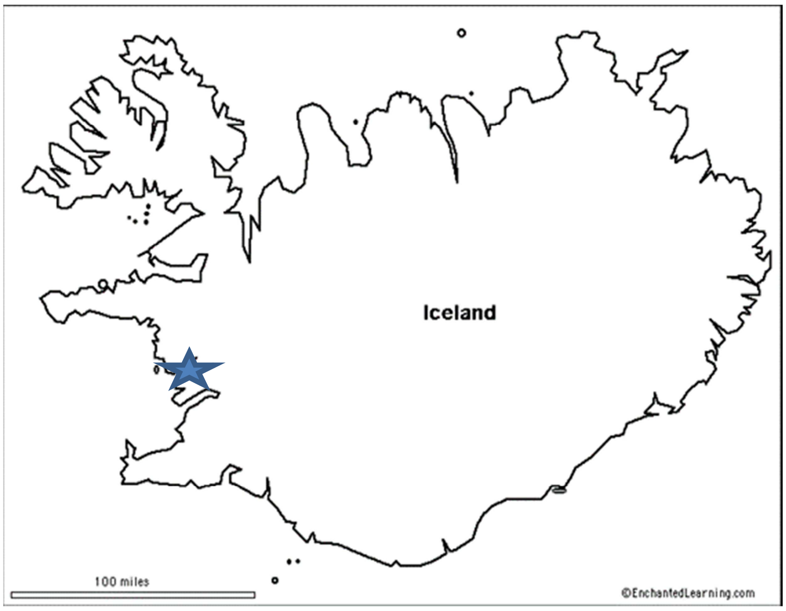

Figure 1. Map of Iceland. Blue star indicates location of Hafnarmelar, the study site.

The natural woodland was dominated by birch trees, shrubs and some grass covering the under-story (Fig. 2). The ground was completely covered by vegetation and litter was visible. The plot had dark, fine textured soil. There were no signs of gravel, at least not at sampling depth.

Figure 2. The natural woodland. (Photo: S. Askelsdottir, 19 June 2015).

The tree plot was dominated by birch trees *(Betula pubescens)*. Initially the area was degraded land surrounding the natural woodland. After reclamation through fertilization, the soil became stable and the birch trees have been colonizing the area. The trees are still at a young stage

(Fig. 3). There was also some grass growing, scattered over the plot. Some litter could also be noticed. The soils were brown, and slightly gravelly at the surface. The soil had a fine texture. Restoration work in the tree plot started in 2004, with 80-100 kg/ha (equivalent of 25 kg/ha N per year) of inorganic fertilizer applied every year until 2015. The plot is used for light grazing in the autumn.

Figure 3. The tree plot. (Photo: S. Askelsdottir, 19 June 2015).

The grass plot was dominated by native grass such as *Festuca richardsonii* (Fig. 4). Bare patches could be noticed too, suggesting an unstable surface, unfinished revegetation and possibly frost heaving. Litter was not visible. The plot was gravelly and some rocks could be noticed in parts of the area. The plot had dark grey soils with coarse texture. 200 kg/ha (equivalent of 50 kg/ha N per year) of inorganic fertilizer has been applied every other year since 2002. The plot is mainly grazed in spring and autumn.

The eroded plot was gravelly with scarce vegetation (Fig 5). The surface was loose and stony and no litter was noticeable. There was no litter in the plot. The soil was brown and had a coarse texture.

Figure 4. The grass plot. (Photo: P. Natanael, 19 June 2015).

Figure 5. Eroded plot. (Photo: S. Askelsdottir, 4 September 2015).

2.2 Soil sampling

Soil samples for bulk density were collected using a core of 5 cm in diameter and 5 cm in length. The samples were collected at 0-5 cm and 5-10 cm depths every 5 m on one transect for each treatment (four samples per transect). One random point was also selected along each transect to select one sample for soil texture analysis (one soil texture sample per treatment).

A soil auger, 2.8 cm in diameter, was used to collect soil samples in the natural woodland and tree plots. Five cores from each sampling point were collected, making a composite sample. It was not possible to use the auger in the eroded and grass plots because they were too gravelly. Instead a shovel was used to dig a hole to a corresponding depth, where soil samples were collected. All samples were collected at a depth of 0-10 cm. These samples were meant for carbon analysis and were collected every 2 m on a transect of 20 m giving a total number of 10 samples per treatment. In the tree plot a sample was collected close to the nearest tree at these 2 m intervals in order to get soil that was highly impacted by trees in terms of carbon accumulation as the trees were still young. Overall, 60 samples were collected. At each study site soil samples for field soil texture were taken for site description.

2.3 Sample handling and preparation

Soil samples meant for carbon analysis were air-dried in a room with proper ventilation. The individual soil samples were then sieved in a 2 mm sieve to remove materials >2 mm. The samples for carbon analysis were ball milled for 24 hours. Samples for bulk density analysis were oven dried at 105°C for 24 hours.

2.4 Soil analysis

2.4.1 Bulk density

The soil samples were sieved to determine soil fractions of <2 mm. Density and the weight of rock fragments were also determined. The BD was calculated using the procedures described by Burt (2004) given by:

$$BD = (ODW-RF-CW)/ [CV-(RF/PD)]$$

where BD = Bulk density of < 2 mm fabric at sampled, field water state (g cm^{-3}); ODW = Oven-dried weight; RF = Weight of rock fragments; CW = Empty core weight; CV = Core volume; PD = Density of rock fragments

This formula was used because the bulk density results were used to calculate carbon stocks, which requires that coarse materials be subtracted so that only the active soil fraction is used. Each depth had its bulk density calculated and an average bulk density for both depths was used to calculate carbon stocks. This was so because the samples for carbon determination were collected from depths 0-10 cm as one depth.

2.4.2 Determination of organic matter and soil organic carbon

Organic matter (OM) calculation aided in the determination of the carbon content. The organic matter was determined using Loss on Ignition (LOI) as described by Rowell (1999). LOI has been used to estimate soil organic carbon for decades through estimation of organic matter loss. Soil samples are first oven dried at 105°C for 24 hours and weights recorded. Then samples are heated at 550°C for 4 hours to burn the organic matter and inorganic carbon. Then samples are then re-heated at 105°C for 3 hours and weighed. The difference in weight is divided by the initial oven weight multiplied by 100 to get the % of organic matter (Rowell 1999). Then the organic matter is converted to % soil organic carbon. Commonly used conversions use the principle that 40-58% of LOI is soil organic carbon (Brady & Weil 1999) using the formula C% = 50/100*LOI. A regression analysis was made to estimate how good LOI was for estimating % C. Then the results from the simple (C% = 50/100*LOI) calculation were compared to the results obtained from the regression.

Twenty subsamples (five from each treatment) were analysed for total carbon (% C) using a vario MAX CN elementar analyser, manufactured by Elementar Analysensysteme GmbH. Carbon results were corrected for dry matter.

Soil carbon was also expressed as stocks. This was calculated by multiplying the soil mass of one ha built on the bulk density of soil at the 0-10 cm depth by the measured % carbon in a plot. To calculate accumulation per year, the stocks in the tree and grass plots were subtracted by the amount in the eroded plot (baseline). Then the amount in the tree plot was divided by 11 years of restoration while the amount of soil carbon from the grass plot was divided by 13 years.

2.5 Statistical analysis

Descriptive statistics were used to find the means for carbon content from the treatments. SAS enterprise guide 6.1 was used to test the significant difference of means of carbon in the different treatments. One way ANOVA analysis was conducted to test significance between values in bulk density, % soil organic carbon content, carbon stocks. A simple regression analysis was run in Excel to determine the relationship between % C and LOI and an equation was developed.

3. RESULTS

3.1 Bulk density

The results indicated variations in the bulk density values among treatments as well as between depths (Table 1). In the 0-5 cm depth, there was no significant difference between the mean bulk densities in eroded and grass plots, and likewise no significant difference between the tree plot and natural woodland. However, there was a significant difference between the bulk densities in eroded and grass plots, on one hand, and tree and natural woodland on the other hand ($p = 0.0016$). Within the depth of 5-10 cm, there was no significant difference for bulk densities among eroded, grass and tree plots. There was a significant difference between the bulk density of the natural woodland, on one hand, and the eroded, grass, and tree plots on the other hand (p = 0.0189). The tree plot and natural woodland were not significantly different.

Table 1. Mean bulk density of <2 mm soil in the two depths. Values with same letters are not significantly different; comparisons were within the same depth.

Treatment	Sampling depth (cm)	Mean bulk density (g/cm^3)	Std. Error
Natural woodland	0-5	0.36a	0.08
Trees	0-5	0.57a	0.09
Grass	0-5	1.15b	0.05
Eroded	0-5	1.28b	0.01
Tree pristine	5-10	0.45a	0.04
Trees	5-10	0.84ab	0.04
Grass	5-10	1.22b	0.02
Eroded	5-10	1.26b	0.21

3.2 Soil carbon

3.2.1 Soil carbon

The natural woodland had the highest mean total carbon of 9.32% (Table 2). There was a significant difference in mean carbon content between natural woodland and the tree plot. There was also a significant difference between the mean carbon amounts in the tree plot and the grass plot (p = 0.0001). However, there was no significant difference in mean carbon content between the grass and eroded plots (p = 0.0566). The two controls, natural woodland and eroded plots, were significantly different in carbon amounts (p = 0.0001).

However, there was no significant difference in soil carbon stocks between the natural woodland and the tree plot (Table 2). This could be due to the differences in the bulk density, as the calculations were made using the average bulk density from the two depths (0-5 cm; 5-10 cm).

Table 2. Percentage mean carbon, carbon stocks and bulk density in the 0-10 cm depth. Values with same letters are not significantly different.

Treatment	% Soil carbon		Soil carbon stocks (t/ha)		Bulk density*
	Mean	Std. Error	Mean	Std. Error	
Natural woodland	9.32a	0.59	38.21a	2.42	0.41
Tree plot	4.91b	0.48	34.38a	3.329	0.7
Grass plot	1.12c	0.15	15.31b	1.867	1.18
Eroded plot	0.76c	0.05	9.70b	0.643	1.27

* Mean of 0-5 and 5-10 cm for each treatment

3.2.2 Loss on Ignition

The LOI results showed higher carbon content in the natural woodland than the tree plot. The eroded plot had the least amount (Table 3).

Table 3. Comparison of mean calculated % soil carbon from Loss on Ignition (LOI), measured soil carbon and the commonly used method of taking 50% LOI as carbon in the 0-10 cm depth for each treatment.

Treatment	% LOI *	% C measured**	% C calculated***	% C at 50% LIO****
Natural woodland	25.62	9.32	9.16	12.81
Tree plot	15.39	4.91	5.17	7.69
Grass plot	4.78	1.12	1.03	2.39
Eroded plot	4.48	0.76	0.92	2.24

* Loss on Ignition for all samples in a plot
** Soil carbon using direct measurement
*** Soil carbon obtained from a simple regression equation between % measured carbon and LOI
**** Soil carbon using the commonly used formula that 50% of LOI is carbon given by the formula (50/100*LOI).

The results showed higher mean values for % C from LOI in the tree plot and the eroded plot than from total carbon analysis. The LOI values were lower in the natural woodland and grass plots than the % C measured. A simple regression equation was developed based on LOI values and the measured % C values (Fig. 6). The % C calculated with the regression equation was closer to the measured % C than calculated by 50% of LOI being carbon (Table 3).

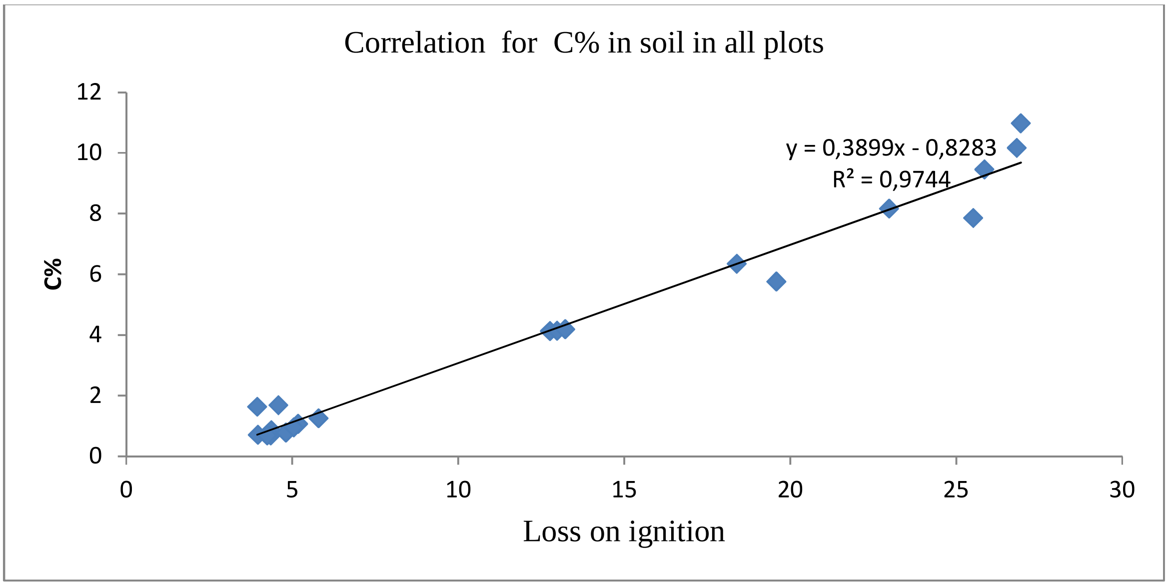

Figure 6. Simple linear regression equation for soil organic C measured against Loss on Ignition (LOI) for all the plots.

4. DISCUSSION

4.1 Bulk density

Bulk density is an important component in the determination of soil carbon content. Comparing between depths, soil bulk densities were lower in the 0-5 cm depth than the 5-10 cm depth except in the eroded plot. Despite being under revegetation, the grass plot had higher bulk density at both depths than the natural woodland and the tree plot. The findings between depths were similar to that of Arnalds et al. (2013) where they found that the soil bulk density at 0-5 cm depth was lower (1.02 g/cm^3) than in the 5-10 cm depth (1.10 g/cm^3) in degraded soils. However, the bulk densities in the grass and eroded plots in this study were higher, suggesting that the soils in these plots were Vitrisols. Icelandic Andosols have low bulk density, ranging from 0.3-0.8 g/cm^3 (Arnalds 2004). A comparison by treatment, correlated with Han et al. (2010) who found higher soil bulk density in grassland than in woodlands and also higher in degraded areas than in reclaimed.

The findings of this study showed that there was more gravel in the soil in degraded areas compared to the natural woodland and the tree reclaimed areas. The lower bulk density in the tree and natural woodland could be attributed to the vegetation, which is a source of organic matter after decay. By estimation, the natural woodland and tree plots had finer soil texture suggesting more developed soil and organic matter. Organic matter-rich soils could have lower bulk density than heavy non-organic materials. These plots also had a higher carbon content compared to the eroded and grass plots. Andosols with higher carbon content have lower bulk densities (Arnalds 2015), usually less than 0.8 g/cm^3 whereas desert soils have bulk densities higher than 0.8 g/cm^3. The bulk densities in the tree plot and natural woodland were indicative of more organic matter content, porosity and good water holding capacity. In this case the higher bulk density in eroded and grass plots is likely to have been due to a low level of organic matter and carbon content and thus a high proportion of mineral material.

4.2 Soil carbon in different treatments

The main focus of this research was to estimate the amounts of soil carbon status restoration measures (with trees and grass) and see if there was a difference between treatments. As expected the natural woodland had the highest soil carbon content, followed by the tree plot. The grass plot and the eroded plot had no significant difference in soil carbon content. The findings correspond to that of Petursdottir et al. (2013) who found 1.1-1.2% carbon in untreated plots and 1.3-1.5% in plots treated with grass and lupine. They also found no significant difference between the soil carbon amounts in untreated plots and grass and lupine plots after 5-7 years of treatment. Their study was done in the same Hafnarmelar area but in the exact same locations.

Several reasons could account for such variations. The natural woodland soil had a higher % carbon, probably because it had more vegetation cover and thus likely higher OM inputs to the soil. This area has possibly not lost the old carbon-rich soil, as was the case with the tree, grass and eroded plots, and hence there had been more time for development of various soil properties. It has possibly not lost the old carbon-rich soil, as was the case with the tree, grass and eroded plots. The area also had more litter deposits which after decomposition release nutrients. The plot might have had more clay content, as indicated by the fine soil texture. Soils that have more clay particles have the ability to hold more carbon (Arnalds et al. 2000; Walker & Desanker 2004). Clay particles adsorb carbon between them making it less likely to get lost to the atmosphere unless disturbed by erosion. This is one of the features of Andosols. Furthermore, slow decomposition due to low soil temperatures retains soil carbon and is typical of soils in cold regions (Arnalds et al. 2013). The tree plot had a similar texture as the natural woodland but lower carbon content. The former had young trees as it was in early stages of restoration. It also had less litter that could feed carbon back into the soil, compared to natural woodland, but more litter compared to the grass and eroded plots. The natural woodland and tree plots had low bulk densities and higher organic matter, which accounts for the higher carbon content. This finding correlates with findings by Gudmundsson et al. (2004), Walker & Desanker (2004) and Arnalds (2015).

Lower carbon levels in the grass plot could be due to limited organic matter build up. The plot had higher bulk density and coarse soil texture. The soil would be expected to have poor water holding capacity and be missing the finer soil particles. These conditions make it more difficult for the soil to hold nutrients and accumulate carbon. Despite not being significantly different from the eroded plot in carbon content, the grass plot showed signs of soil properties development as its trend in bulk density followed the trend in the natural woodland and the tree plot, i.e. it was lower in the 0-5 cm depth than the 5- 10 cm. This shows that there could be some level of organic matter build-up in the upper layers. It would be expected that with time a number of changes in the soil properties could occur. The grass plot is heavily grazed in spring and autumn. It was visibly grazed as some bare patches could be noticed and litter deposition was scarce. It could be possible that the low carbon content was in part due to too much of the above-ground biomass being removed with grazing, as that could lead to low primary productivity and consequently lower organic matter input into the soil. The bare patches expose soil to erosion, making it likely to be lost through run off as the terrain is not flat. However, Petursdottir et al. (2013) found, in an evaluation of the short-term progress of restoration in a similar grass treatment in the area (but not at the exact same location) that summer grazing did not impede the development of soil and vegetation. Other studies have, however, established strong linkages between intensity of grazing, condition of grazed land and carbon quantities in soils (Nianpeng et al. 2012). As an agro-ecosystem, the soil in the grass plot would be expected to have lower carbon than the natural woodland, which was a natural ecosystem (Lal 2014). Improved grazing management of the grass plot area would be advisable. In their study on land use impact on soil carbon sequestration of Inner Mongolian grasslands, Nianpeng et al. (2012) observed that practices like systematic grazing exclusion helped increase the soil carbon, especially in the top 0-50 cm depth.

The eroded plot had the least amount of soil carbon though it was not significantly different from that of the grass plot. The soil was very gritty and loose and the plot had the highest bulk densities at both depths. The plot was bare and exposed to both water and wind erosion. The water and wind erosion could be responsible for loss of more fine materials from the area leaving it with only gravelly materials. Frost heaving in the winter months could also make it difficult for vegetation to establish itself. The quality and quantity of clay influence amounts of stabilized carbon in soils (Yanardag 2014). After comparing coarse textured sandy loam soil and finer textured silt loam soil, Borchers & Perry (1992) found that the latter had higher carbon levels than the former. This would explain lower carbon levels in the eroded and grass plots than in the natural woodland and tree plots, which had vegetation cover and fine textured soil. Since the eroded plot had scarce vegetation cover and consequently very limited litter inputs, there was no source of organic matter. Therefore, it can be concluded that the low soil carbon is likely the result of lack of vegetation cover.

Overall carbon sequestration rates in soils differ because of soil type, topography, history of land use, vegetation cover and hydrology (Marlang et al. 2004; Arnalds et al. 2013). Contrary to the findings in this research, Marlang et al. (2004) in their study on enhancing carbon sequestration in soils in East Tennessee, USA, found that grass plots had more carbon than tree and forest plots. Such differences are bound to occur as the geography of sites and associated factors differ.

4.3 Soil carbon stocks

The sequestration rates estimates were based on soil carbon amount in the 0-10 cm depth in a particular plot and the number of years under restoration. The eroded plot was used as the baseline, although soil properties differed. The sequestration was higher in the tree plot than the grass plot. From the carbon stocks (Table 2) it can be estimated that restoration with grass sequestered 0.4 t C per ha per year and reclamation with trees 2.2 t C per ha per year. The sequestration rate in the grass was lower than the results of Arnalds et al. (2000). They estimated a carbon sequestration of 0.6 t C per ha per year through reclamation of severely degraded sandy soils. In another study in a different area, Arnalds et al. (2013) also found sequestration rates of 0.4-0.63 t C per ha per year which are comparable to the findings in this study in the grass plot.

The sequestration rates in the tree and grass plots were encouraging considering the short period of restoration and the stage of trees in the plot. However, the sequestration rate in the tree plot might have been exaggerated by the sampling method. In the tree plot, sampling was done close to the trees along the chosen transect. As described earlier, this was done to capture the influence of trees on carbon amounts as the trees were still small. The yearly application of fertilizer in the tree plot, compared to the biennial application in the grass plot, might also have influenced the carbon sequestration rates in the tree plot. It could also be speculated that the tree plot might not have been as highly degraded before restoration started as the grass plot.

4.4 The use of Loss on Ignition

The calculated values using LOI were closer to the measured values than the values of the commonly used soil carbon estimation. The commonly used estimation says that 50% of LOI is carbon (Brady & Weil 1999) (Table 3). This means that LOI can be a good estimator for soil organic carbon. It is even closer to direct measurements if specific equations are developed for specific soil types using known carbon values (David 1988; Konen et al. 2002) as was done in this study.

4.5 The Malawi context

The experiences in this research offered the opportunity to acquire knowledge and skills in the processes of carbon analysis. As Malawi implements land restoration programmes in relation to climate change, knowledge of carbon sequestration becomes imperative. Soil carbon analysis in this research was done using two methods; direct carbon measurement (using a vario MAX CN elementar analyser) and LOI. The former is an expensive method in both acquiring and running costs. However, it is efficient and exact in soil carbon measurement. LOI is an inexpensive method though not always very precise. Furthermore, it does not require specialized staff. However, the analysis showed that the % C from the regression equation of LOI was closer to the % C from direct measurement. Therefore, it was concluded that LOI was a good estimation method for soil carbon estimation. Its accuracy improves greatly if it is also possible to do some direct measurements using precise methods and then do regression to get the equation. These equations should be for particular soil types. Therefore, it could be easier to conduct carbon analysis in Malawi if a database of equations were developed based on different soil types, as is the case in other countries like the USA. In countries like Malawi, where it is difficult to afford expensive methods of soil carbon analysis, LOI remains the best option.

5. CONCLUSIONS

This study showed that restoration of degraded land through revegetation can result in a soil carbon increase. The study also found that reclamation with trees in addition to grass could lead to more carbon sequestration in the soil than reclamation with grass only. Soil carbon content in the tree plot was closer to that of the natural woodland. The results also showed that the condition of land and soil also affects the amount of carbon sequestered. The natural woodland and the tree plot had finer soil texture than the grass and eroded plots. This could suggest that land under the tree plot had not been as badly eroded or degraded as in the grass and eroded plots. This also suggests that where land has been properly restored or kept in its natural condition, soil properties improve. It is therefore expected that with time there should be improvement in soil properties in the grass plot.

There is, however, a need to balance restoration of the land and its use. It would be a win-win situation if restored land was given ample time for ecological processes to be fully established and restored before the land is subjected to heavy use (grazing in this case). It can be suggested that the management of the grass plot should be improved; grazing should be limited. Annual fertilization, instead of biennial application, could be another option. From this study, it can be generalized that the FHL project is contributing to sequestration of carbon into the soil. More reclamation endeavours are therefore encouraged.

The results also showed that LOI is a good but not very accurate estimator of soil organic carbon unless equations are developed with respect to known carbon content. It is therefore, important for Malawi to develop the status of soil organic carbon and equations in the different soil types of the country. LOI could be used for estimating soil carbon based on these equations.

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APPENDICES

Appendix 1. Loss on Ignition results

Treat ment		a	b	c	d	e	f	g	h	i	LOI %
Grass plot											
Cruci-ble no.	Sam-ple no.	Weight of cold glass	Weight of hot glass	Weight air dried soil	Weight cold glass+ air dried soil (a+c)	Weight hot glass+ oven dried soil	Weight oven dried soil (e-b)	Weight hot glass+ soil after 550	Weight of soil after 550 (g-b)	Differ-ence between f and h	% OM (i/f)*100)
117	1	18.7293	18.7214	3.0079	21.7372	21.6092	2.8799	21.4344	2.713	0.1669	5.7953
193	2	14.988	14.9816	3.0080	17.996	17.8760	2.888	17.7463	2.7647	0.1233	4.2694
194	3	15.0255	15.0191	3.0000	18.0255	17.9212	2.8957	17.7820	2.7629	0.1328	4.5861
141	4	16.7207	16.7136	3.0075	19.7282	19.6179	2.8972	19.4986	2.785	0.1122	3.8727
142	5	15.236	15.2295	3.0079	18.2439	18.1371	2.9011	18.0161	2.7866	0.1145	3.9468
116	6	16.2555	16.2486	3.0098	19.2653	19.1692	2.9137	19.0349	2.7863	0.1274	4.3724
174	7	14.0998	14.0938	3.0076	17.1074	16.9863	2.8865	16.8480	2.7542	0.1323	4.5834
134	8	16.1023	16.0955	3.0086	19.1109	18.9909	2.8886	18.8345	2.739	0.1496	5.1790
143	9	17.5039	17.4965	3.0011	20.505	20.3990	2.8951	20.2441	2.7476	0.1475	5.0948
172	10	14.8035	14.7972	3.0076	17.8111	17.6808	2.8773	17.5286	2.7314	0.1459	5.0707
Tree plot		a	b	c	d	e	f	g	h	i	j
Cruci-ble no.	Sam-ple no.	Weight of cold glass	Weight of hot glass	Weight air dried soil	Weight cold glass+ air dried soil (a+c)	Weight hot glass+ oven dried soil	Weight oven dried soil (e-b)	Weight hot glass+ soil after 550	Weight of soil after 550 (g-b)	Differ-ence between f and h	% OM (i/f)*100)
138	1	15.3404	15.3339	3.0029	18.3433	18.0250	2.6846	17.5632	2.2293	0.4553	16.9597
151	2	16.3878	16.3808	3.0000	19.3878	19.0497	2.6619	18.5532	2.1724	0.4895	18.3891
176	3	14.8447	14.8384	3.0043	17.849	17.5393	2.6946	17.1276	2.2892	0.4054	15.0449
192	4	15.4883	15.4817	3.0048	18.4931	18.2233	2.735	17.8676	2.3859	0.3491	12.7642
135	5	16.6992	16.6921	3.0050	19.7042	19.4182	2.719	19.0425	2.3504	0.3686	13.5565
152	6	17.7722	17.7647	3.0025	20.7747	20.4946	2.7224	20.1338	2.3691	0.3533	12.9775
139	7	15.5375	15.5309	3.0083	18.5458	18.2794	2.7419	17.9102	2.3793	0.3626	13.2244
122	8	16.329	16.3221	3.0010	19.33	19.0263	2.6973	18.6427	2.3206	0.3767	13.9658
128	9	15.9698	15.963	3.0026	18.9724	18.4610	2.4912	17.9663	2.0033	0.4879	19.5849
133	10	15.4276	15.421	3.0094	18.437	17.8508	2.4232	17.3313	1.9103	0.5129	21.1662

Eroded plot		**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**
Crucible no.	**Sample no.**	**Weight of cold glass**	**Weight of hot glass**	**Weight air dried soil**	**Weight cold glass+ air dried soil (a+c)**	**Weight hot glass+ oven dried soil**	**Weight oven dried soil (e-b)**	**Weight hot glass+ soil after 550**	**Weight of soil after 550 (g-b)**	**Difference between f and h**	**% OM (i/f)*100)**
190	1	15.9607	15.9539	3.0031	18.9638	18.8654	2.9047	18.7369	2.783	0.1217	4.1898
132	2	16.1471	16.1402	3.0004	19.1475	19.0527	2.9056	18.9193	2.7791	0.1265	4.3537
104	3	16.8559	16.8488	3.0013	19.8572	19.7570	2.9011	19.6349	2.7861	0.115	3.9640
171	4	16.8896	16.8824	3.0056	19.8952	19.7765	2.8869	19.6296	2.7472	0.1397	4.8391
136	5	15.2879	15.2814	3.0102	18.2981	18.1852	2.8973	18.0394	2.758	0.1393	4.8079
153	6	16.9955	16.9883	3.0084	20.0039	19.8880	2.8925	19.7348	2.7465	0.146	5.0475
186	7	16.147	16.1401	3.0098	19.1568	19.0635	2.9165	18.9402	2.8001	0.1164	3.9911
191	8	15.1691	15.1626	3.0096	18.1787	18.0586	2.8895	17.9130	2.7504	0.1391	4.8140
170	9	15.7143	15.7076	3.0082	18.7225	18.6214	2.9071	18.4911	2.7835	0.1236	4.2517
150	10	16.5952	16.5881	3.0139	19.6091	19.5170	2.9218	19.4005	2.8124	0.1094	3.7443
Natural woodland		**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**
Crucible no.	**Sample no.**	**Weight of cold glass**	**Weight of hot glass**	**Weight air dried soil**	**Weight cold glass+ air dried soil (a+c)**	**Weight hot glass+ oven dried soil**	**Weight oven dried soil (e-b)**	**Weight hot glass+ soil after 550**	**Weight of soil after 550 (g-b)**	**Difference between f and h**	**% OM (i/f)*100)**
175	1	16.1635	16.1566	3.0027	19.1662	18.8193	2.6558	18.0906	1.934	0.7218	27.1783
127	2	16.6178	16.6107	3.0038	19.6216	19.2731	2.6553	18.5504	1.9397	0.7156	26.9499
188	3	15.4293	15.4227	3.0050	18.4343	18.1006	2.6713	17.4520	2.0293	0.642	24.0332
106	4	16.3649	16.358	3.0052	19.3701	19.0352	2.6703	18.3380	1.98	0.6903	25.8510
102	5	14.4208	14.4146	3.0084	17.4292	17.1012	2.6804	16.4790	2.0644	0.616	22.9816
187	6	14.7969	14.7906	3.0095	17.8064	17.4441	2.6472	16.7655	1.9749	0.6723	25.3966
189	7	15.9754	15.9686	3.0024	18.9778	18.5845	2.6091	17.9121	1.9435	0.6656	25.5107
168	8	15.3906	15.384	3.0073	18.3979	18.0418	2.6512	17.3923	2.0083	0.6429	24.2494
101	9	16.189	16.1821	3.0017	19.1907	18.7039	2.5149	18.1202	1.9381	0.5768	22.9353
154	10	16.8395	16.8323	3.0055	19.845	19.4903	2.6508	18.772	1.9397	0.7111	26.8259

Appendix 2. Direct carbon measurements using vario MAX CN elementar analyser

Treatment and sample number	C %	C/N ratio	Dry matter correction factor	Corrected %C
Eroded plot S# 2	0.664	14.6	0.9634	0.6888
Eroded plot S# 3	0.677	16.0	0.9552	0.7090
Eroded plot S# 5	0.749	15.3	0.9599	0.7804
Eroded plot S# 6	0.907	15.5	0.9507	0.9542
Eroded plot S# 9	0.676	14.9	0.9603	0.7038
Eroded plot S# 9	0.641	15.4	0.9603	0.6675
Grass plot S# 1	1.20	14.4	0.9565	1.2519
Grass plot S# 3	1.52	14.7	0.9574	1.5860
Grass plot S# 3	1.61	14.2	0.9574	1.6767
Grass plot S# 5	0.757	15.9	0.9611	0.7881
Grass plot S# 6	0.830	17.5	0.9613	0.8634
Grass plot S# 8	1.02	16.4	0.9595	1.0631
Natural woodland S# 2	9.44	17.1	0.8601	10.9729
Natural woodland S# 4	8.49	15.2	0.8984	9.4544
Natural woodland S# 5	7.84	14.7	0.9611	8.1556
Natural woodland S# 7	7.55	14.8	0.9613	7.8516
Natural woodland S# 10	8.36	16.8	0.823	10.1605
Tree plot S#2	5.66	15.4	0.8919	6.3443
Tree plot S#4	3.55	16.8	0.8599	4.1232
Tree plot S#6	3.77	16.9	0.9116	4.1343
Tree plot S#7	3.85	16.5	0.9193	4.1851
Tree plot S#9	4.78	15.6	0.8305	5.7584

Note: yellow indicates samples measured repeatedly.

Appendix 3. Dry matter for correcting percentage carbon after direct analysis with vario MAX CN

Treatment		a	b	c	d	e	f	g
Grass plot	Sample number	Weight of container	Weight air dry soil ball milled	Weight container plus air dried soil (a+b)	Weight container plus oven dried soil	Weight moisture (c-d)	Weight oven dried soil (d-a)	Dry matter (dry soil/wet soil) f/b
	1	8.73	19.10	27.83	27.00	0.83	18.27	0.9565
	3	8.66	17.61	26.27	25.52	0.75	16.86	0.9574
	5	8.72	23.4	32.12	31.21	0.91	22.49	0.9611
	6	8.73	14.47	23.2	22.64	0.56	13.91	0.9613
	8	8.72	12.35	21.07	20.57	0.5	11.85	0.9595
Tree plot								
	Sample number	Weight of container	Weight air dry soil ball milled	Weight container plus air dried soil (a+b)	Weight container plus oven dried soil	Weight moisture (c-d)	Weight oven dried soil (d-a)	Dry matter (dry soil/wet soil) f/b
	2	9.15	9.53	18.68	17.65	1.03	8.5	0.8919
	4	9.13	11.42	20.55	18.95	1.6	9.82	0.8599
	6	8.66	8.94	17.6	16.81	0.79	8.15	0.9116
	7	9.25	5.08	14.33	13.92	0.41	4.67	0.9193
	9	8.74	7.67	16.41	15.11	1.3	6.37	0.8305
Eroded plot	Sample number	Weight of container	Weight air dried soil ball milled	Weight container plus air dried soil (a+b)	Weight container plus oven dried soil	Weight moisture (c-d)	Weight oven dried soil (d-a)	Dry matter (dry soil/wet soil) f/b
	2	8.69	18.05	26.74	26.08	0.66	17.39	0.9634
	3	1.12	12.49	13.61	13.05	0.56	11.93	0.9552
	5	1.08	17.70	18.78	18.07	0.71	16.99	0.9599
	6	8.73	17.85	26.58	25.70	0.88	16.97	0.9507
	9	1.12	12.61	13.73	13.23	0.5	12.11	0.9603
Natural woodland	Sample number	Weight of container	Weight air dried soil ball milled	Weight container plus air dried soil (a+b)	Weight container plus oven dried soil	Weight moisture (c-d)	Weight oven dried soil (d-a)	Dry matter (dry soil/wet soil) f/b
	2	8.76	7.86	16.62	15.52	1.1	6.76	0.8601
	4	8.73	3.15	11.88	11.56	0.32	2.83	0.8984
	5	8.65	9.66	18.31	16.95	1.36	8.3	0.8592
	7	8.79	7.69	16.48	14.94	1.54	6.15	0.7997
	10	8.73	8.70	17.43	15.89	1.54	7.16	0.8230

Appendix 4. Comparison of different percentages of carbon using different methods of estimation

Treatment	Sample No.	LOI %	% C measured	% C Calculated	% C at 50% (50/100*LOI)
Grass plot	1	5.8	1.25	1.43	2.9
	3	4.59	1.67	0.96	2.295
	5	3.95	1.63	0.71	1.975
	6	4.37	0.86	0.88	2.185
	8	5.18	1.06	1.19	2.59
Eroded plot	2	4.35	0.69	0.87	2.175
	3	3.96	0.71	0.72	1.98
	5	4.81	0.78	1.05	2.405
	6	5.04	0.95	1.14	2.52
	9	4.25	0.69	0.83	2.125
Tree plot	2	18.39	6.34	6.34	9.195
	4	12.76	4.12	4.15	6.38
	6	12.98	4.13	4.23	6.49
	7	13.22	4.19	4.33	6.61
	9	19.58	5.76	6.81	9.79
Natural woodland	2	26.95	10.97	9.68	13.475
	4	25.85	9.45	9.25	12.925
	5	22.98	8.16	8.13	11.49
	7	25.51	7.85	9.12	12.755
	10	26.83	10.16	9.63	13.415