Kolbjörk: Carbon sequestration and soil development under mountain birch (*Betula pubescens*) in restored areas in southern Iceland

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Abstract
Iceland has suffered from severe soil erosion since settlement with losses up to 60% of pre-settlement vegetation. Large land remediation projects are underway using *Betula pubescens*. A huge potential for carbon sequestration exists by this revegetation of degraded areas. Little is known about soil development when using native forest vegetation for land restoration. This study aims to both estimate the carbon storage and sequestration rate in these systems and establish constrains on the pedogenetic factors and their influence on soil development. A chronosequence of afforested areas, both natural succession from sown plots and planted areas, reaching 60 years back has been established and compared to natural old-growth forests in the same area. 3 subplots were identified for each age group and soil sampled along transects in each plot. Soil profiles were described, sampled and water content sensors installed at representative sites. Profiles showed stronger horizonation with age with a slight lowering of soil pH in the topsoil.

Key Words
Pedogenesis, restoration, Andisol, erosion, Iceland.

Introduction

Climate and scene setting

Iceland is an active volcanic island located on the North Atlantic ridge just below the Arctic Circle (~63°-66° N, 13°-24°W). Total land area is 103 000 km^2. The climate is humid and cool-temperate, characterized by cool summers and mild winters. Shifts between frost and thaw are common. Annual mean temperature ranges from 2-6°C with mean July temperature about 6-10°C (Einarsson 1976). Mean annual precipitation ranges from 600-2000 mm in lowland areas and >400mm in the interior (Einarson 1976). The growing season is short, 89-144 days per year (Friðriksson and Sigurðsson 1983)

Icelandic soils

The soils in Iceland are predominantly volcanic in origin belonging to the Andisol order (Arnalds 2004). The soils are young, having mostly developed since the younger Dryas period around 10 000 years ago. They are heavily influenced by aeolian deposition, in part due to volcanic activity but also due to severe wind erosion in large parts of the country. Other influential factors are the cold maritime climate with intense cryoturbation (Arnalds *et al*. 2000; Arnalds 2008; Arnalds and Kimble 2001). The main broad categories of Icelandic soils are freely drained brown Andisols, both mineral and organic wetlands soils and soils of the barren deserts (Arnalds 2008). The desert soils are typically sandy Andisols with low water holding capacity, limited sources of macronutrients, rich in volcanic glass and have low amounts of allophane clay and organic C compared to vegetated areas (0.08-0.5 kg C/m^2 in desert soils compared to 40-90 kg C/m^2 in brown Andisols) (Arnalds and Kimble 2001). The deserts are erosional surfaces once covered with vegetation (Arnalds and Kimble 2001).

Vegetation and land degradation

The vegetation cover at the time of settlement (AD 874) is estimated to have been about 50-60% with birch woodlands (*Betula pubescens*) covering about 25-30% of the country. (Anonymous 2001). Today, only about 25% of Iceland is covered with continuous vegetation of which only 1% is original birch woodland. Total loss of soil organic carbon (C) is estimated to be 120-500 x 10^6 Mg since settlement; representing a serious environmental problem still on-going with estimated yearly losses 50-100 x 10^3 Mg C year^{-1} (Óskarsson *et. al.* 2004). In response to severe land degradation Iceland has a long history of concern for the land, and restoration efforts have continued for more than 100 years. Carbon sequestration is a major benefit of land restoration and revegetation programs, particularly in the severely degraded desert areas. The carbon storage is 0.01 to 0.5 t C/ha for vegetation, both above and below ground (Aradóttir *et al.* 2000) and the sequestering rate 0.6 t C/ha/yr in soils for reclaimed areas a rate maintained for >50 years (Arnalds 2000). Both numbers are for unforested reclaimed areas.

***Kolbjörk* (CarbBirch) project**

Overview

Kolbjörk is a 3-year project focusing on ecosystem development and potential for carbon sequestration using mountain birch (*Betula pubescens*) for land restoration on severely degraded areas. In view of government plans to reforest large parts of the country with native mountain birch further research on the ecosystem development in afforested areas is essential. Only one study is available for carbon sequestration in afforested areas (Snorrason *et al.*), and none were directed at afforestation of severely degraded land. The Kolbjörk project is a comprehensive study of ecosystem changes, carbon sequestration and carbon flux in reclaimed mountain birch areas. The project covers changes in understory vegetation community composition, carbon fluxes and productivity of plant biomass, colonization of mycorrhizal fungi and soil development in a chronosequence of established tree plots dating back 60 years with comparison to natural old growth forests in the area. Typically restoration efforts are directed at areas that are distant from remnant natural forests. Few studies have analyzed the rate and characteristics of the old growth ecosystem development.

Study area

The research sites are in a severely degraded area close to an active volcano, Hekla in south Iceland (Figure 1). The landscape has been badly eroded since settlement times. The land is inundated on a regular basis with volcanic ejecta from nearby volcanic systems, covering vegetation and causing destabilisation of surfaces by both directly killing vegetation and subsequent erosion due to aeolian movement of tephra cutting and covering above ground biomass. Mature forested systems appear to be tolerant to tephra fall as several oldgrowth forests still exist in the area and probably have survived since before settlement times (Aradóttir 2007). In order to stabilize the area and prevent further erosion due to volcanic events a large reforestation project is underway. The aim is to establish forests over approximately 900 km^2 using native species, both mountain birch and willows (Aradóttir 2007).

Research sites

Three reclaimed forested areas were picked for study and compared to two old growth forests (Figure 2). Reclamation at two sites, Gunnlaugsskógur and Stóri Klofi, commenced about 1940 on severely degraded land that had been devoid of tree cover for a long time. The vegetation has since spread from original plots onto the sand-covered lava. To get two complete chronosequences a third site, Bolholt, was needed, at Bolholt, where planting started in the 80's, also on sand covered lava. The chronosequences are the compared to two natural old growth forests, Hraunteigur and Búrfell.

Sampling scheme

Within each age group in each area, three 20x10m plots were randomly chosen. Each plot was split into two 10x10 subplots, one for sampling and one for monitoring. Soil samples were taken on transects on the plots with 5 sub-samples taken at 2 m intervals combined into one and two replications. Each sample was split into three depth increments 0-5, 5-15 and 15-30 cm. Bulk density was determined both by inner diameter of the soil corer and in small profiles taken close to the areas. In addition soil profile descriptions and horizon sampling was done close to oldest reclaimed plots, pioneering stage plots and unforested plots in the Stóri Klofi area along with Hraunteigur old growth area, with two profiles for each age group. Stóri Klofi was picked as an intensive sampling site due to minimal spatial variability within the area compared with other sites.

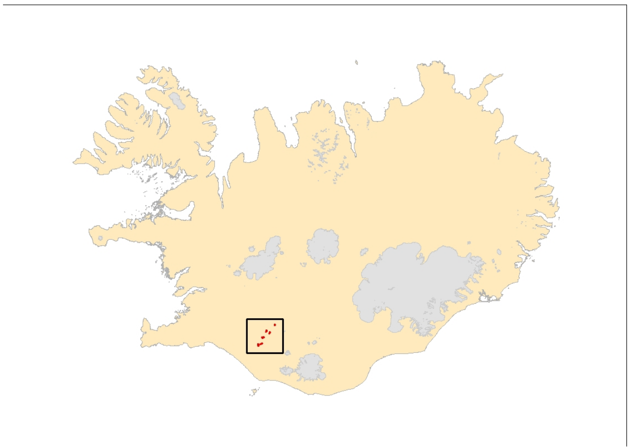

Figure 5. Location of study area

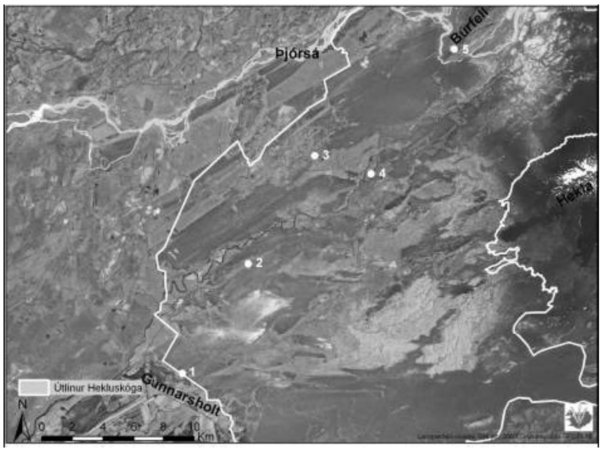

Figure 6. Distribution of study sites. 1 is Gunnlaugsskógur, 2 Bolholt, 3 Stóri Klofi, 4 Hraunteigur and 5 Búrfell. From Halldórsson *et al.* 2009)

Soils in the sample areas

Due to intensive soil erosion and subsequent movement of material with wind and water, the spatial variability of the soils is very great inside each area. In many areas the old soil can be found at less than 30 cm depth from current surface with aeolian and fluvial sand in between. Soils in the old growth areas show effects of aeolian deposition, but limited erosion.

Field description

Soil morphology and horizons were described according to the US Soil Taxonomy. Profiles were sampled by horizon, for analysis and for bulk density measurement. Tephra layers within the profiles were described and sampled. Water content sensors were placed in representative profiles to monitor changes in soil water.

Chemical analysis

All samples: Total organic C and N, was determined by dry combustion. Clay content was determined by flushing with oxalic acid and subsequent analysis with ICP. CEC and AEC measured. pH was measured in KCl, water and NaF. Chosen samples are flushed with pyrophosphate for determination o organic matter in OM-metal complexes. Water retention was also measured on profile samples.

Discussion

By determining the carbon stored in the sites, carbon sequestration rates and potential can be estimated for planned restoration programs. With the large sequestering potential of Andisols this will help achieve the goal of carbon neutrality for the country. Determining rate and extent of soil development after restoration from 'zero', i.e. from severely degraded areas largely devoid of vegetation, in the last 60 years increases understanding of the pedogenetic processes in Iceland and may help understand the revegetation and soil development after the last Ice Age. Stronger horizon formation with time has already been determined visually in the field and the extent of this difference will be further determined in the lab analysis. The amount of amorphous clay in the soils along with variable charge CEC can be used as an indicator of the extent of soil formation (Dahlgren *et al.* 2004). Soil organic matter (SOM) in Andisols is bound up in metal-hummus and amorphous clay-hummus complexes (Dahlgren *et al*. 2005) making the OM recalcitrant and not readily available for decomposition greatly increasing the stability of the SOM.

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