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A study on above- and belowground biomass and carbon stocks as well as sequestration of mountain birch (*Betula pubescens* Ehrh.) along a chronosequence in southern Iceland

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ABSTRACT

Following a period of land degradation lasting more than one thousand years, Iceland has undertaken ambitious restoration and afforestation efforts for one century now. Afforestation has also been a central venture of the Icelandic government in order to meet the commitments assigned by the Kyoto Protocol, because vegetation represents an important carbon sink. The aims of the study are how above- and belowground woody biomass and organic carbon is accumulated along a chronosequence in South Iceland and how afforested and remnant mountain birch areas react as carbon sinks. In summer 2009, 31 monocormic trees (0.1-5.5 m height) were measured and excavated. The excavated trees formed the dataset to establish allometric biomass functions of Icelandic mountain birch. The functions were statistically fitted by using numerical nonlinear regression in Matlab. Tree inventories (n=519) were made at four study sites, whereof three were planted stands and one represented a natural grown woodland. Subsequently, forest biomass and carbon stock and sequestration rates of the four different old sites were estimated by the allometric relationships. The total biomass and carbon stock estimations were in the 10-year old birch stand 3.9 Mg DM ha^{-1} and 2.0 Mg C ha^{-1}, in the 15-year old 21.1 Mg DM ha^{-1} and 11.1 Mg C ha^{-1}, in the 60-year old 166.5 Mg DM ha^{-1} and 87.4 Mg C ha^{-1} and in the old-growth woodland 73.6 Mg DM ha^{-1} and 38.7 Mg C ha^{-1}, respectively. Between 2004 and 2009 the average annual sequestration rates were 0.8 Mg DM ha^{-1} and 0.4 Mg C ha^{-1} (10-years old stand), 3.3 Mg DM ha^{-1} and 1.8 Mg C ha^{-1} (15-years old stand), 1.9 Mg DM ha^{-1} and 1.0 Mg C ha^{-1} (60-years old stand) and 2.0 Mg DM ha^{-1} and 1.1 Mg C ha^{-1} (old-growth), respectively. The ratio between long-time aboveground and belowground organic carbon stock increased along the chronosequence from 2:1 to 3:1. The root systems of mountain birch were stored in a thinner soil layer than expected. The results were well comparable with published studies on Icelandic mountain birch and other tree species.

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1 INTRODUCTION

1.1 BACKGROUND I: ICELAND AND ITS ENVIRONMENTAL HISTORY

1.1.1 Physiogeographical Background

Iceland is an island in the North Atlantic and is located between latitudes 63°23’N and 66°32’N and longitudes 13°30’W and 24°32’W. The landmass is about 103,000 km^2 big. While 75 per cent of the land area rises over 200 m a.s.l., the highest peak (Öraefajökull) of the mountainous country is 2,119 m a.s.l.. The relief consists of highlands in the interior of the country, lowlands especially at the south coast and numerous fjords along most other parts of the coastline (Einarsson 1984; Bjarnason 1991). In this chapter Iceland is introduced by describing the geoecofactors geology, soil, climate/weather, vegetation, human impact.

Geology

Iceland is situated at the junction of the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge and is the biggest landmass along the Mid-Atlantic Ridge. The seafloor spreading between the North American and the Eurasian Plates and the Iceland Hotspot created the Basalt Plateau of about 350,000 km^2 and reaches a height of 3,000 m. The landmass amounts to 30 per cent. The shelf is about 50 to 200 km wide. The formation of the plateau began 25 million years ago and can be divided into three zones. Because of a plate boundary which crosses Iceland from the Southwest to the Northeast the oldest rocks consisting of Tertiary flood basalts are located in the western and eastern part of the island. Pleistocene flood basalts and hyaloclastites form the second zone and are located in the central, southwest and north of the island. Hyaloclastites develop in a subglacial environment. The active rifting builds the neovolcanic zone and contains most of the 31 active volcanic systems in Iceland (Fig. 1). Pleistocene till is also found in areas which were influenced by glaciation. Especially in the south the floodplains consist of deposits of sediment (Arnalds 2000; Thoardarsson & Hoskuldsson 2002; Sigmundsson 2006).

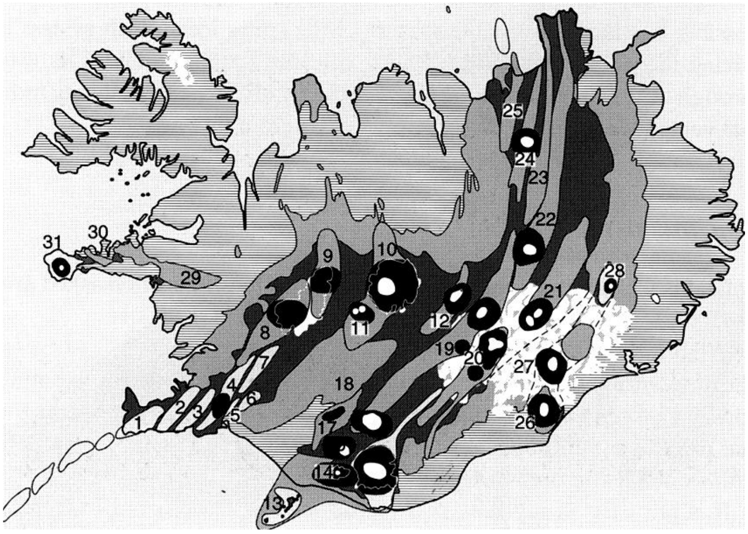


Fig. 1: The principal elements of the Icelandic geology and the 31 active volcano systems. Shown are Tertiary basalt formation (light grey shaded), Plio-Pleistocene formation (grey), Upper Pleistocene formation (dark grey) and volcanic systems with summit crater or caldera (black and white). Glaciers are white colored. Source: Thorardson & Hoskuldsson (2002).

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 & Kimble 2001; Arnalds 2008). The main broad categories of Icelandic soils are freely drained Brown Andisols and Gleyic Andisols, both mineral and organic wetlands soils (Histic Andisols and Histosols) and soils of the barren deserts (Vitrisols and Leptosols) (Arnalds 2008) (Fig. 2). The desert soils are typically sandy Vitrisols with low water holding capacity, limited sources of macronutrients, rich in volcanic glass and low in allophane clay and organic C compared to vegetated areas (> 3 g C kg^{-1} in desert soils compared to 30-80 g C kg^{-1} in undisturbed Andisols) (Arnalds & Kimble 2001). The deserts are erosional surfaces once covered with vegetation (Arnalds & Kimble 2001).

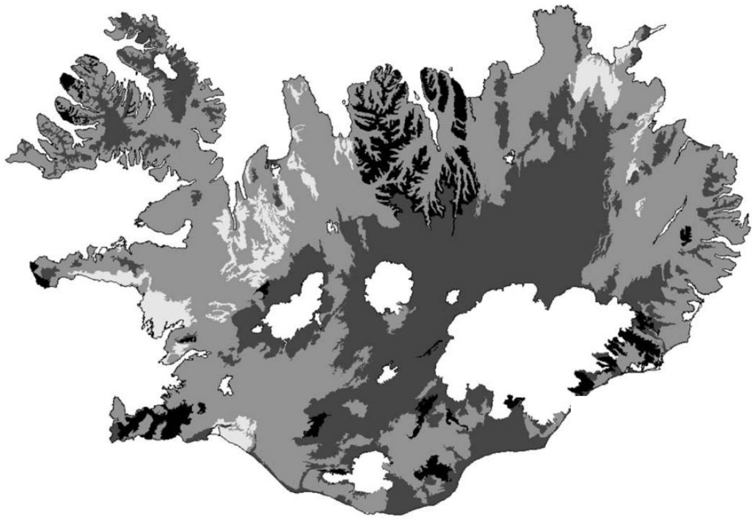


Fig. 2: Soil map of Iceland. Shown are Histosols and Histic Andisols (light grey), Brown and Gleyic Andisols (grey), Vitrisols (dark grey) and Leptosols (black). Glaciers and lakes are white colored. Source: Arnalds (2004).

Climate and Weather

The climate of Iceland is dominated by three main factors: solar radiation, oceanic water transport and atmospheric circulation. Because of its location near the Arctic Circle the solar radiation varies strongly depending on the season. Consequently, a transfer of heat is carried out by oceanic and atmospheric circulations from lower latitudes (Einarsson 1984). At the position of the island in the North Atlantic two water masses of very different origins and properties converge. While the west and south coast is influenced by warm and saline Atlantic water, the coast in the north is affected by the cold East Greenland Current originated in the Arctic Ocean (Jonsson & Valdimarsson 2005). The atmospheric circulation around Iceland is controlled by the polar front, the low pressure centre (Icelandic Low) which is located southwest of the country and the Greenland High. During summer months the polar front is positioned north of Iceland, thus the cyclones originated in the Icelandic Low reach the south coast of the country and bring warm, humid and maritime air masses. In winter time the polar front is situated south of Iceland and the weather in the north is dominated by cold polar air masses. The highlands act as a barrier and foehn effects may appear in the south or north depending on the direction of the air masses. Climographs of three chosen weather stations located at the Southwest coast, the North coast and in the Highlands show the explained climatic situation of Iceland (Tab. 1). Due to the interface between cold and warm air masses the change of the temperature can fluctuate up to 20 °C in a few hours during winter time. Even in summer temperatures below freezing may occur during night (Einarsson 1984; Glawion 1985). According to the classification of Köppen the climate at the south and west coasts is categorized as Cfc and ET at the Westfjords, the Highlands and the northern part of the island (Einarsson 1984; Strässer 1998). The characteristics of temperature and precipitation are shown in Tab 1. Wind is also an important environmental factor in Iceland. At

Gunnarsholt in the southern Icelandic lowlands, the predominant N and NE winds were most commonly between 5 and 10 m s^{-1} (Fig. 3).

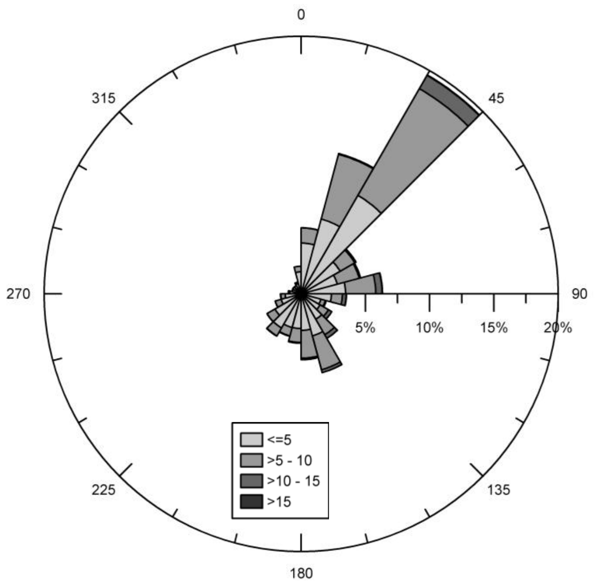
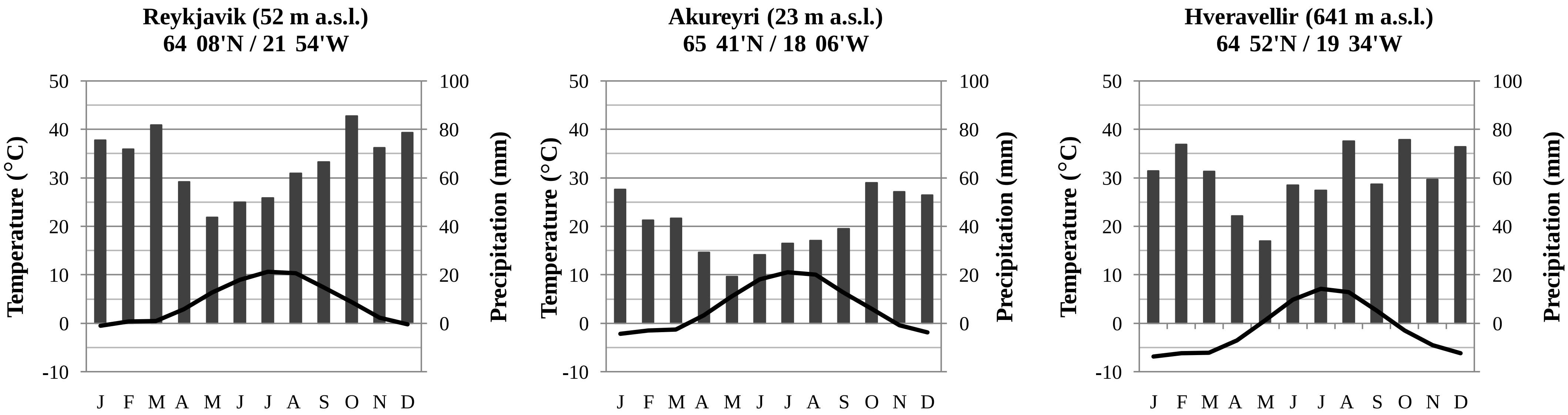


Fig. 3: Wind characteristics at Gunnarsholt in 2009. Wind rose represents the distribution of wind direction (degrees to magnetic north) and wind speed (m s^{-1}). The climate station samples every 30 minutes. Source: B.D. Sigurdsson, unpubl. data.

Tab. 1: Climographs of Reykjavik, Akureyri and Hveravellir. Also shown are mean annual temperature and precipitation. The time series range between 1961 and 1990 for Reykjavik and Akureyri and between 1966 and 1995 for Hveravellir, respectively.



Mean temperature:	4.3 °C	3.2 °C	-1.1 °C
Mean precipitation:	799 mm	490 mm	730 mm

datasource: http://www.vedur.is/Medaltalstoflur-txt/Arsgildi.html [15.10.2010]

Vegetation

During the Holocene the Icelandic plant community has fluctuated (Glawion 1985; Hallsdottir & Caseldine 2005). Pollen studies show that birch woodlands in Iceland began to expand in the late Boreal and early Atlantic chronozone and were most extensive before 6000 ^{14}C yr BP (Hallsdottir 1995; Hallsdottir & Caseldine 2005). Between 6000 and 1200 ^{14}C BP a retrogressive succession was observed towards more open birch woodland. At the same time mires and heathland expanded. Volcanic eruptions and climatic changes had been reasonable factors for the vegetational fluctuations before the country was settled (Hallsdottir & Caseldine 2005). At the time of the settlement at around 870 AD up to two-thirds of the island may have been vegetated, with at least 25 per cent of the area covered with woodlands, mostly mountain birch (Aradottir & Arnalds 2001). After settlement changes in vegetation composition were rapid. While birch woodland disappeared near farms during the first generation, grass heath, dwarf-shrub heath and mires expanded (Hallsdottir & Caseldine 2005). On agriculturally used sites cultivated species appeared (Erlendsson, Edwards & Buckland 2009). At the present the vegetation of Iceland is thought to be semi-natural, resulting from human use for over a millennium and import of plant species for the last 100 years (Bjarnason 1978; Blöndal 1987; Bjarnason 1991).

Betula pubescens Ehrh. is the only native tree species that forms continuous forests in Iceland (Aradottir & Arnalds 2001). Therefore mountain birch woodlands represent the natural climax vegetation. Due to climatic conditions during the early Holocene the distribution and the size of the woodlands fluctuated (Hallsdottir & Caseldine 2005). A recent study analysed the potential distribution for birch forest (Fig. 4) based on 7.9 °C temperature threshold (Wöll 2008). The active growing season of mountain birch in South Iceland is short and occurs during 70 days between June and August (Sigurdsson, unpublished data).

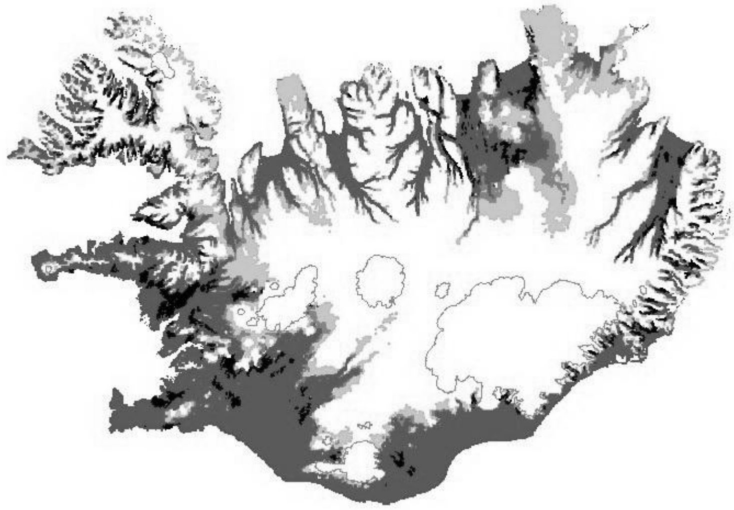


Fig. 4: Potential distribution for birch vegetation based on temperature thresholds. Birch shrub is shown in light grey and birch forest in dark grey. The actual birch shrub/forest cover is shown in black, glaciers are delineated in light grey. The tritherm threshold for birch shrub (=species line) is 7 °C, the one for birch forest (= 2 m tree line) is 7.9 °C. By courtesy of Ch. Wöll, modified.

Human impact

The Norse settled on the island in about 874 AD (Thorarinsson 1961; Grönvold et al. 1995; Dugmore et al. 2000; Hallsdottir & Caseldine 2005). The most common reason which is mentioned in the *Book of Settlement* of Iceland might be the flight of local Norwegian rulers because of the erection of a Norwegian kingdom by Haraldr Fairhair (Karlsson 2000). According to Thorarinsson (1961) about 30,000 people from Scandinavia and the British Isles were living in Iceland at 930 AD. Due to climatic and volcanic events, the size of the population didn't intensely increase and fluctuated between 40,000 and 60,000 in the period from settlement to the middle of the 19th century. The population was entirely rural and predominantly lived along the coast and in the lowlands (Thorarinsson 1961, Statistics Iceland 2010). They were farmers and fishers. Productive livestock such as cattle, horse and sheep were the predominant type of farming. Woodlands were cut close to farm buildings and used for timber, fire wood and charcoal. The open areas served as pastures and hayfields (Aradottir & Arnalds 2001).

The description of Iceland using the given above geoecofactors indicates that the Icelandic ecosystems have developed under extreme conditions. The natural circumstances (e.g. periodic ash deposits, cryoturbation or freeze –thaw cycles) cause the ecosystems to be extremely fragile even under natural circumstances (Aradottir & Arnalds 2001).

1.1.2 *Ecosystem Degradation, Soil Reclamation and Ecosystem Restoration*

Ecosystem Degradation

The ecosystem degradation started soon after the settlement (e.g. Hallsdottir & Caseldine 2005). The reason is believed to be an interaction between natural processes and human impact which were explained in the previous chapter. First, vegetation degradation occurred. Birch woodlands disappeared due to clear-cutting and grazing. (Winter)-Grazing by sheep prevented regeneration by basal sprouting, which is the primary mode for mountain birch. The vegetation composition also changed on pastures in favor of dwarf shrubs and mosses. Trampling caused exposure of the soil. Icelandic vegetation was not capable of closing the gaps because of the ongoing overgrazing and natural influences like freeze-thaw cycles and processes of water and wind which are more intense on unvegetated sites. Therefore soil erosion began and the ecosystems started to degrade (Fig. 5) (Aradottir & Arnalds 2001). The soil erosion in Iceland has also been enhanced by the unstable volcanic and glacial deposits. Therefore soil erosion has especially occurred along the active volcanic belt (Fig. 1). The degradation of vegetation and soil to the point of desertification were not only man-made. Rather it has been an interaction between natural and anthropogenic factors which have culminated in mobile sand dunes, abandonment of farmsteads and reduction of vegetated land down to 25 per cent (Arnalds et al. 1987). According to Aradottir & Arnalds (2001) the current extent of birch woodlands is about 1,165 km^2 while barren deserts and disturbed areas with limited plant production currently hold an expanse of about 50,000 km^2. While recently the countrywide annual soil loss is two to three million tonnes, during historic times soil loss was estimated to be more than 30 million tonnes per year (Arnalds 2000).

Fig. 5: Erosion front near Gunnarsholt. The retreat and the degradation of the ecosystem is nearly linear along the erosion fronts. Recording date: 23.06.2009.

Soil Reclamation and Ecosystem Restoration

In the middle of the 18^{th} century the first effort against soil erosion was undertaken by reverend Björn Halldorsson in Saudlauksdalur. He built stonewalls which protected his homefield from drift sand. After another cold period and numerous sand storms (1860-1890) the Icelandic government passed a law on desert reclamation in 1906 and in 1907 the first director of sand and desert reclamation took up employment (Sveinsson 1953). The Icelandic Soil Conservation Service is possibly the world's oldest (Runolfsson 1987). During the first half of the 20^{th} century areas were protected from grazing by fencing. Further storm walls consisting of timber or lava stones were manually erected perpendicularly to the prevailing direction of the moving sand dunes (Sveinsson 1953). At present, the length of storm walls is estimated to extend several thousand of kilometers (Sveinn Runólfsson, director of SCS, pers. comm.). Lyme grass (*Elymus arenarius*) was seeded to stabilize the caught sand along the walls (Sveinsson 1953).

The farm at Gunnarsholt, which was evacuated due to a large-scale erosion in 1923, has been the headquarter of the Icelandic Soil Conservation Service since 1947 (Fig. 6). With aid of the methods listed above and artificial fertilizer it was possible to start farming in the area again (Sveinsson 1953). In addition, the fields were used as experimental sites for more than 50 grass species imported from the U.S.A., Canada, later also from Norway, Denmark and Alaska (Sveinsson 1953; Runolfsson 1978). The most serious sand drifts in the area were under control by the late 1950s.

By employing aircrafts and agricultural vehicles, revegation of barren land has been more economic since the 1950s (Runolfsson 1987). The revegetated areas have been used as forage production or succession plots to the point of wooded sites (Arnalds et al. 1987). During the last 25 years ecological approaches have been introduced into the restoration methods (Aradottir & Arnalds 2001). Examples are the restoration of native birch woodlands, the use of the exotic nitrogen fixing species (*Lupinus nootkatensis*) and the establishment of woodland islands and encouragement of natural regeneration (Aradottir & Arnalds 2001). Further "there has been a gradual shift to more participatory strategies, community involvement and ecosystem management for multiple benefits" (Arnalds 2005, pp. 113). Thus treated areas have become interesting regarding to the Kyoto Protocol and the sequestration potential of vegetation and soil (Aradottir et al. 2000; Arnalds et al. 2000; Sigurdsson & Snorrason 2000; Ministry for the Environment 2007).

Fig. 6: The farm at Gunnarsholt in 1944 and 2005. The pictures were taken from the same spot. By courtesy of the Icelandic Soil Conservation Service.

Afforestation Efforts of Revegetated Areas in Iceland

The first forest plantation was established in 1899. However seedling planting started intensely in the 1930s. Until 2000 about 84 million trees were planted in Iceland. Not only mountain birch was planted. Corresponding to the import of grass seeds, exotic tree species were also imported. The most important species are Russian and Siberian larch, Sitka spruce, Lutz spruce, white spruce, Engelmann spruce, Norway spruce, Lodgepole pine, stone pine, black cottonwood and different species of alders (Blöndal 1987; Pétursson 1999; Sigurdsson & Snorrason 2000).

With signing the Kyoto Protocol by the Icelandic government, afforestation of treeless areas became another dimension. In addition to the ambition to restore the earlier existing woodlands, carbon sequestration in the terrestrial system was a new argument. Thereby afforestation and also reclamation work received extra financial support. For example the Icelandic government launched a programme to increase the annual carbon sequestration rate in forests, vegetation and soil by 100,000 t CO_2 between 1997 and 2000 (Ministry for the Environment 2007). This is partly the reason that the number of planted seedlings has increased intensely since the mid 1990s (Sigurdsson & Snorrason 2000, Aradottir & Arnalds 2001).

1.2 BACKGROUND II: THE CONTEMPORARY GLOBAL CARBON CYCLE AND CHALLENGES OF ICELAND

1.2.1 The Terrestrial Pool of the Contemporary Global Carbon Cycle

The global carbon cycle is composed of four major reservoirs: atmosphere, oceans, reserves of fossil fuels and terrestrial ecosystems, including vegetation and soils. The reservoir sizes and the fluxes between the reservoirs are shown in Fig. 7. Measurements show that the atmospheric carbon concentration has been increased year by year since the beginning of the industrialization (Houghton 2003). The main reason is the human activity. Land use change and the combustion of fossil fuels caused an increase of the amount of carbon in the active carbon cycle (Fig. 7).

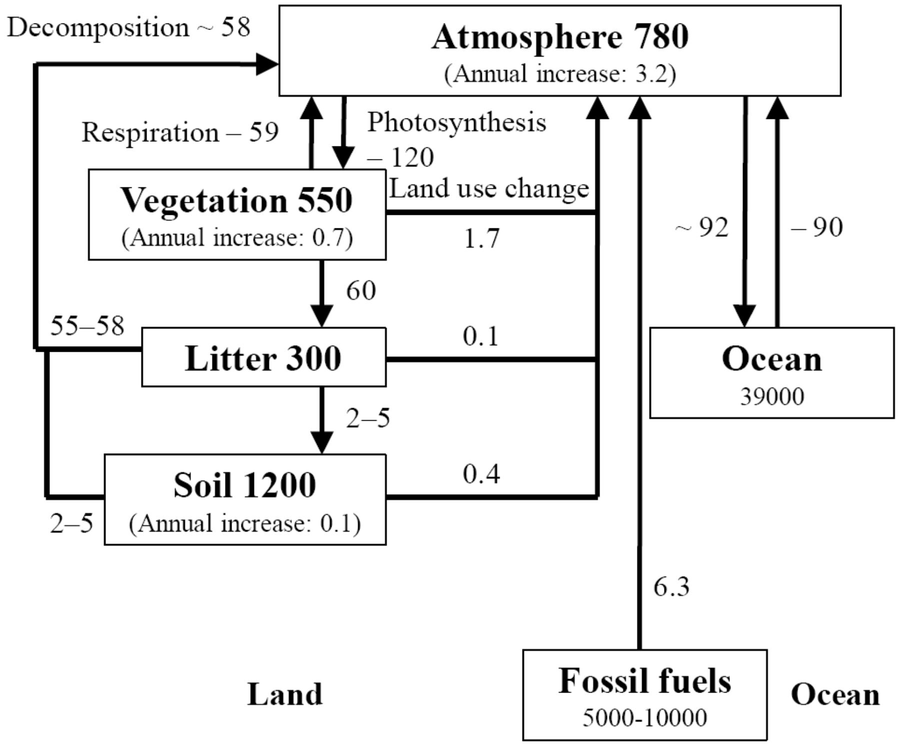


Fig. 7: The contemporary global carbon cycle. Shown are the carbon pools (Pg C) and flows (Pg C yr^{-1}). Source: Houghton (2003), modified.

Before having a look at the strategies of Iceland to reduce the net emission of greenhouse gases to the atmosphere the characteristics and processes of the terrestrial carbon reservoir have to be introduced. The present study keeps busy with the terrestrial reservoir and the interface between the atmosphere and the terrestrial ecosystem. Therefore a more detailed review of the two pools and the interaction between these is needed. The human impact caused an increase of the carbon in the atmosphere by 175 Pg C between 1700 and 2000. In 2000 the atmospheric concentration of carbon was about 368 ppm

(780 Pg C). Most of the atmospheric carbon is CO_2. The rest occurs as methane, carbon monoxide and non-methane hydrocarbons. The terrestrial carbon pool is divided into vegetation, litter and soils. Living vegetation contains less carbon (550 Pg C) than the atmosphere (Houghton 2003). In contrast the global soil and litter pool is 2-3 times larger than the vegetation pool and stores about 1500 to 2300 Pg C depending of the soil depth (Dixon et al. 1994; Jobbagy & Jackson 2000). In the boreal forests the ratio between carbon contained in vegetation or in soil is 1:5 (Dixon et al. 1994).

The average residence time of CO_2 in the atmosphere is about four years. The most important natural flow of carbon from the atmosphere to the terrestrial ecosystem happens via living vegetation. Green plants reduce CO_2 to glucose by using energy from the sun. The reduced carbon is stored in the organic matter as glucose, cellulose, carbohydrates, protein and fats. The oxidation of organic matter (plants and organisms) produces CO_2 and represents the opposite direction of the carbon flux to the atmosphere. Oxidation occurs during two processes of respiration and combustion. Regarding to the global flow of carbon between the atmosphere and the terrestrial reservoir, the annually uptake of atmospheric CO_2 through photosynthesis is about 120 Pg C and is called gross primary production (GPP). Autotrophic respiration of plants causes that about 60 Pg C (NPP) remains in the biomass of plants. Animals and decomposers consume (dead) biomass (heterotrophic respiration) wherefore the net flux of carbon between terrestrial ecosystems and the atmosphere is generally approximately zero. (Houghton 2003). The human impact controls the mentioned flow by land-use change. While deforestation and forest fire increase the amount of oxidized carbon, reforestation and afforestation increase the amount of reduced carbon. According to Grace (2005) more than half of the amount of the terrestrial carbon is attributable to forest biomes while tropical forests have the highest NPP per year. However it’s unclear if the tropical forest biome acts as sink or source for carbon because of land-use change in this region. Forests in North America and Europe were detected as carbon sinks of 0.4 Pg C (Rödenbeck et al. 2003; Grace 2005).

To estimate the carbon balance of the terrestrial ecosystem two different approaches are mainly used: inverse calculations and bookkeeping models (Houghton 2003). The present study can be considered as a bookkeeping or inventory model, which represents a bottom-up approach.

1.2.2 Strategies of Iceland to Reduce Net Emission of Greenhouse Gases

Iceland is a party of the UN Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Therefore the government has compiled a strategy to reduce "the net emissions of greenhouse gases by 50-75 per cent until the year 2050, using 1990 emissions figures as baseline" (Ministry for the Environment 2007, pp. 3). It consists of five points:

1) Fulfilling international obligations
2) Limiting greenhouse gas emissions, with particular emphasis on reducing emissions from fossil fuel use from mobile sources
3) Increasing carbon sequestration
4) Increasing research and development on climate-friendly technology
5) Adapting to climate change

Atmospheric carbon can be stored by land use, land use change and forestry (LULUCF) activities (Watson & Noble 2005). Focusing on carbon sequestration in Iceland the increase of carbon in the terrestrial system is attempted to achieve by afforestation, revegetation, wetland reclamation and land use change. Due to the severe ecosystem degradation during the past centuries the potential of carbon sequestration in the terrestrial system is seen as very high (Ministry for the Environment 2007; Lal 2009). Therefore the government has financially supported the establishment of tree plantations since the beginning of the 1990s (Sigurdsson & Snorrason 2000). The sequestration of carbon from the atmosphere increased by 246 Gg between 1990 and 2004 (Ministry for the Environment 2007). To estimate such values so called national greenhouse gas (GHG) inventories are needed (Hallsdottir et al. 2010). Governments have to record annually the carbon balance of their countries. With reference to the land use change and forestry part of these inventories, methods and parameters are needed to estimate the source and sinks (Brown 2002). The present study is concerned with the improvement of these methods and parameters.

1.3 CURRENT STATE OF RESEARCH

There are several techniques to estimate biomass as well organic carbon stocks of forests. A modern approach is based on remote sensing. With the aid of satellite images or aerial photo images from low flying airplanes, wide-angle cameras, pulse laser profiler and GPS it is possible to estimate biomass stocks of woods, even tropical forests, with high resolution (e.g. Slaymaker et al. 1999; Dong et al. 2003; Fuchs et al. 2009). A different method is to use already existing inventory data on stem volume combined with a so called biomass expansion factors (BEFs). In developed countries forest inventories are periodically carried out. By the BEFs and the tree volume which derived from the inventoried parameters, and is traditionally more common in forestry, the aboveground biomass is calculated (e.g. Lehtonen et al. 2004; Jalkanen et al. 2005).

A big disadvantage of the two explained approaches is the need of a factor to estimate the belowground woody biomass stock. Usually a factor which describes the ratio between aboveground and belowground biomass is used to estimate the biomass below surface (Cairns et al. 1997). To get an idea about accumulated biomass and sequestrated carbon in a tree or a stand a third approach that uses allometric biomass regression functions has been developed (Baskerville 1972). With aid of an independent variable, which is most often the diameter of the tree at a specific height, the biomass is calculated by the allometric function. It describes the relationship between biomass and a measured variable. Together with the forest inventory data on a tree level, the stocks can be estimated (Brown 2002; Zianis et al. 2005). Allometric functions can be calculated for the belowground biomass part provided that the belowground biomass was harvested in an earlier step. Due to consumption of time and costs and different used sampling methods the knowledge of belowground biomass is not on the same established level as for aboveground biomass (Brown 2002). Compared to the BEF method (Lethonen et al. 2004) the advantage of allometric biomass regression function approach is that allometries for above- and belowground biomass are independent of age, due to the allometric function always covers the range of the independent variable. According to Brown (2002) allometric functions are therefore needed to improve the accurancy of belowground woody biomass estimations. Further, estimating belowground stocks with allometries doesn't need any calculation factors. Additionally to stock estimates, sequestration rates are also calculable with allometric functions. Supplementary it needs diameters of different age of a tree.

Worldwide there are many allometric functions available. A database contains most of the functions which deals with species from the Scandinavian area (Zianis et al. 2005; Muukkonen & Mäkipää 2006). Additionaly there are also functions available from Central Europe. For Icelandic mountain birch, Sigurdardottir (2000) published allometries for above- and belowground biomass of a 65-year old seeded stand. Snorrason & Einarsson (2006) also found allometric parameters for three aboveground compartments of 54-year old planted birch trees. Regarding to an applicable tool which is usable for GHG reports the available dataset of already published functions is insufficient (Snorrason & Einarsson 2006). Therefore allometric functions with a wider range of the independent variable are needed. Especially a knowledge of coarse root biomass has to be improved, because it stores about 70 per cent of the whole root biomass (Cairns et al. 1997).

The results of the two already published studies are not applicable for younger stands, especially plantations which have been planted since 1990. Further, Snorrason et al. (2002) calculated the mean annual carbon sequestration rate (MAI) based on the difference between the stocks of the 54- year old stand and a treeless pasture. Due to growth dynamics the sequestration rate of stands is not constant (Cannell & Milne 1995; Körner 2006). Studies on aboveground sequestration rates of Icelandic *Betula pubescens* based on tree ring analysis are also published by Levanic & Eggertsson (2008). Snorrason et al. (2002) found that about 25 per cent of woody biomass of 54-years old trees is stored below surface. This ratio is currently used for the forestry part of Icelandic carbon inventories (Snorrason 2010).

To improve the knowledge base on the changes that occur in ecosystem carbon sequestration following restoration of native mountain birch (*Betula pubescens* Ehrh.) woodlands on eroded lands, the research project *KolBjörk* (CarbBirch) was launched in 2008. There the development of key ecosystem factors were studied in a chronosequence of restored birch woodlands, ranging from 0-60 years in age. Restored woodlands were compared to eroded lands and remnants of original birch woodlands in southern Iceland (Fig. 8 and Tab. 2). The key factors were a) forest growth, b) succession of plant communities, c) soil biota, d) soil chemistry and physics and e) ecosystem carbon stocks and fluxes. The present study contributed to key factors a and e of *KolBjörk*.

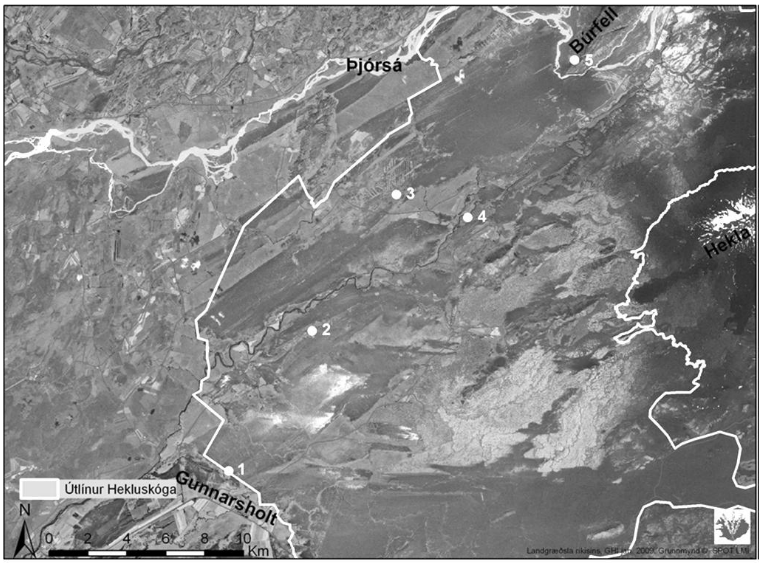


Fig. 8: Locations of the KolBjörk study sites. The sites are within the Hekluskógar project (white boundaries). By courtesy of the Icelandic Soil Conservation Service.

Tab. 2: Classification of the study sites subdivided into succession stages (Halldorsson et al. 2009, modified). Numbers indicate locations of sites shown in (Fig. 8).

Characteristic of the study site	**Study site**
Eroded land	1, 2, 3, 4, 5
Fertilized and revegetated land	1, 2, 3
Stand in the first rotation, 5-20 year old birch trees	1, 2, 3
Stand in the first rotation, 20-30 year old birch trees	1, 2
Stand in the first rotation, 35-45 year old birch trees	1, 3
Stand in the first rotation, 50-60 year old birch trees	1, 3
Old, natural grown woodland / forest	4, 5

1.4 AIMS AND OBJECTIVES

The aims of the present study were how above- and belowground woody biomass and organic carbon is accumulated in the birch Andosol ecosystem along a chronosequence in South Iceland and regarding to the Kyoto Protocol how does afforested and remnant mountain birch areas react as carbon sinks.

Derived from the aims of the study following four objectives were established:

I. Find the allometric parameters for Icelandic mountain birch trees
II. Estimate the woody biomass and carbon stocks
III. Estimate the annual biomass and carbon sequestration rates
IV. Study of the belowground woody biomass

2 MATERIAL AND METHODS

2.1 THE EXPERIMENTAL SITES

The study took place on four sites in South Iceland, close to Gunnarsholt (headquarter of the Icelandic Soil Conservation Service) and the Mt. Hekla volcano (Fig. 9). Three sites represented three different old plantations (B_{10}, B_{15} and G_{60}) and one site (H_{old}) was a remnant of original birch woodland (Fig. 9). All sites used in the present project were also study sites for the previously mentioned KolBjörk project (Halldorsson et al. 2009).

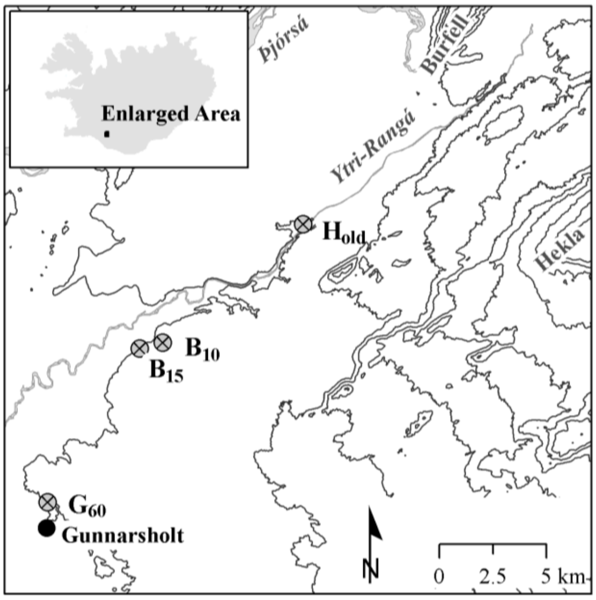


Fig. 9: A topological map (equidistance = 100 m) showing the four study sites (crossed circles) and Gunnarsholt (filled circle), the headquarter of the Icelandic Soil Conservation Service, in South Iceland.

All the study sites were located within the so-called Hekluskógar area, which is in total ca. 900 km^2 of mostly poorly vegetated lava fields and unvegetated sand deserts (Aradottir 2007; Óskarsson 2009). Fig. 9 only shows the Western part of this area. Hekluskógar is a large-scale restoration project, its goal being to restore former mountain birch woodlands and forest soils that were lost in this area in a massive historic soil erosion process that took place in the area around Mt. Hekla during the last centuries. It is planned to restore 620 km^2 of deserts and poorly vegetated lava fields during the next 50 years (Samráðsnefnd Hekluskóga 2005). Soil erosion still occurs in part of this area and sand bowls can occur, especially on windy and dry autumn days (Anonymous 2007). Soil erosion has, however, been mostly stopped and some vegetation restored in some parts of the area by the Soil Conservation Service during the past 80 years (Samráðsnefnd Hekluskóga 2005).

In the original project description of Hekluskogar (Samráðsnefnd Hekluskóga 2005) the general vegetation history of the area is reviewed. It states that the reasons for the catastrophic soil erosion in this area can probably be linked to a large eruption that took place in Mt. Hekla in 1104 AD. This is believed to have been the first eruption in Mt. Hekla after the human settlement in Iceland in the 9th century AD. Mt. Hekla had been dormant for 2000 years before; it is thought that the last eruption took place ca. 900 BC. During the first 200 years of settlement some woodland and forest cover had been removed by burning for pastures, logging and grazing of livestock, and this is believed to have made the still vegetated soils in those areas prone for soil erosion when they got covered by thick tephra layers from the volcanic eruption in 1104 and subsequent eruptions. Since its awakening in 1104 the Mt. Hekla volcano has been very active. It erupted in 1158, 1206, 1222, 1300, 1341, 1389, 1510, 1597, 1637, 1693, 1766, 1845, 1947, 1970, 1980, 1990 and 2000. Each eruption has produced tephra that has been deposited around the volcano and has further increased the risk for erosion starting, especially where woodland cover had been reduced. The soil erosion started locally, but during the last centuries it was intensified by the volcanic episodes, cooling of climate and continuous deforestation by human land-use. The soil erosion had reached catastrophic proportions already in the 17th century, at the beginning of the 20th century basically most of the area was poorly vegetated humid deserts. Only small areas were left with vegetation cover and tick soils, and only few isolated patches of the original mountain birch woodlands have survived (Samráðsnefnd Hekluskóga 2005).

The three main research sites used in this study, Bolholt (B_{10} and B_{15}), Gunnlaugsskógur (G_{60}) and Hraunteigur (H_{OLD}) represented different stages in ecosystem succession of mountain birch that is now found in this area. The last area (Hraunteigur, H_{OLD}) accommodates one of the very few remnants of the original mountain birch woodlands of this area. It is located on narrow ness between two streams that protected it from the approaching sand dunes that characterized the active soil erosion phase of the area. In 1898 the few woodland remains were inventoried in this area (Helgason 1899). At the time the area showed clear signs of unsustainable use, most of the larger trees had been cut for firewood and charcoal making, leaving only smaller trees and bush-like regeneration from root stocks and cut stems. This is, however, one of few sites where it is known that mountain birch has had continuous cover in this Hekluskógar area, and therefore it may be termed ‘old-growth’ woodland. Because of the continuous vegetation cover over long time, this area has accumulated thick loess-like soils, with >2-3 m soil depth. Areas with continuous vegetation cover were sediment traps; therefore soil accumulation took place at places like Hraunteigur or Vatnagardar (Fig. 10). Obviously the rate of soil thickening increased intensely after the eruption (H1104) of the Mt. Hekla volcano in 1104.

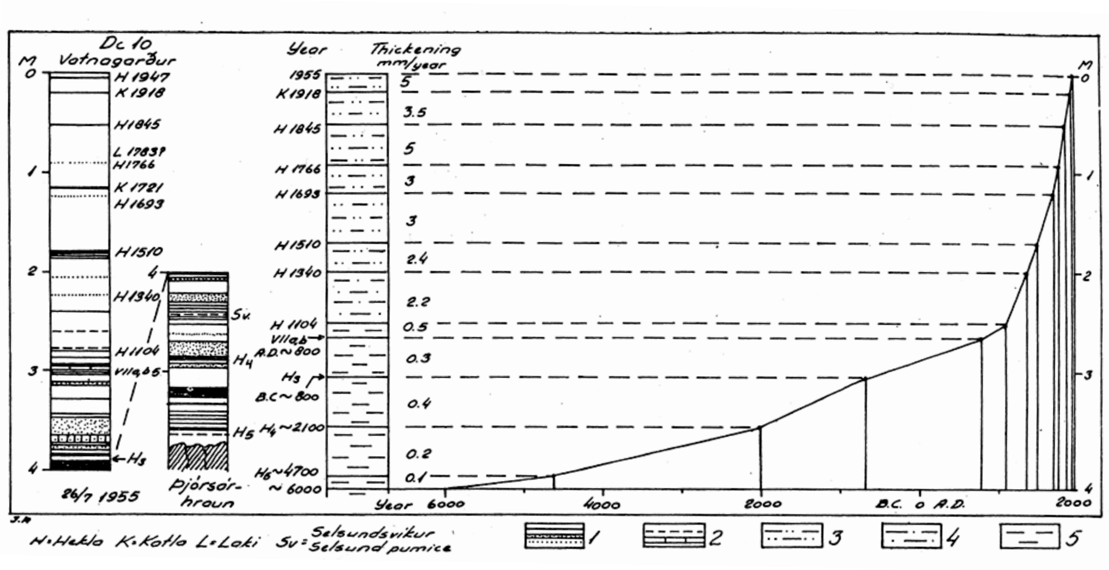


Fig. 10: Soil profile and diagram show tephra layers, rate of soil thickening and variation in coarseness of the soil at Vatnagardar near Hraunteigur (H_{OLD}). Source: Thorarinsson (1961).

The vegetation history of the Bolholt (B_{10} and B_{15}) site is also relatively well known. The location of the two study sites at B is believed to be close to the original location of a farmstead that was inhabited until ca. 200 years ago. According to written history the erosion in this area began in the 15th century and in late 17th century sand dunes were formed that swept through the area, leaving only unvegetated sand desert and denuded lava fields. This led to the abandonment of the farmstead in 1789. The area was left more-or-less unvegetated until 1963, when restoration efforts began. Massive use of fertilizers and grass seeds was successful in mostly stabilizing the sand/tephra blaster that characterized this area and slowly turned large parts of it into moss- and grass heathland (Sveinn Runólfsson, director of SCS, pers. comm.). Parts of this area were later afforested by planting of mountain birch. This activity started in 1989 and has continued since.

The vegetation history of Gunnlaugsskógur (G_{60}) followed largely the same pattern as the study sites at Bolholt, except that the sand dunes reached this area somewhat later. It is believed that this area was turned into a sand and lava desert in late 19th century (Bjarni D. Sigurdsson, pers.comm.). It was protected from livestock grazing during the 1930s and small patches of mountain birch were established in 1939 by direct seeding. After 20 years, birch cover had extended to 9,000 m^2; during the following 24 years, birch cover expanded to 30,000 m^2 (Aradottir 1991; Aradottir and Arnalds 2001; Aradottir & Eysteinsson 2005). G_{60} is one of the oldest examples of organized afforestation of mountain birch in Iceland and also formed the oldest age-class of first-generation mountain birch in the present study.

According to a geoecological perspective the characteristics of the four study sites are shown in Tab. 3.

Tab. 3: Geoecological site characteristics of the study areas in 2009.

Study Site	Coordinates (Icl. System)	Elevation (m asl)	Status [a)]	Bedrock [b)]	Substrate [c)]	Soil type [d)]	Understory Vegetation [g)]	Climate [h)]	
								T_{mean} (°C)	P_{sum} (mm)
B_{10}	446080 / 382404	125	planted	Lava	Patchy tephra and aeolian deposits made of volcanic material	Coarse grained, Vitric Andosol [e)]	*Empetrum nigrum*, *Equisetum arvensis* and *Festuca richardsonii*, further other common species are *Salix herbacea, S. lanata, Calluna vulgaris, Salix phylicifolia, Thymus praecox* and *Agrostis vinealis*	3.5	1’721
B_{15}	444997 / 382117	93	planted	Lava	Tephra and aeolian deposits made of volcanic material	Coarse grained, Vitric Andosol [e)]	*Empetrum nigrum*, *Equisetum arvensis* and *Festuca richardsonii*, further other common species are *Salix herbacea, S. lanata, Calluna vulgaris, Salix phylicifolia, Thymus praecox* and *Agrostis vinealis*	3.6	1’701
G_{60}	440673 / 374919 440808 / 374696 440870 / 374801	100 99 103	planted	Lava	Tephra and aeolian deposits made of volcanic material	Coarse grained, Vitric Andosol [e)]	Agrostis vinealis, *Festuca richardsonii* further other common species are *F. vivipara* and *Equisetum arvensis*	3.4	1’746
H_{old}	452653 / 387930	90	old, natural grown	Lava	Tephra and aeolian deposits made of volcanic material	Vitric Andosol [f)] w. (coarse) tephra layers inbetween	*Agrostic capillaries, Deschampsia flexuosa, Anthoxanthum odoratum* and *Hierocloe odorata*	3.5	1’640

a) Halldorsson et al. 2009
b) Arnalds (2004), Arnalds (pers. comm.)
c) Arnalds (2004), Arnalds (pers. comm.)
d) Arnalds (2004), Arnalds (pers. comm.)
e) (>0.4 Al+1/2 Fe_{ox}) and high glass content, low in C_{org} (< 1%) and low in clay (<5%) (Arnalds 2004)
f) %C (0.5-5%, > 1 m thick), with layers of > 10% clay (Arnalds 2004)
g) Aradottir (unpublished data)
h) Interpolated temperature normals (1961-1990 averages) for the exact positions of the research sites. Data source: Icelandic Meterological Bureau

B_{10}

B_{15}

G_{60}

H_{OLD}

Fig. 11: Pictures of the four different old study sites (B_{10}, B_{15}, G_{60} and H_{OLD}). At B_{10} buckets as foliage traps and flags used for vegetation inventory are installed within an intensive study site of KolBjörk. The picture of G_{60} is provided by A. Aradottir. H_{OLD} is shown during biomass harvest process. All pictures were recorded in 2009.

2.2 METHODS

2.2.1 Objective I: Find the allometric parameters

Field work

Field measurements were carried out in July and August 2009. 31 monocormic trees were randomly selected at B_{10}, B_{15} and H_{OLD}. Prior to harvest, stem diameter over bark was measured every 10 cm from ground level to 130 cm length. Additionally length and height of the trees were collected. After felling at ground level, the canopy was split in three equal parts of same length. The diameter of the cut faces was measured. Stem and branches including leaves were separated and put in paper bags. Coarse roots were excavated and also put in paper bags. According to Vogt et al. (1996) coarse roots were defined as the part of the main stem belowground (rootstock) and roots with a diameter exceeding 2 mm. The toolbox was composed of a slide caliper, GPS, folding rule, leveling board, handsaw, digital sliding caliper, shovel, flags and string. I was in need of the flags to mark and recover remaining roots.

Laboratory

The stem, branches, leaves, root stock and roots (> 2 mm) were dried separately at 85 °C until daily weight loss was less than 1 percent. To accelerate the drying process I sawed up big root stocks and stems into disks with a power saw. The disks and the sawdust were dried at the same conditions. Weighting accuracy was 0.01 g.

Data analysis

According to the basic harvest measurements, allometric equations were used to estimate various tree stand components (stems, branches, leaves, coarse roots and total biomass). To find the model parameters two different approaches were compared. First the allometric parameters were estimated by the commonly used linear regression method (e.g. Snorrason & Einarsson 2006; Bjarnadottir et al. 2007) in SigmaPlot (Systat Software 2008). Second a nonlinear regression approach was chosen to find the model parameters. The analysis was implemented in Matlab using the function *nlinfit*. In order to diminish the influence of outliers, a robust algorithm was chosen that employs an iteratively reweighting least-squares scheme. The *fair* function was used as weighting function (MathWorks 2010). The dataset for the allometric models was created from data of the 31 harvested trees. The power function (Eq. 1) was used to compare the two different regression approaches. Where DM is the weight of the dry biomass (kg), D is the diameter (cm) at a defined length of the stem and a and be are the allometric constants.

$$DM = a \times D^b \qquad \text{(Eq. 1)}$$

Also 100 randomly selected trees of the inventory dataset (see later) were taken as a basis for comparison with already existing allometric functions (Sigurdardottir 2000; Snorrason & Einarsson 2006).

2.2.2 Objective II: Estimate the woody biomass and carbon stocks

Field work

Additionally I made a tree inventory at B_{10}, B_{15}, G_{60} and H_{OLD} in August 2009. Therefore four circular plots were systematically placed at each study site to measure diameter at ground level, 20 cm, 50 cm and 130 cm length of each tree (Fig. 12). Depending on the number of stems (at least 20 stems) within an observation plot, the plot size varied between 15 and 75 m^2. In addition length, dominant height and species composition were recorded. Due to of the small sizes of the stands at G_{60} it was not possible to use the explained setup. Instead of having inventor four inventory plots around one intensive study site of KolBjörk, the inventory was made at three different located stands at Gunnlaugsskogar. The measured plot was displayed at the intersection point of the diagonals of the three intensive study sites of KolBjörk (Tab. 3).

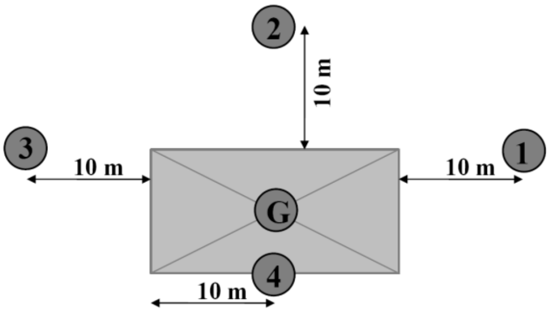


Fig. 12: Setup of the tree inventory. The circular plots (dark grey) varied between 15 and 75 m^2 (radius: 2.19 and 4.89 m, respectively). The light grey rectangle represents an intensive study site of the KolBjörk project. The circle at the center of the rectangle represents the location of the studied plots at G_{60}.

Data analysis

The newly developed allometric parameters were used together with Equation 1, the data of the inventory and C-ratios (Snorrason et al. 2000) to estimate the woody biomass and carbon stocks of the four study sites. Visualization was made by SigmaPlot11 (Systat Software 2008).

2.2.3 Objective III: Estimate the annual biomass and carbon sequestration rates

Field work

During inventory measurements in August 2009, tree ring cores were collected with an increment borer at B_{10}, B_{15}, G_{60} and H_{OLD}. In each case the cores were taken from trees of the highest and the median diameter class. In total 33 samples were collected.

Laboratory

Tree ring measurement was conducted on each sample (66 radii measurements) by using LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany), fitted with a Leica MS5 stereomicroscope, and analysed with the TSAPWin software. The ring width series were plotted and visually synchronized for identification of errors during the measurements (Fritts 1976; Schweingruber 1996).

Data analysis

For the annual sequestration rate, cores of trees of the mean diameter class were used. The measured increments were used to calculate the relative increment of the respective years. Relative increment was counted back for the years between 2004 and 2009. The mean relative increase for each study site and year was used to estimate the diameter sizes of the inventoried trees between 2004 and 2009. The next step was to calculate the biomass and carbon stocks for the 6 years. The method was already explained above. Instead of using D_{50} as independent variable D_{20} was used because I drilled the borer at about 20 cm length. The current annual sequestration rate (CAI) was defined as the difference between two stocks of two successive years. Additionally the mean annual increment (MAI) was calculated over the whole stand age. I assumed that mortality was 0 per cent during the 5 year period. I used Grapher 7 and SigmaPlot11 to visualize the tree ring width and the sequestration rates, respectively (Golden Software 2007; Systat Software 2008).

2.2.4 Objective IV: Study of the belowground woody biomass

Field work

During excavation of the belowground biomass, coarse roots were immediately categorized by size (spool, > 50 mm, 50-10 mm, 10-5 mm, 5-2 mm) and rooting depth (0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm, 50-70 cm, 70-100 cm). The toolbox was composed of the same digging and harvest instruments as used for the total biomass harvest. Because of the oval cross sectional area at the intersect of rootstock and roots, outgoing roots were categorized by taking the average of the minimal and maximal diameter.

Data analysis

For the three differently aged stands (B_{10}, B_{15} and H_{OLD}), woody root biomass accumulation within the top 30 cm of soil in steps of 10 cm was calculated with descriptive statistics. In addition I plotted the belowground biomass of these three birch stands categorized by root thickness and penetration depth. To compare the data with already existing values (Jackson et al. 1996) the extinction coefficients (β) were calculated and the formula (Eq. 2) of Gale & Grigal (1987) was used to visualize the cumulative root fraction in Grapher 7 (Golden Software 2007). Where DM is the cumulative root fraction (%) and D is the root penetration depth (m).

$$DM = 1 - \beta^{D} \qquad \text{(Eq. 2)}$$

3 RESULTS

The basic stand characteristics showed typical properties of woodlands along a chronosequence (Tab. 4). Diameter, average length and dominant height increased continuously with age. Also an increase of the mortality was observed. Mortality was determined as the relative number of standing dead trees. It was 0 % (B_{10} and B_{15}), 11 % (G_{60}) and 21 % (H_{OLD}), respectively. The basal area was significantly higher at G_{60} than at H_{OLD}. Compared to the amount of other tree species at the study sites, the amount of mountain birch individuals decreased by aging of the stand, however it was the dominant species at the study sites (Tab. 4).

Tab. 4: Stand characteristics of the study sites in southern Iceland 2009. The variables are shown as average values of the inventory excepted for the variability of the age which is shown as the range of the age of the sampled trees. BA stands for Basal Area. The tree species composition consists of birch and willow.

Study Site	Variability of the age	D_{50} (cm)	D_{130} (cm)	Average length (m)	Dominant height (m)	BA at DBH (m^2 ha^{-1})	Stand Density (stems ha^{-1})	Tree species composition (%)
B_{10}	5 – 12	1.37	0.44	1.48	2.26	0.35	10,688	B: 98 / W: 2
B_{15}	7 – 20	3.48	2.11	2.19	3.19	3.54	7,077	B: 96 / W: 4
G_{60}	42 – 74	4.64	3.22	3.06	4.42	21.17	21,867	B: 88 / W: 12
H_{OLD}	73 – 82	6.05	4.62	3.17	4.76	15.68	5,882	B: 86 / W: 14

The data of two diameter classes of the harvested trees (D_{50} and D_{130}) was plotted. The analysis showed a very accurate correlation (R^2 = 0.99) between diameters at 50 cm and 130 cm length (Fig. 13). Therefore diameter at 50 cm length was used as independent variable for estimating the woody biomass and organic carbon stocks. However both diameter classes were used to find the parameters for the allometric models. While the dataset for the model of the diameter class D_{50} consisted of 25 sampled trees the dataset for the model of the diameter class D_{130} was built on only 12 sampled trees.

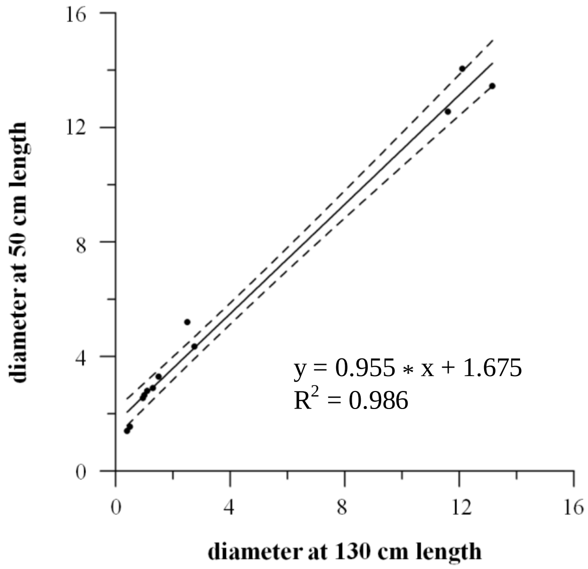


Fig. 13: Correlation between diameter measurement of the harvested trees at 50 cm and 130 cm length, respectively. The dashed lines show the upper and lower boundaries of the 95% confidence interval.

Using the linear approach it was not possible to calculate statistically confirmed parameters for each biomass compartment (Tab. 5 and Tab. 6). In contrast using the nonlinear approach each parameter was found (Tab. 7 and Tab. 8). Regardless of which chosen approach or diameter class the estimated parameters had a good quality (R^2) which was generally around 0.95. Due to the decision that the dataset of the diameter class D_{50} was the basis for further calculations a more detailed look is needed on Tab. 7. The accuracy of these estimated parameters for the several biomass parts, interpreted as R^2, differed to some extent (Tab. 7). The most accurate and precise functions were the ones for total aboveground, stem, leaves and total biomass. The estimated parameters for branches and belowground biomass were somewhat less accurate. The correlation between D_{50} and root stock or roots (> 2 mm) was still fairly accurate (> 0.87).

Tab. 5: Estimated parameters of equation for dry weight estimations of mountain birch (*Betula pubescens* Ehrh.) growing in Iceland. The dataset includes 12 samples. The data was analysed using a *linear regression* approach, with D_{50} as the independent variable.

Components	Parameter	Parameter estimates	R^2	CV (%)
Total biomass	a	0.320	0.948	59.68
	b	1.718		
Aboveground	a	0.224	0.948	59.81
	b	1.728		
Stem [a)]	a	0.087	0.965	50.66
	b	1.827		
Branches	a	0.065	0.926	84.34
	b	1.896		
Leaves [b)]	a	0.059	0.951	41.32
	b	1.278		
Belowground	a	0.096	0.942	62.34
	b	1.694		
Root stock	a	0.036	0.905	81.69
	b	1.618		
Roots (> 2 mm)	a	0.060	0.950	59.06
	b	1.740		

a) Normality Test: Failed (P = 0.010)
b) Constant Variance Test: Failed (P = 0.047)

Tab. 6: Estimated parameters of equation for dry weight estimations of mountain birch (*Betula pubescens* Ehrh.) growing in Iceland. The dataset includes 25 samples. The data was analysed with a linear regression approach, with D_{130} as the independent variable.

Components	Parameter	Parameter estimates	R^2	CV (%)
Total biomass	a	1.074	0.985	23.62
	b	1.499		
Aboveground [a)]	a	0.747	0.988	21.65
	b	1.517		
Stem	a	0.316	0.990	20.51
	b	1.592		
Branches	a	0.238	0.979	31.33
	b	1.647		
Leaves	a	0.189	0.966	21.96
	b	0.912		
Belowground	a	0.326	0.971	32.73
	b	1.460		
Root stock	a	0.106	0.935	52.45
	b	1.468		
Roots (> 2 mm)	a	0.222	0.969	33.81
	b	1.450		

a) Normality Test: Failed (P = 0.043)

Tab. 7: Estimated parameters of equation for dry weight estimations of mountain birch (*Betula pubescens* Ehrh.) growing in Iceland. The dataset includes 25 samples. The data was analysed using a *nonlinear regression* approach, with D_{50} as the independent variable.

Components	Parameter	Parameter estimates	R^2	MSE
Total biomass	a	0.106	0.969	0.975
	b	2.336		
Aboveground	a	0.071	0.970	0.436
	b	2.361		
Stem	a	0.021	0.978	0.073
	b	2.638		
Branches	a	0.019	0.925	0.252
	b	2.591		
Leaves	a	0.057	0.970	0.002
	b	1.322		
Belowground	a	0.034	0.956	0.122
	b	2.293		
Root stock	a	0.004	0.884	0.003
	b	2.717		
Roots (> 2 mm)	a	0.029	0.875	0.125
	b	2.127		

Tab. 8: Estimated parameters of equation for dry weight estimations of mountain birch (*Betula pubescens* Ehrh.) growing in Iceland. The dataset includes 12 samples. The data was analysed using a *nonlinear regression* approach, with D_{130} as the independent variable.

Components	Parameter	Parameter estimates	R^2	MSE
Total biomass	a	0.787	0.976	2.819
	b	1.666		
Aboveground	a	0.592	0.985	0.900
	b	1.648		
Stem	a	0.250	0.950	1.002
	b	1.727		
Branches	a	0.222	0.964	0.306
	b	1.651		
Leaves	a	0.202	0.970	0.011
	b	0.844		
Belowground	a	0.238	0.938	0.430
	b	1.645		
Root stock	a	0.072	0.763	0.331
	b	1.599		
Roots (> 2 mm)	a	0.187	0.902	0.087
	b	1.467		

The visualization of the qualities of the two chosen approaches shows that the nonlinear approach is more accurate than the commonly used approach (Fig. 14 and Tab. 9). Compared to the usually used approach the model based on nonlinear regression slightly underestimated between diameter class 0 and 5 cm but predicted more precisely at higher diameter classes (Fig. 14 and Tab. 9).

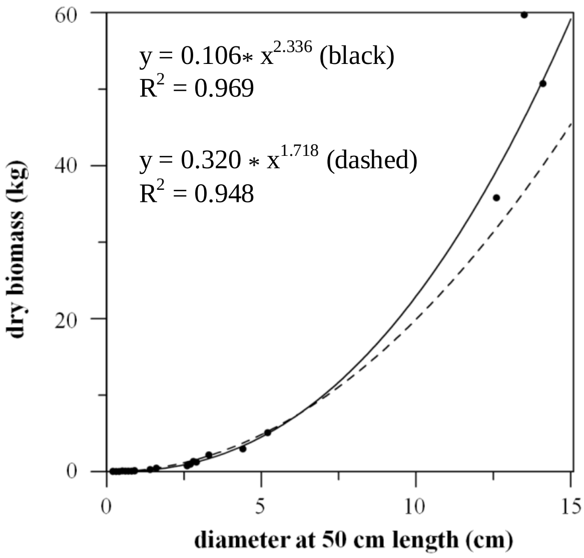


Fig. 14: Graphical account of two different approaches. Total dry biomass is plotted against the diameter at 50 cm length. The function derived from nonlinear regression function is shown as black line, the linear regression model is plotted as dashed line. The residuals of the two calculations are shown in Tab. 9.

Tab. 9: Comparison of the two model types with the harvested biomass. Shown are estimated values of total dry biomass and the residuals in kg. The independent diameter is D_{50}.

Harvested Data	Linear Regression Approach		Nonlinear Regression Approach	
Effective Biomass	Estimated Biomass	Residual	Estimated Biomass	Residual
0.048	0.007	-0.041	0.002	-0.046
0.030	0.007	-0.023	0.002	-0.027
0.045	0.007	-0.038	0.002	-0.043
0.031	0.011	-0.020	0.004	-0.027
0.041	0.016	-0.025	0.006	-0.035
0.039	0.029	-0.010	0.012	-0.026
0.105	0.045	-0.059	0.021	-0.081
0.105	0.045	-0.060	0.021	-0.084
0.082	0.065	-0.016	0.032	-0.050
0.068	0.089	0.021	0.046	-0.022
0.092	0.117	0.026	0.063	-0.029
0.159	0.149	-0.010	0.072	-0.087
0.099	0.149	0.050	0.072	-0.026
0.279	0.366	0.086	0.232	-0.047
0.483	0.480	-0.003	0.295	-0.188
0.780	1.288	0.507	0.943	0.163
0.972	1.390	0.418	1.032	0.059
1.348	1.497	0.149	1.173	-0.175
1.245	1.608	0.363	1.273	0.028
2.207	2.091	-0.116	1.722	-0.485
2.988	3.752	0.764	3.282	0.294
5.104	5.269	0.165	4.980	-0.124
35.796	31.848	-3.948	38.986	3.189
59.708	36.643	-23.065	45.830	-13.878
50.723	40.030	-10.693	50.748	0.025

In order to estimate the woody carbon pool of different old woodlands, the developed allometric functions of the present study and the data of the inventory were used to estimate the biomass accumulation and additionally the carbon storage of different parts of the tree. According to Snorrason et al. (2000) the ratio between woody biomass and carbon contained varied within the tree compartements. It averaged at about 50 %, wherefore the relation between biomass and carbon stocks did not differ that much except for the scale (Fig. 15). Regarding to the carbon stocks the analysis showed an increase of the stocks from B_{10} to G_{60} for each part of the tree. However H_{OLD} always had a lower value than the 60-year old stand of the first generation. These observed characteristics between stand within the first generation and the remnant woodland were not found in the calculated ratios (Tab.10), which were defined as the proportion of carbon between one compartment to the whole stock of a tree. A continuous increase or decrease was observed (Tab. 10). However within a compartment the ratios changed along the chronosequence (Tab. 10). While the carbon storage increased in the root stock, stem and branches, a decrease of the ratio was observed for the coarse root and leaf part of the tree. Over the chronosequence the highest change was found for the leaf section. The comparison between the long-term storage parts of the tree (exclusion of the leaves) showed a change of the ratio from 2:1 to 3:1 in favor of the carbon which is stored in the aboveground part (stem and branches) (Tab. 10).

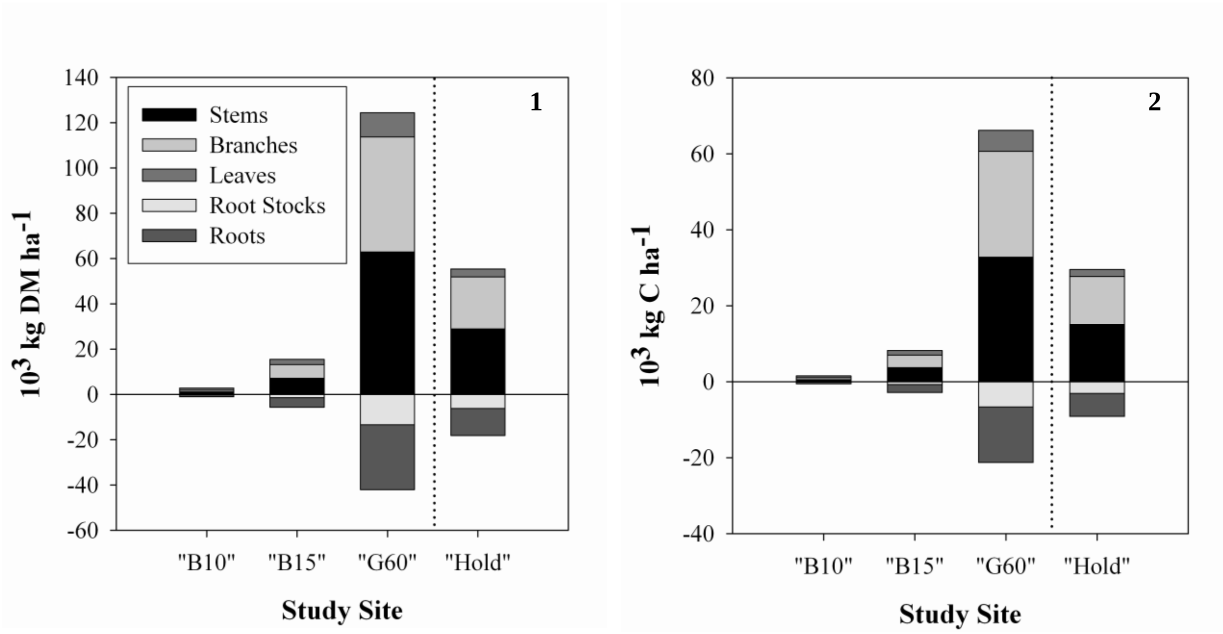


Fig. 15: Different biomass and carbon stocks at the four study sites of different age. While Diagram 1 represents the biomass stocks, Diagram 2 shows the carbon stocks. Belowground biomass and carbon pools are shown as negative values. The legend is the same in both diagrams.

Tab. 10: Woody carbon stocks of the four differently aged study sites. The relative values (%) are defined as the ratios between one part and the whole amount of carbon of the tree.

Study Site	Total	Coarse Roots		Root Stock		Stem		Branches		Leaves		Stem/ Branches		Belowground	
	10^3 kg C ha^{-1}	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%	10^3 kg C ha^{-1}	%
B_{10}	2.0	0.4	21.9	0.1	4.8	0.5	26.1	0.5	23.8	0.5	23.3	1.0	65.2	0.5	34.8
B_{15}	11.1	2.1	19.3	0.7	6.5	3.7	33.5	3.3	29.6	1.2	11.0	7.0	70.9	2.9	29.1
G_{60}	87.4	14.6	16.7	6.7	7.7	32.8	37.5	27.9	31.9	5.5	6.3	60.6	74.0	21.3	26.0
H_{OLD}	38.7	6.1	15.7	3.1	8.1	15.0	38.9	12.6	32.7	1.8	4.7	27.7	75.1	9.2	24.9

A comparison was made between the ratios of the estimated biomass stocks which consist of the allometries and the inventory data (Tab. 11) and the ratios of the effective harvested trees at each site (Tab. 12). Only the ratios of the harvested biomass at H_{OLD} were similar to the estimated ratios from the inventory. The ratios of the two afforestation sites differed considerably for the most part.

Tab. 11: Biomass ratios of the four tree components. The calculations are based on the estimated stocks. The ratios are defined as biomass of the tree components in relation to the total biomass of the tree. Further the root:shoot ratio is defined as the ratio between belowground and the sum of stem and branch biomass.

Study Site	RMR	SMR	BMR	LMR	Root:Shoot
B_{10}	0.27	0.26	0.23	0.24	0.56
B_{15}	0.27	0.34	0.28	0.11	0.43
G_{60}	0.25	0.38	0.31	0.06	0.37
H_{OLD}	0.25	0.39	0.31	0.04	0.35

Tab. 12: Biomass ratios of the four tree components. The calculations are based on the harvested dried samples. The ratios are defined as components of the tree in relation to the total biomass of the tree. Further the root:shoot ratio is defined as the ratio between belowground and the sum of stem and branch biomass.

Study Site	RMR	SMR	BMR	LMR	Root:Shoot
B_{10}	0.29	0.29	0.16	0.27	0.65
B_{15}	0.25	0.29	0.15	0.32	0.57
H_{OLD}	0.27	0.38	0.32	0.04	0.39

The average of the drilled trees indicated that individual trees within the two young plantation sites (B_{10} and B_{15}) only differed in age by about 4 years. While the study site G_{60} had a vast range of 32 years, the range at H_{OLD} was only 9 years. The mean age of the trees at H_{OLD} was 78.4 years (Tab. 13).

Tab. 13: Tree ring analysis focussing on the age of the trees. Shown are the numbers of drilled trees, the average age and the minimal and maximal age of the tree. Also listed is the chosen age of the stand derived from the analysis.

Study Site	N	Mean	Min	Max	Age of the Stand
B_{10}	9	9.6	5	12	10
B_{15}	7	13.9	7	20	15
G_{60}	4	56.0	42	74	60
H_{OLD}	5	78.4	73	82	old growth

Further, the tree ring analysis showed a strong increase of the annual diameter increment for B_{10}, a decrease for B_{15} and G_{60} (Fig. 16). The growth rate at H_{OLD} was stable with little fluctuations. Compared to the trend of the curves the ring widths in 2006 were significant lower for B_{15} and G_{60} or stagnated compared to 2005 (B_{10}). Moreover the annual diameter increment at B_{10} and B_{15} was on a higher level than at G_{60} and H_{OLD} and the variability at the young plantation sites was also higher than at G_{60} and H_{OLD} (Fig. 16).

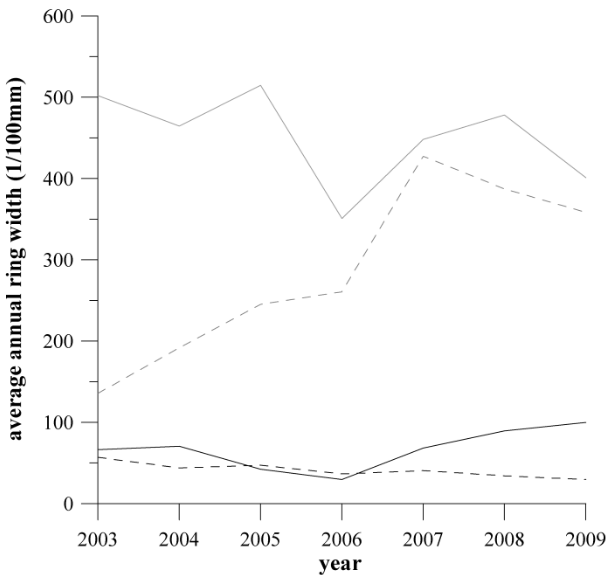


Fig. 16: Comparison of the crossdated average tree ring increment for B_{10} (grey dashed line), B_{15} (grey solid line), G_{60} (black dashed line) and H_{OLD} (black solid line).

The combination of an allometric biomass function, the tree ring analysis and published C-ratios (Snorrason et al. 2000) allowed for calculating the annual woody biomass increment and organic carbon sequestration rates of trees and different aged stands. The annual biomass and carbon sequestration can be displayed as the mean growth rate of a stem or as the accumulation rate per hectare (Fig. 17). The results showed the same characteristics between woody biomass and organic carbon sequestration rates as between biomass and carbon stocks.

The amount of sequestered organic carbon is about half of the accumulated woody biomass. Regarding to the mean sequestration rate of one stem of the mean diameter class at each study site, B_{15} had a continuous increase of the growth rate and a triplication during the analysed years (Fig. 17). An increase was also observed at B_{10}, however on a lower level and with a smoother increase than B_{15}. The sequestration rate at the 60-year old study site tended to decrease between 2004 and 2009. And at H_{OLD} the analysis showed a decrease during the first three years of observation and afterward a significant increase of the accumulation rate.

In general at each study site the mean carbon sequestration rate was lower than 0.5 kg stem^{-1}, except at B_{15} between 2007 and 2009 (Fig. 17). Regarding to the stand-level accumulation rates, in general the same patterns were observed. However the values were located closer together than for the stem calculations. Between 2004 and 2009 the annual accumulation rate of carbon was lower or nearly 1 Mg ha^{-1}, while at B_{15} and H_{OLD} more was stored during the last years (Fig. 17 and Tab. 14). Additionally to the current annual increments (CAI) of the years between 2004 and 2009, the mean annual increments (MAI) over the whole stand age were 0.39 Mg DM ha^{-1} and 0.20 Mg C ha^{-1} (B_{10}), 1.41 Mg DM ha^{-1} and 0.74 Mg C ha^{-1} (B_{15}), 2.77 Mg DM ha^{-1} and 1.46 Mg C ha^{-1} (G_{60}) and 0.92 Mg DM ha^{-1} and 0.48 Mg C ha^{-1} (H_{OLD}), respectively.

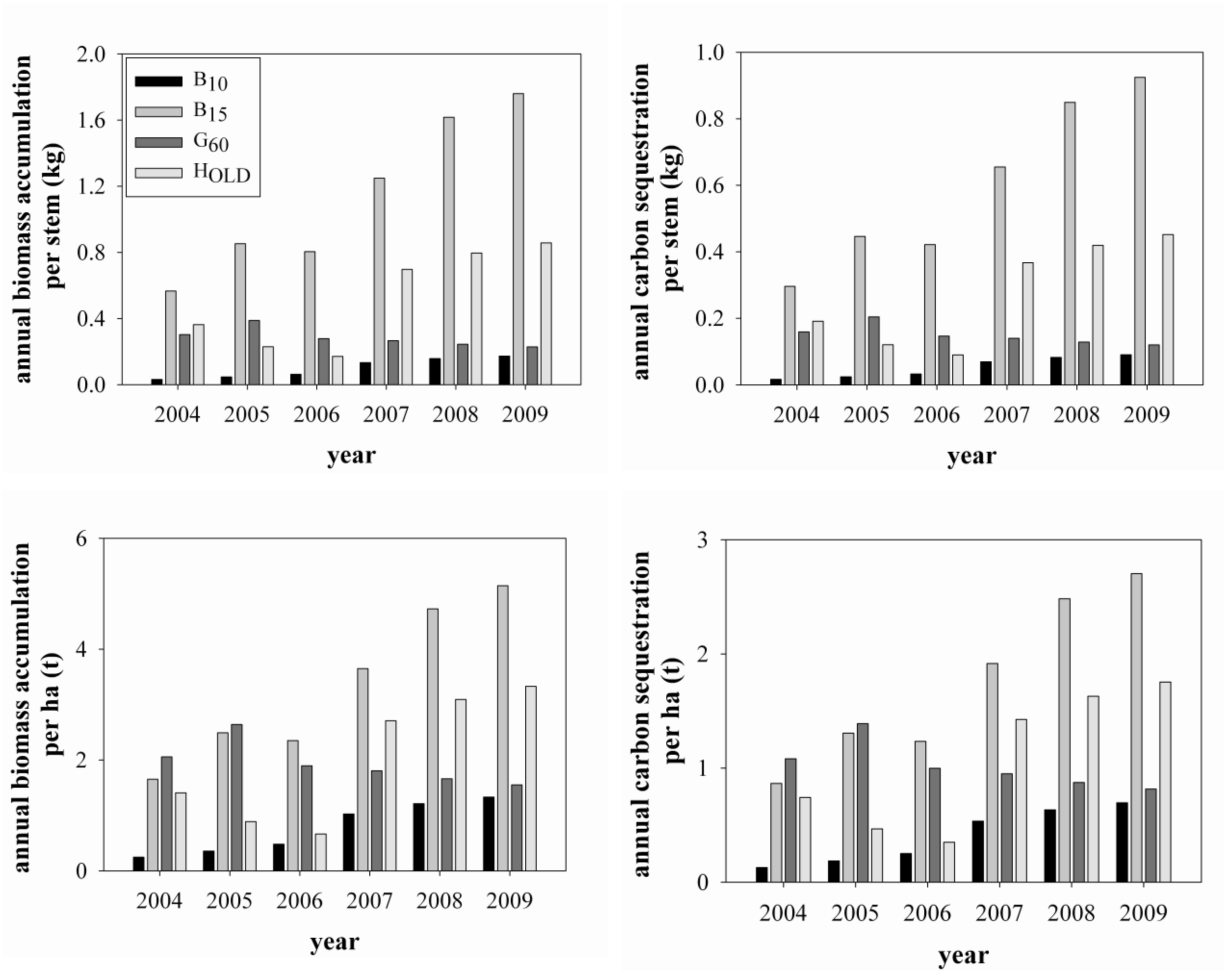


Fig. 17: Annual biomass accumulation and woody carbon sequestration per stem and per hectare at the four study sites based on the period between 2004 and 2009.

Tab. 14: Average of the annual biomass accumulation and woody carbon sequestration rates at the four study sites based on the period between 2004 and 2009. Shown is the accumulation rate per hectare and per stem which is represented by the mean diameter class.

Study Site	**Woody biomass**		**Organic carbon**	
	kg stem^{-1}	**Mg ha^{-1}**	**kg stem^{-1}**	**Mg ha^{-1}**
B_{10}	0.101	0.776	0.053	0.405
B_{15}	1.141	3.336	0.599	1.750
G_{60}	0.285	1.935	0.150	1.018
H_{OLD}	0.519	2.015	0.273	1.061

Focusing on belowground woody biomass stocks, the distribution of the biomass with depth and the rootstock ratio looked similar at B_{10} and B_{15} (Tab. 15). The biomass was stored in roots which were smaller than 50 mm. Most of the root biomass stock was incorporated in the top 20 cm of soil and almost the whole root system lay in the top 30 cm (Fig. 18 and Tab. 15). Nevertheless the root biomass stock in the top 20 cm was larger at B15 than at B_{10}. The coarse root penetration depth at B_{10} and B_{15} was within 0.7 m and 0.5 m, respectively. In comparison coarse roots at the natural grown woodland (H_{OLD}) penetrated deeper than 1 m (diameter class: 5-2 mm) and a many times more biomass was stored as root system at H_{OLD} than at the B_{10} and B_{15}.

At all study sites a slight decrease of root biomass stock and root thickness was generally observed in decreasing root thickness per depth layer (Fig. 18). Compared to the whole coarse root biomass of an age class, the biomass of the rootstock is equal proportionate at B_{10} and B_{15}, however the ratio increased in favor of the rootstock at H_{OLD} (Tab. 15). At H_{OLD} the coarse root biomass accumulation occured in a thicker soil layer than at the two younger, afforested sites, while most of it was stored in the first half meter. However, more than 94 per cent were stored in the top 30 cm (Tab. 15). The depth coefficient (β) also declined by age of the stand (Tab. 15).

Tab. 15: Analysis of belowground biomass. The ratio between rootstock and belowground biomass is defined as α and the extinction coefficient as β. Root biomass within different soil layers includes rootstock biomass.

Class	N	α (%)	β	Root Biomass at 10 cm (%)	Root Biomass at 20 cm (%)	Root Biomass at 30 cm (%)
B_{10}	18	20	0.80	84	97	99
B_{15}	4	20	0.83	84	97	99
H_{OLD}	3	34	0.90	56	87	94

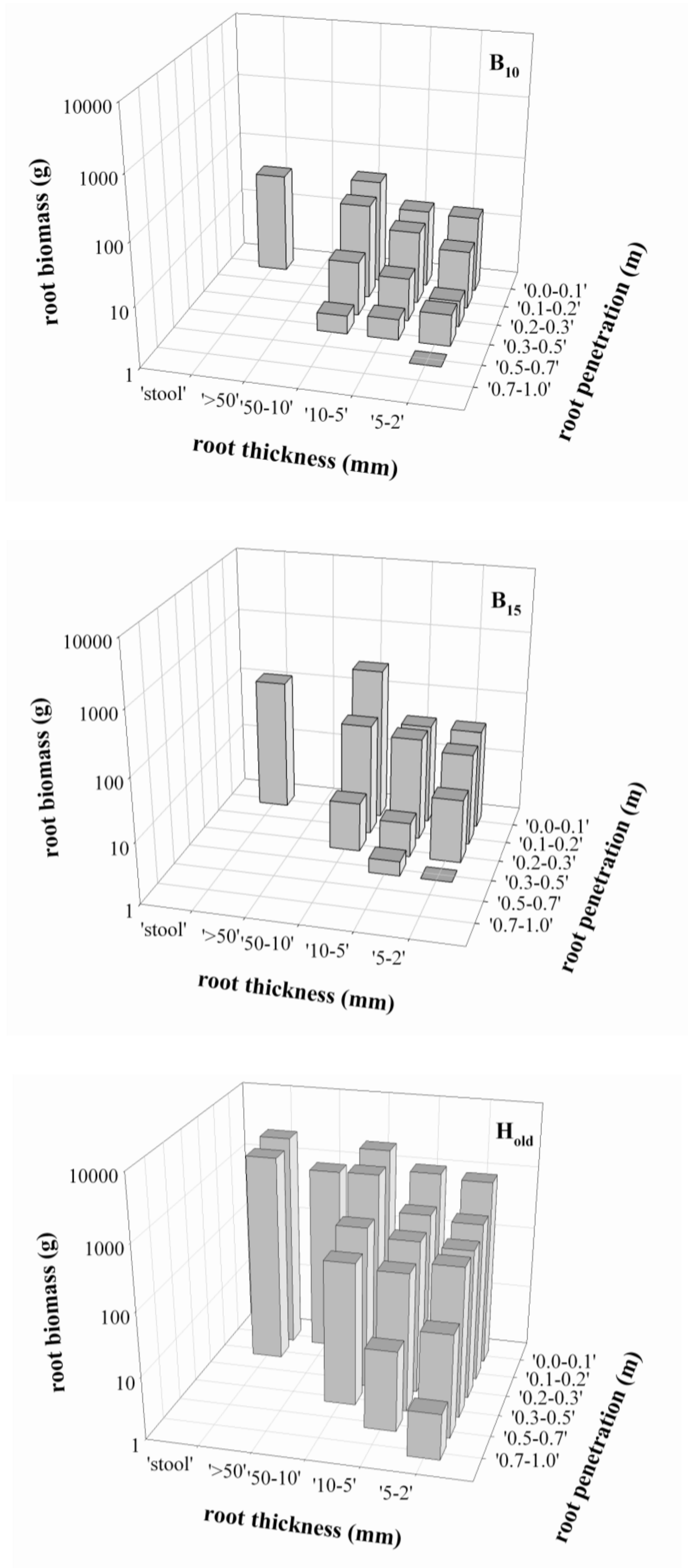


Fig. 18: Root size distribution in different depth layers for B_{10}, B_{15} and H_{OLD}. Rootstock biomass is categorized as *stool*. Note that biomass stock is plotted logarithmically.

4 DISCUSSION

4.1 OBJECTIVE I

FIND THE ALLOMETRIC PARAMETERS

Methods

Due to the need to find allometric parameters for trees of young plantations and the strong correlation between diameter class D_{50} and D_{130} (Fig. 13), I decided to calculate the allometric parameters with the diameter class D_{50}. Nevertheless, 6 sampled trees were smaller than 50 cm therefore the dataset contained information of 25 trees. For *Betula pubescens* Snorrason & Einarsson (2006) also used D_{50} as independent variable.

Icelandic forest scientists usually utilize natural logarithmically transformed data and estimate the parameters according to the methods of Baskerville (1972), Pardé (1980) and Marklund (1988). This is a widely-used method in forest sciences (e.g. Starr et al. 1998; Snorrason & Einarsson 2006; Bjarnadottir et al. 2007; Johansson 2007). According to Davis (2002; 221) logarithmical transformations of the variables X and Y implicate that "the least squares property of regression may be invalidated and a fitted regression may not exhibit the expected behavior." Therefore Baskerville (1972) describes a correction factor, which is defined as the half of the squared standard error of estimate of the function in logarithmical scale. The factor compensates the bias while the data are transformed back to linear scale. Without correction the bias can lead to an underestimation of the allometric model in linear scale. The correction factor was also used during analyses in the present study. However the model derived from linear regression causes a significant underestimation for diameter classes 7cm and higher (Fig. 14 and Tab. 9). The three outliners were not the reason for the problem as the underestimation occurred in a similar way when allometries were generated for the dataset without the three outliners. Thus a different approach was used to estimate the function parameters in the present study. A nonlinear regression approach was chosen to find the model parameters. It was convincingly shown to be more accurate (Fig. 14 and Tab. 9).

How representative is the dataset for the allometric parameters?

Before starting the field work the aim of the biomass harvest was to sample trees at B_{10}, B_{15}, G_{60} and H_{OLD}. The dataset would have included at least three samples per diameter class. All in all, about 53 trees would have been sampled. Due to intensive work and time limit it was not possible to follow the plan. Therefore the target of the field work was to get a dataset which was as homogenous as possible. The decision was made to harvest trees at H_{OLD} which were within the highest diameter class to have samples of the highest diameter class for all study sites. Therefore the dataset of the present study has three outliners which were sampled at H_{OLD}. A comparison was made between these three outliners and the inventory data of H_{OLD} to find out if the three harvested biomass samples were representative (data not shown). The analysis showed that the three outliners of the harvested biomass dataset were within the data range of the inventory. However at each measured diameter section (ground level, D_{20}, D_{50} and D_{130}) they were situated in the upper quartile but are not the maximal values. Without any other statistical analysis (e.g. Chi^2 or ANOVA) it can be assumed that the harvested biomass dataset represented the inventoried dataset and further the characteristics of the stands.

Comparison with already existing allometric parameters

There are several studies on allometries for *Betula pubescens* from Fennoscandia (e.g. Marklund 1988; Starr et al. 1998; Johansson 1999; Bylund & Nordell 2001; Petersson & Stahl 2006; Repola et al. 2007; Repola 2008; Johansson 2007; Hytönen & Saarsalmi 2009). The Finish Forest Research Insitute (METLA) supports a database of allometries. Zianis et al. (2005) and Muukkonen & Mäkipää (2006) published the estimated parameters and formulas in their reviews. The database does not show allometries for Icelandic mountain birch, however there exist two Icelandic publications about biomass functions of *Betula pubescens* (Sigurdardottir 2000; Snorrason & Einarsson 2006).

Allometric biomass functions from harvested trees over a chronosequence of 5 to 80 years were created in the present study. No allometric biomass functions for young birch trees existed in the literature. Snorrason & Einarsson (2006) reported allometric functions for eleven tree species used in Icelandic forestry. For mountain birch, volume, stem and total biomass were estimated for trees with D_{50} ranging from 2.1 to 29.8 cm. The diameters of the present dataset range between 0.2 and 14.1 cm. The present study makes it possible to derive biomass and carbon stocks for smallest diameters trees. That is of high importance for the National Forest Inventory and the Kyoto bookkeeping.

Further this study presents allometries for the leaf and woody belowground compartments which account about 30 per cent of the whole woody biomass and carbon, respectively (Tab. 10). For 60-year old trees, Sigurdardottir (2000) already published biomass functions for coarse roots. However she defined coarse roots as belowground woody biomass which is bigger than 5 mm. Considering the almost equal biomass amounts of the two smallest root categories which were found in the present study and the not equal diameter range of the classes (Fig. 18), roots which are smaller than 5 mm represent a significant part of the coarse root biomass and therefore have to be included in the coarse root faction. Furthermore her results are based on a dataset of only 3 root systems. The very good quality (R^2 = 0.99) of her estimated parameters probably results from the limited data. Another argument backs the inclusion of the coarse root fraction between 2 and 5 mm. Today the Icelandic forest inventory reports woody belowground biomass exclusive fine roots as biomass which is bigger than 2 mm in diameter (Snorrason 2010). Thus the present study presents more accurate data than earlier publications.

To compare the newly developed allometric functions with already published functions by Sigurdardottir (2000) and Snorrason & Einarsson (2006) the estimated parameters based on the nonlinear approach (Tab. 7) and stem biomass were chosen. As dataset I used 100 randomly selected samples which were part of the inventory. The analysis indicated that both already published functions underestimated the stem biomass (Fig. 19). While the maximal residual of Sigurdardottir's (2000) function underestimated the stem biomass by 11.95 kg, the maximal underestimation of Snorrason & Einarsson (2006) was 16.38 kg (Fig. 19). A possible reason might be the previously discussed difference between the two model approaches (Fig. 14).

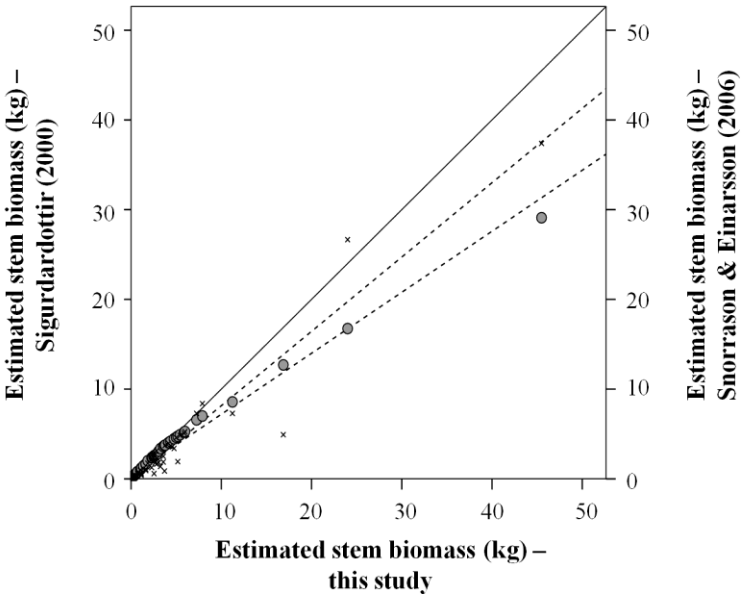


Fig. 19: Comparison of allometric functions to estimate dry stem biomass (kg). The function of this study is represented with 1:1 line. Light grey circles represent the function (R^2 = 0.98) published by Snorrason & Einarsson (2006) and crosses the function (R^2 = 0.93) of Sigurdardottir (2000). Dashed lines indicate linear regressions.

During the initial comparison with two already published allometries, the formula describing the *dbh-h* relationship developed by Näslund (1937) was used to estimate missing heights. For mountain birch in Iceland this function may not be practical because the estimated height based Näslund (1937) would exceed more than two times the effective height of the tree. This is due to the nature of the formula which describes the relationship for *Betula* spp.. Therefore the formula overestimates the height of smaller growing birch species like *Betula pubescens*. Subsequent to this finding, missing height values were replaced by adequate measured values.

4.2 OBJECTIVE II

ESTIMATE THE WOODY BIOMASS AND CARBON STOCKS

Methods

There might be two reasons for the observed characteristics of the biomass ratios (Tab. 11 and Tab. 12). First regarding to the stand characteristics (Tab. 4) the plantation sites differed from the old growth woodland. The young sites had a higher variation of diameter classes compared to the old growth woodland. However, it was not possible to harvest all diameter classes. The RMR and root:shoot ratio were higher at young trees compared to old trees (Tab. 11). Thus the sampling design tended to result in an overestimation of small trees at the plantation sites. The second reason is that the inventory, which represented the stand characteristics, compensated the mentioned overestimation of the small trees. Due to the comprehensive sampling method of the inventory the effective variability is warranted.

Comparison with already existing stock calculations

The high woody biomass and carbon stock at the 60-year old restored woodland compared to the old-growth woodland is mainly explained by difference in their developmental stage. The 60-year old stand was at the thicket stage in its first rotation and self-thinning had not occurred yet. It was therefore much denser (6,800 stems ha^{-1}) than at the old-growth natural woodland (3,882 stems ha^{-1}), which had gone through self-thinning at earlier rotations (Fig. 11) (Smith et al. 1997). This indicates high potential of carbon sequestration in restored birch woodlands in their first rotation, but that the potential will however reduce somewhat when longer timespans of around 100-150 years are considered. This is due to changes in the stand structure in old-growth forests. Maximum age of birch stems is less than 200 years (Eggertsson & Guðmundsson 2002), whereafter new stems are commonly regrown from root sprouts (Aradottir et al. 2001).

A second reason for the high stock at G_{60} could also partly be the small size of the studied woodland. In 1939 reforestation took place by seeding. The studied 60-year old patches were planted with the seedlings from these seedbeds (Aradottir 1991). The small plots are still visible in the surrounding naturally regenerated woodland and the height of trees is significantly higher than the height of the surrounding trees. Therefore the 60-year old parts of the woodland get more light compared to large and continuous birch woodlands (e.g. H_{OLD}). The consequence could be a lower competition for light and a higher photosynthesis rate which results a higher stand density and biomass accumulation.

In Iceland, only few published studies exist on woody carbon stocks in birch woodlands (Sigurdardottir 2000; Snorrason et al. 2002; Sigurdsson et al. 2008). The study of Snorrason et al. (2002) took place in the same 60-year old forest as the present study, but 10 years ago. The values of the present study are slightly higher. Another study on carbon stocks was done in eastern Iceland

(Sigurdardottir 2000). Due to the differently used definitions and the different ecosystem components included, it is not easy to compare the present results with Sigurdardottir (2000). However, for 60-year old birch woodlands Sigurdardottir (2000) estimated a woody carbon stock of about 40 Mg ha^{-1} which is about the half of the present estimation. The C-stocks in the old growth forest (H_{OLD}) are also similar to those found in studies on old-growth forests in eastern Iceland (Sigurðsson et al. 2008). Regarding to the underestimation of the already published allometric functions compared to the newly developed function (Fig. 19) the consequence for stock estimations might be that biomass pool estimations which are calculated with the earlier published allometries are underestimated.

The estimated root:shoot ratio varied between 0.56 and 0.35 (Tab. 11) which is in the same range as earlier published results on *Betula pubescens*. Sigurdardottir (2000) calculated a root:shoot ratio of 0.36. The same study showed a RMR = 0.34, SMR = 0.42, BMR = 0.21 and LMR = 0.04, respectively for 60-years old mountain birch trees. The large difference between the BMR of the present study (Tab. 11) and the BMR of Sigurdardottir (2000) cannot be explained at the moment. The RMR values of the present study varied between 0.27 and 0.25 (Tab. 11). The ratios are within the range (20-30 per cent) which were generally found for forest ecosystems (Kutschera & Lichtenegger 2002). Snorrason et al. (2002) published biomass ratios for different old *Larix sibirica*, a 40-year old *Picea sitchensis* and a 54-year old *Betula pubescens* stand. They calculated a RMR of 0.20 for mountain birch trees. This result is significantly lower than the results of the present study. However in Iceland a RMR of 0.25 is used to estimate woody belowground biomass stocks for all tree species in the National Forest Inventory (Snorrason 2010). The results of the present study confirm the chosen parameter for national biomass and carbon stock estimations. Therefore the newly developed belowground allometries should be used to estimate belowground biomass of *Betula pubescens*. The present results on RMR were also similar to the findings of Vanninen et al. (1996). While the BMR and SMR increased with age of the tree, the RMR was more stable. The consequence is a decrease of the root:shoot ratio (Tab. 11). Very few studies have been done on root biomass in Iceland and only one published study on a 7-year old *Populus trichocarpa* stand by Sigurdsson (2001) was found. An average root:shoot ratio of 0.41 (RMR of 0.29) was calculated which is well comparable with the values of the 10-year old study site (B_{10}).

Advantages of belowground stock calculations derived from an allometric model

Mokany et al. (2006) discussed the possible methods to estimate woody belowground biomass. The advantage of estimating the belowground biomass by an allometric function compared to using the age-dependent RMR factor is to have the possibility to estimate the biomass stock for each tree which is within the range of the allometrie. For example Sigurdardottir (2000) calculated the RMR with 3 sampled root systems. The trees were 65 years old. According to the change of the RMR by aging (Tab. 11), it’s difficult to use the estimated RMR of Sigurdardottir (2000) for younger or birch trees older than 65 years. To estimate belowground stocks of trees with different age we need either new RMR factors or allometric functions for the specific diameter range. In consideration of expenditure of time and lack of money it's more useful to create allometric functions than to calculate RMR for several age classes. The current study presents allometric functions for a diameter range (D_{50}) between 0.2 and 14.1 cm and therefore covers a large diameter range for Icelandic mountain birch. According to the discussion it seems that the estimation of root biomass by an allometric model is more accurate than estimations derived from root:shoot ratios. This argument is also valid when comparing allometric relationships with BEF. A second advantage of the allometric biomass regression function is that it is applicable on tree level inventory data (Zianis et al. 2005). Therefore it's possible to improve the knowledge about the dynamics of tree growth of single trees.

4.3 OBJECTIVE III

ESTIMATE THE ANNUAL BIOMASS AND CARBON SEQUESTRATION RATES

Classification of the study sites

The tree ring analysis showed that at H_{OLD} the stems have an average age of 78.4 years (Tab. 13). However the woodland at Hraunteigur is much older than the present stems. It's a remnant stand and therefore definitely not in the first generation. For this reason the classification of the woodland at Hraunteigur is H_{OLD} and stands for a climax like stand. The three other study sites (B_{10}, B_{15} and G_{60}) were in the first generation period.

Climatic arguments for the observed tree ring patterns in 2006

I observed a stagnation or even a distinctive decreased sequestration rate at each study site in 2006 (Fig. 16). Instead of site characteristics or defoliation by insects the climate might be the key factor of this pattern in 2006. Therefore data of the weather station at Sámsstaðir (63°44' N / 20°07' W) was inspected. The analysis of the air temperature and precipitation between 2003 and 2009 showed similar results to the studies of Eggertsson & Gudmundsson (2002) and Levanic and Eggertsson (2008) (data not shown). Compared to the climatic trend (1961-1990) the mean temperatures for June and July 2006 were only slightly above-average, while those for the rest of the observed years were clearly above-averaged. Levanic & Eggertsson (2008) found a significant positive correlation between tree ring growth and precipitation in January. Their argument was the more snow accumulation in January the higher amount of melt water during growth season. In 2006 more than a doubling of the precipitation is observed in January 2006 compared to the long-term trend. However the mean temperature of January 2006 was 2 °C which is clearly higher than the trend (-0.3 °C) and the study of the data shows that the precipitation fell while temperature was higher than the mean temperature of January 2006. Therefore the water was not stored as snow and was not available for plants during growth season. The analysis shows that the climate in 2006 could possibly be reasonable for the tree ring pattern at each study site in 2006.

Tree ring patterns between 2007 and 2009

At B_{10}, B_{15} and H_{OLD} the study showed a positive response of the sequestration rate between 2007 and 2009. Only at G_{60} a decline of the increment rate was observed during the latter three years (Fig. 16). The comparison was made with sampled trees of the mean diameter class. Focusing on the annual diameter growth within the 60-year old stand the decrease of the increment rate during the latter three years was only observed for the mean diameter class. The dominant diameter class showed a strong increase of the increment rate (Tab. 16). Thus it may be concluded that the 60-year old stand is in the stem-exclusion stage and that the dominant trees gain biomass in favor of trees of the smaller diameter classes.

Tab. 16: Mean annual diameter growth of the sampled trees at G_{60}. Shown are the average increment rates for the mean diameter class and the dominant diameter class.

Year	Mean diameter class (10^{-2} mm)	Dominant diameter class (10^{-2} mm)
2009	30	233
2008	41	222
2007	37	242
2006	47	93
2005	44	172
2004	57	146

Comparison with already existing literature about tree ring analysis and sequestration rates

The measured ring widths (Fig. 16) were comparable with the findings of Decaulne & Saemundsson (2008). At Fnjoskadalur birch trees which are about 50-years old have an increment rate between 0.6 and 1.25 mm. Compared to findings in Fig. 16 the results of Decaulne & Saemundsson (2008) range between the ring widths of the young plantation sites and the two older woodlands in the present study, however closer to the rates of G_{60} than B_{10}, which would be expected for 50-year old trees.

To get information on the annual areal sequestration the rates were charged with the stand densities of each study site. According to the observed years, the average annual biomass sequestration rates (average of the CAI between 2004 and 2009) ranged from 0.8 Mg C ha^{-1} (B_{10}), to 1.9 Mg C ha^{-1} (G_{60}), to 2.0 Mg C ha^{-1} (H_{OLD}), to 3.3 Mg C ha^{-1} (B_{15}). According to the findings of Eggertsson & Guðmundsson (2002) mountain birch tree stems grow older than 80 years. There is no CAI available at the moment for older birch trees than 80 year. The characteristics of the CAI along the chronosequence conform to the findings of Cannell & Milne (1995) and Cannell (2003). During lifetime of a stem the CAI is not linear but increases during a first stage, catch a maximal CAI and decreases after that until the death of the stem. Therefore the increment can be described as a logistic growth curve (Cannel & Milne 1995; Körner 2006). In 2009, CAI was higher than MAI for B_{10}, B_{15} and H_{OLD}. For G_{60} the CAI was lower than the MAI. The already discussed different patterns of the mean and dominant trees at G_{60} also cause different CAI values. The average CAI of the dominant trees at G_{60} is higher than this for the mean diameter class. Therefore CAI of the stand may also be higher than MAI. The maximal CAI of mountain birch stands may not be between B_{15} and G_{60} but can be expected near a 60-year old stand. However the discussion shows that derivation of a possible CAI curve is difficult. Due to different growth stages of the different old stands the diameter classes are different influenced by other diameter classes. For example competition for light, at B_{10} and B_{15} the mean diameter class is not limited as much as at G_{60}. Therefore focused on growth rates a more detailed sampling strategy is needed. However this was not the main goal of the present study.

To get an idea of the carbon increment rate of a stand Snorrason et al. (2002) used a different method. For the 60-year old woodland (G_{60}) the mean annual increment (MAI) was estimated. The MAI is defined as the factor of two carbon stocks where the other was a treeless site. In the study of Snorrason et al. (2002) the age difference between the two sites was 54 years. Snorrason et al. (2002) found a mean annual sequestration rate of about 1 Mg C ha^{-1} compared to 1.46 Mg C ha^{-1} of the present study. However it is not so useful to describe the sequestration rate of a stand by the MAI. The nonlinearity of increment rates was already discussed in the previous paragraph. The same value as Snorrason et al. (2002) calculated Sigurdardottir (2000) for a 60 year old forest in eastern Iceland. It is assumed that Sigurdardottir (2000) used the same method to estimate the MAI as Snorrason et al. (2002). Another study predicted an annual sequestration rate of 1.7 Mg C ha^{-1} for mature forest stands (Oskarsson 2000). The MAI for H_{OLD} of the present study was however only 0.48 Mg C ha^{-1}. Due to possible different definitions and methodical approaches the discrepancy might be explained. The present study assumed that the base level of the stock accumulation was zero. The assumption is approximately correct by calculating MAI on sites which were degraded like B_{10}, B_{15} and G_{60}. At the old growth study site (H_{OLD}) the stand density is reduced because of the self-thinning process. Therefore CAI and MAI per ha is lower compared to a stand about the same age in the first rotation period. Therefore Lal (2009) correctly concluded in his short review about carbon sequestration rates of the Icelandic vegetation that the rates are very variable. The data of the present study verify his statement and show that even over a chronosequence of one tree species sequestration rates are not at all constant and a range with a triplication of the lowest rate is observed. The reason was already mentioned and indicates that the extrapolation which bases on one value is not possible. Further, Malhi et al. (1999) predicts an annual NEP of a Canadian Boreal forest between 1.0 and 2.5 Mg C ha^{-1}.

Does the woody biomass compensate the Icelandic CO_2 emissions in 2007?

Regarding to the Icelandic GHG inventory in 2007 Iceland emitted about 3,289 Gg CO_2 while 312,872 inhabitants lived in the country (Hallsdottir et al. 2009). Because of the photosynthesis process the mentioned amount of CO_2 is the quantity which is just produced as CO_2 by all reported sectors. The consumption per capita was about 10,500 kg CO_2 or 2,866 kg C in 2007. Tab. 17 shows the sequestration rates for one tree per study site in 2007. A higher sequestration rate induces automatically a lower number of trees which is needed to compensate the emission per capita or for the whole population, respectively. Regarding to the size of the necessary woody area, the calculated areas exceed the effective total areas by about three magnitudes. It has to be mentioned that the effective areas are also estimated by simulation (Arnor Snorrason, pers. comm.). Regarding to the carbon storage potential of the Icelandic terrestrial system, calculations with just four different old forest growth stages are generally useless, since the whole woody area of Iceland is not included. However the rough estimate should illustrate that an enormous effort by afforestation and reforestation is needed to compensate (a part of) the annual carbon emission of Iceland and that the emissions are higher than the sequestration of carbon by magnitudes at the moment. According to Sigurdsson et al. (2007) in 2003 afforestation areas which have been planted since 1990 had sequestrated about 3 per cent of Iceland's CO_2 emission in 1990. To increase the sequestration ratio to 11 per cent in 2015 17 million plants have to be planted annually. However the success is uncertain (Sigurdsson et al. 2007).

Tab. 17: Needed trees and area to compensate the Icelandic CO_2 emission in 2007. The calculations base on the GHG report of 2009 and the estimated carbon sequestration rates in 2007 for each study site.

Study Site	C-Sequestration Rate in 2007 (kg/tree)	Trees per inhabitant (n)	Trees for population (n)	Planted seedlings (n)	Needed area (kha)	Effective Area (kha)
B_{10}	0.070	$40.96x10^3$	$12.81x10^9$	$1.01x10^6$ [a)]	1,668	0.32 [b)]
B_{15}	0.655	$4.38x10^3$	$1.37x10^9$	$1.39x10^6$ [a)]	469	0.45 [b)]
G_{60}	0.140	$20.48x10^3$	$6.41x10^9$	$0.27x10^6$ [a)]	942	0.42 [c)]
H_{OLD}	0.367	$7.81x10^3$	$2.44x10^9$	--	630	54.87 [c)]

a) Pétursson (1999)
b) Snorrason & Kjartansson (2004)
c) Hallsdottir et al. (2010)

Carbon sequestration on landscape level

A better way to explain carbon sequestration by biomass on landscape scale is to introduce tree demography. Since the carbon pool is controlled by the age and the size at tree falling (natural gap dynamics) (Körner 2006). At the present study it was assumed that the mortality was zero per cent at each study site. This assumption adulterates the carbon sequestration potential of the woody biomass pool towards a higher potential. In reality tree mortality occurs continuously and effects a carbon flow from the terrestrial system to the atmosphere. Sometimes the mortality is more intense (windthrow, fire, silviculture). These events cause an increased release of carbon back to the atmosphere. Further the present study shows the effect of tree demography to the carbon stocks of different old stands. A 60-year old woodland within the first generation has a significant higher carbon storage potential than an old growth, self-thinned forest which however can be dated as an 80-year old stand.

It must be pointed out that a most effective carbon sequestration by woody biomass would only be maximal warranted if human impact held off. However Icelandic forests and woodlands have more functions than just storing carbon (e.g. soil protection, improve attractiveness of recreation areas, scenic value, habitat, forest products as timber, fuelwood and bedding material) (Blöndal 1993; Eysteinsson 2009). Regarding to carbon sequestration an implementation concept must be therefore increasing the rotation periods of stands and keeping down the size of the silvicultural managed areas so that reaching the peak of the sum of biomass carbon and SOC in mature forest ecosystems is possible (Cannell & Milne 1995, Krankina & Harmon 2006; Hudiburg et al. 2009).

4.4 OBJECTIVE IV

STUDY OF THE BELOWGROUND WOODY BIOMASS

Methods

The methodical approach is a possible explanation for the fact that major roots (> 50 mm) just appeared in the top 10 cm at H_{OLD} (Fig. 18). The onset of the major roots had a nearly oval cross-section before changing gradually into a round cross-section part. Therefore I measured the minimal and maximal diameter of the root at the depth layer boundaries and took the average. This approach could explain the two peaks for the second largest thickness category in the first two depth layers because this category might be overestimated.

Observations during digging up the root systems

During excavation at the two planted sites (B_{10} and B_{15}) I sampled young trees which obviously had been cultured in pots. In the field the taproots were degenerated while white pumice material close to the stump indicated external cultivation. Nursery cultivation of birch seedlings happens in pots during 2 years until planting finally occurs (Magnus Einarsson, pers. comm.). The consequence is a disturbed vertical root growth that may cause a lower β-value than for undisturbed growth conditions. Therefore additionally to the young age of the stand woody belowground biomass is stored in a smooth soil layer. It can be assumed that the mentioned effect of the disturbed vertical growth just exists for the first generation and that natural rejuvenation by seeds or basal sprouts causes a deeper root penetration and biomass storage at the same age but in the follow generations.

Digging up the whole root system needs a lot of motivation and time. However with the applied method I received an idea about the morphology of the mountain birch root system. My findings correlate very well with earlier published results (Kutschera &Lichtenegger 2002). In the natural grown woodland H_{OLD} trees were about 80 years old and the horizontal extension of the coarse roots was radial to the stump. Their length (until ø = 2 mm) was similar to the length of the tree. The thickest roots developed at the stump side. In direction to the bottom of the stump only few smaller coarse roots grew (Fig. 20). Major roots grew first angular downwards and ascended slowly towards soil surface after they reached a maximal depth of about 50 cm. Roots which arose as first roots from major roots grew more or less vertically downwards. They were part of the tap rooting. They branched out several times within short distance wherefore decrease of the root diameter was quick and penetration depth of coarse roots ended at about 1 m (Fig. 20). According to Kutschera & Lichtenegger (2002) appearance of short and strongly divided tap roots is caused by wet and cool soil conditions. At the moment this statement cannot be validated, however it sounds plausible because of seasonal soil frost appearance. Soil moisture and temperature have been studied by another research group of the KolBjörk project but are not published yet. Further, secondary roots which arise from major roots could sprout lateral or underneath with growing tendency upwards (Fig. 20). Further away of the stump lateral sprouting was dominant. Outwards moving coarse roots of mountain birch often continued in the top 5 cm of the soil profile or even between moss and soil layer. These roots were located in the driest and hottest soil part. The afforested sites (B_{10}, B_{15}) showed the phenomenon of rooting at ground surface as well. The findings are well comparable with Kutschera & Lichtenegger (2002). At the end of the root system coarse roots lay in a horizontal position or grew some centimeters downwards.

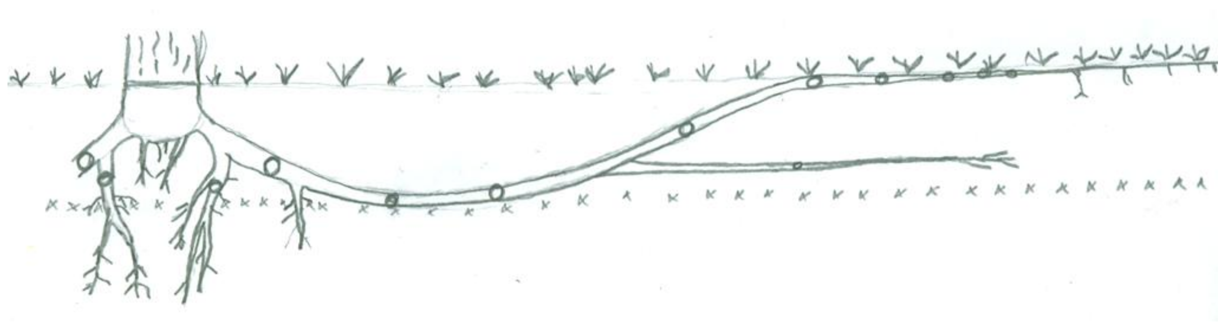


Fig. 20: Drawing of a root system of an 80 year old mountain birch tree. The vertical root penetration depth is about 1 m and the horizontally growth extension is about 4-5 m. Lateral root sprouts are shown as hollow circles. The crosses stand for a coarse grained tephra layer and the ground floor is shown with grass symbols.

Characteristics of the belowground along the chronosequence

At B_{10} and B_{15} the development of the root system between thickness categories showed generally a threefold increase of the biomass in the top 20 cm. Within the thickness category *50-10 mm* in the top

10 cm the factor was even 5.8. Any differences in the vertical expansion were not observed between B_{10} and B_{15}. Even though the soil profile depth was deeper at B_{15} than at B_{10}. The reason might be the more intense development of lateral roots compared to taproots for young trees of *Betula pubescens* (Kutschera & Lichtenegger 2002). Root sprouting and growth take place in the top 20 cm during this period. However the study doesn't show neither horizontally distribution of the root biomass nor root length characteristics. Therefore it is not possible to give any information if either sprouting or horizontal growth of already existing roots is dominant. The analysis confirms that Icelandic mountain birch (*Betula pubescens*, Ehrh.) is a smooth rooting species (Kutschera & Lichtenegger 2002).

Vertical distribution of the belowground biomass

A review of root distributions for terrestrial biomes by Jackson et al. (1996) concluded that 93 per cent and 83 per cent is stored in the top 30 cm in the tundra and boreal biome, respectively. The calculated extinction coefficients (β) for these biomes were 0.914 and 0.943, respectively. Thus root biomass is located in a deeper soil layer in boreal ecosystems (Fig. 21). The study showed an approximation to the tundra extinction coefficient. Mountain birch ecosystems are located geographically between the two mentioned biomes and build the subarctic forest. The boreal biome contains, among other things, coniferious forests and the transition of forests over to woodlands (e.g. *Betula pubescens*), where the tundra biome starts with shrub species (e.g. *Betula nana* and *Salix*) as dominant plants (Schultz 2002). Maybe because of the young age of the stand B_{10} and B_{15} had β-values which were low compared to the analysis of Jackson et al. (1996). The two afforested study sites stored almost the whole root biomass in the top 30 cm (Tab. 15). H_{OLD} had a β-value close to the factor of the tundra biome (Tab. 15), even if it was an old-growth woodland. According to the mentioned ecosystem transition, the curve of H_{OLD} should have continued between the two earlier published curves (Fig. 21).

Icelandic soil profiles are continuously interrupted by crusty tephra layers wherefore deeper rooting could be highly regulated by pedological site characteristics (Thorarinsson 1961, Arnalds 2004). The review of Jackson et al. (1996) doesn't include *Betula pubescens* as species neither in the boreal biome nor in the tundra biome. While coniferous and broad leaf trees built the database for the boreal biome, *Dryas*, *Salix*, *Carex*, *Betula nana* and other tundra species represent the tundra biome. This is another reason why a comparison might be difficult.

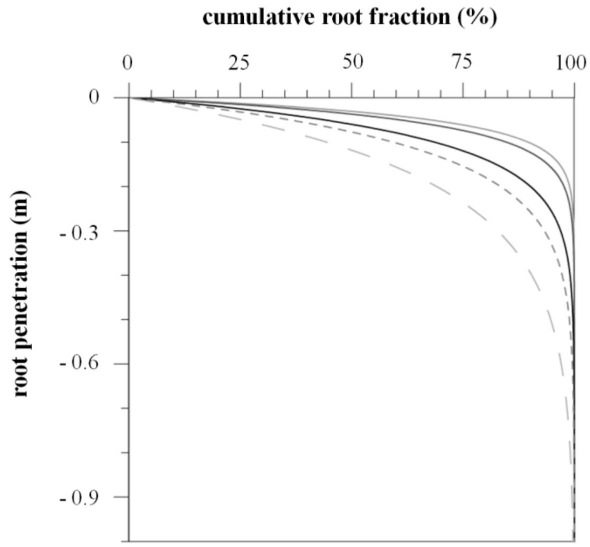


Fig. 21: Comparison of vertical root distribution between the study sites B_{10} (light gray), B_{15} (dark gray) and H_{OLD} (black). Also shown are estimates for tundra (short dashed) and boreal (long dashed) biome of Jackson et al. (1996).

Another study on belowground biomass distribution of birch trees (*Betula pendula*) reasons that 87 per cent (β=0.935) of the belowground biomass is located in the first 30 cm (Curt & Prévosto 2003). Compared to Curt & Prévosto (2003) the present study shows values between 94 and 99 per cent for the same soil layer. The difference of the penetration depth of the two birch species could be explained by the morphology of the two root systems. Taproots of *Betula pendula* penetrate deeper than those of *Betula pubescens* and major roots divide rapidly into smaller coarse roots wherefore biomass accumulation near ground level is lower than for *Betula pubescens* (Kutschera & Lichtenegger 2002).

Canadell et al. (1996) published maximal rooting depth for several biomes. Boreal forests and tundra have a mean root penetration depth of 2.0 m and 0.5 m, respectively. For the tundra ecosystem *Betula nana* was only reported with a rooting depth of 0.5 caused by permafrost. The present study didn't measure the maximal rooting depth. However at H_{OLD} taproots (> 2mm) penetrate several tephra layers and reach still a depth of about 1 m.

The observed distribution of the living organic carbon in the soil layer is well comparable with the distribution of the soil organic matter which was analysed by Jobbagy and Jackson (2000).

Terrestrial carbon sequestration potential of the study sites

Aradottir & Arnalds (2001) described land degradation and soil erosion in Iceland. It caused that recultivation and restoration occur on thin soil layers or on the exposed parent material. Therefore belowground biomass accumulation on plantation sites as at B_{10} will develop within a thinner soil layer than at undisturbed woodlands as H_{OLD}. Accordingly root systems at B_{10} will probably never represent the current situation at H_{OLD}, during the first generation. Regarding the turnover of root biomass, decomposition rate is higher close to the soil surface than in deeper horizons (Persson & Stadenberg 2009). Because of lower soil temperature and less available nutrients the amount of soil fauna which interacts as decomposer is decreasing with soil depth. In spite of the low root turnover in high latitude regions (Gill & Jackson 2000; Lauenroth & Gill 2003) the decomposition of the root biomass might be higher in degraded, thin soil layers compared to those of undisturbed woodlands of the same area because of the mentioned reason. Regarding to carbon sequestration potential plantation sites as B_{10} and B_{15} might be on a lower level than undisturbed sites. The decomposition rate might be increased by an increase of the air temperature regarding to global warming (Denman et al. 2007). However vegetated areas especially woodlands represent sediment catchments (Thorarinsson 1961) wherefore belowground biomass will be stored in deeper layers after sediment will have been accumulated and thicker soil layers will have been established.

The discussion shows the importance of the belowground system regarding to the terrestrial carbon pool. However the storage period depends on the character of the chemical bonds of the carbon. While detritus has a high turnover, already decomposed, humic carbonic material (e.g. humins) has a low turnover (Schlesinger et al. 2000). Thus long-term sequestration of carbon is most effective by accumulating organic compounds as passive soil organic carbon in mineral soil horizons where impacts like further microbial decomposition, erosion and disruption by human activities is low (Steffen et al. 1998; Schlesinger et al. 2000; Valentini et al. 2003). Soil organic carbon is similarly distributed as the living biomass. Thus most of it is stored in the upper soil horizons (Jobbagy and Jackson 2000). To be stored in the mineral soil, the (dead) organic material of woods leaves and ground vegetation has to stay in the stand. Decomposition by soil biota brings the dead organic material from the soil surface into the soil layer. Root debris is also decomposed. The metamorphosis of the new generated humus to more stable compounds takes time and a lot of carbon is removed to the atmosphere by soil respiration during the process. Therefore carbon accumulation in the terrestrial carbon pool is a long-term process (e.g. Valentini et al. 2003). The utilization of terrestrial ecosystems as a carbon storage pool will have its highest benefit if the biomass is let rest in the ecosystem. Otherwise the carbon is just temporary stored and is anthropogenicly used, for example as bioenergy or timber. That would mean that the status quo of the contemporary carbon cycle is only conserved and that the terrestrial pool does not act as a long-term carbon sink.

5 CONCLUSION

This chronosequence study gives results for above- and belowground stocks and sequestration rates for woody biomass and organic carbon of native mountain birch within a diameter range of 0.2-14.1 cm at D_{50}. It presents that the finding of the allometric parameters for all compartments of single trees derived with a nonlinear regression approach was more accurate compared to the most used linear regression approach. Further it can be concluded that plantations on degraded soil profiles which are within the first rotation period stored more woody biomass and therefore also more organic carbon than old grown woodlands at almost the same age. Studies about belowground biomass are rare. The present work provides detailed information of the biomass amount and the structure of coarse root systems of three different aged stands. The study cannot present accurate and detailed information about the strength of the terrestrial carbon sink of Iceland. However, calculations show that current greenhouse gas emissions are significant higher than the sequestration potential of the current afforested mountain birch woodlands.

The present study confirms some parameters used for inventory reports in Iceland. It also shows that due to stands dynamics, age-depended parameters are not useful to estimate carbon stocks on landscape level. To further improve national inventories, allometric functions for young mountain birch based on a countrywide dataset are needed. The knowledge should also be advanced regarding to the behaviour of the belowground biomass on degraded soils. Due to soil profile degradation, restoration and afforestation in the unique Icelandic conditions are insufficiently represented in studies about mountain birch ecosystem of the Scandinavian area.

New questions have emerged due to the present study. The present dataset of the allometric functions should be consolidated by harvesting trees within a diameter range between 6 and 12 cm. The difference between the biomass of monocormic and polycormic mountain birch trees should be tested. Perhaps new allometries for polycormic trees are needed. There is already a publication about the two different growth types, however the aim of the study was different (Bylund & Nordell 2001). To answer the question about a possible higher decomposition rate in degraded soils compared to those in undisturbed soil profiles research is needed. Regarding to the carbon sequestration of the established plantation sites a comparison between carbon stocks and estimations of the carbon footprint of the plantation activity would show when established plantation sites will act absolutely as carbon sinks. The restoration and revegetation of degraded sites, as for example the area of Bolholt, required a lot of fertilizer and seeds which were produced and transported by emitting carbonic bounds to the atmosphere. The question is if Iceland will be emission-free in 2025 like Lal (2009) postulated with his budget accounting. A further research project could be the analysis of the distribution and the quality of the carbonic bounds in soil profiles along the KolBjörk chronosequence to improve the knowledge about processes and storage periods of different carbon structures in the soil.

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