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Carbon sequestration in forest plantations in Iceland

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SUMMARY

The main goal of the current project was to develop methodology for determining the total organic carbon stocks (C-stocks) at afforestation sites, and to estimate their mean annual carbon sequestration (C-sequestration) by stock-change method. This method involves a comparison between C-stocks on afforestation sites and adjacent pastures on the same soil type and with the same pre-planting land-use history.

The total C-stock in a 32-yr old larch stand (*Larix sibirica*) was 276 Mg ha^{-1}, compared to 157 Mg C ha^{-1} on an adjacent grazed pasture. This indicates mean C-sequestration of 2.6 Mg ha^{-1} yr^{-1}. A 54-year old native birch stand (*Betula pubescens*) had total C-stock of 149 Mg ha^{-1} and mean C-sequestration rate of 1.0 Mg ha^{-1} yr^{-1}. A 40-year old Sitka spruce stand (*Picea sitchensis*) had a total C-stock of 431 Mg ha^{-1} and mean C-sequestration rate of 3.0 Mg ha^{-1} yr^{-1}.

The increase in C-stocks at the afforestation sites was mostly due to an accumulation in the trees and the litter layer. Other compartments did not always show significant changes in C-stocks. The largest part of the C-stock was always in the soil organic matter (SOM). High spatial variation in SOM at sites make estimates of C-sequestration of the soil compartment especially difficult. However, in absence of repeated measurements of SOM and aboveground C-stocks on permanent plots, the stock-change approach can give useful information about carbon dynamics of afforestation areas.

Key words: afforestation, biomass components, birch, carbon stocks, coarse roots, fine roots, larch, Sitka spruce, soil organic matter (SOM).

YFIRLIT

Kolefnisbinding með skógrækt á Íslandi

Árið 1997 hleyptu íslensk stjórnvöld af stokkunum átaksverkefni til að auka bindingu kolefnis með skógrækt og landgræðslu, þar sem rannsóknir á kolefnisbindingu með áðurnefndum aðferðum voru sérstaklega styrktar. Í þessari grein er gerður samanburður á kolefnisforða skóglauss beitilands og nærliggjandi misgamalla skógræktarsvæða af sambærilegum uppruna til að meta árlega meðalkolefnisbindingu sem fæst með skógrækt.

Heildarkolefnisforði í 32 ára gömlum lerkiskógi á Fljótsdalshérði var 276 tonn C ha^{-1}, þar af voru 64 tonn í ofanjarðarhluta trjánna, 16 tonn í grófrótum þeirra, 11 tonn í föllnum barrnálum, sinu og botngróðri, 9 tonn í fínrótum og 176 tonn C ha^{-1} í jarðvegi. Á samanburðarsvæði utan skógar var kolefnisforðinn alls 157 tonn ha^{-1}, þar af voru 6 tonn í sinu og jurtkenndum gróðri, 8 tonn í fínrótum og 144 tonn í jarðvegi. Árleg meðalkolefnisbinding í lerkiskóginum var því um 2,6–3,0 tonn C ha^{-1} $ár^{-1}$, eftir því hvort jarðvegsbindingin var talin með eða ekki. Kolefnisbinding í álíka gömlum lerkiskógi í Varmahlíð í Skagafirði var mjög svipuð (2,4–3,3 tonn ha^{-1} $ár^{-1}$), þrátt fyrir erfiðari vaxtarskilyrði þar. Hjá öðrum trjátegundum var mældur eftirfarandi kolefnisforði og kolefnisbinding; í 54 ára gömlum birkiskógi á Suðurlandi var forðinn 149 tonn C ha^{-1} og bindingin 1,0–1,3 tonn C ha^{-1} $ár^{-1}$; í 40 ára sitkagreniskógi á Suðurlandi var forðinn 431 tonn C ha^{-1} og bindingin 3,0–3,5 tonn C ha^{-1} $ár^{-1}$.

Rannsóknin leiddi í ljós að stærsti hluti kolefnisforða skóglenda var í jarðveginum. Mikill breytileiki var á dreifingu kolefnisforðans í dýpri jarðvegslögum, sem gerði samanburðaraðferð þá sem hér var beitt erfiða. Þrátt fyrir þetta sýna niðurstöðurnar að þessi aðferð er vel brúkleg við úttektir á kolefnisbindingu skóglendis á meðan ekki eru til endurteknar mælingar á kolefnisforða á sama mælistað yfir lengri tímabil.

INTRODUCTION

Atmospheric CO_2 concentration has increased by 90 mmol mol^{-1} from its pre-industrial level of 280 mmol mol^{-1} (Keeling and Whorf, 2002). There is increasing concern that the Earth's climate is changing because of the rising atmospheric concentrations of CO_2 and other green house gasses. This concern is not recent; it can be traced back to the late 19th century and the Swedish chemist Svante Arrhenius, who recognised that atmospheric CO_2 plays a critical role in regulating Earth's temperature (von Storch and Stehr, 2000). Much scientific and political debate has centred on the potential of afforestation to act as a major terrestrial sink for atmospheric CO_2 (e.g. IPCC, 2000; House *et al*., 2002), which effectively could mitigate the atmospheric increase. In recent years numerous studies have been initiated in different countries to quantify mitigation potential of different woody ecosystems (e.g. Mund *et al*., 2002; Nabuurs *et al*., 2000; Seely *et al*., 2002; Sigurðardóttir, 2000; Sigurdsson, 2001; Valentini *et al*., 2000; Vesterdal, 2002).

The first study that measured carbon stocks (C-stocks) of woody ecosystems in Iceland was published by Jónsson (1985), where both above- and belowground compartments of a lodgepole pine (*Pinus contorta*) plantation in northern Iceland were measured (see also Jónsson and Óskarsson, 1996). Few other studies have quantified C-stocks or annual carbon sequestration (C-sequestration) of plantation forests in Iceland. Sigurðardóttir (2000) studied C-stocks of planted Siberian larch (*Larix sibirica*), birch (*Betula pubescens*) and lodgepole pine sites in eastern Iceland. Net ecosystem sequestration was measured directly with eddy covariance technique over an young black cottonwood (*Populus trichocarpa*) plantation in southern Iceland in 1997 (Valentini *et al*., 2000). Annual carbon uptake in 1994 of the same plantation was also estimated from ecophysiological measurements of carbon uptake and efflux (Sigurdsson, 2001).

The present study was initiated in 1997 as a part of a larger governmentally sponsored research project on C-sequestration (Óskarsson, 2000). The main goals of this project were: (a) to quantify the C-sequestration potential of afforestation of treeless landscapes and of revegetation of eroded lands, and (b) to develop a robust methodology to estimate C-sequestration by afforestation and revegetation (Óskarsson, 2000). Some preliminary results of the main project have been published as reports (Arnalds *et al*., 1999; Arnalds, 2000; Snorrason *et al.*, 2000; Óskarsson, 2000). Data on C-sequestration by reclamation were also published in Aradóttir *et al*. (2000), and soil C-stocks were reported and discussed in Arnalds *et al*. (2000). Using those results and some historical data on afforestation and revegetation, an attempt was made to estimate total annual C-sequestration of all afforestation and revegetation sites in Iceland (Sigurdsson and Snorrason, 2000). The objective of this paper is to report measures of C-stocks in some plantation forests in Iceland with a focus on the aboveground

Table 1. Main characteristics of afforestation and control sites chosen for the present study.
1. tafla. Helstu kennitölur fyrir skógræktar- og beitarsvæði sem valin voru til rannsóknar.

Regions:	East					North		South			
Location:	Mjóanes and Hafursá					Varmahlíð		Gunnarsholt		Tunguskógur	
Latitude:	65°08'					65°33'		63°52'		63°44'	
Altitude:	25–50 m					50 m		100 m		100 m	
Species:	Larch	Control	Larch	Larch	Control	Larch	Control	Birch	Control	Spruce	Control
Established	1983		1983	1962		1967		1939		1960	
Measured	1999	1999	1998	1998	1998	2000	2000	1998		1999	1999
Age	16		16	32		34		54		40	
Soil depth	Shallow	Shallow	Deep	Deep	Deep	Medium	Medium	Medium	Medium	Deep	Deep
Abbreviation[a)]	$L16^s$	$L0^s$	$L16^d$	$L32^d$	$L0^d$	$L34^m$	$L0^m$	$B54^m$	$B0^m$	$S40^d$	$S0^d$
Number of plots	1	1	1	4	4	2	2	2	2	1	1

a) L=larch, B=birch and S=spruce. Number after uppercase letter = planting age (number of years after planting, except for birch where supposed planting age is set to be 5 years after direct seeding). In unplanted control sites the age is set to 0 (zero). Superscripts: s= shallow soil (under 30 cm depth), m= medium deep soil (30–49 cm depth), d= deep soil (more than 50 cm depth).

C-stocks and mean annual C-sequestration rates. An accompanying paper will go in more depth into distribution of carbon in forest soils.

MATERIAL AND METHODS

Choice of sites

Siberian larch and birch are the most used tree species for afforestation in Iceland, and Sitka spruce is the third most used species (Pétursson, 2002). Those three tree species were selected for the present study. At each study site, plots were laid out within the forest and on treeless comparison site on as similar land as possible, on the basis of vegetation, soil characteristics, slope, exposure and elevation. Furthermore, the comparison sites were laid out as close to the forest sites as possible, so that growing conditions would be comparable.

Site description

The study took place in three regions in Iceland. In eastern Iceland, three Siberian larch stands and two comparable treeless sites were studied. In northern Iceland, one larch stand and one comparable treeless site were studied. In southern Iceland one birch and one Sitka spruce (*Picea sitchensis*) sites along with two comparable treeless sites were studied. More detailed description of the sites can be found in Table 1.

The study in eastern Iceland took place at Mjóanes and Hafursá. A 16-year-old larch stand on deep soils ($L16^d$) had dominant height of 5.5 m and had 3400 stems ha^{-1}. That is close to the average planting density of such stands today (Héraðsskógar, 1995). The stand had not been thinned since planting and was approaching canopy closure, but still had rather rich and diverse ground vegetation. The 32-year-old larch stand ($L32^d$) on deep soil had dominant height of 9.2 m and stand density of 3100 trees ha^{-1}. It had been thinned from ca 5000 trees ha^{-1} in 1989, but denser planting was a common practice before ca 1985. The $L32^d$ stand was very dense when the study took place, self-thinning had started, and the ground vegetation was sparse and speciespoor. One comparable treeless, fully vegetated grazed site on deep soil was studied ($L0^d$). One young larch stand on thin sparsely vegetated soil ($L16^s$) was also studied. Dominant height was 4.9 m and stand density was 2500 trees ha^{-1}. The stand had not been thinned, but low density is explained by early mortality due to frost heave and drought. One comparable sparsely vegetated treeless site on thin soils was studied ($L0^s$).

The study in northern Iceland took place at Varmahlíð, which has 1.0°C lower mean annual temperature than the study site in eastern Iceland (Einarsson, 1976). The larch stand ($L34^m$) in Varmahlíð was of similar age and dominant height (9.0 m) as the oldest stand at Mjóanes and Hafursá but on medium thick soils. It had never been thinned and had a stand density of 5350 trees ha^{-1}. There was a heavy light competition between trees and self-thinning had started some years ago. The comparable treeless site was on grazed but fully vegetated medium deep soils ($L0^m$) on a similar slope as the forest.

The study in southern Iceland took place in Gunnarsholt (birch) and Tunguskógur (Sitka spruce). The mean annual temperature of both those sites is 1.3–2.0°C higher than for Varmahlíð, but Tunguskógur has 0.7°C higher mean annual temperature than Gunnarsholt (Einarsson, 1976). The birch woodland in Gunnarsholt ($B54^m$) had dominant height of 7.6 m. It was established in 1939 by direct sowing on medium thick scarified soils. The sowing resulted in dense regeneration and present stand density of 7600 trees ha^{-1}, despite heavy self-thinning in the past few years. The comparable treeless site ($B0^m$) was on adjacent grazed pasture. The Sitka spruce plantation ($S40^d$) was established in 1960 on deep and fertile soils and had dominant height of 11.7 m. It had never been thinned and had a stand density of 3700 trees ha^{-1}. The planting density was ca 6000 trees ha^{-1}, but the stand suffered considerable mortality in severe spring frost in 1963 (Ragnarsson, 1964). The stand was very dense, but in good health and little self-thinning. However, there was almost no ground vegetation and dead moss indicated that complete canopy closure was fairly recent. The comparable treeless site ($S0^d$) was a grazed pasture on a deep soil on a slope opposite the plantation.

Sampling program

The sampling was carried out during August and September when the vegetation was at its peak, which is recommended when biomass studies are done (Grier *et al.*, 1981). At each site 1–4 main sampling plots of 100 m^2 (10×10 m) were established (Table 1).

A number of measurements were made on whole plots. All living trees were counted and measured for height and diameter at breast height (conifers) or at 0.5 m height (birch). Sub-samples were taken from the main plots to quantify the C-stocks of trees, ground vegetation, litter, fine roots and soil.

The tree with basal area closest to the plot's mean (GM-tree) was in all cases chosen for destructive sampling. Total stem volume was found by sectioning (Philips, 1994). It was assumed that the GM-tree had stem volume closest to the plot mean and hence that the relationship between basal area and volume is linear in even-aged monocultures (Husch *et al*., 1972).

The harvested trees were then divided into dead and living branches, stems, coarse roots, and each component was weighed for total fresh mass (FM). The coarse roots where defined as the part of the main stem that was belowground and the roots with a diameter exceeding 0.5 cm (Vogt *et al*., *1*996). For the two larch forests on deep soil at eastern Iceland ($L16^d$ and $L32^d$) the coarse roots were only measured 1 m^2 pit adjacent the stem base of the harvested GM-tree. At other sites all coarse roots of the GM-trees were dug up. Sub-samples were immediately taken from each FM-component of the trees and weighed for FM and dried at 105°C and weighed again for dry mass (DM).

Some additional trees were also felled in the younger larch stand, birch and spruce stands.

They too were measured for stem volume and in some cases for FM, DM and carbon concentration [C].

Ground vegetation and litter was harvested on five randomly distributed 50×50 cm sub-plots within the main plot. The only exception was on forest sites where the fifth sub-plot was always adjacent to the GM-tree. Ground vegetation and litter were dried at 70°C and weighed for DM.

Fine-root biomass was determined by taking a core with a corer at the fifth sub-plot. Soil was washed away and the root samples were dried at 105°C for 24 hours and weighed for DM.

Soil C-stock was determined by taking separate cores with an auger at each sub-plot, after the vegetation and litter layer had been removed. Samples for determining bulk density were taken from the side of soil pits adjacent to the fifth subplot. The soil samples were dried at 70°C, sieved through 2.0 mm gauge strainer before the carbon content was assessed. The coarser soil fraction (small stones and fine roots) was weighed for DM.

Both the fine roots and soil cores were divided into 10 cm depth intervals. Attempt was made to sample all organic soils and fine roots. On some sites sampling went down to 200 cm depth.

Total carbon concentration [C] was analysed for all components by Leco CR-12. Tree samples were analysed for six different biomass fractions on 15 of the 34 harvested trees. These where; foliage, life branches, dead branches, stem, root stock and coarse roots. Carbon content of ground vegetation and litter was determined for two out of five sub-plots, but [C] of all fine root- and soil sample were analysed.

Data analysis

The methodology used in this study has been termed 'stock change approach', i.e. C-stocks of afforestation sites of known age and comparable adjacent treeless sites are compared to estimate the mean annual C-sequestration of the forest plantations (Gower *et al.*, *19*87; Gower *et al.*, 1992). Stem volume (v) of birch trees on main-plots was estimated from the equation:

$$v = e^{-1.809} \times d_{0.5}^{2.554} \times h^{-0.484} \quad (1)$$

where $d_{0.5}$ is diameter at 0.5 m height and h is the height. Equation (1) was made from multiple linear regression (lnv= a+lnd+lnh, fitted with; lnv= –1.809+2.554×lnd–0.484×lnh, r^2=0.996) of the measured stem volume of 12 felled and sectioned trees on main-plots.

Volumes of Siberian larch and Sitka spruce were calculated from equations given in Norby (1990) and Bauger (1995), respectively. All GM-tree C-stocks were estimated using the DM/FM ratio of the sub-samples, the total FM and [C] of each component. C-stock of the GM-tree ($C_{GM\text{-}tree}$) was converted to C-stock on each main plot ($C_{main\ plot}$) by the equation:

$$C_{main\ plot} = C_{GM\text{-}tree} \times (v_{mean}/v_{GM\text{-}tree}) \times n_{main\ plot} \quad (2)$$

where v_{mean} is the mean volume of the trees in each main plot, $v_{GM\text{-}tree}$ is the volume of the GM-tree and $n_{main\ plot}$ is the number of trees on main plot. C-stock in ground vegetation was found by multiplying total DM on sub-plots, [C] and the area ratio between the main- and sub-plots. C-stock in fine root was estimated by converting [C] on soil volume base to an area base (g C_{roots} m^{-2}). Soil C-stock was estimated by the same method as for fine roots; e.g. soil bulk density (g DM cm^{-3}) was used to convert [C] of soil to C-stock on an area base.

RESULTS

Mean tree height, mean diameter at breast height, total basal area, total stem volume, and mean annual volume increment of afforestation sites are shown in Table 2. Both the older larch forests ($L32^d$ and $L34^m$) had mean annual increment (MAI) of 5.7 m^3 ha^{-1} yr^{-1}, Sitka spruce forest of similar age had 39% higher MAI or 7.9 m^3 ha^{-1} yr^{-1}, the native birch woodland only had MAI of 2.7 m^3 ha^{-1} yr^{-1} (Table 2). Biomass ratios of the three main biomass components are shown in Table 3. The coarse root ratio (RMR) was quite similar for all species and ages, only varying from 18% to 22%. As was to be

Table 2. Mean tree height (h, m), mean diameter at breast height ($d_{1,3}$, cm), total basal area (G, m^2 ha^{-1}), total stem volume (V, m^3 ha^{-1}), and mean annual increment (MAI, m^3 ha^{-1} yr^{-1}) of bole volume. Numbers are mean values for main plots ± standard error of the mean where more than one main plots were sampled per forest.
2. tafla. Meðaltal trjáhæðar (h, m), brjósthæðarþvermáls ($d_{1,3}$, cm), grunnflöts (G, m^2 ha^{-1}), bolrúmmáls (V, m^3 ha^{-1}) og árlegs rúmmálsvaxtar (MAI, m^3 ha^{-1} $ár^{-1}$). Sýnd er staðalkekkja (±) meðaltalsins, þar sem fleiri en einn mæliflötur var mældur í skógi.

	$L16^s$	$L16^d$	$L32^d$	$L34^m$	$B54^m$	$S40^d$
h	3.5	4.2	8.4±0.2	7.4±0.0	5.8±0.1	10.7
$d_{1,3}$	4.0	6.7	12.3±0.7	9.7±0.1	7.2±0.0	13.9
G	4	13	40±2	44±3	36±2	60
V	10	35	182±7	194±12	145±11	316
MAI	0.6	2.2	5.7±0.2	5.7±0.4	2.7±0.2	7.9

Table 3. Biomass ratios of the three main components of the sampled trees (DM of component as a fraction of total DM). Branch mass ratio (BMR) contains both branches and foliage, stem mass ratio (SMR) and coarse root ratio (RMR). Numbers are mean values for sampled trees ± standard error.
3. tafla. Lífmassahlutföll greina (BMR), bols (SMR) og grófróta (RMR) allra trjáa sem voru uppskorin. Birt er meðaltal felldra trjáa á hverjum mælistað, auk staðalskekkju (±).

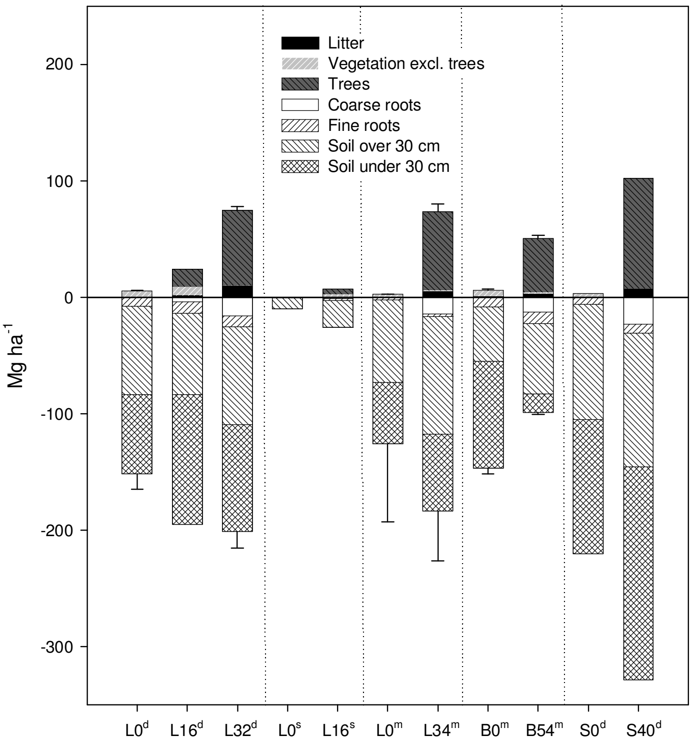
	L16	$L32^d$	$L34^m$	$S40^d$	$B54^m$	Mean
No. of samples	3	4	2	5	2	
BMR	0.33±0.02	0.23±0.02	0.27±0.01	0.27±0.03	0.21±0.03	0.27
SMR	0.45±0.02	0.57±0.01	0.55±0.02	0.53±0.03	0.59±0.02	0.54
RMR	0.22±0.02	0.20±0.01	0.18±0.03	0.19±0.02	0.20±0.00	0.20

expected, both the branch mass ratio (BMR) and stem mass ratio (SMR) varied systematically with age of the larch trees (Table 3).

Total C-stock at all study sites are shown in Figure 1. The aboveground compartments are shown as positive values, and the error bars indicate variability in the total aboveground C-stock. The aboveground C-stocks are divided into trees, ground vegetation and litter. The belowground compartments are shown as negative values, and the error bars indicate variability in the total belowground C-stock. The belowground C-stocks are divided into coarse roots, fine roots, organic matter in soils above 30 cm in depth and organic matter in soils below 30 cm depth. The standard error of the estimate for the belowground C-stocks was always greater than for the aboveground C-stocks (Figure 1).

Total C-stock of the forest plantations, both above- and belowground, was on average 227 Mg C ha^{-1}, but the treeless pastures had on average 134 Mg C ha^{-1}. This indicated 69% mean increase in total C-stock in forest plantations that were 16–54 years of age (Figure 1). The forests had on average 25% (SE ±2.9%) of their total C-stock in aboveground compartments, but the pastures had only 3% (SE ±0.5%) of their C-stock in aboveground compartments (Figure 1). The increase in aboveground C-stock was mostly due to more carbon accumulated in woody biomass and litter, which always increased following afforestation. C-stock in ground vegetation increased in younger larch forests, but decreased in older larch forests, and under birch and spruce (Figure 1).

Figure 2 shows the apparent C-stock change following the afforestation. At the three sites



with replicated sampling the increase in total C-stocks above 30 cm soil depth was significant, as well as C-stock in trees aboveground and coarse roots (P<0.05; Figure 2). The C-stock changes of other components were mostly positive, indicating a net C-sequestration following afforestation, but they were not always consistent or significant for all species (Figure 2).

Figure 1. Total carbon stock on each site measured (error bars show standard error of total above- and belowground stocks of replicated measurements).
1. mynd. Heildarkolefnisforði á mældum svæðum (skekkjustika sýnir staðalskekkju kolefnisforða ofan- og neðanjarðar þar sem mælingar voru endurteknar).

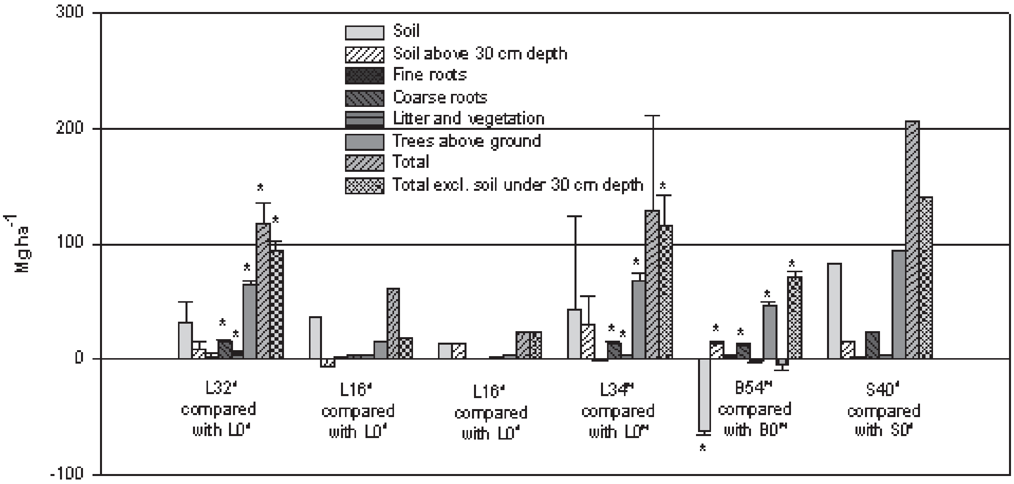


Figure 2. Apparent C-stock change between afforestation sites and pastures. Error bars show standard error of the difference where more than one main-plot was measured. A star (*) signifies that the change was significantly different from zero (a two sample t-test (Zar, 1984), P<0.05).
2. mynd. Mismunur á kolefnisforða skógræktarsvæða og skóglausra samanburðarsvæða. Skekkjustika sýnir mismun meðtals á svæðum með endurteknar mælingar. Stjarna (*) segir til um hvort mismunur var marktækt frábrugðinn núlli (P gildi <0,05).

The annual ecosystem C-sequestration rate of different afforestation sites is shown in Figure 3, both including the soil over 30 cm depth and the fine-root compartments and excluding these compartments. Mean annual C-sequestration rate of the younger larch forests and the native birch woodland was 1.0–1.5 Mg C ha^{-1} yr^{-1} when the soil and the fine-root compartments were included. The older larch forests and the Sitka spruce had mean annual C-sequestration rate of 3.0–3.5 Mg C ha^{-1} yr^{-1}. When the soil and the fine roots were excluded then the older forests sequestered approx. 2.5–3.0 Mg C ha^{-1} yr^{-1} (Figure 3).

DISCUSSION

Methodological issues

Some equations have been made to convert volume or volume increment of different tree species into C-stock or rate of C-sequestration (Birdsey, 1992; Winjum and Schroeder, 1997). Numerous equations have also been made to describe the relationship between dry mass and more easily measured factors, e.g. diameter at breast height and dry mass of various tree components (Grier and Logan, 1977; Gholz, 1982; Czabowskyj *et al.*, 1985; Harding and Grigal, 1985; Gower *et al.*, 1987; Gower *et al.*, 1992; Vanninen *et al.*, 1996; Mäkelä and Vanninen, 1998). Dry mass can then easily be converted to C-stock with additional information about [C]. No such equations exist, however, for Siberian larch, the main tree species in Icelandic forestry (Pétursson, 2002). Unfortunately, such equations could not be developed in the present study because of too few samples. The simplest method for estimating woody C-stock (stand biomass) per area is to multiply the dry mass of the mean basal area tree by the number of stems on the plot. It is however more accurate to use the mean stem volume, since trees of the same basal area can be of different height and therefore of different volume and dry mass. In the present study the volume of the mean basal area tree was corrected for the deviation from the mean stem volume before the total C-stock was estimated (see Equation 2).

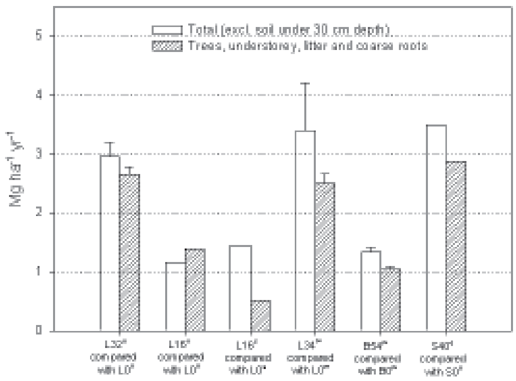


Figure 3. Mean annual C-sequestration of afforestation sites. Open bars include C-sequestration in all aboveground C-stocks, roots and SOM above 30 cm depth, filled bars exclude SOM and fine roots. Standard error is shown where more than one main-plot was measured.

4. mynd. Árleg meðalkolefnisbinding skógræktarsvæða með (opnar súlur) og án (fylltar súlur) kolefnisbindingar í jarðvegi (0–30 cm dýpi) og fínrótum. Sýnd er staðalskekkja þeirra staða sem höfðu endurteknar mælingar.

How representative are the results?

How representative are the present results for C-sequestration of Icelandic woodlands? To answer that, lets first state that the observed C-sequestration mainly took place in the aboveground compartments; namely in annual wood increment (see Figure 2). This question can therefore be answered by comparing the study sites with other growth measurements from throughout the country.

Siberian larch: Volume increment measured in $L32^d$ (Table 2) was not as high as was observed in a nearby larch forest named Guttormslundur, when it was at the same age (Benedikz, 1975). Other yield studies in the region give similar results as MAI of $L32^d$ (Snorrason, 1986; Sigurjónsdóttir, 1993). The $L34^m$ larch had, however, slightly higher dominant height than predicted for larch stands of this age in this region of north Iceland (Snorrason, 1986). Hence, it is possible to conclude that the data presented here for larch was slightly below the average yield class for east inland region but slightly above the average yield class for some regions of northen Iceland.

Sitka spruce: The annual volume increment of S40[d], 7.9 m^3 ha^{-1} yr^{-1}, was probably well above the average increment for Sitka spruce (Table 2). According to data of Freysteinsson (1995, 1996) and Blöndal (1996) average annual volume increment of 30–50 year Sitka spruce is 4.5 m^3 ha^{-1} yr^{-1} (ranging from 0.9 to 9.4 m^3 ha^{-1} yr^{-1}).

Birch: No national growth data are available to state with confidence if the birch stand measured is as productive as other planted or seeded birch woodlands. However, when compared to the preliminary figures from a countrywide survey of plantations made in 1999 (Snorrason, unpublished data) we found that the average height for birch 50 years and older was 5.7 m (SD=1.59; n=236), which is close to the mean tree height of the birch stand (see Table 2). This indicates that the birch stand at Gunnarsholt is close to average national site class for planted or seeded birch.

The C-sequestration rates observed in this study for Siberian larch and birch are by no means maximum values. Based on the above comparison between growth measures from the study sites and from elsewhere, we conclude that only in the case of Sitka spruce are the observed C-sequestration values relatively high. This is an important finding, since lower values have generally been used in estimates of C-sequestration potentials for Siberian larch. In a study on national C-sequestration potentials, Jónsson and Óskarsson (1996) used for example an annual increment of 0.3–2.3 and 0.9–2.7 Mg C ha^{-1} yr^{-1} for larch and spruce, respectively. Their maximum values are well below the results obtained in the present study. Furthermore, in the governmental project from 1996 (Ministry for the Environment, 2000), afforestation was divided into general afforestation with a mean annual C-sequestration rate of 0.5 Mg C ha^{-1} yr^{-1} and commercial afforestation (plantations) with mere 1.1 Mg ha^{-1} yr^{-1}. These estimates now seem to be much too low.

Mean annual C-sequestration and the rotation length

It is important to note that the mean annual C-sequestration rates will change with the age of the forest. Presumably the C-sequestration in wood will go through similar systematic changes as MAI of stem volume; i.e. with a sigmoid change during the earlier stage and a gradual decrease when the forest reaches higher age (Fitje and Strand, 1973). Managed forests are, however, usually harvested when they are close to maximum MAI (at the end of the rotation period). The forests studied here were relatively young, or 16–54 years of age (Table 1), and had therefore presumably not yet reached maximum MAI. The 40-year-old Sitka spruce in Tunguskógur should have rotation of 65–75 years, according to Scottish yield tables (Hamilton and Christie, 1971). The two Siberian larch forests, which were in their thirties (L32[d] and L34[m]), should have over 100 year rotation, according to Swedish yield curves (Martinsson, 1990). Similarly the 54-year-old birch (B54[m]) forest should have rotation of 90–100 years, according to Norwegian data (Institutt for skogskjøtsel, 1985). The C-sequestration potential in the woody compartment should therefore not have been overestimated in the present study.

Icelandic forest plantations are generally very young. Weighed mean age of all Icelandic plantations planted since 1899 (weighed with their area) is only 17 years (Sigurdsson and Snorrason, 2000). Therefore it is better to use the present C-sequestration rates for estimating their mean annual C-sequestration than mean rates based on whole rotations. A mean annual C-sequestration rate will, however, always overestimate the real C-sequestration for very young forests, because of the sigmoid increase in MAI when calculated at young age (Kilbride *et al.*, 1999).

Stand versus landscape C-sequestration

It is important to make clear distinction between C-sequestration values that are estimated on a landscape scale and values like those of the present study that are estimated from within homogeneous stands. The former values include many open areas, such as tractor paths, extraction allies, forest roads and natural spaces caused by ponds, wet patches and rocks. When C-sequestration rates of studies like this one are to be used on a landscape scale, it is important that the forest maps being used for estimations of total forest area are accurate, and do not include other surface types within the forest class. Hence the total C-stock and C-sequestration values obtained here are only valid for net-forested area. This may be the main reason why our results may seem rather high, compared to some other published data (e.g. IPCC, 2000). Winjum and Schroeder (1997) reported for example that the maximum C-sequestration potential of forest plantations in the boreal zone was 0.96 Mg ha^{-1} yr^{-1}. This is only one third to half of what was found in the present study (Figure 3).

Apparent versus total C-sequestration

One of the stands ($L32^d$) had been thinned prior to the study, and the thinning was not included when the mean annual increment of the stem wood was calculated (Table 2). Wood from thinnings and fellings is usually excluded when total C-stock and C-sequestration rates of afforestation areas are estimated (IPCC, 2000). Some have advocated that live-cycle studies of products from such wood should be used to estimate mean C-sequestration for this component (IPCC, 2000).

Soil C-stocks and C-sequestration

Coarse roots. In the boreal forest zone the belowground portion of tree biomass (RMR) varies from 19–39% and in the cold-temperate zone from 13–28% (Vogt *et al*., 1996). The data presented here are in accordance with these findings (Table 3). Even if older trees mostly add to the aboveground biomass through stem increment, which results in constantly decreasing BMR, then RMR is much more stable throughout the rotation (Vanninen *et al*., 1996). The data here on RMR may therefore be used for estimating C-stocks in coarse roots for other studies on same tree species.

Fine roots. The fine root C-stock was variable between sites, but less so between similar site types (Figure 1). Such high variability is known from other studies and is why many samples are needed to compare fine-root mass between sites (Persson, 1978). In the present study the variability was too great to see any significant changes in the fine-root mass after afforestation (Figure 2).

Soil organic matter. The carbon store in soil organic matter (SOM) was the largest component in the C-budget of the afforestation sites (Figure 1). Spatial variability in this component was however much larger than for the aboveground components (see error bars in Figure 1). It is therefore difficult to estimate C-sequestration in soils accurately without taking many samples. In the present study there was a general trend for C accumulation in soils of afforestation areas, but the trend was only significant for $L16^s$, which had small C-stock at the time of afforestation (Figure 2).

It is obvious in Figure 2 that we did not always succeed in selecting comparable sites in terms of soil depth and deep-layer C-stock. The afforestation plots for birch and Sitka spruce are not really comparable to their pasture equivalents. The soil layer in the $B54^m$ plot was only 30 cm thick, resting directly on pure sand, whereas a similar sand layer in the $B0^m$ was only 30 cm thick resting on organic soil (peat) that continued down to the bottom of the profile. The soil depth is very important when soil C-stock is estimated and therefore it is better to compare to a definite soil depth (30 cm) when changes in C-stocks are studied.

CONCLUSIONS

Much work remains to be done before all questions now being asked by policy makers and the general public about C-sequestration by afforestation in Iceland have been answered. This study gives some first results for C-sequestration potential of plantations of Siberian larch, Sitka spruce and the native birch.

The C-sequestration of the afforestation sites was mostly explained by an accumulation in wood (above- and belowground) and the litter layer. However, the largest C-stock was always found in the SOM, but high spatial variation made estimates of C-sequestration of this compartment especially difficult. In absence of repeated measurements of SOM and aboveground C-stocks on permanent plots, the stock-change approach can give useful information about carbon dynamics of afforestation areas.

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REFERENCES

Aradóttir, Ása L., Kristín **Svavarsdóttir**, Þorbergur H. **Jónsson** & Grétar **Guðbergsson**, 2000. Carbon accumulation in vegetation and soils by reclamation of degraded areas. *Icelandic Agricultural Sciences* **13**: 99–113.

Arnalds, Ólafur, 2000. Rannsóknir á kolefnisbindingu í landgræðslu og skógrækt. In: *Ráðanautafundur 2000*. Farmers' Association of Iceland, Agricultural Research Institute & Hvanneyri Agricultural University: 113–115.

Arnalds, Ólafur, Ása L. **Aradóttir**, Arnór **Snorrason**, Grétar **Guðbergsson**, Þorbergur H. **Jónsson** & Anna M. **Ágústsdóttir**, 1999. Organic carbon sequestration by restoration og severely degraded areas in Iceland. Preliminary results. *Rala Report* **197**: 19 pp.

Arnalds, Ólafur, Grétar **Guðbergsson** & Jón **Guðmundsson**, 2000. Carbon sequestration and reclamation of severely degraded soils in Iceland. *Icelandic Agricultural Sciences* **13**: 87–97.

Benedikz, Þórarinn, 1975. Vaxtarmælingar á lerki í Hallormsstaðaskógi vorið 1974. In: *Ársrit Skógræktarfélags Íslands 1975*: 56–59.

Bauger, E., 1995. Funksjoner og tabeller for kubering av stående trær. Furu, gran og sitkagran på Vestlandet. *Rapport fra Skogforsk No.* **16**. Norsk institutt for skogforskning, Ås: 26 pp.

Birdsey, R.A., 1992. *Carbon Storage and Accumulation in United States Forest Ecosystems.* United States Department of Agriculture Forest Service. General Technical Report W0-59: 23 pp.

Blöndal, Sigurður, 1996. Sitkagrenið sækir fram. Í tilefni nýjustu vaxtarmælinga. In: *Ársrit Skógræktarfélags Íslands 1996*: 27–38.

Czapowskyj, M.M., J.J. **Robison**, R.D. **Briggs** & E.H. **White**, 1985. *Component Biomass Equations for Black Spruce in Maine*. Research paper NE-564. Northeastern Forest Experiment Station, Forest Service, United States Department of Agriculture.

Einarsson, Markús Á., 1976. *Veðurfar á Íslandi (Climate in Iceland).* Iðunn, Reykjavík: 150 pp.

Fitje, A. & L. **Strand**, 1973. *Tremålingslære.* Universitetsforlaget, Oslo: 146 pp.

Freysteinsson, Gunnar, 1995. *Boniteringskurver for sitkagran (*Picea sitchensis *(Bong.) Carr.) på sörvest-Island.* Hovedoppgave ved Institutt for skogfag. Norges landbrukshøgskole, Ås: 58 pp.

Freysteinsson, Gunnar, 1996. *Greinagerð um mælingar á viðarvexti á Suðurlandi sumarið 1996.* Iceland Forest Service. Report: 7 pp.

Gholz, H.L., 1982. Enviromental limits on aboveground net primary production, leaf area, and biomass in vegetation zones of Pacific Northwest. *Ecology* **63(2)**: 469–481.

Gower, S.T., C.C. **Grier**, J.D. **Vogt** & K.A. **Vogt**, 1987. Allometric relations of deciduous (*Larix occindentalis*) and evergreen conifers (*Pinus contorta* and *Pseudotsuga menziesii*) of the Cascade Mountains in central Washington. *Canadian Journal of Forest Research* **17(7)**: 630–634.

Gower, S.T., K.A. **Vogt** & C.C. **Grier**, 1992. Carbon dynamics of Rocky Mountain Douglas-fir: Influence of water and nutrient availability. *Ecological Monographs* **62(1)**: 43–65.

Grier, C.C. & R.L. **Logan**, 1977. Old-growth *Pseudotsuga menziesii* communities of a Western Oregon watershed: Biomass distribution and production budgets. *Ecological Monographs* **47(4)**: 373–400.

Grier, C.C., K.A. **Vogt**, M.R. **Keyes** & R.L. **Edmonds**, 1981. Biomass distribution and above- and below-ground production in young and mature Abies Amabilis zone ecosystems of the Washington Caccades. *Canadian Journal of Forest Research* **11**: 155–167.

Hamilton, G.J. & J.M. **Christie**, 1971. *Forest Management Tables (Metric).* Forestry Commission Booklet No. 34. London Her Majesty's Stationery Office: 274 pp.

Harding, R.B. & D.F. **Grigal**, 1985. Individual tree biomass estimation equations for plantation-grown white spruce in northern Minnesota. *Canadian Journal of Forest Research* **15**: 738–739.

Héraðsskógar, 1995. *A natural Resource for New Times*. Héraðsskógar Afforestation Project, Egilsstaðir, Iceland: 48 pp.

House, J.I., I.C. **Prentice** & C. **Le Quéré**, 2002. Maximum impacts of future reforestation or deforestation on atmospheric CO_2. *Global Change Biology* **8**: 1047–1052.

Husch, B., I.C. **Miller** & T.W. **Beers**, 1972. *Forest Mensuration.* 2nd edn. Ronald Press Company, New York: 410 pp.

IPCC, 2000. *Land Use, Land Use Change and Forestry* (eds R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo & D.J. Doken). Cambridge University Press, Cambridge: 377 pp.

Institutt for skogskjøtsel, 1985. *Bjørk Or Osp. Veiledning for det praktiske skogbruk.* 3. opplag. Institutt for skogskjøtsel, Norges landbrukshøgskole: 187 pp.

Jónsson, Thorbergur H., 1985. *Distribution of Root Biomass in a Stand of* Pinus contorta *Dougl. Growing on Stratified Palagonite Loess Soil in N.E. Iceland*. Honours thesis, University of Aberdeen: 82 pp.

Jónsson, Þorbergur H. & Úlfur **Óskarsson**, 1996. Skógrækt og landgræðsla til að nema koltvísýring og andrúmslofti. In: *Ársrit Skógræktarfélags Íslands 1996*: 65–87.

Keeling C.D. & T.P. **Whorf**, 2002. Atmospheric CO_2 records from sites in the SIO air sampling network – Mauna Loa. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. Oak Ridge, Tenn.

Kilbride, C., K. **Byrne** & J. **Gardiner**, 1999. *Carbon Sequestration and Irish Forests.* Project Report. COFORD: 34 pp.

Martinsson, O., 1990. *Den ryska lärkens höjdutveckling och volymproduktion i norra Sverige*. Rapporter. No. 29-1990. Institutionen för skogsskötsel, Sveriges lantbruksuniversitet: 59 pp.

Mäkelä, A. & P. **Vanninen**, 1998. Impacts of size and competition on tree form and distribution of aboveground biomass in Scots pine. *Canadian Journal of Forest Research* **28**: 216–227.

Ministry for the Environment, 2000. *Land Use, Land Use Change and Forestry*: Submission by Iceland. Special report to SBSTA. Ministry for the Environment, Reykjavík: 13 pp.

Mund, M., E. **Kummetz**, M. **Hein**, G.A. **Bauer** & E.-D. **Schulze**, 2002. Growth and carbon stocks of a spruce forest chronosequence in central Europe. *Forest Ecology and Management* **171**: 275–296.

Nabuurs, G.-J., F. **Mohren** & H. **Dolman**, 2000. Monitoring and reporting carbon stocks and fluxes in Dutch forests. *Biotechnology, Agronomy, Society and Environment* **4**: 308–310.

Norby, M., 1990. *Volym- och formtalsfunktioner för* Larix sukaczewii *och* Larix sibirica *på Island.* Examensarbete i ämnet skogsskötsel. Institutionen för skogsskötsel, Sveriges lantbruksuniversitet, Umeå: 35 pp.

Óskarsson, Úlfur, 2000. *Binding kolefnis í gróðri og jarðvegi (Carbon Sequestration in Vegetation and Soil).* Áfangaskýrsla 1999. Land Reclamation and Afforestation Initiative 1997–2000: 30 pp.

Persson, H., 1978. Root dynamics in a young Scots Pine stand in central Sweden. *Oikos* **30**: 508–519.

Pétursson, Jón Geir, 2002. Skógræktarstarfið árið 2001. Tölulegar upplýsingar. *Skógræktarritið* **2002(2)**: 107–109.

Philips, S.M., 1994. *Measuring Trees and Forests*. 2nd edn. CABI Publishing, Wallingford: 310 pp.

Ragnarsson, Haukur, 1964. Trjáskemmdir vorið 1963. In: *Ársrit Skógræktarfélags Íslands 1964*: 25–26.

Seely, B., C. **Welham** & H. **Kimmins**, 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management* **169**: 123–135.

Sigurðardóttir, Ragnhildur, 2000. *Effects of Different Forest Types on Total Ecosystem Carbon Sequestration in Hallormsstaður Forest, Eastern Iceland*. PhD-thesis, Yale University: 193 pp.

Sigurdsson, Bjarni D., 2001. Environmental control of carbon uptake and growth in a *Populus trichocarpa* plantation in Iceland. *Acta Universitatis Agriculturae Sueciae, Silvestria* **174**: 64 pp.

Sigurdsson, Bjarni D. & Arnór **Snorrason**, 2000. Carbon sequestration by afforestation and revegetation as a means of limiting net-CO_2 emissions in Iceland. *Biotechnology, Agronomy, Society and Environment* **4**: 303–307.

Sigurjónsdóttir, Sigrún, 1993. *Lerk på Island. Volum- og variationsberegninger.* Semesteroppgave. Nord-Trøndelag Distrikthøgskole, Seksjon for skogbruk: 27 pp.

Snorrason, Arnór, 1986. Larix *i Island. Sammenligning av arter, provenienser og voksesteder.* Institutt for skogskjøtsel, Norges landbrukshøgskole, Ås: 124 pp.

Snorrason, Arnór, Þorbergur H. **Jónsson**, Kristín **Svavarsdóttir**, Grétar **Guðbergsson** & Tumi **Traustason**, 2000. Rannsóknir á kolefnisbindingu ræktaðra skóga á Íslandi. *Skórgræktarritið* **2000 (1)**: 71–89.

Valentini, R., G. **Matteucci**, A.J. **Dolman**, E.-D. **Schulze**, C. **Rebmann**, E.J. **Moors**, A. **Granier**, P. **Gross**, N.O. **Jensen**, K. **Pilegaard**, A. **Lindroth**, A. **Grelle**, C. **Bernhofer**, T. **Grünwald**, M. **Aubinet**, R. **Ceulemans**, A.S. **Kowalski**, T. **Vesala**, Ü. **Rannik**, P. **Berbigier**, D. **Loustau**, Jón **Guðmundsson**, Halldór **Thorgeirsson**, A. **Ibrom**, K. **Morgenstern**, R. **Clement**, J. **Moncrieff**, L. **Montagnani**, S. **Minerbi** & P.G. **Jarvis**, 2000. Respiration as the main determinant of carbon balance in European forests. *Nature* **404**: 861–865.

Vanninen, P., H. **Ylitalo**, R., **Sievänen** & A. **Mäkelä**, 1996. Effects of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). *Trees* **10**: 231–238.

Vesterdal, L., E. **Ritter** & P. **Gundersen**, 2002. Change in soil organic carbon following afforestation of former arable land. *Forest Ecology and Management* **169**: 137–147.

Vogt, K.A., D.J. **Vogt**, P.A. **Palmiotto**, P. **Boon**, J. **O'Hara** & H. **Asbjornsen**, 1996. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type og species. *Plant and Soil* **187**: 159–219.

von Storch, H. & N. **Stehr**, 2000. Climate change in perspective. Our concerns about global warming have an age-long resonance. *Nature* **405**: 615.

Winjum, J.K. & P.E. **Schroeder**, 1997. Forest plantations of the world: their extent, ecological attributes, and carbon storage. *Agricultural and Forest Meteorology* **84**: 153–167.

Zar, J.H., 1984. *Biostatistical Analysis*. Prentice-Hall Inc., Englewood Cliffs, New Jersey 07632: 718 pp.

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