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# Estimate of annual carbon balance of a young Siberian larch (*Larix sibirica*) plantation in Iceland

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ABSTRACT

The aim of present study was to estimate the annual carbon balance of a young *Larix sibirica* plantation on former heathland pasture in Iceland. The data covered 1 yr of measurements, year 2005. The daily NEE varied from about +7.7 to −22.5 g $CO_2$ $m^{-2}$ $d^{-1}$ in October and July, respectively, resulting in annual sequestration of –727 g $CO_2$ $m^{-2}$ $a^{-1}$. This annual carbon balance falls within the observed range of published annual NEEs for other plantation forests. Daily net uptake started in middle of April, when thawing of the soil surface began and it increased as the spring progressed. During a cold spell in the middle of May, the air temperature dropped below zero for some days, resulting in a decline of carbon uptake and a slow recovery of the ecosystem. Such freezing incidents are expected to become more frequent at northern latitudes in warmer future climate and their impact should, therefore, be studied further. Moreover, longer time series of measurements on NEE are needed to reveal the effect of weather conditions on long-term carbon balance. Corrections for small errors in winter and night fluxes from open-path gas analysers also need to be developed.

## 1. Introduction

Terrestrial ecosystems in northern latitudes are believed to play an important role in the global carbon balance. Recent studies show that the Northern Hemisphere acts as a strong $CO_2$ sink (e.g. Gurney et al., 2004) and increasing concern has centred on the role of boreal forests as a key ecosystems in the global carbon cycle. To quantify and better understand the role of forests in the global carbon balance, measurements on fluxes of $CO_2$, using eddy covariance technique, have been conducted at numerous locations around the world (e.g. Aubinet et al., 2000). The eddy covariance technique gives the net ecosystem exchange (NEE), which may be separated into two components, gross primary production (GPP), that is, the assimilation of $CO_2$ by the trees and the ground vegetation, and the total ecosystem respiration ($R_e$), that is, the sum of heterotrophic and autotrophic respiration in the ecosystem. The uncertainty of such micrometeorological estimates is of the order ±50 g $m^{-2}$ $yr^{-1}$ under nearly ideal conditions (Baldocchi, 2003).

Afforestation of treeless land causes a net carbon sequestration in biomass, both above and belowground, while the effect on soil organic matter is more variable (Guo and Gifford, 2002; Huang et al., 2007; Hyvönen et al., 2007). Measurements of gas exchange and carbon stock changes in Iceland are relatively scarce. In 1996 Icelandic authorities decided to sponsor large-scale projects for enhancing carbon (C) sequestration by afforestation and revegetation, in order to mitigate global warming. This was prior to the appearance of the Kyoto protocol and was the outcome of an increasing concern about climatic change due to the anthropogenic rise in the atmospheric concentration of $CO_2$. This decision by the authorities spurred a number of studies on carbon stocks of woody ecosystems in Iceland. Most of them quantified C stocks or annual carbon sequestration using a stock-change method, which is based on harvest measurements and soil coring of afforested areas and comparable treeless sites (Sigurdardottir, 2000; Sigurdsson and Snorrason, 2000; Snorrason et al., 2002). These studies yielded different average C-sequestration rates, varying between ca. 350 and 550 g $CO_2$ $m^{-2}$ $a^{-1}$ for 15–30-year-old Siberian larch (*Larix sibirica* Ledeb.) plantations and as much as 1.100–1.300 $CO_2$ $m^{-2}$ $a^{-1}$ in middle aged Siberian larch and Sitka spruce [*Picea sitchensis* (Bong.) Carr.] plantations. This method can only be used to estimate average change in C stocks over a period of at least 10 yr and the need to compare two sites to estimate the net C change limits its accuracy (Sigurdsson et al., 2005). Only one study, using direct measurements of net ecosystem $CO_2$

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sequestration with the eddy covariance technique, has been carried out in Iceland, in a young black cottonwood (*Populus trichocarpa* Torr. and Grey) plantation in southern Iceland (Valentini et al., 2000). It yielded ca. 370 g m$^{-2}$ annual $CO_2$ sequestration.

During the past 15 yr, Siberian larch has been the most planted tree species in Iceland. Currently, the rate of afforestation is ca. 2400 ha yr$^{-1}$, with Siberian larch, native mountain birch (*Betula pubescens* Ehrh.) and Sikta spruce being used in similar proportions, accounting for 67% of the total annual afforestation (Gunnarsson, 2006). In 2005 the total area of planted forests in Iceland was 28 900 ha, or 0.28% of the total surface area (Sigurdsson et al., 2007). The use of Siberian larch in forestry in the Nordic countries has been limited (Lyck and Bergstedt, 2004). The Siberian larch is, however, one of the economically and ecologically most important tree species in Russia. The area covered by Siberian larch amounts to nearly 14% of the total area of Russian forests (Lyck and Bergstedt, 2004). It is therefore a key species to study in terms of the global carbon balance.

The climate in Iceland is maritime, characterized by rather short, cold summers and relatively mild winters. Rather short growing season and unstable weather conditions are common in Iceland. It has been predicted that climate warming will increase the risk of frost damage to trees in the boreal zone (Cannell and Smith, 1986; Linkosalo et al., 2000; Slaney, 2006). In Iceland, mild winters, with periods of thawing and early springs result in relatively frequent dehardening of Siberian larch and some other boreal tree species, which then can lead to frost damage during sudden periods of late-spring freezing. Icelandic conditions can, therefore, in some ways be seen as future scenario for large areas of Scandinavia and other northern areas with more continental climate.

The main aim of this paper is to present the results of a study on the $CO_2$ balance in a young afforested Siberian larch plantation in eastern Iceland. To our knowledge these are the first published year-round NEE data on this type of an ecosystem. The present study is, therefore, an important input to the global data sets of such measurements and the NEE measurements are also a useful tool to verify the stock-change method that has been used to estimate C sequestration in Iceland so far. Other aims were to report the effect of spring frost damage on the carbon balance and discuss the effect of applying correction for an additional heat transfer caused by the open-path gas analyser used in the study (Burba et al., 2006).

## 2. Material and methods

### 2.1. Site description

The study site was a 13-year-old afforested area in Vallanes, eastern Iceland (65°19′N, 14°56′W, elevation 60 m a.s.l.) (Fig. 1). The site was previously a mountain birch woodland, but it was probably cleared in the 16th or 17th century, when historical records show that birch woodlands mostly disappeared in this area (Guttormsson and Blöndal, 2005). Some remains from charcoal-making (wood-coal) have been found at the site at ca. 35 cm depth, well below a volcanic ash layer in the soil deposited during an eruption in Mt. Askja in 1874, thus proving that the area had been a birch woodland earlier. The site was a grazed heathland pasture prior to afforestation in 1992. At the time of afforestation the site was protected from livestock grazing, ploughed and planted with Siberian larch mixed with some lodgepole pine [*Pinus contorta* (Loudon) Douglas]. The basic stand characteristics in 2005 are found in Table 1.

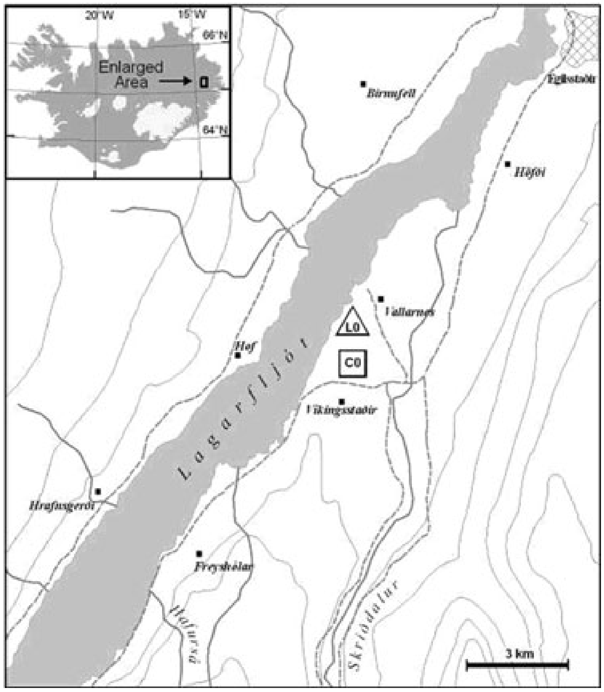


*Fig. 1.* Map of the study site in eastern Iceland. Triangle represents the measurement site (L0) and square represents a comparable heathland (C0).

*Table 1.* Site characteristics in 2005 for Vallanes, eastern Iceland

| Site characteristics | Variables |
|---|---|
| Tree composition | Larch = 95% and Pine = 5% |
| Stand density | 3400 trees ha$^{-1}$ |
| Diameter at 50 cm | 2.87 cm |
| Diameter at BH | 1.32 cm |
| Dominant height | 3.34 m |
| Basal area at BH | 1.16 m$^2$ |
| LAI of trees | 0.73 m$^2$ m$^{-2}$ |
| LAI of ground vegetation | 1.38 m$^2$ m$^{-2}$ |
| Canopy structure | Open |

The ground vegetation is representative of extensive areas in eastern and northern Iceland, which are commonly used for afforestation. The vegetation consists mainly of dwarf bushes (*Betula nana* L. and *Vaccinium uliginosum* L.), grasses and bryophytes (Sigurdsson et al., 2005). The soil type in Vallanes is Brown Andosol, one of the most common soil types in Iceland (Arnalds, 2004). It is a volcanic soil that tends to be high in amorphous clays and organic matter. Andosols, out of all the mineral soils, are second to none in the amount of organic carbon stored per unit area, storing on average 32 kg C $m^{-2}$ worldwide (Batjes, 1996). Further information on site conditions can be found in Sigurdsson et al. (2005).

In 2005 mean annual air temperature at Vallanes was 4.1 °C (Fig. 2) and the mean annual precipitation was 605 mm. The mean 24-h temperature varied between 12.2 °C in July to −0.9 °C in February and the mean maximum daytime temperatures were 13.7, 17.4 and 13.1 °C in June, July and August, respectively. The warmest air temperature was measured on the 15th of July, 22.9 °C, while the coldest was −14.3 °C on the 5th of February (Fig. 2). The surface soil layer froze in early October and thawed in mid-April. The soil at 30 cm depth did not freeze until late December and thawed in the end of May (Fig. 2).

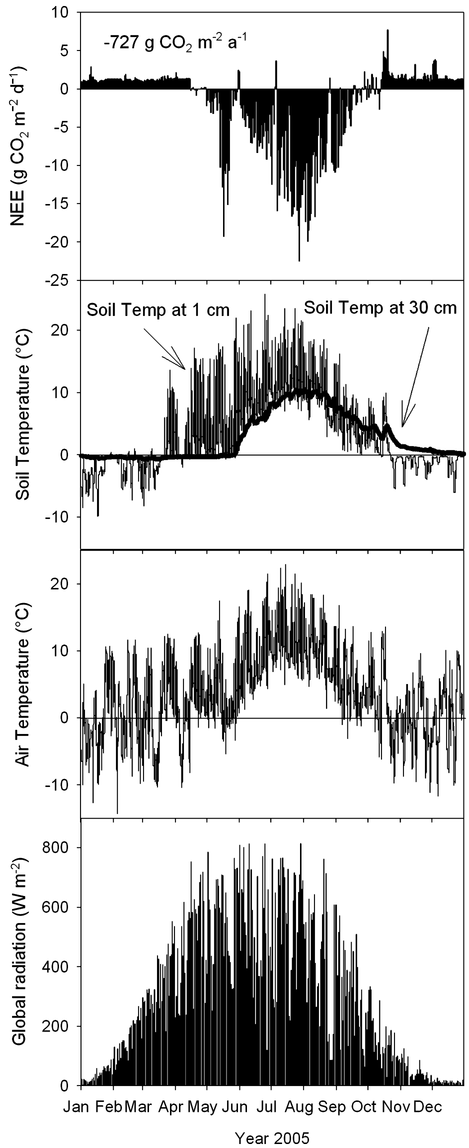


*Fig. 2.* Daily NEE and climatic characteristics (global radiation, soil and air temperatures) for 2005 in Vallanes.

## 2.2. Eddy covariance measurements

Eddy covariance measurements started in Vallanes in September 2003 and will continue through the year 2007. Here we present data for 2005. The eddy covariance system was mounted at a height of 4.5 m in a 7 m high mast located centrally in the 60 ha plantation. The wind mainly comes from north and south and the fetch, that is, the distance from the mast to the end of the stand is approximately 300 m in each direction. The plantation is typical for afforestation areas in Iceland, containing not only one homogeneous vegetation cover but also some patches of mire and inactive rock surfaces.

The eddy covariance system (Insitu Flux Systems AB, Ockelbo, Sweden), was an open path system with an LI-7500 $CO_2/H_2$ O infrared gas analyser (LI_COR, Lincoln NE, USA) and Gill Solent R3 3-d sonic anemometer (Gill Instruments, Lymington Hampshire, UK). It was remotely controlled, with power provided by a gasoline generator and two 100 W wind generators. The generator was stationed in the most uncommon wind direction relative to the flux tower. The system measured the exchange rates of $CO_2$, $H_2O$, sensible heat flux and friction velocity ($u^*$). Sampling was made at 20 Hz. The data were averaged for 30-min periods, using linear detrending with the EcoFlux (In Situ Flux Systems AB) software.

An automatic weather station was an integral part of the eddy system, with weather data stored in a Campbell CR10X datalogger (Campbell Scientific Ltd.). Air temperature and humidity were measured at 2 m height (Rotronic Hydroclip), soil temperature was measured at depths of 1, 10 and 30 cm (TO3R Tojo soil temperature sensors), soil moisture was measured at 5–10 cm depth (Watermark 257 soil water potential sensor), soil heat flux was measured at two locations at 1 cm depth (HFP01 SC Hukseflux thermal sensors), and net radiation and global radiation were measured at a height of 6.0 m (Kipp & Zonen NR Lite net radiometer and LI-200SZ Pyranometer). Precipitation data were taken from an official Icelandic Meteorological Institute weather station, located about 10 km northwest of the study site (Egilsstadir). Due to technical problems, two breaks in the meteorological measurements occurred during 2005, one in late June (6 d) and the other at the end of November (4 d). In these cases, air temperature data from the Egilsstadir weather station were utilized.

### 2.3. Biomass and soil carbon stock

The estimation of the change in living biomass was based on tree measurements. The trees were measured on 8 randomly placed 100 $m^2$ circular plots. The measured quantities were diameter at 0.5 and 1.3 m height and the height of the living crown. The tree stand characteristics were then used to estimate the biomass of various tree stand components (stems, branches, needles and total biomass) using site-specific biomass functions (Brinker, 2007). From these we calculated dry mass and carbon accumulation in the plantation during the study period. The carbon content of the dry mass was assumed to be 50% (Snorrason et al., 2002).

The leaf area index (LAI) of the forest canopy and the forest floor vegetation was measured three times during the growing season with a pair of LAI-2000 Plant Canopy Analyzers (LI-COR, Inc., NE). One instrument was placed in a nearby clearing and the other was used to take readings within the stand. Measurements were made during an overcast day, sensor heads always faced north, and a 180° lens cap was used. About 200 points, distributed along eight 50 m long transects, were measured.

Physical and chemical properties of the soil were measured at a depth-interval of 0–10, 10–20 and 20–30 cm. A soil drill was used to collect cores from subplots (24 samples total). The samples were dried at 85 °C for 48 h and analysed at the Center of Chemical Analyses (ICETEC), Reykjavik, Iceland. Soil samples were also taken for comparison from an adjacent open heathland pasture (Vikingsstadir; Fig. 1), which is comparable to the Vallanes site prior to afforestation in 1992. Samples for determining bulk density were taken from soil pits that were dug at all subplots. In order to estimate the soil C stock, the soil bulk density (g DM $cm^{-3}$) and repeated measurements of soil depth were used to convert the concentration of C to C stock per area in the top 30 cm soil layer.

During the growing season, soil respiration was measured three times with a portable closed-path EGM-4, $CO_2$ infrared gas analyser (PP Systems, Hertfordshire, UK) with blackened CPY-2 canopy assimilation chamber (15 cm diameter). For measuring always the same points, permanent plastic collars were installed in May 2005 and the vegetation inside was left intact. Each time, measurements were made at 40 points in each surface type within the ecosystem (forest floor, mire and inactive rock).

### 2.4. Data processing and gap filling

Total flux data cover for 2005 was 75%. Most of the gaps were related to technical failure of the generator that powered the instruments and most of them also occurred during the winter period. The extend of the longest data gap was 22 d (18 January–9 February). A WPL correction was applied to correct for latent heat and air density fluctuations (Webb et al., 1980). The flux data were then quality checked, screened for spikes and an abnormally high difference in vapour pressure measured by the sonic anemometer and the Rotronic Hydroclip. Turbulent conditions were never considered to be insufficient in this young plantation, since no relationship between friction velocity ($u^*$) and NEE was obtained (Fig. 3). This may be explained by the high average wind speed at the measurement site (in 2005, 4.2 m $s^{-1}$) and the openness of the site. The atmospheric storage term was calculated from the concentration data measured at the height of 4.5 m and added to the measured NEE. In most cases the storage term was found to be negligible, also because of the openness and low dominant height in the plantation. A positive value of NEE indicates flux from the ecosystem to the atmosphere and a negative value indicates uptake of $CO_2$ from the atmosphere to the ecosystem. In addition, low but apparent spikes of $CO_2$ uptake during the off-season period (15 October–15 April) were removed. This step will be further addressed in the results and discussion sections. These later removals reduced the data cover during the whole year down to approximately 65%.

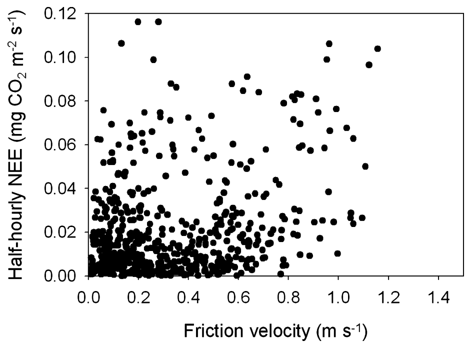


*Fig. 3.* Half-hourly NEE versus friction velocity at Vallanes in 2005 during four winter months (November–February).

Further quality checking of the data was done by analysing the energy balance closure of the site. Available energy, estimated as net radiative flux density ($R_n$) minus the soil heat flux density ($G_s$), was compared with the sum of the turbulent fluxes of heat (H) and latent heat (LE) from the eddy covariance system (Aubinet et al., 2000). The energy balance of the measurement site was found acceptable with a closure of 83% (Fig. 4). The intercept for the site was 8.6 W $m^{-2}$ and the maximal levels of $R_n$, H, LE and $G_s$ during the mid-growing season were 445, 305, 191 and 61 W $m^{-2}$, respectively.

We also compared independent chamber flux measurements from soil respiration campaigns made at the site with the flux measurements from the tower (Fig. 5). For this comparison an additional correction was made to the measured eddy covariance fluxes, namely the so-called 'Burba' correction (Burba et al., 2006). The empirical Burba correction is caused by the fact that the open path gas analyser experiences additional heat dissipation from the body of the sensor which in turn can affect the measurement of the $CO_2$ concentrations. It has been

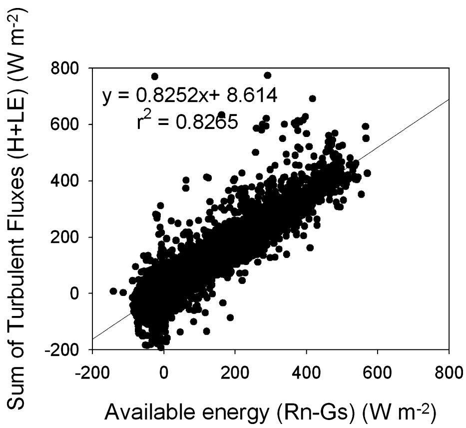


*Fig. 4.* Energy balance for 2005 of a young *Larix sibirica* plantation in eastern Iceland.

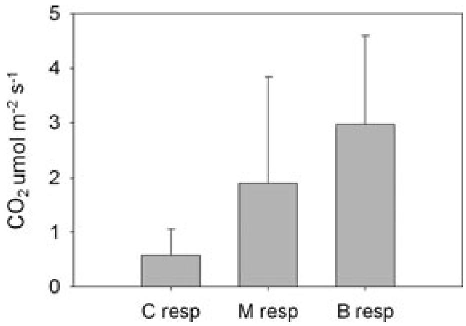


*Fig. 5.* Comparison of measured daytime soil respiration on 3 July ($n = 25$) and measured night-time flux during 1–4 July ($n = 21$). Soil respiration is represented as *C*, measured flux as M and Burba corrected flux as *B*. The soil respiration is a weighted average of measurements on three different surface types. Error bars indicate the standard deviation.

suggested that this correction, which is an additional WPL term, should be applied to flux measurements with open path sensors. The tower measurements were based on night-time fluxes ($R_e$) for the same nights for which the soil respiration had been measured during the daytime. The soil respiration from the chamber measurements was estimated as an area-weighted average from the three main surface types in the ecosystem: mire, inactive rock and forest floor. The up-scaled chamber measurements were lower than both of the tower flux estimates (Fig. 5), with the Burba corrected values being the highest. Based on this comparison and the unrealistically high efflux values that the Burba correction produced for our site in general, it was decided not to use it for the annual C balance calculations for Vallanes.

To be able to calculate the annual $CO_2$ balance for the site, the gaps in the data had to be filled. Ecosystem respiration ($R_e$) was estimated using a temperature-dependent function based on night-time fluxes (Lloyd and Taylor, 1994; Falge et al., 2001) according to the following equation:

$$R_e = R_{ref} \exp\left[E_0\left(\frac{1}{273 - 227.13} - \frac{1}{K - 227.13}\right)\right], \qquad (1)$$

where $R_{ref}$ is a parameter describing the total respiration rate at the reference temperature, $E_0$ is a coefficient for ecosystem respiration and $K$ is the best-fitting temperature in Kelvin. Before fitting eq. (1) to the data, all daytime values were removed to guarantee high data quality. During winter, (15 October–15 April) the reference temperature was set to 0 °C. Soil temperature at 10 cm gave the best correlation for the winter period (ANOVA $p < 0.001$, $r = 0.32$, $r^2 = 0.11$). During the growing season, (16 April–14 October) the ecosystem respiration was also parametrized by eq. (1). The parametrization was done separately for three periods: spring, summer and autumn. The reference temperature during the summer was set to 10 °C and the best correlation for all periods was found with soil temperature at 10 cm. Equation (1) significantly fitted the measured data in all cases ($p < 0.001$) and r was 0.28, 0.21, 0.29 and $r^2$ was 0.08, 0.05 and 0.08 for spring, summer and autumn, respectively. The daytime $R_e$ and the gaps in the night-time values were estimated for the whole year, based on these four $R_e$ functions. For the growing season (16 April–14 October), Gross primary production (GPP) was estimated by subtracting the measured NEE from the modelled $R_e$. GPP was fitted by a light response curve (Roberntz and Stockfors, 1998):

$$\mathrm{GPP} = \frac{\alpha I_i + \mathrm{GPP_{max}} - \sqrt{(\alpha I_i + \mathrm{GPP_{max}})^2 - 4\alpha I_i \mathrm{GPP_{max}}\theta}}{2\theta} - R_e, \qquad (2)$$

where $\alpha$ is the quantum yield, $\mathrm{GPP_{max}}$ is the light saturated GPP in $\mu$mol m$^{-2}$ s$^{-1}$, $\theta$ is the convexity (unitless, 0–1), $R_e$ is the ecosystem respiration in $\mu$mol m$^{-2}$ s$^{-1}$, and $I_i$ is irradiance (global radiation) in W m$^{-2}$. Before the light response of GPP was found, the growing season was divided into the same three periods as for eq. (1) and all night values were removed. The light relationship was highly significant for both summer and autumn ($p < 0.001$, $r$ was 0.68 and 0.71 and $r^2$ was 0.46 and 0.50, for summer and autumn, respectively), but the spring period parametrization had to be done in three smaller steps due to frost damage that greatly decreased the uptake in mid-May. Where data were missing, the gaps in NEE were filled by subtracting the modelled $R_e$ from the modelled GPP.

## 3. Results

### 3.1. Ecosystem $CO_2$ fluxes and annual carbon balance

The gap-filled, daily NEE data for 2005 are shown in Fig. 2. By summing up the daily $CO_2$ balance over the whole year, an annual carbon sequestration of $-727$ g $CO_2$ m$^{-2}$ a$^{-1}$ was obtained. The daily NEE varied from about +7.7 to $-22.5$ g $CO_2$ m$^{-2}$ d$^{-1}$ with the greatest $CO_2$ loss on 20 October and the greatest $CO_2$ uptake on 28 July.

From mid-October to mid-April, the daily $CO_2$ loss was on average +1.5 g $CO_2$ m$^{-2}$ d$^{-1}$, not showing much seasonal variation. In mid-April, when the daily average temperature started

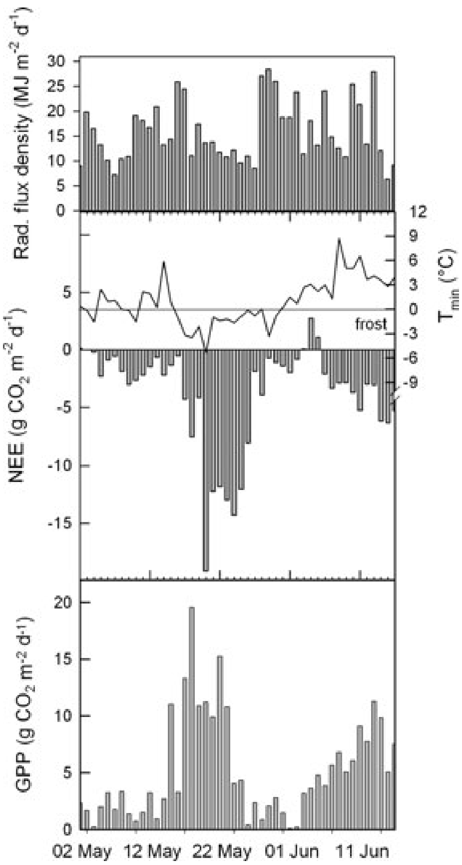


*Fig. 6.* Daily irradiance (MJ $m^{-2}$ $d^{-1}$), minimum temperature ($T_{min}$), gross primary production (GPP) and net ecosystem exchange (NEE) of an young *Larix sibirica* plantation in eastern Iceland during a 6 week period in spring 2005.

to rise above zero and the soil had started to thaw the first days of daily net uptake became apparent (Fig. 2). The $CO_2$ uptake (negative NEE values) increased steadily to mid-May, indicating rising activity and leaf area both by trees and understory (Fig. 2). However, during 16–19 May the air temperature dropped below zero for a period of 4 d (minimum temperature $-5.4$ °C). This late spring frost clearly affected the assimilation of the vegetation and a sharp decline in GPP was observed (Fig. 6). Both the carbon uptake (GPP) and the carbon balance (NEE) of the plantation dropped to zero and then slowly started to increase again (Fig. 6). It took some weeks for the ecosystem to reach previous GPP and NEE values at given irradiance and temperature as were observed before the frost event (Fig. 6).

As the summer progressed, the daytime $CO_2$ uptake increased with a peak in late July (Fig. 2). Some days of daily $CO_2$ loss were observed on cloudy and rainy summer days. In the latter half of August, NEE started to decrease along with decreasing temperature and irradiance (Fig. 2). For the last 3 months of the year, the ecosystem was again loosing $CO_2$, without showing any clear diurnal variation.

### *3.2. Carbon stock in soil and biomass*

Compared to an adjacent and comparable treeless heathland pasture, the afforestation area had 1000 g $m^{-2}$ more carbon in the top 30 cm of the soil (Table 2). This equals a net annual $CO_2$ sequestration of 280 g $CO_2$ $m^2$ $a^{-1}$, since the site was established in 1992. This difference was, however, not significant due to high within-site variability (One-way ANOVA, $p = 0.492$). Allometric analysis of aboveground tree growth in 2005 resulted in a total C stock of 231 g C $m^{-2}$. Therefore, the annual accumulation in stem- and branchwood resulted in a sequestration of 65 g $CO_2$ $m^{-2}$ $a^{-1}$. When compared to the treeless site, the ground vegetation C stock at Vallanes was 258 g C $m^{-2}$ resulting in a sequestration of 23 g $CO_2$ $m^{-2}$ $a^{-1}$ since the time of afforestation (Sigurdsson et al., 2005). Other ecosystem carbon stocks that are not reported here are litter and roots, which are both likely to have increased following the afforestation.

## 4. Discussion

### *4.1. Evaluation of findings*

The Vallanes plantation sequestered 727 g $CO_2$ $m^{-2}$ in 2005, or 198 g C $m^{-2}$, according to the eddy flux measurements (Fig. 2). Recent flux measurements distributed over many boreal forest stands, with a range of stand age, species and management histories, have generally yielded annual carbon balances that vary between 370 g $CO_2$ $m^{-2}$ $a^{-1}$ efflux and 1270 g $CO_2$ $m^{-2}$ $a^{-1}$ sequestration (e.g. Malhi et al., 1999; Suni et al., 2003; Saigusa et al., 2005). Much higher net ecosystem exchanges have also been observed, for example, 2830–3450 g $CO_2$ $m^{-2}$ $a^{-1}$ in a Sitka spruce plantation in Scotland (Black et al., 2005). It can be stated that the present study falls well within the observed range of annual NEEs.

A recent review on flux measurements by Hyvönen et al. (2007) concluded that young forest stands (<25-year old) are generally stronger C sinks than old stands and that NEE usually peaks at an age varying from 10 to 60 yr in different forest types. Because of the site preparations at Vallanes, which included ploughing, it was not expected that the plantation would be such a strong carbon sink. Recent studies that have evaluated the NEE of forest plantations of different ages have generally found that initially after harvest and site preparation there is a period of negative carbon balance (annual efflux) before the trees have produced a new canopy (Kowalski et al., 2004). When Vallanes was protected from grazing of livestock and afforested, there was a rapid increase in ground vegetation (Sigurdsson et al., 2005) that may have amplified the carbon uptake at the site. In the other flux study conducted over an afforestation area in Iceland, a 7-year-old plantation of fast growing black cottonwood, an annual C sequestration of ca. 370 g $CO_2$ $m^{-2}$ was found (Valentini et al., 2000). These results are in good agreement with the present study.

*Table 2.* Soil characteristics at the afforested area (Vallanes) and a comparable heathland (Vikingsstadir)

| | Depth cm | Bulk density (g $cm^{-3}$) | C (mg $g^{-1}$) | N (mg $g^{-1}$) | C/N ratio | C (kg $m^{-2}$) |
|---|---|---|---|---|---|---|
| Vallanes | 0–10 | 0.64 | 81.53 | 4.27 | 19 | 5.2 |
| | 10–20 | 0.87 | 41.19 | 2.62 | 16 | 3.6 |
| | 20–30 | 0.87 | 30.32 | 2.20 | 14 | 2.6 |
| Vikingsstadir | 0–10 | 0.53 | 98.44 | 4.66 | 21 | 5.2 |
| | 10–20 | 0.61 | 46.96 | 3.14 | 15 | 2.9 |
| | 20–30 | 0.61 | 37.00 | 2.51 | 15 | 2.3 |

The eddy covariance measurements of NEE should be equal to the sum of all separate $CO_2$ sinks or sources in the ecosystem. By carrying out additional tree growth, harvest measurements and soil coring, it was found that the Vallanes plantation was indeed a net sink for $CO_2$. The top 30 cm of the soil of the plantation contained on average 1000 g C $m^{-2}$ more than in the adjacent pasture (Table 2); this equals about 3700 g $CO_2$ $m^{-2}$ or ca. 280 g $CO_2$ $m^{-2}$ $a^{-1}$ sequestration since the afforestation took place in 1992. This change was, however, not statistically significant so we can only claim that there was no indication for a net C loss from the soil compartment. It is highly likely that the soil was a net source during the first year after the initial site preparation and the soil C sequestration may, therefore, have been considerably higher in the more recent years. The trees and the understory added 65 and 27 g $CO_2$ $m^{-2}$ $a^{-1}$, respectively. An unknown factor here is the increment of roots and additional contribution by litter from trees as well as from ground vegetation, which also contributes to the build-up of the carbon pool (Snorrason et al., 2002).

The year 2005 in Vallanes was slightly warmer and drier than a normal year. The mean annual temperature for 1961–1990, of a near-by synoptic station at Hallormsstadur, was 3.4 °C and the mean annual precipitation 738 mm (The Icelandic Meteorological Office, pers. comm.). The conditions were, therefore, favourable for tree growth. The assimilation of the ecosystem started at the end of April but was then greatly affected by the spring frost in mid-May. The frost mainly affected NEE via loss of photosynthesis (GPP), probably both because of physical loss of newly flushed leafs and needles, and because of damages of the photosynthesis system of perennial foliage of understory plants (dwarf bushes and moss). Interestingly, it takes the ecosystem some time to reach the same assimilation rate again. The annual $CO_2$ sequestration in 2005, therefore, would have been larger if there had not been the frost spell in May (Fig. 6). How much larger, would be an interesting study to make, with the help of a process-based simulation model such as BIOMASS (McMurtrie et al., 1990; Bergh et al., 2003).

Other stock-change studies done on Siberian larch in Iceland have reported carbon accumulation in the top 30 cm layer in three 16–35-year-old afforestation sites (Snorrason et al., 2002). The aboveground part of the 13-year-old trees in Vallanes only sequestered 65 g $CO_2$ $m^{-2}$, or 9% of the measured annual $CO_2$ sink. In an earlier study done in Iceland on a black cottonwood plantation at a similar developmental stage (Valentini et al., 2000), only ca. 15% of the annual $CO_2$ sequestration was accumulated in the trees (Sigurdsson, 2001). As the trees grow and start to dominate the carbon uptake, more of the assimilated carbon is likely to be stored in woody biomass. A Japanese study on a 50-year-old cool-temperate deciduous forest growing on volcanic soils showed that ca. 26–39% of the measured NEE could be explained by the aboveground growth of trees (Ohtsuka et al., 2005; Saigusa et al., 2005). In a dense Sitka spruce stand in Scotland with LAI of 8.7 as much as 85% of the measured flux was explained by accumulation in the woody biomass (Black et al., 2005). In the present study, the ecosystem had most likely not yet reached stabilization after the change of land use, that is, changing from a heavily grazed heathland to a protected afforested area. Such a land-use change has been shown to increase ground vegetation productivity during a period before the planted trees reach canopy closure and overstory shading reduces its growth potential (Sigurdsson et al., 2005). It is therefore not unrealistic that most of the measured NEE was stored in the surface and belowground compartments, but not in aboveground woody biomass.

### 4.2. *Evaluation of possible errors in estimation of annual carbon balance*

Closure of the energy balance is a useful parameter to check the reliability of a data set (Aubinet et al., 2000). At our site the energy balance closure (83%) was found to be in the same order as for many other sites (e.g. Wilson et al., 2002). Considering the uncertainty of the other measurements, that is, net radiation and soil heat flux, which typically are in the order of 10%, the energy balance closure is considered satisfactory.

The annual balance can be affected by several possible errors, with the gap-filling of missing data being one of the most likely sources of error. To minimize the error we used four seasonal temperature response curves to estimate $R_e$. This approach has been commonly used when flux data are gap-filled (Falge et al., 2001; Black et al., 2005). Due to the maritime climate conditions in Iceland, the variation in the temperature data was relatively low and the range in night-time efflux values (+NEE) was relatively small. This made it impossible to divide the winter into different seasonal models. Even if the different $R_e$ models were highly significant, their explanatory power was typically only around 10–20% of the observed variability in the night-time fluxes. The modelling of the daytime GPP was easier and gave much better correlations because of the larger range in both flux and irradiance.

Another possible source of error is related to the open-path gas analyser used in the flux measurements in the present study. Recently, Burba et al. (2006) indicated that there may be a small error in winter fluxes, related to internal heat dissipation from the open path analyser. These errors can cause a false carbon uptake measurement, especially in cold climates. In the process of quality checking the present data, some instances of small uptake peaks were observed during the off-season and dark nights. Burba et al. (2006) also made a correction to apply to flux data. When this correction was tried on all measured values from 2005, it resulted in an unrealistic 230% change in the annual balance, turning the plantation into a strong $CO_2$ source. It certainly removed all uptake of $CO_2$ during off-season periods but it also greatly affected both winter and summer fluxes (data not shown). When we compared our data with independent soil respiration measurements made at the site, the Burba corrected flux values were found to deviate more than uncorrected values (Fig. 5). Also, harvest measurements and soil coring did not indicate that the site was a net source of $CO_2$. The Burba correction, which does not contain any wind speed dependent term, therefore did not seem to be applicable to our site conditions, possibly because of the frequent high wind speeds.

The representativeness of the flux measurements with respect to source area in relation to the surrounding vegetation was checked by applying the simple footprint model of Kljun et al. (2004) for a number of typical weather conditions. The 90% value was found to be well within the boundary of the stand for most conditions (data not shown), the reason being the low measurement height and the large roughness of the open site. We thus conclude that the footprint question hardly contributed to the uncertainty in the measured annual budget.

## 5. Conclusions

These first published year-round measurements on $CO_2$ exchange above an afforested Siberian larch plantation in Iceland show that the ecosystem was a strong sink 13 yr after site preparation. Only 12% of the total sequestration was explained by the accumulation in the aboveground part of the trees and understory. In order to get a more reliable insight into the carbon balance of young afforestation areas, the net carbon accumulation in litter, roots and soil should be studied in more detail. Furthermore, longer time series of data needs to be analysed to validate the findings of this paper, since weather variability clearly affected the results.

The seasonal carbon uptake was greatly affected by a late spring frost. Such spring frost spells are expected to become more frequent in Scandinavia with warmer future climate. The effect of such a phenomenon on the annual carbon balance of boreal forests should therefore be studied further.

There is a need to further develop the correction for small error in winter and night fluxes related to internal heat dissipation from open-path analysers. In our cool, windy and oceanic climate the Burba correction resulted in unrealistic 230% change in the annual balance, with substantial changes occurring both in winter and summer.

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