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Seasonal and annual variation of carbon fluxes in a young Siberian larch *(Larix sibirica)* plantation in Iceland

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Abstract

This study reports 3-year measurements (2004–2006) of net ecosystem exchange (NEE) over a 12–14 year old Siberian larch forest in Iceland established on previously grazed heath land pasture that had been site-prepared prior to planting. The study
5 evaluated interannual and seasonal variation of NEE and its component fluxes, gross primary production (GPP) and ecosystem respiration (R_e), with the aim to clarify how climatic factors controlled the site's carbon balance. The young plantation acted as a relatively strong sink for CO_2 during all of the three years, with a net sequestration of −375, −566 and −245 g CO_2 m^{-2} for years 2004, 2005 and 2006, respectively. The
10 annual carbon balance was strongly influenced by climatic factors leading to a high inter-annual variability in NEE. This variation was more related to variation in carbon efflux (R_e) than carbon uptake (GPP). The abiotic factors that showed the strongest correlation to R_e were air temperature during the growing season and soil water potential. The GPP mostly followed the seasonal pattern in irradiance, except in 2005,
15 when the plantation experienced severe spring frost damage that set the GPP back to zero. It was not expected that the rather slow-growing Siberian larch plantation would be such a strong sink for atmospheric CO_2 only twelve years after site preparation and afforestation.

1 Introduction

20 Net ecosystem exchange (NEE) between the biosphere and the atmosphere results from the difference between two large fluxes: ecosystem respiration (R_e) and gross primary production (GPP). Since GPP and R_e have partially distinctly different responses to climate drivers (e.g. Reichstein et al., 2007), and since the response to fluctuating environmental conditions is complex, a small change in either process can significantly
25 impact the net exchange. It is therefore of importance to acquire a detailed understanding of the underlying processes which govern ecosystem function.

Numerous studies on fluxes of CO_2 using the eddy covariance technique have been conducted and much new insight into the processes that control the exchange of CO_2 has been gained (Valentini et al., 2000; Black et al., 2005; Hyvönen et al., 2007). Measurements of environmental drivers, such as temperature, irradiance, precipitation and soil water status provide the data necessary to investigate how variation in these factors drive variation in NEE, GPP and R_e (e.g. Lindroth et al., 1998; Lagergren et al., 2008). The variation is complex and operates on seasonal, interannual and longer time scales.

In the past century, the global temperature has risen by 0.74°C and precipitation patterns have changed (IPCC, 2007). In the northern boreal zone, annual temperature has risen and precipitation has increased (e.g. Heimann and Reichstein, 2008). The IPCC (2007a) predicts that northern latitudes will continue to warm more rapidly than the global average in the 21st century. Most of the warming is predicted to take place during winters (IPCC, 2007), when vegetation is dormant. Various modelling studies have indicated that a warmer and a more variable winter climate may both disturb tree phenology (e.g. Linkosalo et al., 2000) and increase R_e more than GPP, leading to an annual decrease in NEE (Medlyn et al., 2005; Hyvönen et al., 2007).

Many previous studies have identified key factors regulating the NEE of northern forests, such as the onset of warming in the spring (Black et al., 2000), time of soil thaw and snowmelt (Goulden et al, 1998), length of the growing season (Carrara et al., 2003), site management (Hyvönen et al., 2007), stand age (Lagergren et al., 2006; Tang et al., 2009), and disturbance (Lindroth et al., 2009). Lindroth et al. (2008) showed that leaf area index (LAI) explained most of the between site differences in parameters controlling photosynthesis and respiration in northern forest ecosystems. Recently Magnani et al. (2008) also demonstrated the strong impact of nitrogen deposition on the NEE averaged over the whole rotation length. The impact of drought on CO_2 exchange in several European forests was demonstrated by Granier et al. (2007) and Dunn et al. (2007) showed that water table depth influenced inter annual variation of the carbon budget of a black spruce forest in Canada.

Measurements of in situ CO_2 gas exchange in Iceland are scarce. Magnússon (1992) and Sigurdsson (2009) measured R_e, GPP and NEE on a young volcanic island and Cook et al. (1998) measured photosynthesis of plants around natural CO_2 springs in western Iceland. Most other gas exchange measurements have been made in forest or woodland ecosystems. A black cottonwood (*Populus trichocarpa*) plantation has been intensively studied, including both component and eddy covariance fluxes (Valentini et al., 2000; Falge et al., 2002; Law et al., 2002; Sigurdsson et al., 2002; Bergh et al., 2003; Jónsson, 2007). Furthermore, some studies have been conducted in downy birch woodlands (Guðmundsdóttir and Sigurdsson, 2005). Finally Bjarnadottir et al. (2007a) and Lindroth et al. (2008) reported on one-year NEE measurements on the same Siberian larch plantation as presented in this paper.

Forests and woodlands in Iceland covers ca. 157 000 ha, whereof 1/4 is planted forest (Traustason and Snorrason, 2008). During the past 20 years, Siberian larch has been the most planted tree species in Iceland. Currently, the total rate of afforestation is ca. 2500 ha per year, with Siberian larch, native downy birch (*Betula pubescens* Ehrh.) and Sitka spruce being used in similar proportions, accounting for 65% of the total annual afforestation (Gunnarsson, 2008). The use of Siberian larch in forestry in the Nordic countries is in general very limited (Lyck and Bergstedt, 2004). The Siberian larch is, however, one of the economically and ecologically most important tree species in Russia, where it covers nearly 14% of the total forest area (Lyck and Bergstedt, 2004). It is therefore a key species to study in terms of the global carbon balance.

According to the Kyoto protocol, carbon sequestration of all afforested areas since 1990 should be deducted from national greenhouse gas (GHG) emissions (UNFCCC 1998). A total of 67% of the afforestation in Iceland has taken place since 1990 (Gunnarsson, 2008). Iceland is also a country with a small population and the total annual GHG emissions only amount to ca 3500 Gg CO_2 (Ministry for the Environment, 2006). Therefore even a small increase in afforestation area can play a large role in Iceland,

probably more than in most other countries. The present study took place in an af-
forested area, planted in 1992, and is thus defined as a "Kyoto-forest".

The aim of the present study was to investigate the carbon balance of a recently
(∼13 year) afforested heathland in eastern Iceland, in order to determine its sink or
source strength. Furthermore, the aim was to better understand the processes affect-
ing the carbon balance and the responses to environmental forcing on instantaneous,
seasonal, annual and interannual timescales.

2 Material and methods

2.1 Site description

The study took place in an afforested area in East-Iceland, named Vallanes. The site
was a grazed heathland pasture prior to its afforestation in 1992. In 1991 the site was
protected from livestock grazing and site-prepared by a Finnish TTS-10 disc trencher
(TTS Forest Oy, Finland). The trencher scrapes vegetation off the surface and creates
pairs of continuous furrows 10–20 cm deep and 20–40 cm wide and mounds the spoil
into a ridge about 20 cm high. In spring 1992 the site was planted with Siberian larch
(*Larix sibirica* Ledeb.), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var *. contorta*)
and Sitka spruce (*Picea sitchensis* (Bong.) Carr) in 95:4:1 mixture. Further information
on site conditions can be found in Table 1, Sigurdsson et al. (2005) and Bjarnadottir
et al. (2007a). The ground vegetation consists mainly of dwarf shrubs (*Betula nana* L.
and *Vaccinium uliginosum* L.), grasses and bryophytes (Sigurdsson et al., 2005). The
soil type in Vallanes is Brown Andosol (volcanic soil), one of the most common soil
types in Iceland (Arnalds, 2004).

2.2 Annual tree growth and leaf area index

Annual growth was estimated from tree measurements. The trees were measured on
eight randomly placed 100 m^2 circular plots each year. The measured quantities were

diameter at 0.5 and 1.3 m height and the height of the living crown. These variables were used to estimate the biomass of various tree stand components (e.g. needle and total biomass) using site-specific biomass functions (Bjarnadottir et al., 2007b). Needle biomass was converted to maximum annual tree leaf area by using weighted average specific leaf area (SLA; 7.7 m^2/kg DM) determined for three canopy layers on 30 sample trees. Maximum annual leaf area index (LAI) was derived by adding information about average stand density (trees per m^2).

The seasonal course of leaf area index (LAI) of the forest canopy and the forest floor vegetation was measured several times during the growing season each year, with a pair of LAI 2000 Plant Canopy Analyzers (Li-Cor Inc., Lincoln, NE, USA). One instrument was placed in a nearby clearing and the other was used to take readings within the stand. About 200 points distributed along eight 50 m long transects, were measured.

2.3 Environmental variables

Basic meteorological data, such as air temperature, soil temperature, precipitation, net and global radiation and soil heat flux were collected at the site. Technical problems occurred several times during the measurements, which led to data loss. In such cases, data from the Egilsstadir synoptic station, 12 km away, were used. A detailed description of the meteorological instrumentation can be found in Bjarnadottir et al. (2007a).

2.4 Flux measurements

Eddy covariance measurements at the experimental site Vallanes, started in late 2003. This paper presents continuous data for three years, 2004–2006. As described by Bjarnadottir et al. (2007a), CO_2 exchange was measured by the eddy covariance technique. The eddy covariance system was an open path system with and LI-7500 CO_2/H_2O infrared gas analyzer (LI_COR, Lincoln NE, USA) and Gill Solent R3 3-d sonic anemometer (Gill Instruments, Lymington Hampshire, UK). The system was mounted

at the height of 4.5 m in a 7 m high mast located centrally in the 60 ha plantation (Table 1). It measured exchange rates of CO_2, H_2O, sensible heat flux and friction velocity (u^*), with a sampling rate of 20 Hz. The data were averaged for 30-min periods, using linear detrending with the EcoFlux (In Situ Flux Systems AB) software.

2.5 Analysis

Total flux cover during three years of measurements was 70%. A WPL correction was applied to correct for latent heat and air density fluctuations (Webb et al., 1980). The flux data were quality checked, screened for spikes and an abnormally high difference in vapour be pressure data obtained between the gas analyser and the relative humidity and temperature sensor (Hygroclip, Rotronic, Switzerland). Turbulent conditions were not considered to be insufficient since no relationship between friction velocity (u^*) and NEE was obtained. This may be explained by the high average wind speed and the openness at the measurement site. The atmospheric storage term was calculated from the CO_2 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, because of the openness and low dominant height in the plantation. Further quality checking of the data was done by analysing the energy balance closure of the site (e.g. Aubinet et al., 2000). 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, for all the three years. The energy balance of the measurement site was found acceptable with a closure of 81%, 83% and 89% for 2004–2006, respectively (data not shown).

Burba et al. (2006) pointed out that open path analysers may show small negative winter and night fluxes as an effect of internal heat dissipation from the analyser's head. Therefore, low but apparent spikes of CO_2 uptake during off season periods were removed. In order to calculate the annual CO_2 balance, gaps from technical problems and quality check filtering, had to be filled.

Gaps of less than two hours were filled by linear interpolation between earlier and

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later measurements. Longer gaps were filled by calculating NEE from its component fluxes, ecosystem respiration (R_e) and gross primary production (GPP), that were modelled from meteorological data with nonlinear regressions using Sigmaplot 2008 (v. 10.0; SPSS Inc.IL, USA) statistical package.

Each year of data was divided into four intervals (winter: 16 October–15 April, spring: 16 April–15 June, summer: 16 June–15 August and autumn: 16 August–15 October) and R_e and GPP were modelled separately for each period. Ecosystem respiration ($g\,CO_2\,m^{-2}\,30\,min^{-1}$) was modelled from measured temperature with a temperature-dependent function (Lloyd and Taylor, 1994; Falge et al., 2001) that was derived from night-time fluxes:

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

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 fit temperature in Kelvin. During winter time, the reference temperature was set to $0°C$, whereas during the growing season the reference temperature was set to $10°C$.

Gross Primary Production ($g\,CO_2\,m^{-2}\,30\,min^{-1}$) was calculated from daytime NEE by adding to it R_e from Eq. (1) for each 30 min period. Light response of GPP was then modelled from measured irradiance by a light response curve (Roberntz and Stockfors, 1998):

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

where α is the quantum yield, GPP_{max} is the light saturated GPP in $\mu mol\,m^{-2}\,s^{-1}$, θ is the convexity (unitless, 0-1), and I_i is irradiance (global radiation) in $W\,m^{-2}$.

Daytime gaps in NEE were then filled with:

$$NEE_{day} = GPP + R_e, \tag{3}$$

In May 2004, data was missing for 29 consequent days in May, which left too little data for Eq. (2) to be fitted. Therefore, Eq. (2) from the summer period was used with a scaling factor that represented the seasonal course of LAI during the spring period. Two point measurements of LAI (see earlier) were available from this period as well as photographs taken at regular intervals. The LAI development in spring 2004 was reconstructed from these data, and was best described by a sigmoid curve. In spring 2005, GPP$_{max}$ was strongly affected by a frost spell and therefore Eq. (2) had to be fitted separately for early and late spring.

2.6 Statistical analysis

Linear regression analysis was used to study which physical factors were best correlated with the seasonal and annual carbon fluxes (SigmaPlot 2008, v 10.0).

3 Results

3.1 Seasonal variation in physical factors

The climate in Vallanes during the study period was typical for the maritime climate that characterizes Iceland; rather short, cool summers and relatively mild winters (Fig. 1). The irradiance clearly showed the northern location of the site (64° N), with short days in December only receiving ca. $0.08\,\mathrm{MJ\,m^{-2}\,day^{-1}}$, and 24-h light at midsummer, with ca. $28.5\,\mathrm{MJ\,m^{-2}\,day^{-1}}$ during clear days (Fig. 1a). The daily mean air temperature fluctuated around zero°C during winter, not going below −13°C over the measurement period (Fig. 1b). The minimum 30-min air temperature recorded was −17.1°C in November 2006. The 10–30 cm soil layer typically froze in early October and thawed in mid-April, while the surface soil froze and thawed as air temperature fluctuated around zero (Fig. 1c). The daily mean air and surface soil temperature in summer did generally not exceed 15°C (Fig. 1b and c), while maximum 30-min air temperature was 29.1°C

in August 2004 (Fig. 1b). Soil temperature at 30 cm was highest in August 2004, but did generally not exceed 13°C (Fig. 1c). Mean annual precipitation was 501 mm and fell during all months of the year (Fig. 1d). The precipitation did show a clear seasonal course, with most of the rainfall occurring during autumn and early winter. Measurements on soil water potential (SWP) during unfrozen conditions also showed a clear seasonal pattern (Fig. 1e). SWP remained close to zero after soil thaw until late June, indicating water saturation. As the growing season proceeded, the water potential only fell to ca. −0.05 to −0.1 MPa, indicating that soil was still close to field capacity or at least with enough available water for plant growth. During autumns, the water potential returned back to very low values, as the precipitation increased (Fig. 1d and e).

3.2 Annual variation in physical factors

Little annual variation was seen in the irradiance; it was 2804, 2667, 2868 MJ m^{-2} for the three subsequent years (Fig. 1a). The amount received during the growing season (defined later), was 2066, 2023 and 2283 MJ m^{-2}; i.e. 2006 received most energy to drive the primary production, or approximately 11–13% more than 2004 and 2005, respectively. The mean annual air temperature during the experimental period was 6.7, 5.6 and 6.8°C for years 2004–2006, respectively, indicating that 2005 was the coldest of the three years, while 2004 was slightly warmer than 2006 (Fig. 1b). Mean annual soil temperature at 10–30 cm soil depth was 5.6, 4.1 and 5.4 for the three subsequent years and the same pattern was observed in soil temperature at the upper most 10 cm where the annual values were 6.9, 5.6 and 6.7 (Fig. 1c). The annual precipitation was 457, 463 and 585 mm for years 2004–2006, respectively (Fig. 1d). The soil water potential in 5–10 cm depth never moved far away from field capacity, as indicated earlier, but still there was a clear annual variation in how low (how negative) it became in July and August. The average value of SWP during the growing season for the three years was −0.028, −0.024 and −0.040 MPa respectively. That indicates that the 2006 growing season was considerably dryer than the two preceding years, even if its annual precipitation was 26–28% higher (Fig. 1d and e).

3.3 Total CO$_2$-balance and the length of growing season

The eddy covariance measurements started 12 years after the plantation was established on ploughed, previously heavily grazed heathland and continued for three subsequent years. Figure 2 shows the accumulated net ecosystem exchange (NEE) of the
5 plantation over the measurement period. Negative values indicate a net accumulation from the atmosphere. Due to the high latitude of the study site, seasonal variation in net uptake and efflux was pronounced. The NEE shifted from being a source during winters and to becoming a relatively strong sink during summers. The accumulated NEE over the three years was $-1{,}185$ g CO$_2$ m^{-2} (Fig. 2). That equals 323 g C m^{-2}, or
10 ca. 650 g DM m^{-2} (6.5 t DM ha^{-1}) assuming 0.50 C-fraction of biomass.

The onset and end of the annual growing season was defined as the period when daily NEE stayed negative (spring) or positive (autumn) for at least four consequent days. The length of the growing season varied between the years, with 136, 151 and 161 days in 2004, 2005 and 2006, respectively (Fig. 2). The growing season of 2006
15 was 18% and 7% longer than for years 2004 and 2005, respectively. This extension was both due to earlier spring and later autumn in 2006 than the other years (Fig. 2).

3.4 Seasonal and annual variation in NEE

From the end of September until mid-April the ecosystem acted as a CO$_2$ source with ecosystem respiration (R$_e$) being the controlling factor in the site's NEE (Fig. 3; positive
20 values). The R$_e$ showed distinct autumn tops following leaf fall in the mostly deciduous ecosystem, and there was a clear increasing trend over the three years. During spring, summer and autumn the gross primary production (GPP) was, however, the main controlling factor in NEE (Fig. 3; negative values). The GPP mostly followed the seasonal pattern in irradiance (Fig. 1a), except in 2005 when the ecosystem experienced severe
25 frost damage after leaf flush in mid-May that set the GPP back to zero (Fig. 3).

The ecosystem acted as a sink for CO$_2$ during all of the three years, with a net sequestration of 375, 566 and 245 g CO$_2$ m^{-2} for years 2004, 2005 and 2006, respec-

tively. There was, however, a strong inter-annual variation in measured NEE, or 131% difference between the lowest (2006) and the highest (2005) year (Fig. 3). It is obvious that the inter-annual variation in NEE was more linked to annual differences in plant respiration and decomposition of soil organic matter (R_e), than carbon uptake (GPP; Fig. 3). The R_e was 27% and 37% lower in 2005 than in 2004 and 2006, respectively. This resulted in the highest NEE for 2005, even if it also had 22% and 13% lower GPP than in 2006 and 2004, respectively (Fig. 3). The reduction in GPP for year 2005 was probably linked to the frost damage that occurred that year, and will be discussed in more detail later.

Another peculiar phenomenon in NEE was the abrupt switch from a net source to a net sink in spring (Fig. 3), which occurred approximately at the same time as the soil frost in 10–30 cm depth melted (Fig. 1c). Respiration rate at given temperature decreased dramatically during springtime (Fig. 4). This occurred at the same time as soil water potential was close to zero (Fig. 1e). Obviously water logging in spring decreased decomposition of organic matter (heterotrophic respiration) when the soil profile thawed, a well-known phenomena in wetter soils (Davidson et al., 1998), and then when the plants flushed and became active, GPP increased rapidly and, thus, also NEE.

3.5 Seasonality in temperature response of ecosystem respiration

There was a clear seasonal difference in estimated ecosystem respiration at 0°C (Fig. 4) for spring, summer and autumn (Table 2; R_{ref} values, note that winters had different base temperatures). The R_e at 0°C was always close to 1 g CO_2m^{-2} 30-min^{-1}, except in the spring when it was close to zero (Fig. 4). During spring the R_e was probably mostly made out of the autotrophic respiration, since the heterotrophic respiration was very low due to water logging. During the other seasons, even in the winter when part of the soil profile was frozen but not water saturated, the heterotrophic respiration was dominating the base respiration at low air temperatures. It is important to note that high water table level was probably an important contributor to the observed seasonal

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variation in R_e in this otherwise non-water saturated ecosystem.

There was also a clear seasonal variation in air temperature sensitivity of the R_e (Fig. 4); it was usually higher during spring and autumn than in winter and summer (Table 2; higher E0 values). This pattern could possibly be explained if temperature sensitivity (expressed as E0 or Q_{10} value) of the mostly aboveground autotrophic respiration was higher than for soil heterotrophic respiration; i.e. related to R_e consisting of higher proportion of autotrophic respiration with higher temperature sensitivity in relation to heterotrophic respiration during these seasons when the soil profile was closer to water-saturation.

3.6 Annual variation in ecosystem respiration

In an ecosystem such as a young forest plantation, it is to be expected that the amount of living biomass changes rapidly, yielding more substrate for plant respiration. This could indeed been seen when the annual temperature response of R_e at was compared (Fig. 4; Table 2). Year 2006 showed the highest respiration at a given temperature (Table 2; R_{ref} values=base respiration), indicating that the total respiration of the ecosystem was steadily increasing during the study period. The temperature sensitivity (Table 2; E0 values) was also highest in 2006 for all of the years. If autotrophic respiration had higher temperature sensitivity, this could be explained by the proportion of aboveground autotrophic respiration was becoming an increasing part of the total R_e as the plantation became older.

Figure 5a shows how annual biomass accumulation was correlated to annual R_e. The relationship was not very strong, it only explained ca. 30% of the annual variation (r^2=0.31). Various other biomass relationships were tested but none yielded better correlation with annual variation in R_e. There seems therefore that even if the "substrate factor" clearly contributed to the annual change in R_e, it was not the main determining factor.

A physical factor commonly used for explaining variation in R_e is soil temperature. In our study it did however not yield the strongest relationship with the observed seasonal

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variation in R_e, instead it was air temperature (Fig. 4). Similar results appeared when annual variation in R_e was compared to temperature; mean annual soil temperature at 10–30 cm depth was the best soil temperature variable tested (r^2=0.74), but still the mean annual air temperature (r^2=0.85) and seasonal average soil water potential (r^2=0.84), were more strongly correlated to annual R_e than soil temperature (Fig. 5b, c, e). Apparently the high R_e in 2006 was to large extent caused by longer and warmer growing season (Fig. 5c) and also by increased depth of unsaturated soil which was indicated by higher water potential (Fig. 5e).

3.7 Modelling of gross primary production and seasonal variation

The intercepts of the initial slope of the GPP light response curves shown in Fig. 6 can be viewed as a measure of photosynthetic capacity in medium to low light. If the capacity changes, the initial slope of the light response curve should move (up for an increase or down for a decrease). No change was observed in this part of the curves (Fig. 6). The top part of the curves (GPP at high irradiance) showed a steady increase over the three years (Fig. 6). This can either be caused by increased light interception or increased photosynthetic capacity. Since no increase at low or medium irradiance was observed, this probably indicated increased annual light interception in the ecosystem. Maximum LAI increased from 1.34 to 3.37 from 2004 to 2006 (Fig. 7a), which strongly supports this hypothesis.

3.8 Annual variation in GPP

Annual GPP is mainly controlled by three factors: (a) the photosynthetic capacity of the ecosystem, (b) the amount of leaf area intercepting the incoming radiation and (c) the length of the season where the leaf area is active (Fig. 2). Apparently photosynthetic capacity per unit leaf area did not change over the three years, while there were indications that light interception in the ecosystem had increased (see earlier). Light interception is mostly a function of the ecosystem's leaf area index (LAI). Indeed, both

total and tree LAI increased during the study period. Maximum tree LAI was 0.33, 0.73 and 0.89 (data not shown) and maximum total LAI (trees and understory) was 1.34, 2.11 and 3.37 for 2004–2006, respectively (Fig. 7a). This clearly explained the increasing 30-min GPP flux at high light (Fig. 6), but did it explain the changes in an-
5 nual GPP that occurred? When total GPP was compared to maximum LAI, no clear relationship was found (Fig. 7a, r^2=0.10) and neither when it was compared to inter-ception index of trees (LAI of trees × length of the growing season; Fig. 7b; r^2=0.11). The best explanatory physical parameter for annual GPP was the total irradiance dur-ing the growing season (Fig. 7c; r^2=0.71). Total irradiance was highest in 2006 and
10 lowest in 2005, which was mainly an effect of shorter growing season in 2005.

When different physical factors were compared to annual GPP (data mostly not shown, but see Fig. 7), year 2005 generally fell out of the linear trend between 2004 and 2006. The effect of the frost damage in spring 2005, and the setback of the GPP at that time, was the most probable explanation for this. The low GPP in 2005 was,
15 however, also partly explained by a shorter growing season that year (Fig. 7c). The reduction in GPP did however not lead to lower NEE (Fig. 2), because the drop in R_e was even larger in 2005 (Fig. 6). Instead 2005 had the highest NEE and the year with the highest GPP, 2006, had the lowest NEE (Fig. 2). The variation in the annual carbon sequestration (NEE) was therefore more strongly related to variation in respiration (R_e)
20 than carbon uptake (GPP).

4 Discussion

Plantations are generally believed to be strong CO_2 sources for a period following site preparation and establishment, because of loss of soil organic carbon (Hyvönen et al., 2007). It is unclear at what time afforestation sites become a significant CO_2 sinks
25 (Paul et al., 2002; Kowalski et al., 2004), and few studies are available on ecosystem fluxes of such areas during the establishment phase. The present study was conducted 12–14 years after the site was site-prepared and afforested, but already it was a strong

sink of $-395\,\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}$. These results are in line with earlier published NEE of $-370\,\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}$, for a seven year old black cottonwood plantation in southern Iceland (Valentini et al., 2000). At that site the sod was stripped away before planting. In a recent study where German grassland was ploughed and afforested with 10 different
5 broadleaf and coniferous tree species, NEE was found to be $-223\,\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}$, three years after establishment (Don et al., 2009). To our knowledge, these three studies are the only published results on NEE in young afforested areas on upland soils. It is noteworthy that all indicate a CO_2 sink relatively soon after establishment, which is in contrast to what has been generally believed.
10 A sink of $-395\,\text{g}\,CO_2\,\text{m}^{-2}\,\text{year}^{-1}$ is relatively high for a young open forest, but in reviews on mature stands both lower and much higher values of NEE have been observed. Baldocchi et al. (2001), Law et al. (2002) and Hyvönen et al. (2007) reported NEE ranging between $+370$ and $-3200\,\text{g}\,CO_2\,\text{m}^{-2}$ in northern forests. Among those sites there are some mature boreal forests which have been found to be net sources of
15 CO_2. For instance, the Swedish Norunda forest and the Belgian Brasschaat forest have been found to lose CO_2 because of historical drainage and changes in management respectively (Lindroth et al., 1998; Carrara et al., 2003).

There were apparent seasonal shifts in the temperature sensitivity of R_e during all the three study years. A hypothesis was made that this could be explained by au-
20 totrophic respiration having higher temperature sensitivity than the heterotrophic respiration. What have other studies found? Schindlbacher et al. (2008) recently found that autotrophic respiration had double as high short term Q_{10} values than heterotrophic respiration in a mature Norway spruce forest. They have also shown that if the Q_{10} response is based on longer time steps (24-h mean values), this difference was much
25 smaller (Schindlbacher et al., 2008). Most authors seem however to assume that heterotrophic respiration has higher Q_{10} value than autotrophic respiration, because soil respiration typically has higher Q_{10} value than leaf- or stem respiration (e.g. Medlyn et al., 2005). This assumption may however not be so simple, since approximately 50% of the soil respiration in a coniferous forest is coming from autotrophic processes

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(Högberg et al., 2009). Indeed, it is stated in a recent review that this issue is still quite poorly studied or understood (Davidson et al., 2006).

The annual carbon balance in the present study was strongly influenced by meteorological factors leading to a high inter-annual variability, which was mainly linked to annual variation in carbon efflux (R_e). This was in agreement with findings of Valentini et al. (2000), who reported that R_e was the main determining factor for latitude variation in NEE. In the present study, it was noteworthy that annual NEE was lowest in the same years as GPP was highest, due to high R_e (Fig. 3).

Annual R_e mainly changes between years for two different reasons: Firstly because of changes in the amount of respiration substrate in the ecosystem which may be indicated by the rate of base respiration (R_{ref} in Table 2). Such an increase in base respiration has been reported during establishment phase of forest plantations (Tang et al., 2009). Secondly because of annual difference in physical factors controlling R_e, either plant respiration or decomposition of organic matter. Commonly reported physical factors that control R_e are soil temperature (Davidson et al, 2006) and drought (Dunn et al., 2007). The physical factors showing the strongest correlation to R_e in the present study were air temperature and soil water potential (Fig. 5). It was surprising that air temperature was better correlated with annual variation in R_e than soil temperature (Fig. 5). As a conclusion, our results indicate that both substrate amount and physical factors contributed to the annual variation in R_e and therefore also in NEE.

The length of the growing season has frequently been shown to be strongly correlated to NEE (e.g. Piao et al., 2008). Initiation of photosynthesis in boreal forests is largely regulated by air temperature (Goulden et al., 1998; Bergh et al., 2003) whereas decreasing day length determines the end of the growing season (Suni et al., 2003). It has been pointed out that increases in growing season length in boreal regions could make the forests stronger sinks (NEE) through an increase in GPP (e.g. Morales et al., 2007). In the present study the length of the growing season (Fig. 7b) did indeed increase GPP, but not NEE. Similarly, Dunn et al. (2007) and Piao et al. (2008) found that the length of growing season had little effect on annual NEE, since longer growing

season both enhanced GPP and R$_e$. Another flux study in Finland, Denmark and Sweden, suggested that the length of the growing season was not one of the main drivers for annual variability in NEE in that region (Lagergren et al., 2008).

It can be stated that in some respect the present maritime climate conditions in Iceland can be seen as a scenario for the future climate in parts of the northern boreal zone, where winter temperatures are predicted to increase and become more variable and with less pronounced seasonal shifts (IPCC, 2007). Therefore, Iceland provides an excellent opportunity to test ideas about ecosystem response to projected climatic warming. In the present study, major frost damage occurred at the site in May 2005, ca. 2–3 weeks after the ecosystem had started to assimilate carbon. This climatic variation reset both GPP and NEE to zero and apparently the photosynthesizing plant tissues had to be regrown or restored (Fig. 3). The effect of this was 21% and 12% less annual GPP per same growing season length compared to 2004 and 2006, respectively.

The closure of the energy balance is a useful parameter to check the reliability of the data set (Aubinet et al., 2000). At our site, the energy balance closure for all the three years was found to be in the same order as for many other sites (e.g. Wilson et al., 2002) and therefore considered satisfactory. The annual carbon balance can be affected by several possible errors. Clearly, the gap-filling strategy impacts on the magnitude of the flux estimates. In the present study we used seasonal light- and temperature-response curves to minimize the risk of error. There exist a number of different methods for gap-filling. Many of them have shown to give good results, including the one chosen here (Falge et al., 2001).

5 Conclusions

Twelve years after plowing and afforestation the young *Larix* plantation in Vallanes was already a strong sink for atmospheric CO$_2$. This study makes a contribution to the literature on northern subarctic/boreal ecosystem characterized by maritime climate.

Although present dataset only consisted of three years, it permitted us to analyze seasonal and inter-annual variation in NEE, GPP and R_e. It also gave the opportunity to characterize the response of a "Kyoto forest" to physical factors, such as light, temperature, precipitation, soil water status, etc. It was quite clear in the present study that plant respiration and decomposition of organic matter were the main drivers for annual variation in NEE.

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Table 1. Site description for Vallanes, eastern Iceland.

Site characteristics in year 2005	
Coordinates	65°11′11.8″N; 14°33′32.2″W,
Elevation	59 m a.s.l.
Size of the plantation	60.4 ha
Shortest distance to edge	230 m
Stand density	3400 trees ha^{-1}
Diameter at 50 cm	2.87 cm
Diameter at BH	1.32 cm
Basal area at BH	1.16 m^2
Dominant height	3.34 m
Canopy structure	open
Topography	rather flat with few <5 m hills

Table 2. The values of base respiration at given temperature (R_{ref} values) and values of temperature sensitivity (E0 values). During winter time base temperature was set to 0°C but during spring, summer and autumn, base temperature was set to 10°C.

Year	R_{ref}				E0			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
2004	0.7243	2.1797	2.0520	0.5862	202.11	151.68	309.29	106.59
2005	0.6255	2.1625	1.9864	0.7461	800.52	142.35	328.89	63.41
2006	0.9534	3.0004	2.4737	1.1885	820.26	257.95	369.93	184.12

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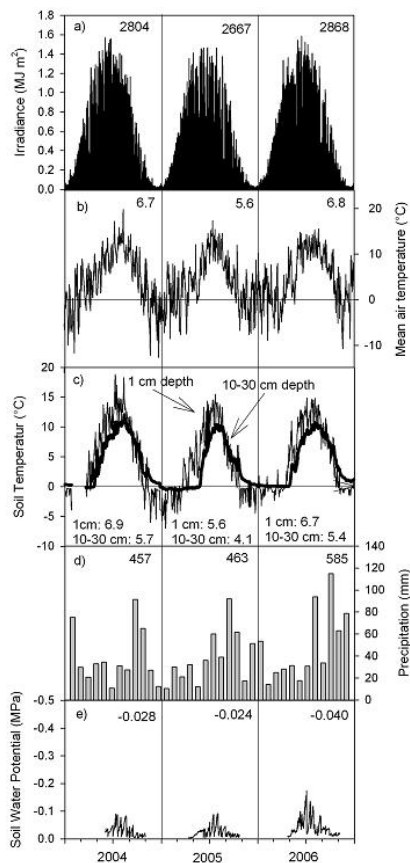
Fig. 1. Climatic characteristics; **(a)** short wave irradiance (MJ m^{-2}), **(b)** air temperature (°C), **(c)** soil temperature (°C) at 1 cm and 10–30 cm depths, **(d)** precipitation (mm) and e) soil water potential (MPa) in 2004–2006. Numbers in the corner represent the annual sum (a and b) or the annual average value (b, c and d) of each year.
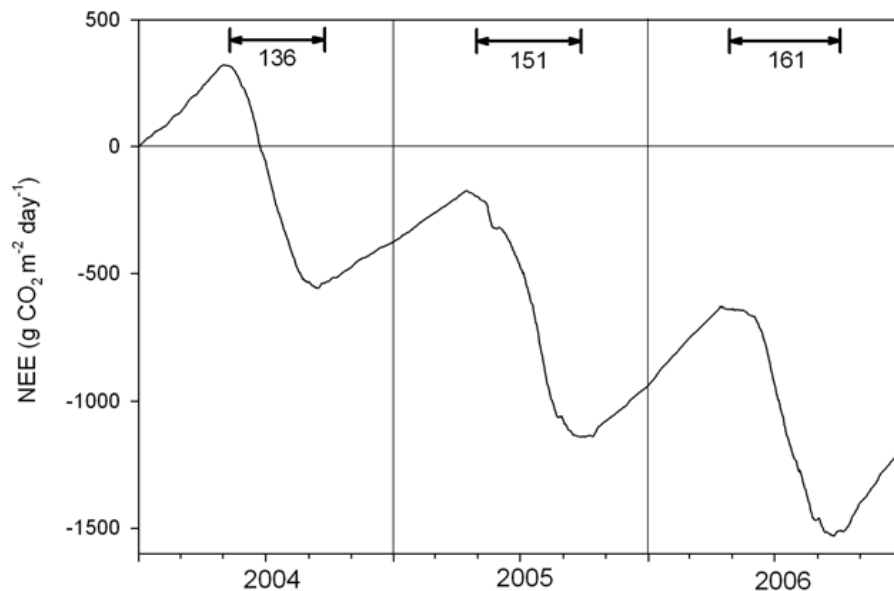
Fig. 2. Cumulative carbon balance at Vallanes, Iceland. Arrows indicate the start and the end of the growing season and numbers the length of the growing season.

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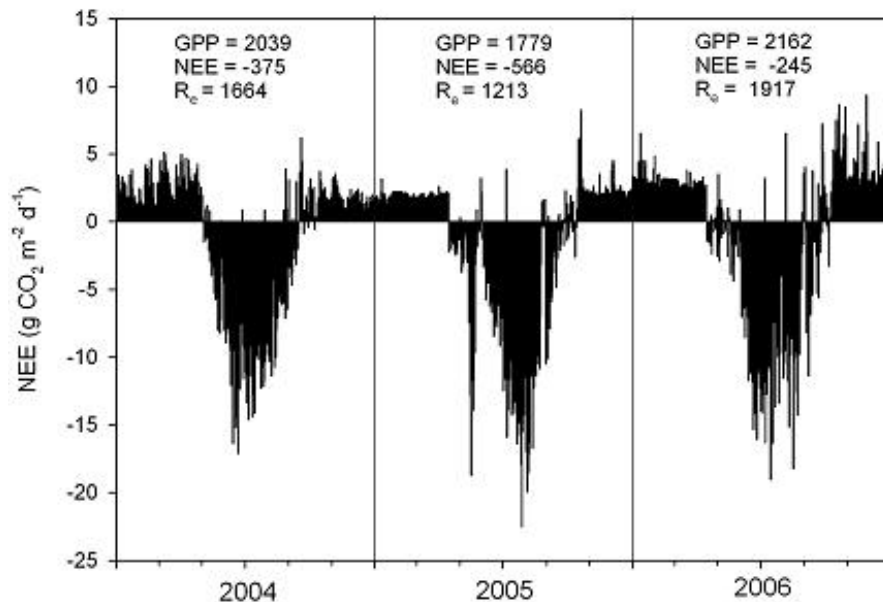
Fig. 3. Daily Net Ecosystem Exchange (NEE) for years 2004–2006 in Vallanes, Iceland. Also shown are annual sums for Gross Primary Production (GPP; $g\ CO_2\ m^{-2}\ year^{-1}$) and Ecosystem Respiration (R_e; $g\ CO_2\ m^{-2}\ year^{-1}$).
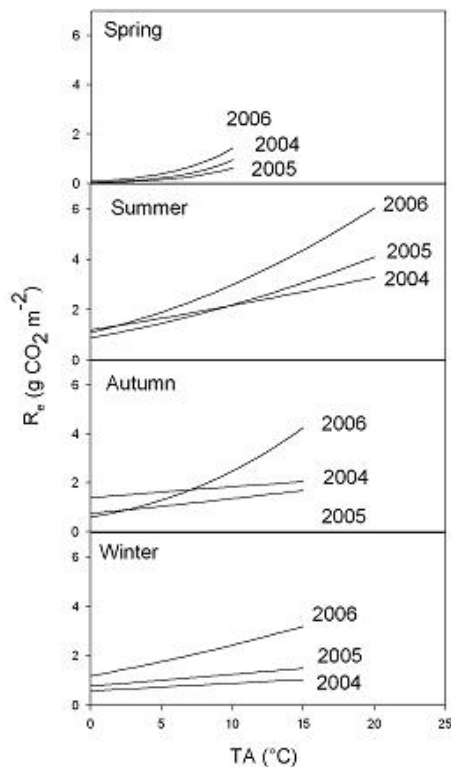
Fig. 4. Respiration (R_e) as a function of air temperature during spring, summer, autumn and winter. R_e is represented as 30 min. average values.
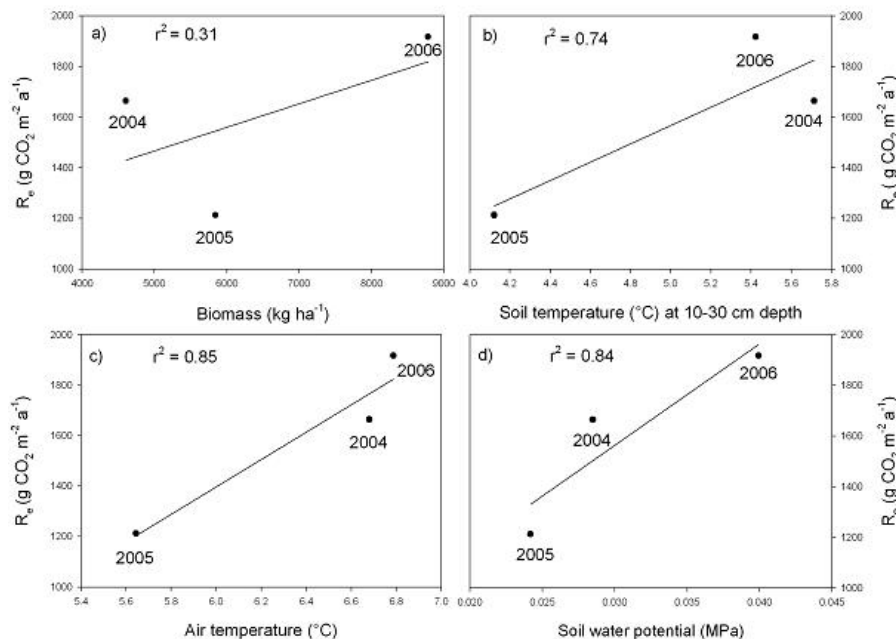
Fig. 5. Annual respiration (R_e) as a function of **(a)** biomass, **(b)** mean annual soil temperature at 10–30 cm depth, **(c)** mean annual air temperature and **(d)** average soil water potential.
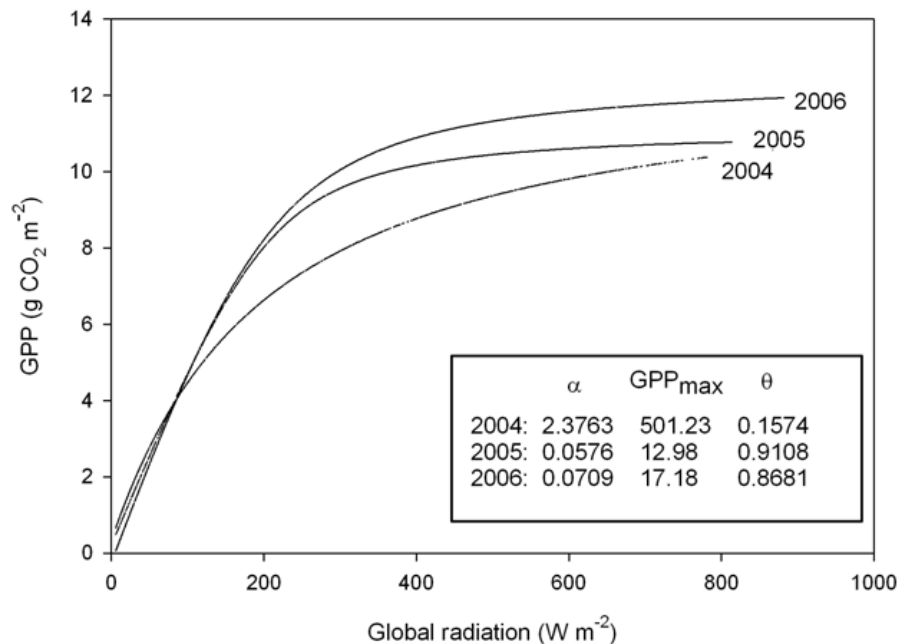
Fig. 6. Gross Primary Production (GPP) as a function of global radiation during the growing season. GPP is represented as 30 min average values.
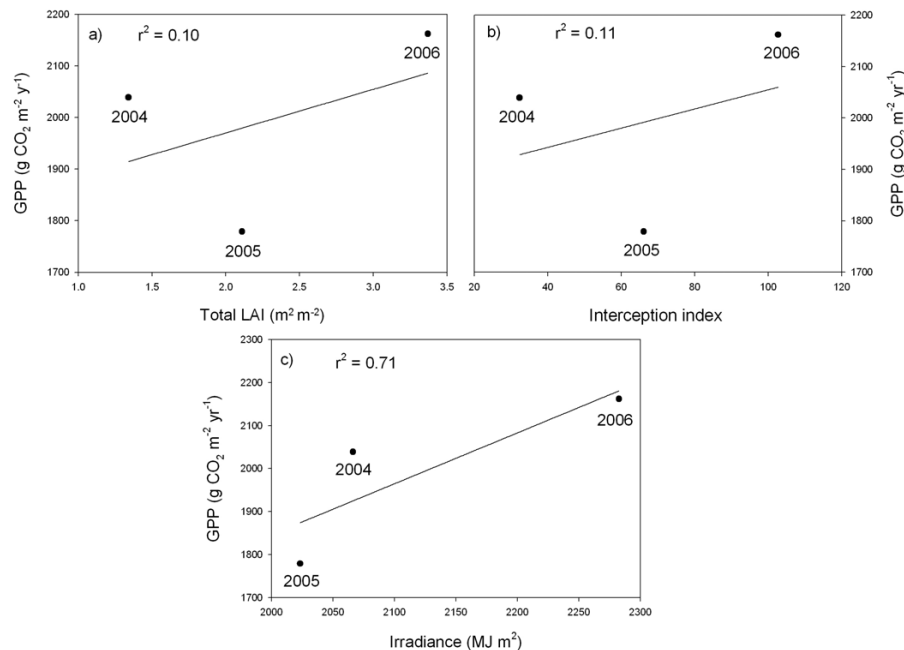
Fig. 7. Annual GPP as a function of **(a)** total LAI of trees and understory, **(b)** interception index and **(c)** irradiance during the growing season.