

A young afforestation area in Iceland was a moderate sink to CO₂ only a decade after scarification and establishment

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Abstract. This study reports on three years (2004–2006) of measurements of net ecosystem exchange (NEE) over a young Siberian larch plantation in Iceland established on previously grazed heathland pasture that had been scarified prior to planting. The study evaluated the 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 CO₂ during all of the three years, with an annual net sequestration of -102 , -154 , and -67 g C m⁻² for 2004, 2005, and 2006, respectively. 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, 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 CO₂ only twelve years after site preparation and afforestation.

2007), and since the response to fluctuating environmental conditions is complex, a small change in either process can significantly impact the NEE. It is therefore of importance to acquire a detailed understanding of the underlying processes which govern the carbon cycle and NEE.

Numerous studies on fluxes of CO₂ using the eddy covariance technique have been conducted and much new insight into the processes that control the exchange of CO₂ 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. 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. (2007) also demonstrated the strong impact of nitrogen deposition on the NEE averaged over the whole rotation length. The impact of drought on CO₂ exchange in several European forests was demonstrated by Granier et al. (2007) and Dunn et al. (2007) showed that water table depth influenced interannual variation of the carbon budget of a black spruce (*Picea mariana* Mill.) forest in Canada.

1 Introduction

Net ecosystem exchange (NEE) between the biosphere and the atmosphere results from the difference between two large fluxes: gross primary production (GPP) and ecosystem respiration (R_e). Since GPP and R_e have partially distinctly different responses to climate drivers (e.g. Reichstein et al.,



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Forests and woodlands in Iceland cover ca. 157 000 ha, whereof 1/4 is planted forest (Traustason and Snorrason, 2008). During the past 20 years, Siberian larch (*Larix sibirica* Ledeb.) has been the most used tree species for afforestation in Iceland (Gunnarsson, 2008). The use of Siberian larch in forestry in the Nordic countries is limited, but it 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 Icelandic and the global carbon balance.

Measurements of in situ CO₂ gas exchange in Iceland are scarce. Magnússon (1992) and Sigurdsson (2009) measured GPP, R_e, and NEE on a young volcanic island and Cook et al. (1998) measured photosynthesis of plants around natural CO₂ springs in western Iceland. Most other gas exchange measurements have been made in forest or woodland ecosystems. A black cottonwood (*Populus trichocarpa* Torr. & Gray) 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 (*Betula pubescens* Ehrh.) 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.

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 affecting the site's carbon balance and its 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, lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and Sitka spruce in a 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 Val-

lanes 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 m² circular plots each year. The measured quantities were diameter at 0.5 and 1.3 m height and the height of the live 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 m²/kg DM) determined for three canopy layers on 30 sample trees. Maximum annual projected leaf area index (LAI) was derived by adding information about average stand density (trees per m²).

The seasonal course of projected 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 Egilsstaðir 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, as described by Bjarnadottir et al. (2007a). This paper presents continuous data for three years, 2004–2006. The eddy covariance system was an open path system with a LI-7500 CO₂/H₂O 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 CO₂, H₂O, 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 software (In Situ Flux Systems AB, Ockelbo, Sweden).

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 stand edge from the EC tower	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

2.5 Analysis

Total flux cover during the three years of measurements was 70%. A WPL correction was applied to correct for latent heat and air density fluctuations (cf. Webb et al., 1980). The flux data were quality checked, screened for spikes and abnormal values by comparing the vapour pressure measured by the gas analyser with the vapour pressure measured by an independent relative humidity and temperature sensor (Hygroclip, Rotronic, Switzerland). Turbulent conditions were not considered to be insufficient since no relationship between 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 CO₂ 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 minus the soil heat flux density, was compared with the sum of the turbulent fluxes of heat, and latent heat 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 CO₂ uptake during off season periods were removed. In order to calculate the annual CO₂ 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 later measurements. Longer gaps were filled by calculating NEE from its component fluxes, ecosystem respiration (R_e) and gross primary pro-

duction (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 ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) 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:

$$R_e = R_{\text{ref}} \times \exp \left[E_0 \times \left(\frac{1}{T_{\text{ref}} - T_0} - \frac{1}{T_K - T_0} \right) \right], \quad (1)$$

where R_{ref} is a fitted parameter describing the total respiration rate at the reference temperature (T_{ref} in K), E_0 is a fitted coefficient for ecosystem respiration, T_0 is a fixed temperature of 227 K and T_K is soil or air temperature in K. During winter time, the T_{ref} was set to 0°C (273.15 K), whereas during the spring, summer and autumn the T_{ref} was set to +10°C (283.15 K).

Rate of Gross Primary Production ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) was calculated from daytime NEE by subtracting it from R_e from Eq. (1) for each 30-min period. Light response of GPP was modelled from measured irradiance by a light response curve (Roberntz and Stockfors, 1998):

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

where α is the quantum yield, GPP_{max} is the light saturated GPP in $\mu\text{mol m}^{-2} \text{ s}^{-1}$, 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:

$$\text{NEE}_{\text{day}} = -(\text{GPP} - R_e). \quad (3)$$

In May 2004, data was missing for 29 consequent days, 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 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 (SigmaPlot 2008, v. 10.0) was used to study which physical factors were best correlated with the seasonal and annual carbon fluxes.

3 Results

3.1 Seasonal variation in physical factors

The climate in Vallanes was maritime, with short cool summers and relatively mild winters (Fig. 1). The irradiance clearly reflected the northern location of the site (65° N), with short days in December only receiving ca. 0.08 MJ m⁻² day⁻¹, and 24-h light at midsummer, with ca. 28.5 MJ m⁻² during clear days (Fig. 1a). The daily mean air temperature fluctuated around zero °C during winter and did not fall below -13°C during 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). Winter precipitation fell either as snow or rain, but because of the relatively mild winter-temperature, the snow cover was never maintained long. 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) and did show a clear seasonal variation, 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), where the 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 close to zero (water saturation), 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, showing that 2005 was the coldest of the three years (Fig. 1b). Mean annual soil temperature at 10–30 cm soil depth was 5.6, 4.1, and 5.4°C 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°C (Fig. 1c). The annual precipitation was 457, 463, and 585 mm for years 2004–2006, respectively (Fig. 1d). The

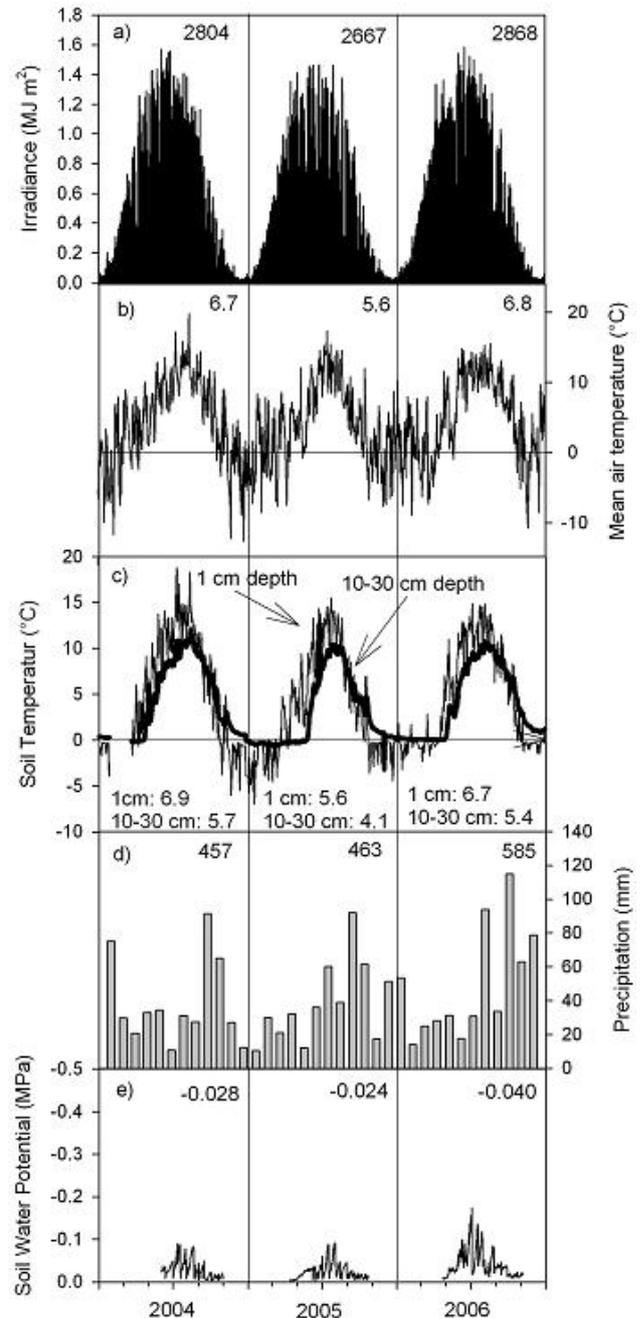


Fig. 1. Climatic characteristics; (a) short wave irradiance (MJ m⁻²), (b) air temperature (°C), (c) soil temperature (°C) at 1 cm and 10–30 cm depths, (d) precipitation (mm), and (e) soil water potential (MPa) in 2004–2006. Numbers in the corner represent the annual sum (a and d) or the annual average value (b, c and e) of each year.

soil water potential in 5–10 cm depth never moved far away from field capacity, but still there was a clear annual variation in 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 CO₂-balance and the length of growing season

The eddy covariance measurements started 12 years after the plantation was established on scarified, previously heavily grazed heathland, and continued for three subsequent years. The accumulated net ecosystem exchange (NEE) of the plantation over the measurement period is shown in Fig. 2. Negative values indicate a net accumulation from the atmosphere. As an effect of 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 to becoming a relatively strong sink during summers. The accumulated NEE over the three years was -1.185 g CO₂ m⁻² (Fig. 2). That equals 323 g C m⁻², or ca. 650 g DM m⁻² (6.5 t DM ha⁻¹) assuming a 50% carbon content of the 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 was 18% and 7% longer than for years 2004 and 2005, respectively. This extension was both an effect of 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 CO₂ source with ecosystem respiration (R_e) being the controlling factor of NEE (Fig. 3; positive values). The R_e showed distinct autumn peaks 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 of NEE (Fig. 3; negative values). The GPP mostly followed the seasonal pattern in irradiance (Fig. 1a), except in 2005 when the trees experienced severe frost damage after leaf flush in mid-May that set the GPP back to zero (Fig. 3).

There was an abrupt switch in NEE from a net source to a net sink in spring (Fig. 3), which occurred approximately at the same time as the soil thawed at 10–30 cm depth (Fig. 1c). The respiration rate at given temperature decreased dramatically during springtime (Fig. 4; the y-intercept) when the soil water potential changed to close to zero (Fig. 1e).

The ecosystem acted as a sink for CO₂ during all of the three years, with an annual net sequestration of -375 , -566 and -245 g CO₂ m⁻² for 2004, 2005 and 2006, respectively. There was, however, a strong interannual variation in measured NEE, or 131% difference between the lowest (2006)

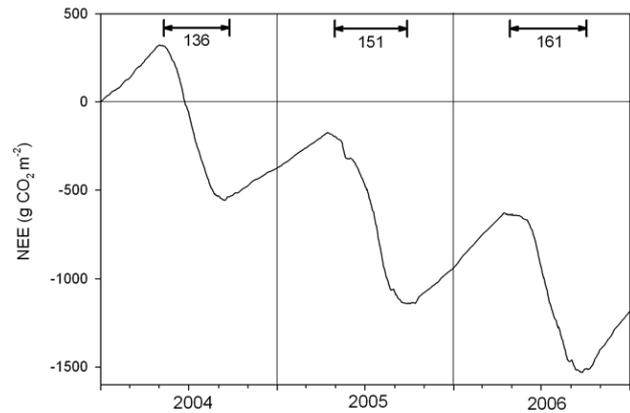


Fig. 2. Cumulative daily carbon balance at Vallanes, Iceland. Arrows indicate the start and the end of the growing season and numbers the length of the growing season.

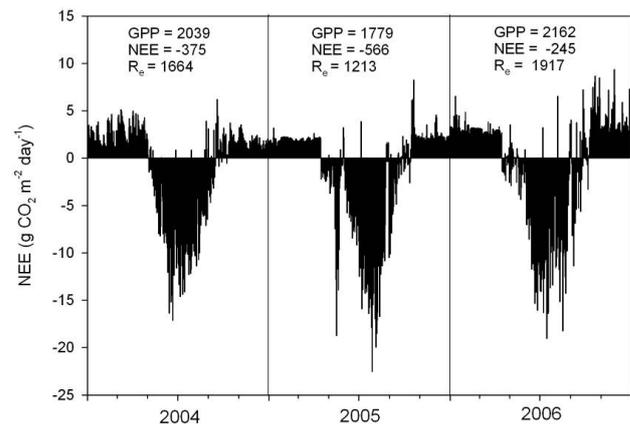


Fig. 3. Daily Net Ecosystem Exchange (NEE; g CO₂ m⁻² day⁻¹) for years 2004–2006 in Vallanes, Iceland. Also shown are annual sums for NEE, Gross Primary Production (GPP) and Ecosystem Respiration (R_e); all in g CO₂ m⁻² year⁻¹.

and the highest (2005) year (Fig. 3). The interannual variation in NEE seemed to be more linked to annual differences in ecosystem respiration (R_e) than the annual carbon uptake (GPP; Fig. 3). The R_e was, however, 27% and 37% lower in 2005 than in 2004, and 2006, respectively. This resulted in the highest measured NEE for 2005, in spite of that year having 22% and 13% lower GPP than in 2006 and 2004, respectively (Fig. 3).

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 μ mol CO₂ m⁻² s⁻¹, except in the spring when it was close

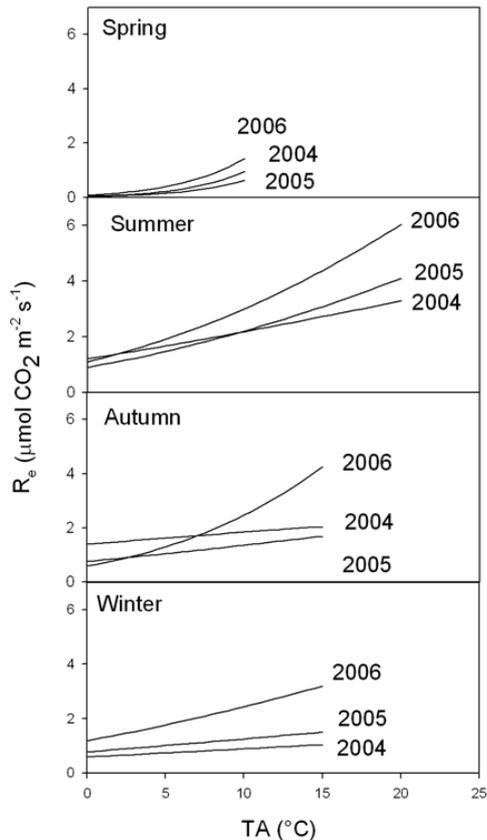


Fig. 4. Ecosystem Respiration (R_e ; $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$) as a function of air temperature during spring, summer, autumn and winter in 2004–2006. The curves were fitted by Eq. (1).

to zero (Fig. 4). 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 E_0 values).

3.6 Annual variation in ecosystem respiration

The annual R_e was positively correlated to the measured annual biomass accumulation (Fig. 5a), but the relationship was not significant and only explained ca. 30% of the annual variation ($r^2=0.31$; $P=0.62$). Various other biomass relationships were tested, but none gave a better correlation with annual variation in R_e . There seems therefore that even if the “substrate factor” clearly contributed to the annual changes in R_e , it was not the main determining factor. Similar positive correlations appeared when annual variation in R_e was compared to temperature (Fig. 5). Mean annual soil temperature at 10–30 cm depth was the best soil temperature variable tested ($r^2=0.74$), but the mean annual air temperature ($r^2=0.85$), and seasonal average soil water potential ($r^2=0.84$), were still more strongly correlated to annual R_e than soil temperature (Fig. 5b, c and e). Apparently the high R_e in 2006 was to some extent caused by a longer and warmer

Table 2. The values of base respiration at a given temperature (R_{ref} ; $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$), values of temperature sensitivity (E_0 ; exponent) and the statistical outcome of fitting Eq. (1) to the measured data (r^2 and P). During winter time base temperature was set to 0°C, but during spring, summer, and autumn, base temperature was set to 10°C.

Year	Spring	Summer	Autumn	Winter
	R_{ref}			
2004	0.73	2.18	2.05	0.59
2005	0.63	2.16	1.99	0.75
2006	0.95	3.00	2.47	1.19
	E_0			
2004	202	152	309	107
2005	800	142	329	63
2006	820	258	370	184
	r^2			
2004	0.11	0.10	0.13	0.05
2005	0.04	0.04	0.08	0.04
2006	0.05	0.05	0.06	0.07
	P-value			
2004	0.02	< 0.001	< 0.001	< 0.001
2005	0.006	0.001	< 0.001	< 0.001
2006	< 0.001	< 0.001	< 0.001	< 0.001

growing season (Fig. 5c) and also by increased depth of the ground water level that year (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 and/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 1.3 to 3.4 from 2004 to 2006 (Fig. 7a), which strongly supports this assumption.

Both total and tree LAI increased during the study period. Maximum tree LAI was 0.3, 0.7 and 0.9 (data not shown) and maximum total LAI (trees and understory) was 1.3, 2.1 and 3.4 for 2004–2006, respectively (Fig. 7a). 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 interception index of trees (LAI of trees \times length of the growing season; Fig. 7b; $r^2=0.11$). The best explanatory physical parameter for annual GPP was the total irradiance

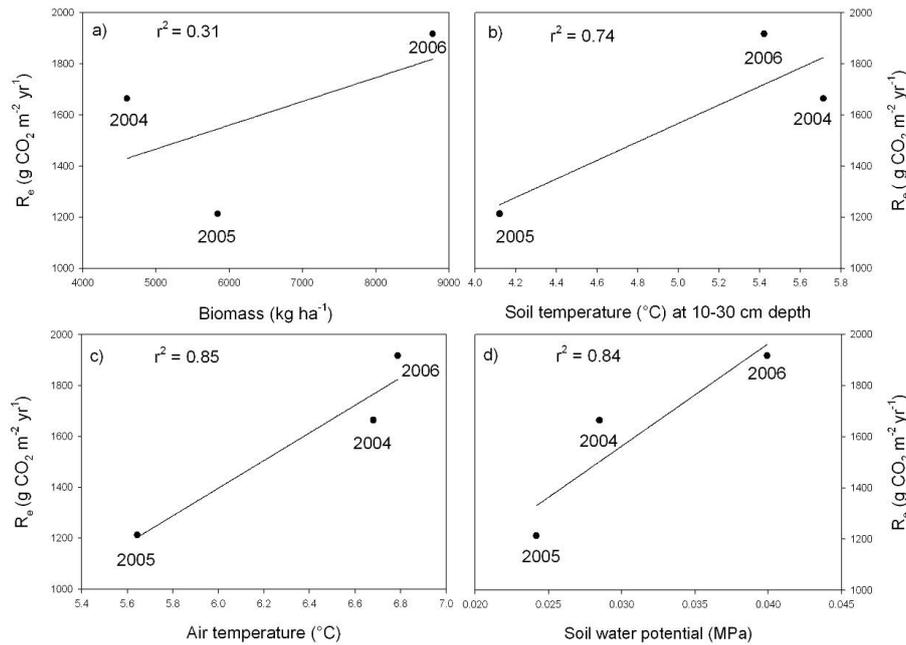


Fig. 5. Annual Ecosystem Respiration (R_e) as a function of (a) biomass, (b) mean annual soil temperature at 10–30 cm depth, (c) mean annual air temperature and (d) average soil water potential.

during the growing season (Fig. 7c; $r^2=0.71$). Total irradiance was highest in 2006 and lowest in 2005, which was mainly an effect of shorter growing season in 2005.

4 Discussion

4.1 Carbon balance of young afforestation areas

The CO₂ balance of young afforestation areas has important policy implications. According to the Kyoto protocol, carbon sequestration of all afforested areas since 1990 should be deducted from national greenhouse gas (GHG) emissions (UNFCCC, 1998). The present study took place in an afforested area, planted in 1992, and is thus defined as a “Kyoto-forest”. Plantations are generally believed to be strong CO₂ 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 significant CO₂ sinks (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 moderate 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 a grassland in Germany was ploughed and afforested with 10 different

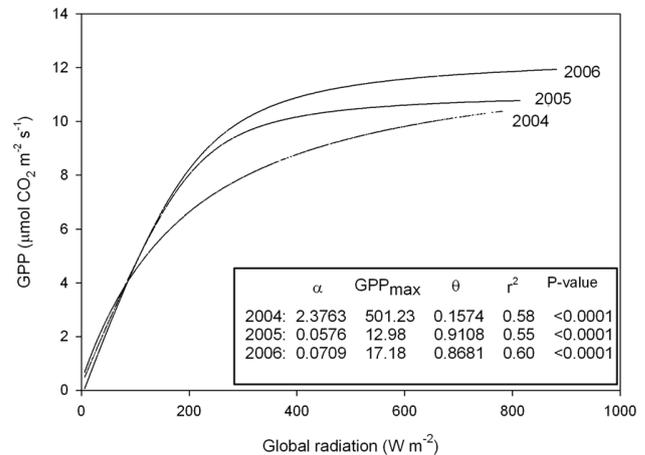


Fig. 6. Gross Primary Production (GPP; $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) as a function of global radiation during the growing season. Also shown are the light-response parameters parameters and the statistical outcome of fitting Eq. (2) to the measured data (r^2 and P).

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 CO₂ sink relatively soon after establishment, which is in contrast to what has been generally believed (Hyvönen et al., 2007).

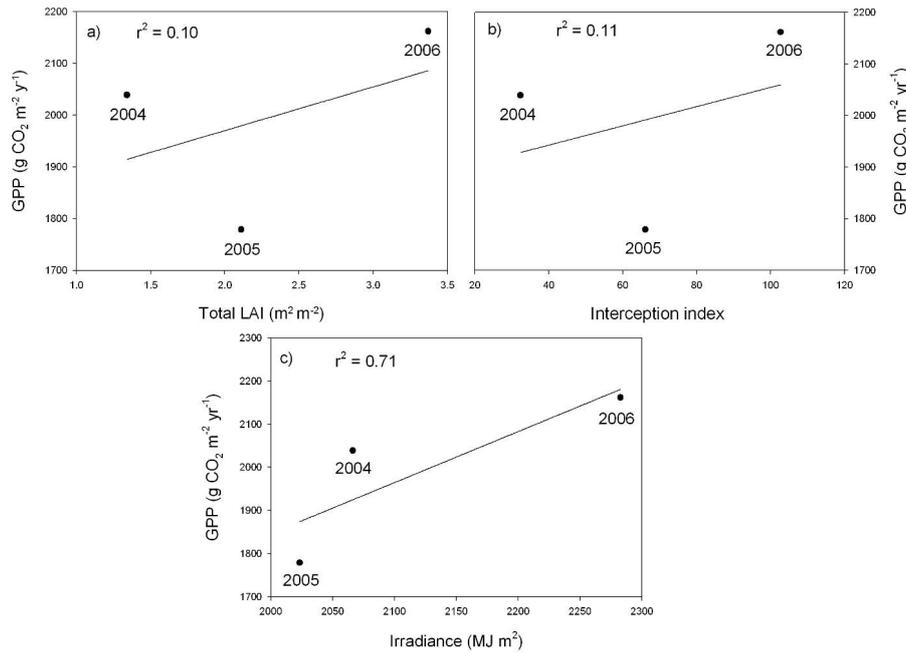


Fig. 7. Annual GPP as a function of (a) total LAI of trees and understory, (b) interception index and (c) irradiance during the growing season.

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 CO₂. For instance, the Swedish Norunda forest and the Belgian Brasschaat forest have been found to lose CO₂ because of historical drainage and changes in management, respectively (Lindroth et al., 1998; Carrara et al., 2003).

4.2 Observed variation in CO₂ fluxes

The GPP of a high-latitude forest 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 (Medlyn et al., 2005; Hyvönen et al., 2007). Apparently photosynthetic capacity per unit leaf area did not change much over the three years, while there were clear indications that the total light interception in the ecosystem did increase, which was to be expected in such a young forest plantation in its establishment phase. The total irradiance during the growing season was also shown to be of high importance for the change in the annual GPP of the Vallanes plantation.

The length of the growing season has frequently been shown to be strongly correlated to GPP and NEE (e.g. Piao et al., 2008). The onset of photosynthesis in boreal forests after

winter is largely regulated by air temperature (e.g. Goulden et al., 1998; Suni et al., 2003a) and the time of soil thaw (e.g. Troeng and Linder, 1982; Bergh and Linder, 1999) whereas decreasing day length determines the end of the growing season (Suni et al., 2003b). 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 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 . Other flux studies in Finland, Denmark and Sweden, similarly 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).

The year 2005 had the lowest GPP of the three study years. The effect of the frost damage in spring 2005, and the setback of the GPP at that time, was however only partly responsible for this. It was also explained by a shorter growing season that year. The reduction in GPP in 2005 did however not lead to lower NEE, because the drop in R_e was even larger in 2005. Instead 2005 had the highest NEE and the year with the highest GPP, 2006, had the lowest NEE. The variation in the annual carbon sequestration (NEE) was therefore more strongly related to variation in respiration (R_e) than carbon uptake (GPP). The relative importance of R_e for the annual NEE was in general agreement with the findings of Valentini et al. (2000), who reported that R_e was the main determining factor for latitudinal variation in NEE.

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 (cf. 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 abiotic factors that control R_e are soil temperature (Davidson et al., 2006) and drought (Dunn et al., 2007). The factors showing the strongest correlation to R_e in the present study were air temperature and soil water potential. As a conclusion, our results indicate that both substrate amount and abiotic factors contributed to the annual variation in R_e and therefore also in NEE.

4.3 Seasonal changes in R_e

A physical factor commonly used for explaining seasonal variation in R_e is soil temperature (e.g. Medlyn et al., 2005). In the present study it did, however, not give the strongest relationship with the observed seasonal variation in R_e , instead it was air temperature. Similar results have been presented by e.g. Xu et al. (2001) for a ponderosa pine plantation in the Sierra Nevada Mountains.

There were apparent seasonal shifts in the temperature sensitivity of R_e during all the three study years. These shifts could possibly be explained by autotrophic respiration having higher temperature sensitivity than the 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. Schindlbacher et al. (2008) recently found that autotrophic respiration in a mature Norway spruce forest, had twice as high short-term Q_{10} values as heterotrophic respiration, and that if the Q_{10} response is based on longer time steps (24-h mean values), this difference was much 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 (cf. 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 (Högberg et al., 2009). In a recent review, Davidson et al. (2006) stated that this issue is still quite poorly studied or understood.

In the present study, the intercept of the R_e -temperature relationship was greatly reduced during spring. At that time R_e was probably mostly made out of autotrophic respiration, due to water logging when the soil frost thawed (from surface, down). During other seasons, even in the winter when part of the soil profile was frozen but not water saturated, the heterotrophic respiration may have dominated the base respiration at low air temperatures. This was, indeed, seen

as higher and rather constant R_e -temperature intercept. It is important to note that high spring ground water table was probably an important contributor to the observed seasonal variation in R_e and hence NEE in this otherwise non-water saturated ecosystem. Water logging in spring may have decreased decomposition of organic matter (heterotrophic respiration) when the soil profile thawed, a well-known phenomena in wetter soils (Davidson et al., 1998).

4.4 Do the warm maritime winters in Iceland represent the future?

In the northern boreal zone, annual temperature has risen and precipitation has increased in the recent decades (e.g. Heimann and Reichstein, 2008). The IPCC (2007) 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). 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 repaired (Fig. 3). The effect of this was 21% and 12% less annual GPP per same growing season length compared to 2004 and 2006, respectively.

4.5 Methodological issues

The present study only covered three years, which is the minimum time period that could be used to report on interannual variation in ecosystem fluxes. Therefore the part of the present study focusing on the annual variation in ecosystem fluxes should rather be viewed as means to deepen the understanding of which processes were most important in the site's carbon balance, rather than it gave valid answers on the true annual variation in ecosystem fluxes over longer periods.

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 site preparation and afforestation the young *Larix* plantation in Vallanes was already a sink for atmospheric CO₂. Although present dataset only consisted of three years, it permitted us to analyze seasonal and interannual 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, and soil water status. It was 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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