Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity

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Abstract

We present results from two years' net ecosystem flux measurements above a boreal forest in central Sweden. Fluxes were measured with an eddy correlation system based on a sonic anemometer and a closed path CO_2 and H_2O gas analyser. The measurements show that the forest acted as a source during this period, and that the annual balance is highly sensitive to changes in temperature. The accumulated flux of carbon dioxide during the full two-year period was in the range 480–1600 g CO_2 m^{-2}. The broad range is caused by uncertainty regarding assessment of the night-time fluxes. Although annual mean temperature remained close to normal, the results are partly explained by higher than normal respiration, due to abnormal temperature distribution and reduced soil moisture during one growing season. The finding that a closed forest can be a source of carbon over such a long period as two years contrasts sharply with the common belief that forests are always carbon sinks.

Keywords: carbon dioxide, eddy correlation, photosynthesis, respiration

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Introduction

There is now increasing evidence that the 'missing sink' in the global carbon budget should be sought in the Northern hemisphere (Schimel 1995; Keeling *et al.* 1996). The boreal forest has been indicated as one of the terrestrial ecosystems which may have a larger sink strength than expected so far. There is also concern that increasing temperatures may reduce sink strength (Plochl & Cramer 1995), and that some northern-hemisphere ecosystems, which now store large amounts of carbon, will even become sources, and further increase global warming.

Most estimates of carbon sequestration by forests have so far been based on calculation of individual compartment fluxes, summed over the whole ecosystem and integrated over time to reach an annual budget. The uncertainty of these estimates is, however, considerable (Tans *et al.* 1990). Technical development has now made it possible to measure the net ecosystem flux of carbon dioxide directly by the *eddy covariance method*. This will remove some of the uncertainties when compartment values are scaled up to ecosystems, and it will provide data with high time-resolution, which will give new

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insight into the processes that control carbon fluxes. An important question in this context is how sensitive the carbon balance is to variations in climate. Recent studies of a rainforest (Grace *et al.* 1995) and a temperate deciduous forest (Goulden *et al.* 1996) have shown that the carbon balance is quite sensitive to temperature, which implies that source/sink strength is vulnerable to climate changes. There is an urgent need for more information from other types of ecosystem; several new studies into this topic have therefore recently been initiated.

In this paper we present results from two years of almost continuous measurements of net ecosystem carbon dioxide fluxes over a boreal forest in central Sweden. The fluxes are measured by a newly developed eddy correlation system which have showed good long-term capability (Grelle & Lindroth 1996).

Materials and methods

The forest in this study consists of mixed Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), stands growing on a boulder-rich sandy till in central Sweden (60°5'N, 17°29'E, alt. 45 m). It is a managed forest, regenerated by leaving seed trees after harvest. The topography is flat, with forest of about the

same height (20–25 m) extending at least 1 km in all directions. The stands within the 1 km range of the tower consists mainly of old and middle aged forest. About one quarter of the area consists of 100-years or older stands, half of the area of 50–100 years old stands and one quarter of stands which are younger than 50 years. The canopy density varies mainly depending on species composition and the leaf area index is coarsely estimated to be in the range 3–6 where pine dominated stands generally are thinner and spruce dominated are more dense. The ground vegetation consists mainly of mosses with occasional stands of dwarf shrubs. The mean annual production in this area is 5–6 m^3 of wood.

The mean annual temperature is 5.4 °C and the annual precipiation is 520 mm at Ultuna, about 35 km southeast of the site. The growing season (threshold of 5 °C) normally lasts from mid-April to the second half of October.

Fluxes of carbon dioxide were measured by three eddy correlation systems, placed on a tower at 35, 70 and 100 m above the soil surface, starting at the end of May 1994. The system was designed specifically for long-term measurements, with demonstrated good performance (Grelle & Lindroth 1996; Grelle 1997). A footprint analysis, based on the simplified model by Schmid (1994) showed that the 35 m instrument, about 10 m above the top of the canopy, had its source areas within the forested fetch and was thus most representative of the forest. The 70 and 100 m levels had footprints extending beyond the forest, especially at night, and data from these levels were therefore not used in this study. The measurements cover ≈ 95% of the period concerned. Gaps in the half-hourly data set were initially filled by means of adjusted data from the other levels, when available, otherwise by linear interpolation between adjacent values. Fluxes are counted as positive when they are directed upwards.

There are some methodological questions regarding measurement of fluxes under stable conditions at night by eddy correlation (EC). When atmospheric mixing is poor, the EC-systems sometimes seems to give too low fluxes. This phenomenon is not so serious for water fluxes, which are close to zero at night. However, for carbon dioxide, this is a serious problem, because respiration goes on at night and should give a flux of the same magnitude, but with opposite sign, as the daytime flux when photosynthesis is active. The cause of the absence of a flux above the forest at night is not clear: it can be either that the EC-systems does not capture the fluxes, or that there is a build-up of carbon dioxide below the measurement level, which is released in form of 'plumes' and, thus, may not be 'seen' by the instruments, or that there is a horizontal drainage of CO_2. The latter phenomenon is not likely to occur in stands with a flat topography. Nevertheless, it may be assumed that

ecosystem respiration should go on at a relatively steady rate also at night, being mainly controlled by temperature; therefore, corrections must be applied to the measured rates. Analysis of the problem showed that the EC-system gave 'stable' fluxes when the friction velocity, u_*, was above 0.4–0.5 m s^{-1} and that it ocasionally 'lost' more and more of the flux with decreasing friction velocity. Data were corrected in two steps. First, a functional relationship between ecosystem respiration and air temperature was determined (see Fig. 5) for nocturnal conditions with $u_* > 0.5$ m s^{-1}. Secondly, this relationship was used to estimate and replace nocturnal values where $u_* < 0.5$ m s^{-1}. Because of these methodological problems, and the uncertainty that they bring, we present both corrected and noncorrected values when it concern the accumulated long-term budget.

The CO_2-flux from the forest floor and the CO_2 exchange by branches were semicontinuously measured by open chamber systems (Iritz *et al.* 1997; Morén & Lindroth 1997) allowing simultaneous and continuous measurements on 2 separate chambers, either branch or soil or a combination of both. Data reported here come from the period in June 1996 when 2 soil chambers and 1 branch chamber were run simultaneously in an adjacent 70 y-old stand. The soil chambers were placed on a rectangular steel frame, 0.3 m wide and 2 m long inserted ≈ 0.05 m into the ground. The chamber itself is large enough to include the dwarf shrubs. The branch chamber enclosed a branch of pine in the upper part of the canopy. The chambers are transparent, open ended and continuously ventilated at a rate of 0.3–0.5 m s^{-1}. This means that the air is changed 10–20 times per minute and the excess heating is keept small. The flux is estimated as the concentration difference before and after the air has passed the surface (soil or foliage) times the rate of mass flow of air through the chamber divided by the area covered by the frame, or, in case of branch chambers, the area of the needles enclosed in the chamber. The concentration difference of CO_2 and H_2O is measured by an infrared gas analyser (LI-6262, LI-COR Inc., USA). In this paper, the chamber data are only used to provide a comparison with the night-time fluxes from the eddy correlation system. Therefore, chamber data was scaled to unit ground area in the following simplistic way; soil efflux was estimated as the arithmetic mean of the 2 soil chambers and canopy respiration was estimated as the measured flux multiplied by the leaf area index which was 6 in this stand. Stem respiration is relatively small and therefore the sum of these two components are assumed to represent the ecosystem respiration at night. It need to be stressed that this simple scaling can not be used to compare daytime fluxes but it should give a resonably good estimate of the night-time fluxes.
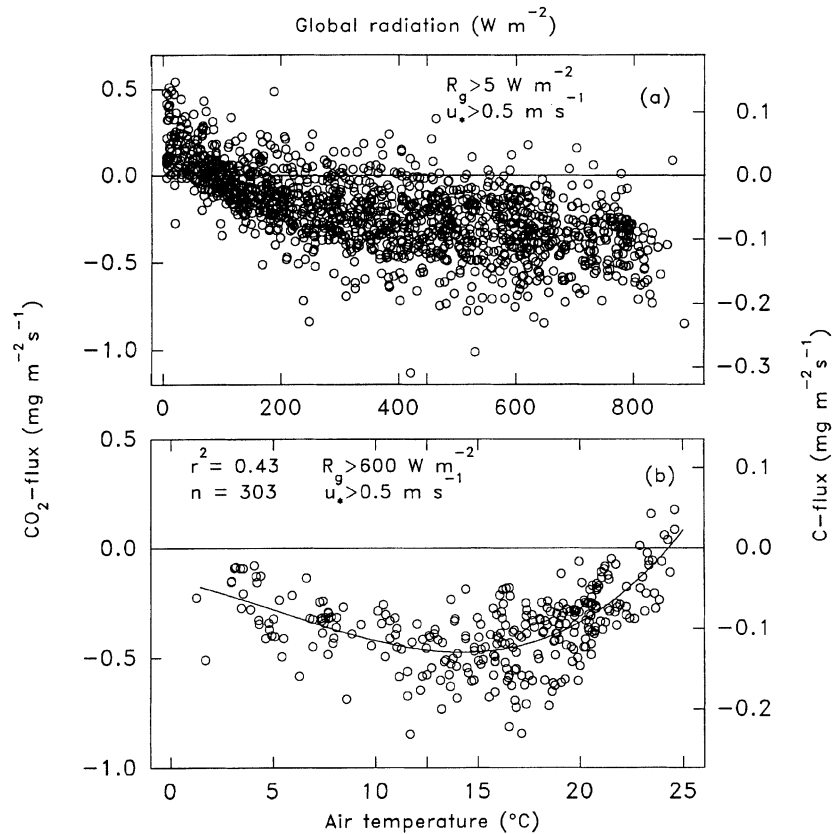
Fig. 1 Half-hourly CO_2-fluxes during the period 1 April to 15 July 1995 plotted against (a) global radiation during daytime and (b) air temperature for global radiation above 600 W m^{-2}. Only data with friction velocities above 0.5 m s^{-1} are used.

Results

Plotting half-hourly daytime CO_2-fluxes against global radiation, R_g, for a selected period (1 April – 15 July) in 1995 when there was no soil moisture deficit (Grelle *et al.* 1997) but still a large range in temperature, shows that the fluxes are predominantly positive below about 100 W m^{-2} and predominantly negative above about 200 W m^{-2}. The flux decreases almost linearly with increasing global radiation up to about 200–300 W m^{-2} (Fig. 1a). Above this level of radiation, the scatter increases considerably and the sensitivity to radiation is much weaker. Even at very high radiation levels, close to zero and even positive fluxes can be observed. Selecting only high radiation levels ($R_g > 600$ W m^{-2}) where uptake is less sensitive to radiation shows that the CO_2-flux depends also on temperature (Fig. 1b). The fitted third degree polynomial explains about 43% of the variations and the minimum is around 14 °C. It is noticeable that the fluxes are becoming positive, i.e. the system is losing carbon to the atmosphere, when the temperature is above 23–24 °C; however, it should be borne in mind that these are situations with near maximum irradiance. In this analysis only data with relatively good mixing of the atmosphere ($u_* > 0.5$ m s^{-1}) were used. The main effect was that the scatter was reduced compared to using all data.
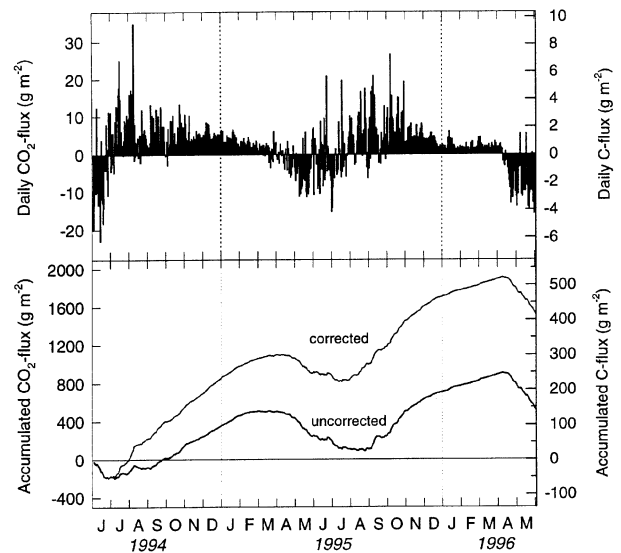

Fig. 2 The 2-year (1 June 1994–31 May 1996) seasonal course of (a) daily sums of net CO_2-fluxes (night-time corrected) and (b) accumulated daily values.

The temporal variation (Fig. 2a) of daily sums of carbon dioxide fluxes (night-time corrected) shows clear seasonal variation, with minimum values, typically – 10 to – 15 and more rarely down to – 20 g CO_2 m^{-2} per day in late

spring/early summer (April–June) and maximum values of the same magnitude but opposite sign in late summer/ autumn (July –September). Even in the middle of the summer, a majority of days show positive values, i.e. the forest is acting as a source of carbon with respect to the atmosphere. In the summer period (June–August), there were 57 days with positive values in 1994 and 49 days in 1995. Days with positive values are highly correlated to overcast and warm weather situations. Also note-worthy in the seasonal curves are the consistent positive values during winter (Fig. 2a). The warm winter of 1994/ 95 shows rather large positive fluxes, with typical daily values around 5 g m^{-2}. Even the cold winter of 1995/96, with a mean (November–February) air temperature of – 6 °C, shows small but significant positive values. The cold winter, with deep soil frost, was followed by a swift weather change at the beginning of April, with relatively warm air and clear skies. This led to an immediate change to large negative fluxes, which continued throughout the period shown here. These large negative fluxes are probably the result of the trees photosynthesizing at normal rates, while the soil respiration rates were substan-tially reduced because of the low soil temperature. Split-ting the period into two whole-year cycles, 1 June–31 May 1995 and 1 June 1995–31 May 1996, respectively, shows that the first period exported 922 and the second 596 g CO_2 m^{-2} into the atmosphere, i.e. a minor variation between the years. The accumulated flux of carbon dioxide during the whole two-year period was 1518 g CO_2 m^{-2}, i.e. this forest is a source of carbon rather than a sink (Fig. 2b). For comparision, the uncorrected accumulated net flux, also positive with 514 g CO_2 m^{-2} over the 2-year period, is also shown in Fig. 2(b). We consider these two values, ± 6% on each, to represent an upper and lower limit, respectively, of the true 2-year net exchange.

The temporal distribution of sources and sinks is best shown by combining mean monthly diurnal curves into a 2D-plot (Fig. 3) over a complete year, in this case 1995. The sink period shows up as a somewhat asymmetrical 'bulls eye' in the centre of the picture, with maximum sink strength about an hour before noon. Maximum source strength is similarly shifted slightly towards autumn. It is also evident that uptake begins relatively early in spring and continues into late autumn. The variation in distribution of source/sink processes, demon-strated by this picture, stresses the importance of the night-time fluxes, and the need to study complete annual cycles when budgets are to be estimated.

The respiration of the ecosystem is apparently a key process when annual budgets are concerned. Measure-ments during darkness, when photosynthesis is effec-tively zero, provide a means of obtaining total 'dark' respiration of the system. The chamber measurements,
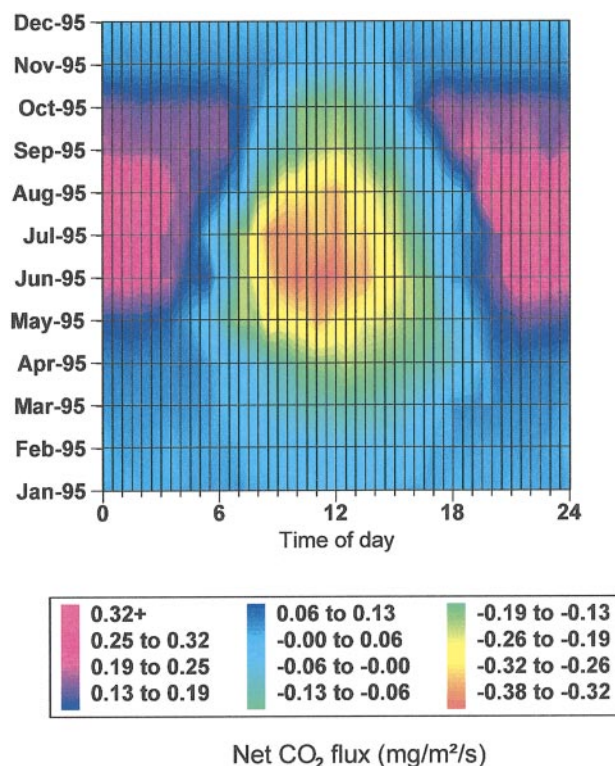

Fig. 3 Temporal distribution of average net ecosystem fluxes of CO_2 during 1995. The shift from sink to source corresponds to the change in colour from green to light blue.

scaled to stand level, show fairly good agreement with the measured fluxes at night (Fig. 4). The night between 9 and 10 June is an example of a night where the friction velocity dropped to almost zero and where the eddy correlation system recorded practically zero flux. The flux measured by the chambers continued at about the same level as previous night and the night after. The night between 8 and 9 June was also a calm night with low friction velocity, almost similar to the night between 9 and 10 June, but here the eddy correlation system recorded fluxes close to the chamber values. This compar-ison show that the two independent systems give reason-ably similar values and that measured night-time fluxes need to be corrected.

Respiration is highly dependent on the temperature of the respiring matter, and the problem is that within an ecosystem, several compartments at different temper-atures contribute to the total respiration. This makes it difficult to obtain a single representative temperature for the whole forest ecosystem. Our aim was to make the simplest possible model of ecosystem respiration. We therefore tested how well different temperatures in soil and air explained total respiration. There were two reasons why we finally chose to use air temperature, measured at a reference level above the canopy, as the dependent variable describing total ecosystem respiration

Fig. 4 Temporal development of CO_2-fluxes measured by eddy correlation system and chambers during a period in June 1996. The dashed vertical lines indicate the length of the night-time period. Chamber data are scaled to stand level using 2 soil chambers and 1 branch chamber. Comparison is only relevant for the night-time periods.
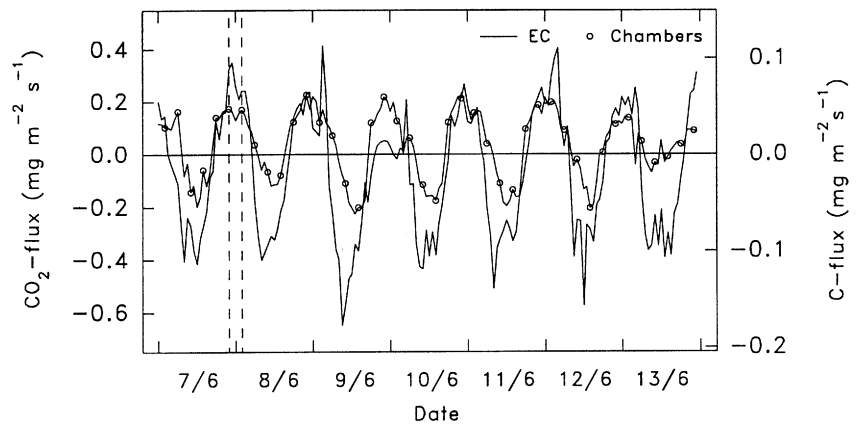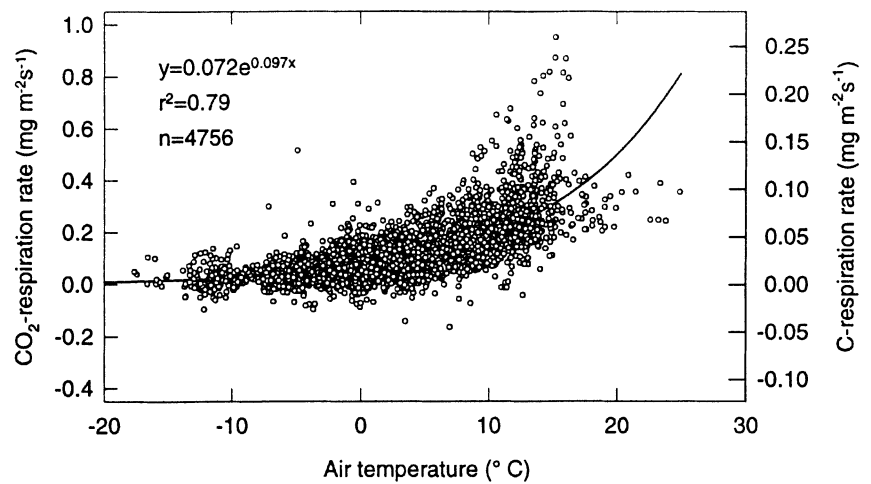

Fig. 5 Half-hourly CO_2-fluxes plotted against air temperature for night-time values with friction velocity above $0.5~ms^{-1}$.

as an exponential function (Fig. 5). First, we found only very small differences in explanatory power of the different temperature measures. Secondly, it is a climatological parameter which can be used, e. g. to quantify variations in respiration caused by variations in temperature.

The relationship between total respiration and temperature was used to estimate the accumulated total (dark) respiration during 1995 (Fig. 6). Since the net flux was measured, it was also possible to estimate gross photosynthesis as the difference between these two components
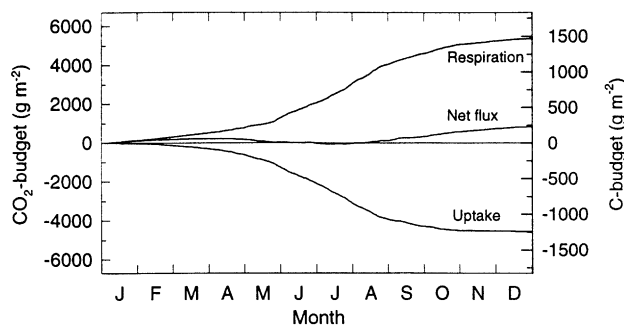

Fig. 6 The CO_2-budget during 1995.

(Fig. 6). It is evident from this graph that the net carbon flux is in a delicate balance between two large terms, respiration and uptake. A small shift in one of them can have a large impact on the balance, and can even change the balance from positive to negative or *vice versa*. As indicated by Fig. 5, respiration is quite sensitive to temperature, and it is interesting to see how sensitive the annual balance is to a change in temperature. A sensitivity test was made by simply adding 1 K to all half-hourly measured temperatures, then using the functional relationship of Fig. 5 to estimate a new annual total respiration. To estimate the effect on the balance, we also have to consider the effect of temperature on photosynthesis. The boreal forest is a temperature-limited ecosystem, and it is reasonable to assume that an increase in temperature is followed by an increase in photosynthesis. The effect will largely depend on how the increased temperature is distributed within the year. If most of the increase falls in winter and spring, with an earlier start of the growing season as a consequence, then the net annual photosynthesis could increase (Bergh *et al.* 1997) by the order of 5%. To simplify, we assumed the net uptake to increase by 0, 5, and 10% to analyse the effect on the total carbon
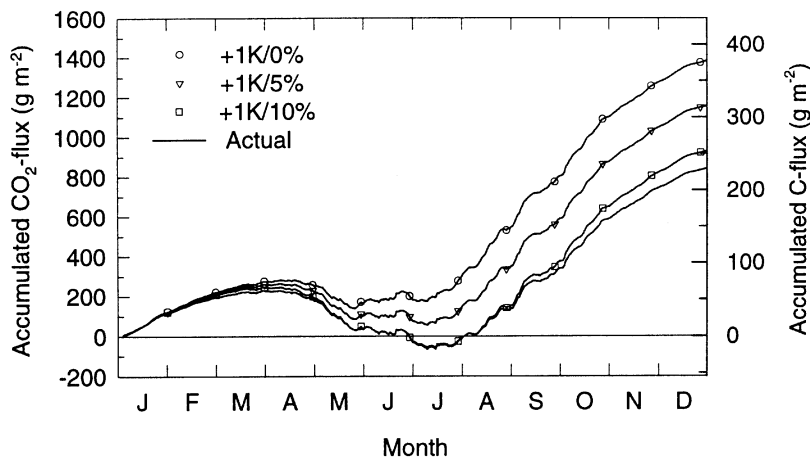
Fig. 7 The accumulated net ecosystem flux sensitivity to a change in temperature. The 0% alternative show the temperature effect on respiration alone while the others show a combined effect of increased temperature (1K) and increased photosynthesis by 5 and 10%, respectively.

balance. Annual respiration increased by 542 g CO_2 m^{-2} or by 10% for the imposed 1 K increase in temperature (Fig. 7). This corresponds to 64% of the balance. The final result of the temperature increase, however, depends very much on the effect on photosynthesis. Photosynthesis need to increase by about 12% to compensate for the increase in respiration (Fig. 6). This is not likely, and it is therefore reasonable to assume that the balance will grow more positive with increasing temperature.

Discussion

An assessment of the accuracy with which the net fluxes of CO_2 is measured is not so easy because of the observed night-time anomalies. The eddy correlation systems used here have shown very good performance and the long-term closure of the energy balance is typically 96–98% (Grelle & Lindroth 1996; Grelle 1997). Grelle (1997) has made a detailed error analysis of the system and the conclusion is that the error in the long term measurement of the CO_2 component is 5.7%. This error does not include the methodological problems associated with the night-time fluxes. The results obtained here stress, however, that this problem needs more attention in order to make more accurate estimations of long-term budgets.

The maximum uptake rates were in the order of –0.5 mg CO_2 m^{-2} s^{-1} (Fig. 1) which is higher compared to values reported for an old jack pine forest in Canada by Baldocchi *et al.* (1997), who reported typical midsummer maximum uptake rates in the order of –0.2 to –0.3 mg CO_2 m^{-2} s^{-1} but lower compared to rates in the order of –1.2 mg CO_2 m^{-2} s^{-1} as reported by Black *et al.* (1997) for a boreal aspen forest. Our maximum rates are in the lower end of the range found for temperate forests (Baldocchi *et al.* 1997). The temperature sensitivity of the net CO_2-flux at high irradiance has an optimum at about 14–15 °C. This value coincides with optimal values for photosynthesis as reported for Norway spruce (Berg

1997) and Scots pine (Troeng & Linder 1982) in Sweden. The rapid decrease of the uptake when the temperature increases above the optimal value is probably more an effect of rapidly increasing respiration than an effect of decreasing photosynthesis. The response curves for photosynthesis are generally relatively flat for conifers (Teskey *et al.* 1995) and an increase of 10 K above the optimum typically reduces the photosynthesis by 10–20%. Here, the uptake is completely eliminated and the net carbon flux becomes even positive when the temperature increases 10 K above the optimum value. What we see is the combined effect of an exponentially increasing ecosystem respiration and a slowly decreasing photosynthesis.

Comparing daily sums with the old jack pine studied by Baldocchi *et al.* (1997) shows that, in spite of higher maximum uptake rates in our forest, the jackpine had a larger net uptake. Daily sums of carbon dioxide exchange ranged between –4.0 and 2.0 g C m^{-2} d^{-1} in the jack pine during the heart of the growing season while corresponding values in our forest were – 2.2–5.5 g C m^{-2} d^{-1}. The jack pine accumulated 47 g C m^{-2} during 23 May and 16 September 1994 (117 days) while the corresponding values for our forest were between –8 and 61 g C m^{-2} during the same period in 1995. The two values represent uncorrected and corrected values, respectively.

The temperature sensitivity of our boreal forest seems to be similar to that reported for an undisturbed rain forest (Grace *et al.* 1995). They found that the annual uptake of carbon decreased by about 6 mol C m^{-2} for a 0.5 K increase in temperature. This is about half of the values we found for a temperature increase twice as large.

The cause of the positive balance recorded over the two-year period is not easy to ascertain. It is not reasonable that a forest loses carbon to the atmosphere in a long-term perspective. However, there is a large pool of carbon in the soil, which makes it possible to obtain positive balances during short periods. To test whether the positive

balance could be explained by a climate warmer than normal, data collected at Ultuna, about 35 km south of the forest, were used. There was no sign of a temperature anomaly, because the mean temperature over the two-year period was only 0.1 °C above the 30-year average (1961–90). However, the strong nonlinearity between respiration and temperature suggests that annual averages of temperature are unsuitable as a tool for judging the effect on respiration. Therefore, respiration was estimated using the function described above, with actual mean monthly temperature as input, as well as with the normal (1961–90 mean) monthly values as input. Comparison of these two values shows that the respiration during the 2-year period actually was in the order of 5% larger compared to 'normal'. Application of this relative difference to the two-year respiration of the forest gives a potential increase of 550 g CO_2 m^{-2} due to variations in climate. This value constitutes about 36% of the two-year balance (night-time corrected). Another factor which explains the positive balance is reduced uptake caused by low soil moisture during the summer of 1994. An analysis of tree transpiration in two stands close to the tower, using sap-flow measurements, showed that transpiration was severely reduced (Cienciala *et al.* 1997) below the potential values in July and August 1994. The effect of the drought on tree growth was also clearly visible. In 1995, too, there was a short period of reduced transpiration in late summer/autumn. Cienciala *et al.* (1997) used the FOREST-BGC model (Running & Gower 1991) to estimate the effect of the drought on photosynthesis and they found a reduction of about 30% in 1994 and much less, about 5% in 1995.

It may be speculated that an additional explanation to our results could be sought in the observed tendency towards increased cloudiness and warmer nights in the Northern hemisphere (Karl *et al.* 1993). Both of these factors work in the direction of increased respiration and reduced photosynthesis, consequently towards a more positive carbon balance. Seen in the light of the demonstrated temperature sensitivity, this explanation should not be ruled out without further consideration.

It should also be kept in mind that this is a managed forest which, for instance, have been ditched some 20 years ago in order to improve productivity. A lowering of the water table generally increases productivity but it also increases decomposition of organic matter in the soil. The balance between these two effects is difficult to assess but it might provide another explanation to the positive balances that we are recording.

In conclusion, we have shown that the carbon balance of a boreal forest is quite sensitive to changes in temperature and that the temperature effect on photosynthesis will determine the net effect on the carbon balance. We have also shown that the forest can act as a source of carbon over substantial periods, and that the daily net flux can be bi-directional even in high summer. It is also evident that fairly comprehensive simulation models, covering full annual cycles, are needed to explain the effects of climate on the carbon balance.

Acknowledgements

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