Respiration as the main determinant of carbon balance in European forests


Carbon exchange between the terrestrial biosphere and the atmosphere is one of the key processes that need to be assessed in the context of the Kyoto Protocol1. Several studies suggest that the terrestrial biosphere is gaining carbon2–4, but these estimates are obtained primarily by indirect methods, and the factors that control terrestrial carbon exchange, its magnitude and primary locations, are under debate. Here we present data of net ecosystem carbon exchange, collected between 1996 and 1998 from 15 European forests, which confirm that many European forest ecosystems act as carbon sinks. The annual carbon balances range from an uptake of 6.6 tonnes of carbon per hectare per year to a release of nearly 1 T C ha−1 yr−1, with a large variability between forests. The data show a significant increase of carbon uptake with decreasing latitude, whereas the gross primary production seems to be largely independent of latitude. Our observations indicate that, in general, ecosystem respiration determines net ecosystem carbon exchange. Also, for an accurate assessment of the carbon balance in a particular forest ecosystem, remote sensing of the normalized difference vegetation index or estimates based on forest inventories may not be sufficient.

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The terrestrial sink for carbon is estimated to be of the order of 2 ± 1 Gt C yr⁻¹ (ref. 1). In the Northern Hemisphere, the terrestrial biosphere is currently absorbing carbon according to several studies²–⁴. These studies use different techniques dependent on indirect estimates of the carbon fluxes, like isotopic analysis and inversion methods from CO₂ concentration measurements⁵–⁷; remote sensing⁸; growth trend analysis⁹–¹² and modelling. All these methods provide the necessary global and continental scale perspective for carbon balance calculations. However, these studies suffer from uncertainties in the assumptions used. For instance, in the inverse modelling studies the anthropogenic sources and sinks are frequently prescribed a priori and they lack adequate representation of the carbon balance at local scales. Their use in addressing small temporal and spatial changes in the carbon balance is therefore rather limited. The net carbon exchange of terrestrial ecosystems is the result of a delicate balance between uptake (photosynthesis) and loss (respiration), and shows a strong diurnal, seasonal and annual variability. Under favourable conditions, the net ecosystem flux is dominated by photosynthesis during daytime, and by respiration at night and for deciduous ecosystems in leafless periods. The influence of climate and growing-season length can in some cases shift a terrestrial ecosystem from a sink to a source of carbon¹³–¹⁴. Global- and continental-scale techniques are of limited use in addressing one of the key questions raised by the Kyoto Protocol, namely how to calculate the changes in “carbon stocks” associated with land use changes and forestry activities during the commitment period. Indeed, one of the major effects of land-use changes, including the afforestation, reforestation and deforestation of land, is to change soil organic matter (SOM), by both build up and decomposition¹⁵. For most ecosystems, the changes in stocks of soil carbon in a 4–5 year period are unfortunately within the errors of the survey techniques used. Remote sensing approaches also appear inadequate for such purposes, because they have limited capability for estimating below canopy processes such as soil respiration.

In this context, the direct, long-term measurement of carbon fluxes by the eddy covariance technique¹⁶ offers the possibility of assessing on a local scale the carbon sequestration rates of forests and of different land-uses. The technique can also provide a better understanding of the vulnerability of the carbon balance of ecosystems to climate variability, and can be used to validate ecosystem models and to provide data for land surface exchange schemes in global models¹⁷.

Automated eddy covariance measurements of CO₂ fluxes have been made routinely over 15 forests in Europe since 1996 within the EUROFLUX network¹⁸. In 1998, the network approach was expanded in the US (AMERIFLUX) and plans exist to implement similar networks in Brazil (the Large Scale Biosphere Atmosphere

Table 1 Main characteristics of the EUROFLUX and associated sites

<table>
<thead>
<tr>
<th>Site²</th>
<th>Latitude</th>
<th>Species²</th>
<th>Ecosystem type³</th>
<th>Elevation (m a.s.l.)</th>
<th>T (°C)</th>
<th>P (mm)</th>
<th>Age (y)</th>
<th>LAI (m²)</th>
<th>Period of observation</th>
<th>NEE (t C ha⁻¹ yr⁻¹)</th>
<th>RE (t C ha⁻¹ yr⁻¹)</th>
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<tbody>
<tr>
<td>1 Italy 2</td>
<td>41°45’</td>
<td>M, BE</td>
<td>N</td>
<td>3</td>
<td>15.3</td>
<td>770</td>
<td>50</td>
<td>3.5</td>
<td>1997</td>
<td>-6.6</td>
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<td>NM</td>
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<td>PNM</td>
<td>60</td>
<td>13.7</td>
<td>936</td>
<td>29</td>
<td>2.8</td>
<td>13/07/96–12/07/97</td>
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<td>46°18’</td>
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<td>NM</td>
<td>1,720</td>
<td>4.1</td>
<td>1,010</td>
<td>80</td>
<td>4</td>
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<td>NM</td>
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<tr>
<td>12 Belgium 2</td>
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<td>M, C+BD</td>
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<td>10</td>
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<td>19 Unit. King. 1</td>
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<td>24 Finland 1</td>
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<td>PNM</td>
<td>170</td>
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<td>669</td>
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</tr>
<tr>
<td>25 Iceland 1</td>
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<td>IMP</td>
<td>78</td>
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<td>1997</td>
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<td>100</td>
<td>4.5</td>
<td>1993–94</td>
<td>-4.7</td>
<td>5.4</td>
</tr>
</tbody>
</table>

*The site number refers to the data labels in figures. Sites are nominated as in the EUROFLUX project.
†M, mixed; BE, broad-leaved evergreen; BD, broad-leaved deciduous; C, coniferous.
‡NM, natural origin and managed; PNM, planted stand with traditional forest management; IMP, intensively managed plantation.
§Leaf area index, projected basis.
∥Period for the flux data presented; all the sites are currently measuring fluxes.
¶Net ecosystem exchange (see Methods).
#Total ecosystem respiration (see Methods).
Figure 1 Net ecosystem exchange (NEE) of the EUROFLUX sites plotted against latitude. Closed symbols, forest of natural origin and planted stands with traditional forest management; open symbols, intensively managed plantations. According to the eddy covariance theory, a negative sign indicates that carbon is absorbed by the forest, while a positive sign indicates that carbon is released by the forest to the atmosphere.

Figure 2 Gross primary production (GPP) of the EUROFLUX sites plotted against latitude. Closed symbols, forest of natural origin and planted stands with traditional forest management; open symbols, intensively managed plantations.

Figure 3 The ratio of net ecosystem exchange (NEE) and total ecosystem respiration (RE) plotted against latitude. Closed symbols, forest of natural origin and planted stands with traditional forest management; open symbols, intensively managed plantations.

Experiment in Amazonia, South East Asia (the GEWEX Asian Monsoon Experiment) and Siberia. These tower sites are now forming a global network, FLUXXNET\textsuperscript{16}, with standard measurement protocols, data quality control and storage systems\textsuperscript{15}. The flux stations measure the net flux of carbon entering or leaving the ecosystem. This is the flux which provides a measure of net ecosystem exchange (NEE), and, if summed annually, provides a direct estimate of the annual ecosystem carbon balance (excluding disturbances by harvest and fire which give rise to net biome productivity)\textsuperscript{17}. In several studies the accuracy of annual sums has been estimated to be about 5%, or typically 0.3 t C ha\textsuperscript{-1} yr\textsuperscript{-1} (refs 18, 19), with the error influence decreasing with increasing size of the flux data set\textsuperscript{20}.

To reduce the uncertainty associated with site-to-site variation in flux measurement methods and calculations and to make comparisons between sites, the EUROFLUX network was designed with the same hardware and software specifications at all sites\textsuperscript{15}. The EUROFLUX results for 1996–98 show a sink strength of up to 6.6–6.7 t C ha\textsuperscript{-1} yr\textsuperscript{-1} for two forests in Southern Europe and for a Sitka spruce plantation in Scotland, and indicate that European old boreal forests are close to equilibrium and may switch from being a carbon source one year to a carbon sink the next (Table 1). Within the same biome, younger stands still gain carbon, although at a lower rate than temperate forests, Mediterranean forests or fast-growing plantations. Despite the wide range of species composition, stand structure, soils, tree age, site disturbance history and year-to-year variability, a consistent latitudinal trend in NEE is found (Fig. 1). Indeed a multivariate statistical analysis on the effect of the single factors (latitude, precipitation, ecosystem type, elevation, mean annual temperature, age, management type, leaf area index) on NEE, showed that latitude is the most significant single variable model ($r^2 = 0.55$, $P < 0.001$). Latitude is not a phenomenological driving variable per se, however it is a good proxy for the actions of a multiplicity of factors (for example, radiation balance, length of growing season, frost events, disturbance regime).

The trend indicates that high-latitude forests generally show lower and more variable carbon sequestration rates than low-latitude forests. The several forests growing within 50° and 52° N show a pronounced variability, with NEE ranging from an uptake of less than 1 t C ha\textsuperscript{-1} yr\textsuperscript{-1} (site Germany 1, point 7) to 5.4 t C ha\textsuperscript{-1} yr\textsuperscript{-1} (site Germany 2, point 11). In this latitudinal band, the variability can be related to stand, soil and climate characteristics, ranging from continental to maritime. With its maritime proximity, the intensively managed and fertilized fast-growing spruce plantation (site United Kingdom 1, points 19, 20) falls off the latitudinal trend, with a higher uptake of carbon than more continental stands located at similar latitude. Despite the large variation of NEE, gross primary production (GPP) is rather conservative across sites and latitude, indicating that other components of the carbon balance are responsible for the observed variation in NEE (Fig. 2). It is noteworthy that the young spruce plantation has the largest values of GPP, indicating strong stimulation of photosynthesis, while the young poplar plantation (point 25) growing in a cold climate at 64° N shows the smallest GPP.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Latitude (°N) & NEE (t C ha\textsuperscript{-1} yr\textsuperscript{-1}) & GPP (t C ha\textsuperscript{-1} yr\textsuperscript{-1}) \\
\hline
35 & -6.0 & -24.0 \\
40 & -4.0 & -22.0 \\
45 & -2.0 & -20.0 \\
50 & 0.0 & -18.0 \\
55 & 2.0 & -16.0 \\
60 & 4.0 & -14.0 \\
65 & 6.0 & -12.0 \\
70 & 8.0 & -10.0 \\
\hline
\end{tabular}
\end{table}
The observed variation in NEE across sites can be explained by the relative importance of ecosystem respiration (RE) in relation to NEE. The ratio NEE/RE increases with latitude (Fig. 3) indicating that RE becomes more important for northern sites and can explain the decrease of NEE previously shown. Generally, while GPP tends to be constant across sites, annual ecosystem respiration increases with latitude, despite the general decrease of mean annual air temperature (Table 1). It is well known that temperature has a strong effect on soil and plant respiration. For single sites our data also show a significant relationship between temperature and ecosystem respiration for both short and annual timescales. However, when a plot of RE versus temperature is drawn across all sites the relationship is not significant, indicating that mean annual air temperature may not be an important contributing factor to forest ecosystem respiration on a broader scale.

In forests, total ecosystem respiration tends to be dominated by root and microbial soil respiration. Boreal soils contain a larger amount than temperate soils of soil organic matter (SOM) in a labile form that is prone to rapid decomposition. The effective temperature sensitivity ($Q_{10}$) of SOM decomposition is much higher in colder than in warmer climates and temperature increases in cold regions are likely to affect decomposition rates more than net primary productivity. There is also evidence that northern latitudes have warmed by more than 4°C, while southern latitudes have warmed less. This may have resulted in non-steady state conditions for SOM which could explain relative enhancement of respiration in the north compared to the south.

In this respect, land-use change and site history could also be important. For example, site Sweden 1 (points 21–23) is losing carbon as a result of past soil drainage, while the high respiration rates of the maritime spruce plantation may be linked to preparation of the site by ploughing, the favourable maritime climate and fertilization. Furthermore the relatively low rates of respiration of the southern sites may be the result of drought limitations to soil respiration.

The carbon balance is ultimately a delicate equilibrium between the two large fluxes of photosynthesis and respiration, and this appears to be particularly true for boreal European ecosystems, making them very vulnerable to disturbances in climate. Indeed, annual variability for these high latitude sites is very pronounced, as shown by the remarkable variation in NEE from year to year; warm winters tend to switch old boreal stands from a sink to a source of carbon by increasing the annual amount of respiration (site Sweden 1; Table 1). In other boreal ecosystems, year-to-year changes in timing of the thawing of the soil in the spring are important for the carbon balance.

The direct flux estimates of carbon exchange provide a useful tool for understanding the overall carbon balance processes of terrestrial ecosystems. Indeed, partial accounting of carbon dynamics can easily lead to erroneous conclusions. For example, plant biomass is currently increasing in all the EUROFLUX sites, even though some of these sites have a carbon budget close to neutral and one is losing carbon on a yearly basis. Similarly, the increases in plant growth at northern latitudes estimated by remote sensing of the normalized difference vegetation index (NDVI) must be examined critically in the light of these results, confirming the need to consider ecosystem respiration. Also forest inventory-based carbon balance estimates should be carefully examined in relation to comprehensive carbon budget accounting. Furthermore, flux tower networks can provide at local scale realistic constraints on the global carbon balance estimates.

**Methods**

**Instruments**

In the EUROFLUX network, the same CO$_2$/H$_2$O infrared gas analyser (LI-6262, Licor Inc.) and sonic anemometer (Solent, Gill Inst.) are used. All the analysers are calibrated against the same CO$_2$ standard (NOAA Climatic Monitoring and Diagnostics Laboratory, Boulder, Colorado). The software for eddy covariance data acquisition and calculation have been extensively tested and compared against reference data sets, resulting in a maximum variation of calculated fluxes of less than 1% (ref. 15).

**Data treatment**

The collected data are quality controlled, corrected for frequency losses and sensor separation and, when needed, corrected for night-time fluxes under stable conditions with low wind speed or friction velocity typically less than 0.2 ms$^{-1}$ (refs 14, 15).

NEE values for the entire year are obtained by summation of fluxes measured on a 30-min time step. The average coverage of directly measured data for all of the sites was more than 70% of the annual half-hour periods (60–95%). Fluxes in stable conditions and data gaps have been filled through site-based functional relationships using meteorological variables, such as radiation during the day and temperature during the night. Small gaps (a few half-hours) during single days were filled by simple interpolation. For data gap filling procedure see Supplementary Information.

GPP values have been obtained by summing annual NEE and ecosystem respiration (RE). RE comes from the summation of night-time fluxes (all sites), whole-day fluxes for leafless periods (deciduous forests) and of the day-to-day respiration.

Night-time and leafless-period fluxes are obtained by summation of the fluxes measured by eddy covariance on a 30-min time step, including the CO$_2$ storage component. Daytime respiration has been obtained by extrapolating the night-time fluxes to the rest of the day, using functional relationships with soil or air temperature.

Statistically based analysis, based on different procedures, namely the forward and stepwise selections and the maximum R-square improvement, was used to test the controlling factors on NEE.

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Determination of relative growth rates of natural quartz crystals

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Although the theory describing crystal growth in the geological environment is well established1–6, there are few quantitative studies that delimit the absolute time involved in the growth of natural crystals4–6. The actual mechanisms responsible for the variation in size and shape of individual crystal faces are, in fact, not well understood. Here we describe a micro-infrared spectroscopic study of a single, gem-quality quartz crystal that allows us to measure the size, shape and relative growth rate of each of the crystal faces that are active throughout its growth history. We demonstrate that the abundances of hydrogen-bearing impurities can serve as ‘speedometers’ to monitor the growth rate of advancing crystal faces. Our technique can be applied to crystals from a variety of geological environments to determine their growth histories. Within the electronics industry, the technique might facilitate the production of defect-free synthetic crystals required for high-quality resonators and, ultimately, might allow determination of the absolute time involved in geological processes such as the crystallization of magmas, fluid flow in metamorphism and the sealing of open cracks in earthquake rupture zones.

Euhedral quartz crystals grown in hydrothermal metamorphic environments reveal classic trigonal structural form7. Crystals grow into fluid-filled cavities typically with six well-defined [1010] ‘m’ prism faces, three prominent [0111] ‘r’ faces, and three [1011] ‘z’ faces (Fig. 1). Despite the limited number of observable active growth faces, every natural hydrothermal quartz crystal has a unique crystal morphology, analogous to human fingerprints and snowflakes. Unfortunately, the final morphology of the crystal cannot be inverted uniquely to determine the relative growth rates of each face during growth. If a priori knowledge of the sizes of individual growth faces throughout the crystal’s growth history are known, relative growth rates of faces within single crystals can be constrained8. Such knowledge has been ascertained by examining ‘ghost’ features of transparent crystals and by cathodoluminescence analyses9,10. However, neither inter-crystalline comparisons nor quantitative constraints of absolute growth rates of common metamorphic minerals are, as yet, available.

Although quartz is one of the purest minerals known, no crystal is pure SiO2. Conventional infrared studies have shown that many of the impurities in quartz crystals are hydrogen-bearing species that form point defects in the crystal lattice11,12. Individual cations bond to the oxygen atom of the hydroxyl group with variable strength, and the O–H stretching motion absorbs energy at wavelengths characteristic of the individual species resulting in a sharp absorbance peak in the region between 3,600 and 1,000 cm−1 (ref. 13). Three hydrous species are especially common in natural quartz crystals: (1) AlOH species that absorb energy at 3,380 cm−1; (2) LiOH species that absorb energy at 3,480 cm−1; and (3) HOH species that absorb a relatively broad band of energy centred at 3,400 cm−1. Spectroscopic studies have demonstrated that AlOH defects are oriented in the crystal structure such that O–H bonds extend nearly horizontally into channels that run parallel to the c-axis11,14. Al3+ replaces Si4+ in the rigid silicate lattice, and the H+ serves to charge-balance the substitution. In contrast, HOH and LiOH species are incorporated as neutrally charged molecules and are not integral to the crystal lattice. The HOH species probably exist as isolated molecules (but may exist within minute clusters that are too small to allow formation of an ice phase)15,16. The broad absorbance spectrum indicates that these species are hydrogen-bonded to varying degrees within the crystalline structure15. Because H-bearing defects are believed to alter strongly the rheological properties of nominally anhydrous minerals and thereby affect the rheology of the upper mantle and the lower crust, much experimental and theoretical work has investigated the nature of H-uptake in major anhydrous phases15–19. In addition, H-bearing impurities are known to affect crystal quality relevant to the development of high-frequency devices used in the electronics industry20,21. Although these studies have broadened our understanding of the crystallography associated with the uptake of H-bearing defects, none have accounted for the large range in impurity concentrations observed in single natural crystals or in crystals across the spectrum of geological environments.

The results of our spectroscopic measurements for each of the traverses taken across levels 3, 7 and 8 of the crystal are illustrated in maps A, B and C in Fig. 2a. Map A in Fig. 2a illustrates the variation

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Figure 1 Photographs of the Brazilian quartz specimen analysed in this study, showing the specimen before sectioning. Diagrams next to the photographs show the three prominent ‘z’ and the three subordinate ‘r’ rhombohedral growth faces at the tip of the crystal, as well as the well-defined six ‘m’ prism faces. Scale bar, 1 cm.