Modelling Net Ecosystem Carbon Exchange (NEE) of a Forest Ecosystem in Middle Europe

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Abstract: The net ecosystem exchange of carbon dioxide was modelled based on Eddy Covariance (EC) measurements of carbon dioxide fluxes above an old spruce stand at the Anchor Station Tharandt/Germany (since 1996) and long-term meteorological and hydrological observations of an adjacent water catchment (Wernersbach).

The modelling itself is based on a regression analysis between the net CO_2 exchange at the Anchor Station and the canopy conductance of the watershed on a daily scale. First model results that used a canopy conductance obtained from the Penman-Monteith equation could be improved by using the combined Shuttleworth-Wallace resistances. The model results are presented and compared with measured data and annual wood increments obtained from tree ring analysis. Results from this study suggest that a coupling of water and carbon cycle, or water vapour and carbon exchange, respectively, can prove to be a successful way of modelling the ecosystems carbon exchange.

Keywords: *NEE, carbon exchange, Eddy Covariance, canopy conductance, Shuttleworth-Wallace*

1. INTRODUCTION

As various measurements show, there is an increasing CO_2 concentration in the atmosphere. This is of special concern because the large biogeochemical cycles have an important role in the earth's climate system). Continuous long term measurements of atmospheric carbon fluxes make it possible to study the carbon exchange processes and the carbon storage within the ecosystem as well as the ecosystems reaction to climate changes.

Within the projects EUROFLUX and CARBOEUROFLUX, energy and CO_2 fluxes have been continuously measured at the Anchor Station Tharandt since 1996. These measurements were used to model the carbon Net Ecosystem Exchange (NEE). For this purpose a regression analysis between NEE and the canopy conductance of an adjacent watershed is used. The canopy conductance was obtained from the Penman-Monteith equation using a modelled transpiration rate (hydrological model BROOK90, Federer, 1995). Finally the idea was to include the carbon simulation into BROOK90 and also to use the Shuttleworth-Wallace (SW) resistances from the BROOK90 model to calculate the canopy conductance.

2. CALCULATING THE CARBON BALANCE FROM EDDY COVARIANCE MEASUREMENTS

2.1. Measurement Site

The Anchor Station Tharandt is a 110-year-old stand of spruce (Picea abies) near Dresden, Germany (50°58'N, 13°34'E). The canopy height is about 27m, the tree density 477/ha and the leaf area index is 7.6 (projected) and 20.6 (total).

The continuous measurements at the stations micromet-tower include Eddy Covariance (EC) measurements of water and carbon fluxes with a time interval of 30 min. CO_2 concentrations are recorded at 9 different heights covering a range from 0.2m to 42m.

Soil respiration measurements (chamber measurements) were taken in autumn/winter 2000/2001. Using this data, a verification of night time CO_2 fluxes (EC method) was performed.

2.2. Applied Corrections

In addition to the usual corrections of EC flux measurements (e.g. cospectral damping loss), it is necessary to exclude periods with insufficient turbulence (particularly with regard to night time conditions), as the overall atmospheric exchange is represented by the EC measurements under sufficient turbulence only. Because of these excluded periods and some measurement failures there are some data gaps. To fill these gaps, with the aim of calculating daily values of the CO_2 exchange the daytime and night time half-hourly NEE were modeled separately using non-linear regression methods (parameterised for periods with sufficient atmospheric turbulence conditions). For further information about this procedure see FALGE et al., 2001, and GRÜNWALD, 2003.

3. MODELLING THE CARBON NET ECOSYSTEM EXCHANGE BY COUPLING WATER AND CARBON FLUXES

3.1. General Assumption

The NEE is the sum of all CO_2 sinks and sources within the ecosystem which are subject to the atmospheric transport. It consists of four terms - the turbulent flux, the storage change, and the non-turbulent flux in vertical and horizontal direction. According to AUBINET et al. (2000) it can be described as:

$$\int_0^{z_r} \frac{S}{\partial t} dz = (\overline{w'c'})_r + \int_0^{z_r} \frac{\partial c}{\partial t} dz + \int_0^{z_r} \overline{w_r} \frac{\partial c}{\partial z} dz + \int_0^{z_r} \bar{u} \frac{\partial c}{\partial x} dz \tag{1}$$

where (z_r) represents the turbulent CO_2 flux in the reference level of the EC measurement, c is the atmospheric CO_2 concentration, w_r is the vertical wind speed in the reference level and u the horizontal wind speed in the respective layer. The turbulent flux (term 1) is usually the most important part of the exchange processes as it covers the turbulent transport of CO_2 throughout the reference level. The second term describes the storage changes within the canopy below the reference level. It may be disregarded for long time periods (i.e. years or vegetation periods). Continuous measurements of the non-turbulent exchange are not available. Therefore a direct consideration in terms of the balancing of the CO_2 exchange is not possible. Until data from measurement campaigns is available for validation it is assumed that this part is indirectly taken into account by the corrections applied (acc. to 2.2).

However, based on the EC measurements, daily totals of the NEE are derivable. These values are some of the input data required to test the coupling of carbon and water cycles on an ecosystem scale (acc. to DOLMAN et al., 2003):

$$g_c = a + \frac{b \cdot NEE \cdot rH}{c_{CO_2}} \tag{2}$$

where g_c *(m/s)* is the overall canopy conductance (canopy and soil), *NEE (gC/m^2)* the net ecosystem exchange of carbon dioxide, *rH (%)* the relative humidity, c_{CO2} *(ppm)* is the atmospheric CO_2 concentration, *a* and *b* are regression parameters for a linear fit. The basis for this procedure is the generally acknowledged relationship between stomatal conductance and assimilation at least at the leaf level (Leuning, 1995).

The equation above allows the calculation of NEE from the surface values of humidity, CO_2 and the overall surface conductance g_c. The calculation of a reliable surface conductance is of major importance for receiving a reasonable regression. So far the surface conductance g_c has been calculated from the Penman-Monteith equation and the watershed transpiration, which was obtained from the hydrological model BROOK90. Aiming to get rid of this backwards procedure, the idea of using the BROOK90 model and the included SW equations for the whole calculation appeared to be realistic. The calculation of the SW resistances in the BROOK90 model is done according to SHUTTLEWORTH & GURNEY (1990).

3.2. *Calculating the surface conductance g_c from the Penman-Monteith equation*

Penman and Monteith use two resistances to describe evaporation. The aerodynamic resistance r_a characterises the exchange of water between canopy and atmosphere. The canopy surface resistance r_c describes the resistance within the canopy stand (leaf or bulk stomata resistance) against water diffusion from the inner leaf to the atmosphere. The reciprocal value $1/r_c$ is the surface conductance g_c. The concept is shown in Figure 1.

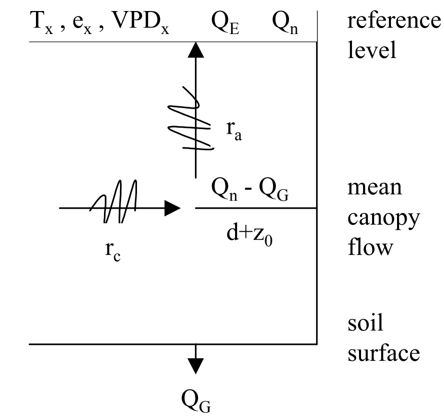
Based on the Penman-Monteith equation, g_c can be calculated using the wind profile to determine the aerodynamic resistance r_a as follows

$$r_a = \frac{\left(\ln\left(z - d/z_0\right)\right)^2}{x \cdot u + y} \tag{3}$$

where *x* and *y* are parameters of the wind function, *u (m/s)* is the wind speed, z_0 *(m)* the roughness length and *d (m)* is the zero plane displacement.

$$g_c = \left[\frac{\left(r_a \cdot \Delta \cdot R_n + \rho_a \cdot 1005 VPD/T\right) - r_a \cdot \Delta}{\gamma - r_a}\right]^{-1} \tag{4}$$

with r_a *(s/m)* being the aerodynamic resistance, R_n *(W/m²)* the net radiation, ρ_a *(g/m³)* density of air, *VPD (hPa)* is the vapour pressure deficit, γ *(hPa/K)* the psychrometer constant, Δ *(hPa/K)* the change of vapour pressure with temperature and T *(mm/d)* is the transpiration.



T temperature Q_E latent heat flux
e vapour pressure Q_G soil heat flux
z_0 roughness length Q_n net radiation
d zero plane displacement
r_a aerodynamic resistance
r_c canopy surface resistance
VPD vapour pressure deficit
Indices:
x = measurement height for net radiation
0 = canopy height

Figure 1. Resistance model of Penman-Monteith; illustration according to LAFLEUR and ROUSE (1990)

3.3. Calculating g_c from the Shuttleworth-Wallace approach

The Shuttleworth-Wallace (SW) equations contain five resistances as shown in Figure 2. The SW aerodynamic resistance theoretically equals the PM aerodynamic resistance as far as both models assume the equality of the resistances for water vapour transport and the transport of sensible heat ($r_{aE} \cong r_{aH}$), which is not entirely correct (Oke, 1987). Therefore it should be possible to use the SW aerodynamic resistance, with a renewed regression for the calculation of g_c from the Penman-Monteith equation. This is possible even though the two aerodynamic resistances do not exactly match each other.

Furthermore, it is assumed that the PM canopy resistance contains the influences of the four other SW resistances, so these SW resistances can be combined to the canopy surface conductance.

According to Kirchhoff's law the surface conductance can be calculated as follows:

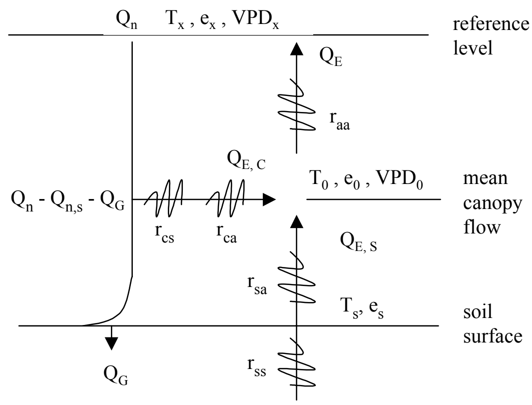
$$r_{SW,1} = r_{cs} + r_{ca} \tag{5}$$

$$r_{SW,2} = r_{sa} + r_{ss} \tag{6}$$

$$\frac{1}{r_c} = \frac{1}{r_{SW,1}} + \frac{1}{r_{SW,2}} \tag{7}$$

$$r = r_{aa} + \frac{(r_{sc} + r_{ca}) \cdot (r_{ss} + r_{sa})}{r_{sc} + r_{ca} + r_{ss} + r_{sa}} \tag{8}$$

$$g_{c,SW} = 1/r \tag{9}$$



T temperature r_{aa} aerodynamic resistance
e vapour pressure r_{cs} canopy (stomata) resistance
Q_G soil heat flux r_{ca} leaf boundary resistance
Q_n net radiation r_{sa} resistance within the canopy
z_0 roughness length r_{ss} soil resistance
d zero plane displacement
VPD vapour pressure deficit
Indices: x = measurement height for net radiation
0 = canopy height
s = soil surface

Figure 2. Shuttleworth-Wallace approach; illustration according to LAFLEUR and ROUSE (1990)

4. MODELLING NEE

For modelling the Net Ecosystem Exchange of carbon dioxide (NEE), a regression between canopy conductance and carbon flux was used as described in section 3.1. This analysis was performed using data for the period of 1997 to 1999.

As explained in section 3, it seems reasonable to calculate NEE using a regression between surface conductance and carbon flux. Therefore, reliable surface conductance values need to be determined. Figure 3 shows the comparison of the different calculated surface conductance values.

The SW resistances were obtained from the BROOK90 hydrological model, which was used to calculate evaporation and transpiration. This method provided good results. A problem occurred during the winter months when the BROOK90 model sets the soil resistance r_{ss} to zero if snow is simulated, which caused extraordinary high conductance values. As the winter values of r_{ss} at temperatures around 0°C without snow range from 500 to 700 s/m, r_{ss} was set to 600 s/m for snow. This change was only used for the calculation of the surface conductance and does not influence the original BROOK90 calculations.

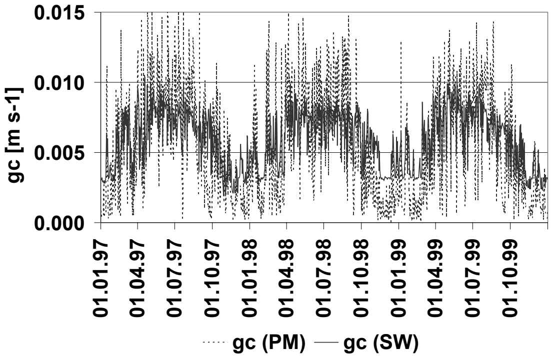


Figure 3. Surface conductance calculated based on the Penman-Monteith and Shuttleworth-Wallace approach, respectively

4.1. Model Parameterisation Using Different Humidity Measures

i) relative humidity

Results from regressions with the aerodynamic resistance r_{aa} from the Shuttleworth-Wallace model are similar to those with the aerodynamic resistance calculated with PM (equation (2)). The stability index could be improved marginally using the combined SW resistance (from R2=0.46 to R2=0.52). Good results could be achieved using just the SW stomata resistance r_{cs} to determine the surface conductance ($gc=1/r_{cs}$). This regression as well as the one using the combined resistances is shown in Figure 4a and 4b.

Both plots show a slightly curved shape to the left, which suggests there may be a certain degree of inaccuracy of later simulation results. Nevertheless the stability index has been improved significantly in comparison to regressions using PM aerodynamic resistances and transpiration to determine the surface conductance. The strong regression calculating g_c from r_{cs} alone was unexpected, and due to the good results, this possibility was also considered in the further study.

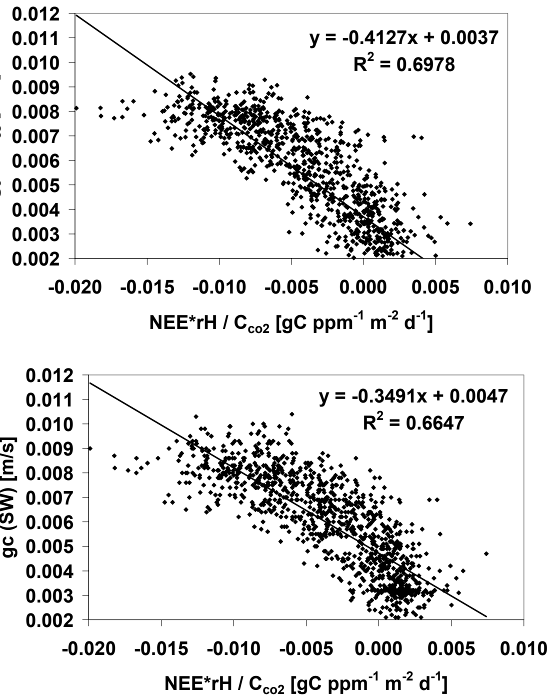


Figure 4. Regressions between different calculated surface conductance values and carbon flux using relative humidity
top: gc calculated from the SW stomata resistance
bottom: gc from the combined SW resistances

ii) alternative humidity measures

The use of relative humidity did not appear to be the only or absolutely right possibility for these calculations. Therefore other humidity measures, such as vapour pressure deficit (VPD), vapour pressure (e) and absolute humidity (aH) were considered. Using absolute humidity and vapour pressure, an extraordinary bent shape becomes obvious, so in spite of the good stability index these alternatives were not analysed any further at this stage. A regression using VPD and the combined SW resistances did not achieve a high stability index. But using only the SW stomata resistance and VPD a good stability index of 0.67 was again obtained.

5. MODEL RESULTS

5.1. Validation Period

Due to problems with the measurement system in the first year of measurements, the data from 1996 has been disregarded and the period from 1997 to 1999 was used for model validation.

Looking at the daily values of NEE over the years it can be noticed that the model results using relative humidity all lie within the range of measured NEE (Figure6). This differs from other humidity measures, where extreme values of up to +/- 20 gC/(m^2d) were calculated. Therefore these versions were not considered any further. As can be seen in Figure 6, the measured NEE covers a range of approximately +3 to –9 gC/(m^2d) with its maxima in winter and its minima in summer. This means that the spruce ecosystem mainly acts as a carbon sink during summer and as a carbon source in winter.

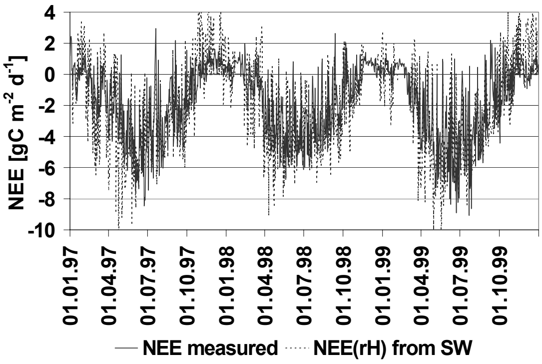


Figure 6. Net Ecosystem Exchange of carbon dioxide (NEE), measured and modelled using the combined Shuttleworth-Wallace resistances to calculate the surface conductance g_c

Overall, good results were obtained from the calculations using rH and g_c from SW or g_c=1/r_{sc}. The version of the combined SW resistances was chosen to simulate a longer period of time which is described in the next section.

5.2 Model Period 1972-2002

To be able to calculate NEE over this longer time period (1972-2002) it was necessary to use CO_2 concentrations of a different site for the years without own measurements in Tharandt. Of the two available sites in Germany the closest station Waldhof (about 300 km north west of the Tharandt) was chosen The model results as well as precipitation and transpiration are plotted in Figure 7.

An additional possibility to evaluate the model results is a comparison with the annual increment of wood (Figure 8). First results from calculations of the volumetric wood increments based on profile analyses made from trees harvested at the Anchor Station Tharandt in 2001 are given by *Gerold* (2003). The analysis still being in progress gives results back to the year 1984 so far. The conversion to gC m^{-2} a^{-1} was calculated from the volumetric wood increment of the trunk using the dry density of wood (ρ_w=0.39 t/m^3) considering 30% of the trunk wood increment for needles, branches and roots and assuming 50% of the wood mass as carbon mass (Löwe et al., 2000). As shown in Figure 8 the carbon equivalents show only about 63% of the modelled CO_2 sinks. IBROM (2001) gives for an old spruce stand near Göttingen, Germany even lower values. For the year 1997 a net CO_2 exchange of –472 gC$m^{-2}a^{-1}$ was determined based on EC measurements. The subsurface and overground growth is given with 115 gC$m^{-2}a^{-1}$ (24% of NEE).

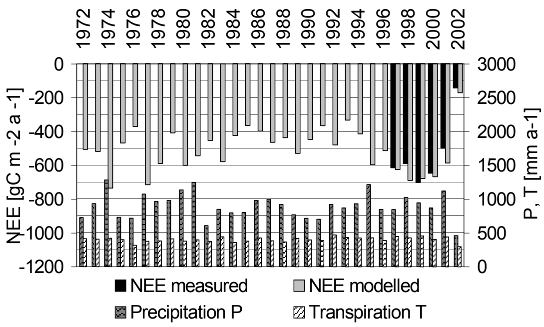


Figure 7. NEE model results for the time period of 1972 to June 2002, calculated using relative humidity and g_c (SW)

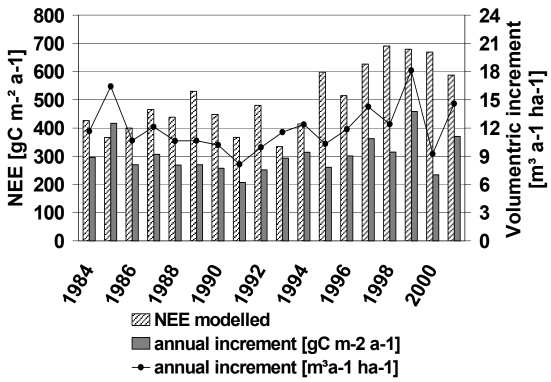


Figure 8. Annual volumetric increment of wood (Gerold, 2003) and modelled NEE

6. CONCLUSIONS

The study shows that using relative humidity for calculating surface conductance seems to be the most successful way so far. The calculated daily values, as well as the annual sums, lie within a realistic range and do not need to be corrected as it had to be done using alternative humidity measures.

As far as it is suggested from the short period of measurements, the model results are reasonably reliable. Also the comparison with the annual wood increment confirms this interpretation. Although calculations of wood increments are done with various uncertainties, it can be used at least to indicate a general trend. A possible reasons for the observed differences between CO_2 sinks and results from tree profile analyses besides the estimations made for the conversion to C equivalents might be that the analysed trees may not represent the source area of the CO_2 fluxes (Grünwald, 2002).

Attempting to relate precipitation and transpiration to NEE, no obvious connection could be found. For the driest year (1982), no especially small sink was modelled. But the dry years from 1989 to 1991 suggest a decrease of NEE within a row of dry years. Generally, a higher sensitivity of the carbon balance than the water balance according to climate changes can be assumed. However, it should be noted that the observed annual sink for carbon dioxide can be expected to be reduced due to a possibly underestimation of the ecosystem respiration components by the EC method according to the current calculations. Further research including measurements of non turbulent transport should be undertaken to verify the results.

7. ACKNOWLEDGEMENTS

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