CARBON DIOXIDE AND WATER VAPOUR FLUX DENSITIES OVER A GRASSLAND AREA IN THE NETHERLANDS

ADRIE F. G. JACOBS,* BERT G. HEUSINKVELD and ALBERT A. M. HOLTSLAG

Wageningen University, Meteorology and Air Quality Group, Duivendaal 2, NL-6701 AP Wageningen, The Netherlands

ABSTRACT

Measurements of carbon dioxide and water vapour flux densities were carried out for a grassland area in the centre of the Netherlands during a 12 month continuous experiment using the eddy-covariance technique. *Lolium perenne* and *Poa trivialis* mainly dominated the vegetation of the area. The leaf area index (LAI) of the grassland varied between 2.5 and 3.4, depending on the mowing scheme at the site. Fluxes are also calculated by using a canopy model in which the canopy resistance is related to the assimilation rate ($A-g_s$ model). The calculated evapotranspiration fluxes agree within 7% of the measured fluxes ($R^2 = 0.93$; SEE = 23 W m^{-2}). The calculated net carbon dioxide fluxes agree within 12% of the measured fluxes ($R^2 = 0.79$; SEE = 0.16 mg m^{-2}s^{-1}). The net carbon dioxide fluxes consist of two opposite components: the uptake via assimilation and release via soil and plant respiration. It appears that nearly the whole year round the assimilation term dominates, which means an accumulation of carbon dioxide if no other exchange processes are present. For 2002 a net carbon uptake was found of 6.8 tonnes ha^{-1}. Copyright © 2003 Royal Meteorological Society.

1. INTRODUCTION

The carbon cycle refers to the great natural recycling of carbon atoms, where the fixation of atmospheric carbon dioxide (CO_2) through photosynthesis and the simultaneous or subsequent release of CO_2 through respiration are the two most important ones in nature. Through these processes, carbon is cycled continuously through three main global reservoirs: the oceans, the atmosphere, and the terrestrial biosphere, including vegetation and soils (Nitschelm *et al*., 1997). Over time, human activities have altered the amount of carbon that flows through and is stored in the various reservoirs. To stop rising concentrations of CO_2 in the atmosphere, countries are actively seeking ways to increase carbon storage capacity on land. The large amount of land area covered by grasslands, as well as the relatively unexplored potential for grassland soils to store carbon, has increased interest in the carbon cycles of these ecosystems (Van Ginkel *et al*., 1999, 2000).

About 60% of agricultural land in the Netherlands consists of grasslands, which means that the behaviour of the exchange of water vapour and CO_2 of grassland areas is important for the total water and CO_2 budgets. Here, rotational grazing is the most common land use of grasslands in the Netherlands. In the past, it was known that forests sometimes act as so-called long-term carbon sinks, absorbing more of the greenhouse gas CO_2 than they released. Nowadays, it is suggested that grasslands appear to demonstrate the same property (Hu *et al*., 2001), which can be of great interest in the light of the global warming discussion. CO_2 accumulation in grasslands has been observed during short-term measurements, where the role of fungi was crucial. It is interesting to find out whether this role remains on a long-term basis.

* Correspondence to: Adrie F. G. Jacobs, Wageningen University, Meteorology and Air Quality Group, Duivendaal 2, NL-6701 AP Wageningen, The Netherlands; e-mail: adrie.jacobs@wur.nl

The objectives of the present study are as follows. First, to quantify the surface fluxes of water vapour and CO_2 in the grassland area region in the centre of the Netherlands over the course of the entire year. Second, to apply model calculations in order to understand better the physiological and biophysical mechanisms that control the exchange mechanism of water vapour and CO_2. Here, the so-called $A-g_s$ model is used, which is a model that couples the photosynthetic assimilation A to the leaf stomatal conductance g_s (Goudriaan *et al.*, 1985; Jacobs and De Bruin, 1992). An advantage of this model is that the calculations will be based on common atmospheric variables, which are measured on a routine basis at a common meteorological observation site. In doing so, the advantage is that gaps in the relatively difficult eddy-covariance flux measurements of water vapour and CO_2 can easily be completed with the evaluated model.

2. THEORY

Here, we briefly explain the $A-g_s$ model and its background. Following Jacobs (1994) and Jacobs and DeBruin (1992), we show how the photosynthetic assimilation and its resulting canopy conductance are calculated as a function of environmental variables.

The in- and out-flow of CO_2 and water vapour occurs through molecular diffusion through the stomata. As a result, the net flow density of the CO_2, A_n, which results from the difference between the gross assimilation rate A_g and the dark respiration R_d can be described as

$$A_n = A_g - R_d = g_{l,c}(C_s - C_i) \tag{1}$$

Here, C_s is the CO_2 concentration at the leaf surface, C_i is the CO_2 concentration in the leaf interior and $g_{l,c}$ is the leaf conductance for CO_2. Both A_g and R_d result from photochemical reactions. Typically, they vary as a function of the photosynthetically active radiation (PAR) the leaf temperature T_l and the internal CO_2 concentration C_i. Plant physiological models for A_g and R_d are used in practice successfully (Collatz *et al.*, 1991), but they can still be improved for controlling factors such as plant water condition (Ronda *et al.*, 2001) or plant nutrient condition (Jacobs *et al.*, 2003).

In laboratory experiments, the internal CO_2 concentration is often found to be a fraction of the external CO_2 concentration. When sufficient amounts of solar radiation density are available, it appears that the ratio of the internal and external concentration is only a function of the water vapour deficit (Goudriaan *et al.*, 1985; Jacobs, 1994; Zhang and Nobel, 1996) and can be expressed by (Jacobs, 1994)

$$\frac{C_i - \Gamma}{C_s - \Gamma} = f_o \left(1 - \frac{D_s}{D_o}\right) + f_{min} \frac{D_s}{D_o} \tag{2a}$$

where D_s is the vapour pressure deficit at plant level, Γ is the CO_2 compensation point, f_o is the maximum value of the ratio of C_i to C_s, D_o is the value of D_s at which the stomata close, and f_{min} is a minimum value of the ratio of C_i to C_s. Because the second term on the right-hand side is very small (Jacobs and De Bruin, 1992), Equation (2a) can be simplified by

$$\frac{C_i - \Gamma}{C_s - \Gamma} = f_o \left(1 - \frac{D_s}{D_o}\right) \tag{2b}$$

Combining Equations (1) and (2b) gives a relation for the conductance to CO_2 at leaf level:

$$g_{l,c} = g_{min} + \frac{a_1 A_g}{(C_s - \Gamma)\left(1 + \dfrac{D_s}{D_*}\right)} \tag{3}$$

where g_{min} is the minimum conductance and a_1 and D_* are empirical quantities that are functions of both f_o and D_o (Ronda *et al.*, 2001). It must be noted that in Equation (3), g_{min} was added afterwards in order to account for the cuticular conductance.

The assimilation can be seriously affected by soil water stresses, especially during summertime with a low water table. Here, we follow a correction for water stress as suggested by Ronda *et al.* (2001):

$$A_g = A_g^* f(\theta) \tag{4}$$

where A_g^* is the unstressed gross assimilation rate, θ is the mean moisture content in the root zone and $f(\theta)$ a soil moisture correction function taken as

$$f(\theta) = 2\beta(\theta) - \beta^2(\theta) \tag{5}$$

and

$$\beta(\theta) = \max\left[0, \min\left(1, \frac{\theta - WP}{FC - WP}\right)\right] \tag{6}$$

where FC and WP are soil moisture contents at field capacity and permanent wilting point respectively. At our site, the field capacity and permanent wilting point have the numerical values of FC = 0.52 and WP = 0.32 respectively.

The canopy conductance to CO_2 $g_{c,c}$, is found by integrating the stomatal conductance over the canopy (Ronda *et al.*, 2001):

$$g_{c,c} = \frac{g_{\min}}{1.6}LAI + \frac{a_1 A_g LAI}{(C_s - \Gamma)\left(1 + \frac{D_s}{D_*}\right)}\left\{1 - \frac{1}{K_x LAI}[E_1(y\, e^{-K_x LAI}) - E_1(y)]\right\} \tag{7}$$

Here LAI is the one-sided leaf area index, K_x is the inside canopy extinction coefficient for photosynthetically active radiation, E_1 is the exponential integral defined as (Abramowitz and Stegun, 1965)

$$E_1(z) = \int_z^\infty \frac{e^{-t}}{t}\, dt$$

and y is given by

$$y = \frac{\alpha K_x P_l}{A_g} \tag{8}$$

Here, z stands for height, the variable t in the exponential integral is a dummy variable and the factor 1.6 in Equation (7) is the ratio between molecular diffusivities of water vapour and CO_2 in air. In Equation (8), α is the light-use efficiency and P_l is the incoming photosynthetically active radiation at the top of the canopy.

Equations (1) and (7), together with the physiological model, define the relation between the net assimilation A_n and the crop conductance $g_{c,c}$ according to

$$A_n = \frac{g_a g_{c,c}}{g_a + g_{c,c}}(C_a - C_i) = \frac{g_{c,c}}{1 + \frac{g_{c,c}}{g_a}}(C_a - C_i) \tag{9}$$

where g_a is the aerodynamic conductance, C_a is the ambient CO_2 concentration and C_i is the CO_2 concentration in the leaf interior calculated with Equation (2b). Note that A_n and $g_{c,c}$ can be computed when the LAI and the type of plant (C3 or C4) are known in addition to the vapour pressure deficit D_s (here evaluated as $e_s(T_l) - e$), the temperature at leaf level T_l, and the amount of incoming photosynthetically active radiation (PAR, here evaluated as PAR $= 0.5R_g$, where R_g is the incoming shortwave radiation).

The canopy conductance for water vapour $g_{c,w}$ is closely related to the canopy conductance for CO_2 $g_{c,c}$ according to

$$g_{c,w} = 1.6 \, g_{c,c} \tag{10}$$

where the factor 1.6 results from the ratio of the molecular diffusivities of water vapour and CO_2 in air. The transpiration rate of the vegetation LE can be written as (Beljaars and Holtslag, 1991)

$$LE = \rho L \frac{\varepsilon}{p} \frac{g_a g_{c,w}}{g_a + g_{c,w}} D_s = \rho L g_{c,w} \frac{\varepsilon}{p} \frac{D_s}{1 + \frac{g_{c,w}}{g_a}} \tag{11}$$

where ρ is the density of the air, L is the latent heat of vaporization, $\varepsilon = 0.622$ is the ratio of the molar masses of water vapour and dry air, and p is atmospheric pressure. A more detailed description of the model can be found in Ronda *et al.* (2001) and Jacobs *et al.* (2003). The parameter values are taken as in Ronda *et al.* (2001), unless stated elsewhere in the following sections.

The soil surface CO_2 flux is complex and is mainly caused by heterotrophic microbial decomposition and plant root respiration in grasslands (Norman *et al.*, 1992). The soil respiration is likely to depend on soil temperature (Norman *et al.*, 1992) and soil water content (Grammerer, 1989). In this study, the soil surface respiration R_s has been calculated with a simple Van't Hoff type of expression (e.g. Lloyd and Taylor, 1994; Van't Hoff, 1898):

$$R_s = R_o e^{b T_s} \tag{12}$$

where T_s is the mean soil temperature of the upper soil, R_o and b constants with numerical values fitted every month. In this study the soil temperature at 5 cm depth appears to give the best statistical fit. The constants R_o and b in this expression were derived statistically by selecting nocturnal periods only where the friction velocity u_* exceeded 0.1 m s^{-1}, in order to ensure sufficient turbulent mixing. Statistically, it appeared for this grassland area that above the threshold criterion, $u_* \geq 0.1 \text{ m s}^{-1}$, the best fit for Equation (12) was obtained for the respiration. The numerical values used in the present study are listed in Table I. The Van't Hoff relation is based on the Q_{10} response function, where Q_{10} is the value in which the function increases for a temperature increase of $10\,°C$. In Tables II and III the soil/plant and meteorological variables needed to run the model calculations are given.

The net ecosystem exchange for CO_2 (NEE) has been evaluated as the net effect of the assimilation flux A_n and the soil respiration flux R_s, i.e.

$$\text{NEE} = A_n + R_s \tag{13}$$

Table I. The annual course of the respiration coefficients (Equation (12)) as applied in the present study. Note that the term b is constant during the whole period

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R_o (mg m^{-2} s^{-1})	0.060	0.060	0.060	0.060	0.050	0.030	0.020	0.015	0.025	0.030	0.050	0.060
b(K^{-1})	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158

Table II. Plant and soil parameters needed to run the model

Leaf area index	LAI
Soil moisture retention Curve	pF-curve
Type of plant	C3, C4

Table III. Variables needed to run the model and how these variables are evaluated
in the present calculations

Variable	Evaluated
Dry bulb temperature T_a	Direct measurement at 2 m
Wet bulb temperature T_w	Direct measurement at 2 m
Leaf temperature T_l	From longwave outgoing radiation
5 cm soil temperature T_s	Direct measurement
Moisture deficit	$e_s(T_l) - e(2 \text{ m})$
Photosynthetic active radiation (PAR)	From global radiation Q_s
Friction velocity u_*	Direct measurement
Precipitation N	Direct measurement
Freatic surface z_f	Direct measurement
Soil moisture	Water balance

Bear in mind that the assimilation flux is directed towards the Earth's surface, which means this is a negative flux, whereas the soil respiration flux is directed from the Earth's surface and, consequently, is positive.

3. EXPERIMENTAL LAY-OUT

The experiments were done at a grassland area of the Wageningen University meteorological observatory, Haarweg Station, in the centre of the Netherlands (lat. 51°58′N, long. 5°38′W, altitude +7 m) during a 1 year period in 2002 and 2003. The dominating plant species in this perennial grassland were *Lolium perenne* and *Poa trivialis*. The soil at the site is predominantly a heavy clay resulting from the back-swamps of the river Rhine. The grass had an LAI varying between 2.5 and 3.4, depending on the mowing scheme. At the measurement site the mowed grass is not removed. The LAI was measured by the leaf tracing technique as described by Kvet and Marshall (1971). Throughout the year 2002, the water table varied depending on the season from 0.0 to 0.9 m below surface level with a mean depth of 0.72 m, as can be inferred from the plotted values in Figure 1. Moreover, in Figure 1, the precipitation regime N has been plotted along with the mean soil volumetric moisture content θ (see later).

A lattice tower was instrumented with an eddy-covariance system installed at a height of 4 m. This system included: a three-dimensional (3-D) sonic anemometer (3-D Solent Res. Gill Instruments Ltd, model A1012R2), a fine-wire thermocouple (home made) and an open path infrared CO_2 and H_2O gas analyser (IRGA) (LI-COR Inc., Lincoln, NE, model LI-7500). The 3-D sonic anemometer and the IRGA were placed 0.05 m apart.

In a thermometer screen an aspirated psychrometer was installed to estimate the air temperature and the air humidity. The incoming shortwave radiation R_g was measured with an aspirated pyranometer (Kipp & Zonen, model CM11). As mentioned earlier, the shortwave radiometer was used to evaluate the PAR (PAR = $0.5R_g$). The outgoing longwave radiation R_{Lo} was measured with a pyrgeometer (Kipp & Zonen, model CG1). With this quantity, the leaf temperature of the grass cover was evaluated using

$$T_l = \sqrt[4]{\frac{R_{Lo}}{\varepsilon\sigma}} \tag{14}$$

where σ is the Stefan–Bolzmann constant and ε is the emissivity of the grass cover, taken as 0.98 in the present study (Campbell and Norman, 1997).

Sensitive cup anemometers (stalling speed 0.15 m s^{-1}) measured the wind speeds at 2 and 10 m heights above the surface and a wind vane at 10 m estimated the wind direction. The soil temperature profile was measured by Pt-100 element at depths 0.05, 0.10, 0.20, 0.50 and 1 m. As discussed earlier, only the soil temperature at 0.05 m depth was used to estimate the soil respiration term.
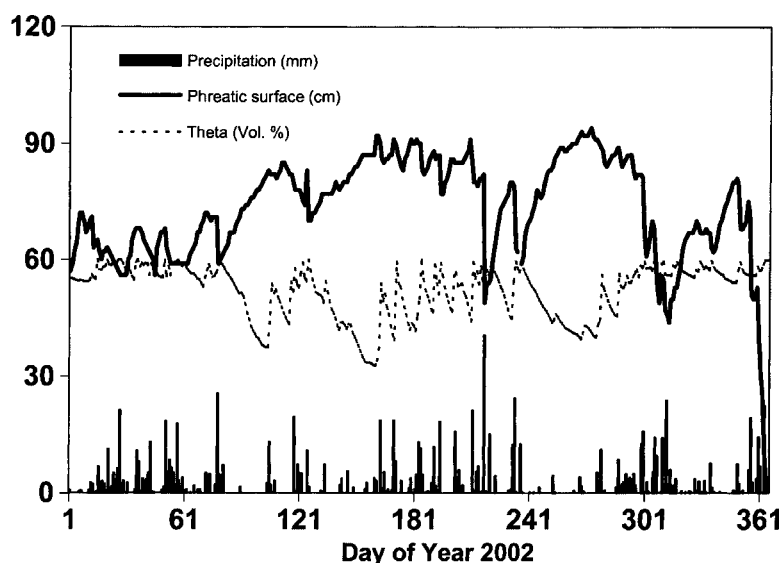
Figure 1. Annual course of the freatic level, the precipitation regime and the volumetric soil moisture content at the experimental grassland site in 2002

To estimate the mean moisture content in the root zone, a simple bucket model is applied. This means that the water balance rules the mean water content θ in the root zone according to

$$\theta(t + \Delta t) = \theta(t) + \frac{N - E\,\Delta t}{z_f} \tag{15}$$

where N (mm) is precipitation amount within the time interval between t and $t + \Delta t$, E (mm s^{-1}) is the evapotranspiration rate and z_f (mm) is the depth of the phreatic surface. As mentioned earlier, the volumetric moisture results θ, obtained with Equation (15), are also plotted in Figure 1.

The slow-response meteorological instruments were sampled at 0.25 Hz. At 30 min intervals, data were averaged and stored in data loggers for later processing. The fast-response sonic anemometer, the IRGA system and the fine-wire thermocouple were sampled at 20.8 Hz.

The raw data of the eddy-covariance system were stored on a PC and processed later, using a first-order recursive digital filter with a time constant of 200 s (McMillen, 1988). Here, a moving average was subtracted from every sample to obtain the fluctuating value of all the measured components. A software program (Van den Hurk, 1996) performed the necessary corrections, including coordinate rotation (McMillen, 1986), Webb corrections (Webb *et al.*, 1980) and frequency-response corrections (Moore, 1986), required for calculation of the half-hour-averaged flux densities. The power and co-spectra of the eddy-covariance measurements (not shown) and the ability to close the surface energy balance were analysed to test the quality of the data.

4. RESULTS

To appreciate the meteorological conditions of the centre of the Netherlands in 2002, the most important monthly averaged variables are plotted in Figure 2, as well as some climate variables. From this we can infer that the start of the year 2002 was relatively warm and wet, followed by a relatively normal but dry spring period. The summer was warm and wet followed by a normal but very wet autumn. An exception was September, which was extremely dry. The incoming global radiation, which is an important variable for the assimilation process, behaved relatively smoothly the whole year round and nearly agreed with the climatological behaviour. In Figure 2 the soil temperatures at 5 cm depth have also been plotted, because
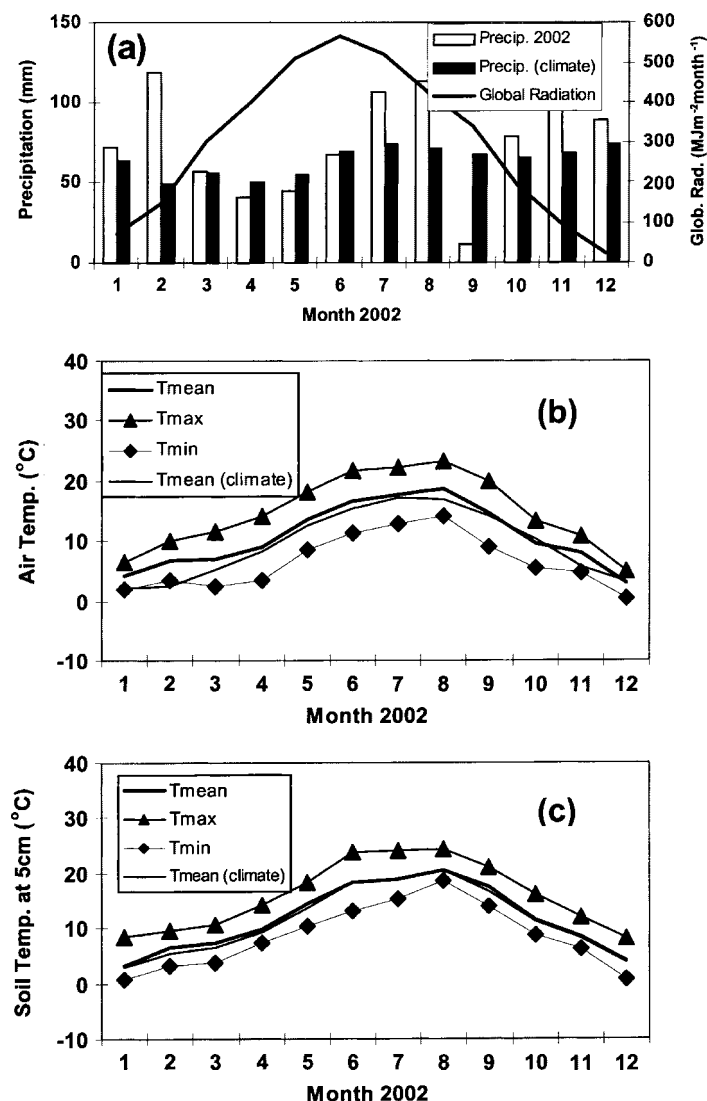
Figure 2. The annual courses of the monthly averaged most important atmospheric variables in 2002. In addition, the climatic means during the last 30 year period (1971–2000) have been given

the soil temperature mainly dominates the soil respiration (Equation (12)). From the mean annual courses of the soil temperatures we can infer that the actual mean soil temperature at this depth follows the long-term climatological behaviour.

Measurements were carried out the whole year round in 2002. The eddy-covariance data, however, showed some missing periods due to instrumentation failures. Model calculations have completed these missing periods. Eddy-covariance measurements were missing during some weeks in January, June and September. Comparisons between the experimental results and model simulations have been executed in order to provide an idea as to the reliability of the model simulations. Next, an example of such a comparison will be discussed for the period between May and July. All other periods behaved similarly.

In Figure 3, the measurement and simulation results of the evapotranspiration and NEE have been plotted. In this graph, the eddy-covariance data during rainy periods have been skipped because of the unreliable behaviour of the sonic anemometer and IRGA system during wet periods. From this we can infer that the model simulations follow the eddy-covariance data well.
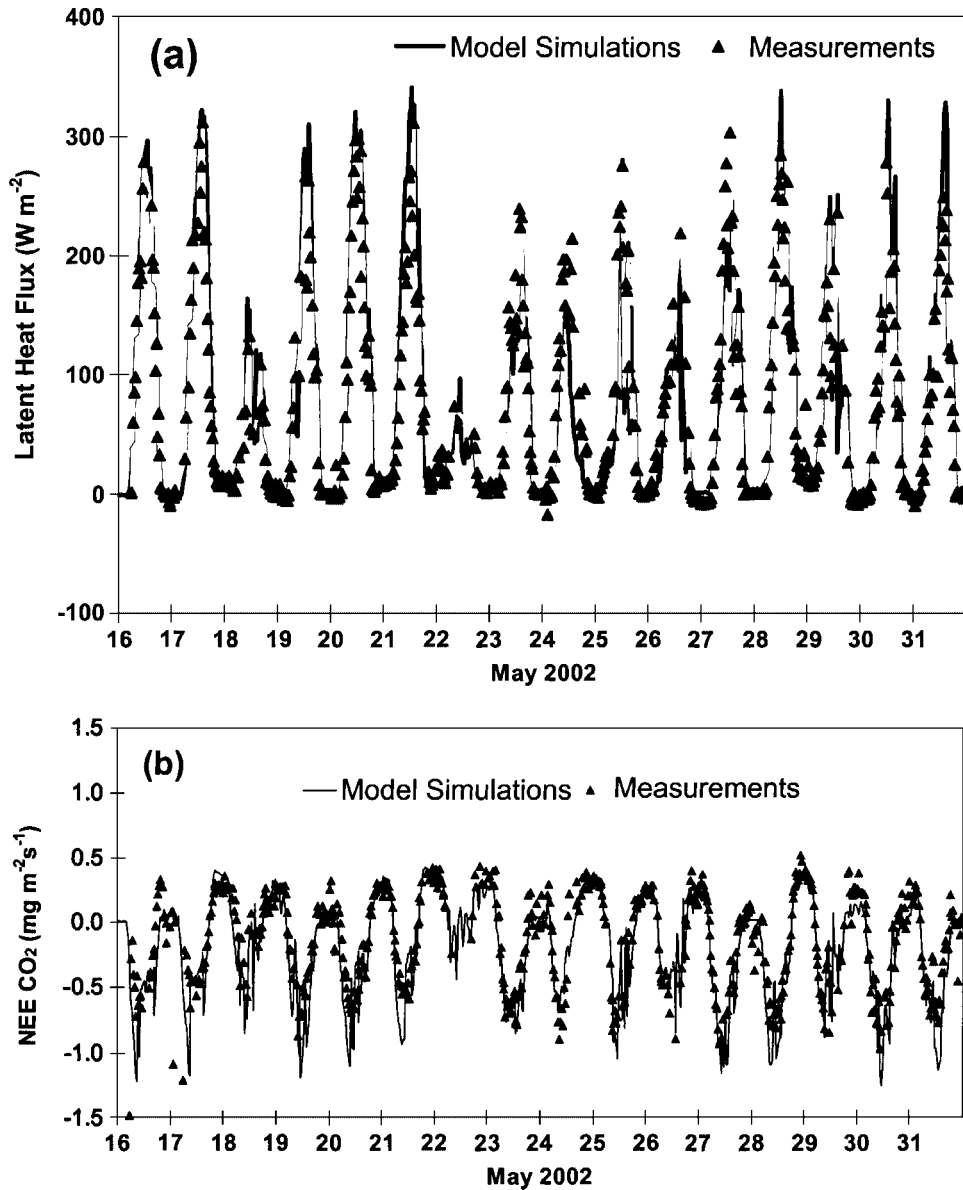
Figure 3. The courses of the daily model simulation and eddy-covariance measurements during the selected period in May 2002: (a) the behaviour of the evapotranspiration fluxes; (b) the net CO_2 fluxes

Figure 4 shows scattergrams of the experimental results and the $A-g_s$ model simulations between May and July. In Figure 4(a), the scattergram of the measured and simulated latent heat fluxes has been given, along with the unbiased linear regression line. The equation for the linear regression forced through zero between the experimental results x and the model results y is found to be $y = 1.07x$ (regression coefficient: $R^2 = 0.93$; standard error of estimate SEE = 23 W m^{-2}). From this result we infer that the model overestimates the experiments by about 7%. However, within the experimental uncertainty, this result is excellent.

In Figure 4(b) the scattergram of the measured and the simulated net CO_2 fluxes, NEE, has been given for the same selected period along with the unbiased linear regression line. The equation for the linear regression forced through zero between the experimental results x and the model results y is found to be $y = 1.12x$ (regression coefficient: $R^2 = 0.79$; SEE = 0.16 mg m^{-2}s^{-1}). From this result we infer that the
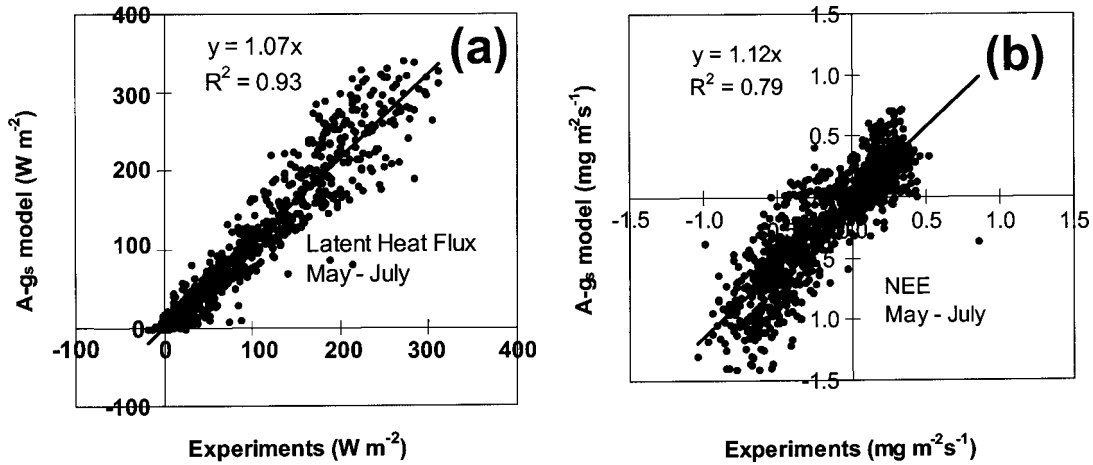
Figure 4. Scattergrams of the simulated and measured fluxes during a 3 month period (May–July) in 2002: (a) The evapotranspiration fluxes; (b) the net CO_2 fluxes

model overestimates the experiments by about 12%. However, within the experimental uncertainty, this result is also excellent for simulation studies. It must be noted that the relative error in the net flux of CO_2 must be larger, since the net flux consists of the difference of two large terms (NEE $= R_s + A_n$). For the period selected, the courses of the simulated assimilation A_n and the simulated respiration R_s fluxes are depicted in Figure 5. From the result of Figure 5 it can clearly be observed that both terms are important in the net CO_2 exchange process and that during the period selected the assimilation process A_n is dominant.

In Figure 6, the in- and out-going water fluxes throughout the year 2002 have been plotted. Here, the amounts per half-month have been depicted in order to obtain more details of the precipitation and evapotranspiration process throughout the year. It can clearly be observed that the start and the end of the year 2002 were extremely wet, which resulted in a positive precipitation surplus and in an increase of the phreatic surface along with an increase of the volumetric water content. Also, it can be observed that during the summer half-year the precipitation surplus was clearly negative, which agrees with a normal summer for
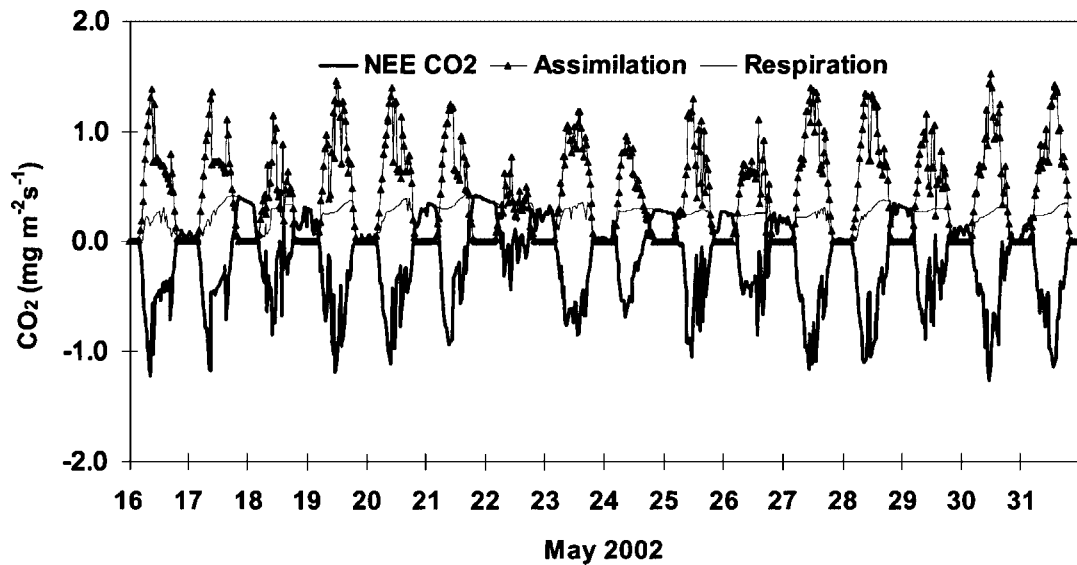

Figure 5. The courses of the simulated assimilation, respiration and net CO_2 fluxes during the selected period in May 2002
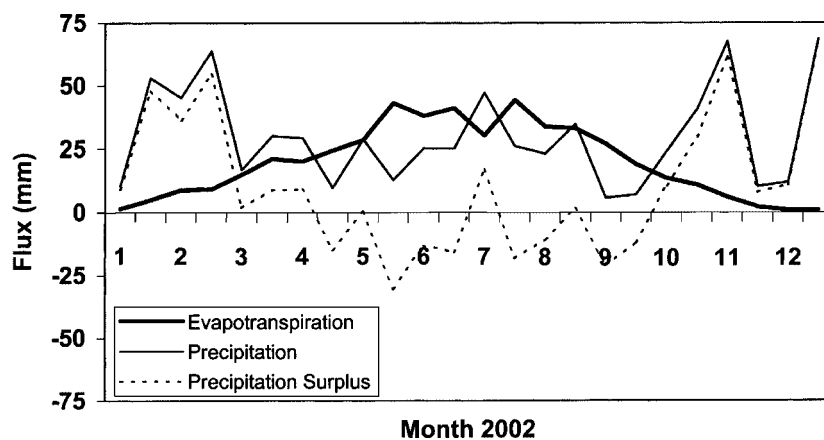
Figure 6. The courses of the total half-month amounts of the measured precipitation, evapotranspiration and the precipitation surplus throughout the year 2002

a moderate climate. It is interesting to note that, during dry spells (e.g. second half of April and May and throughout September), the evapotranspiration was hardly affected by shortage of water. From Figure 1 it can be observed that, during these dry spells, the phreatic surface lowered relatively fast along with a decrease of the volumetric water content, which suggests that the evaporative water is extracted from the ground water and the water in the unsaturated zone above the water table.

The annual courses of the simulated assimilation, respiration and NEE of CO_2 fluxes are depicted in Figure 7(a). Again, the flux densities per half-month have been given in order to show more details about the CO_2 exchanges processes. Moreover, in Figure 7(b) the NEE of CO_2 has been depicted in mean weekly amounts, in order to offer a better feeling for the behaviour of this flux. From Figure 7 it can clearly be observed that NEE is nearly always negative. This means that the grassland area behaves as a sink for CO_2 nearly all year round. Only the first half of August appears to be an exception. The same net sink behaviour for CO_2 was found by Suyker and Verma (2001) for a native tall grass prairie.

From the results plotted in Figure 7(b) we conclude that the grassland area behaved as a clear sink for CO_2 in 2002. This means that, during this particular year, CO_2 is accumulated in this area. As a total amount it is found that about 6.8 tonnes of carbon per hectare per year is stored if no other exchange processes take place. These accumulated amounts are of the same order of magnitude that is often observed in mid-latitude forests (Wolfsy *et al.*, 1993; Goulden *et al.*, 1996; Valentini *et al.*, 2000). However, to be sure that this annual net accumulation result is not an exception, it must be noted that, first, long-term observations are needed. That is why we intend to continue our observations for a couple of years. Second, as mentioned earlier, other processes can take place in which the stored CO_2 is transferred and released again in other gases, e.g. in methane. To be sure of this, additional observations are needed and we have planned to do this in the near future.

The calculated respiration term in Figure 7(a) shows an annual cycle with a clear depression during the summer period. During this period of the year the highest soil temperatures occur (Figure 2(c)); consequently, it is to be expected that then the highest respiration must be observed (Equation 12). This depression in respiration, however, agrees with the period of the year with the lowest water table, and consequently with the lowest soil moisture content, as can be observed from Figure 1. From Table I it can be inferred that R_o is about a factor of two lower during this period, which suggests that, in our case, the soil respiration is highly dependent on the soil moisture as well. Often, it is suggested that soil moisture does not play an important role in the respiration process and can be neglected (Lloyd and Taylor, 1994; Suyker and Verma, 2001; Soegaard *et al.*, 2003); also, in very dry climates only, that soil moisture can seriously affect the soil respiration process (Suyker and Verma, 2001; Soegaard *et al.*, 2003). The results from Figure 7(a) suggest that more attention must be focused on the soil respiration process. In future, our measurements will be extended with additional
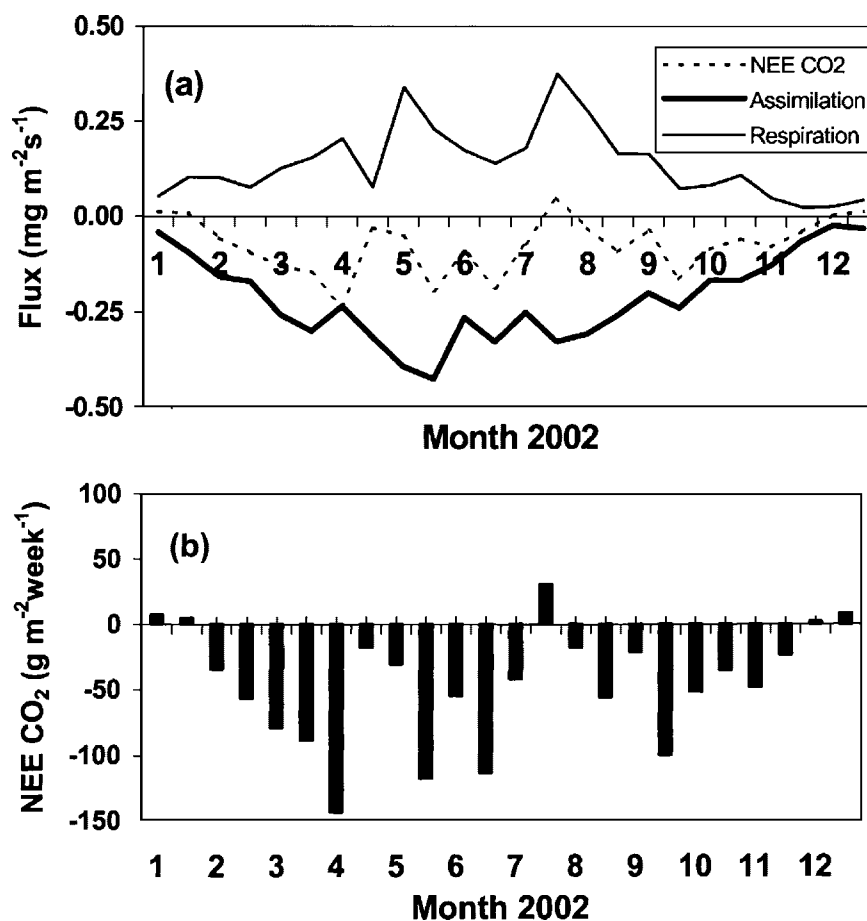
Figure 7. (a) The courses of the total half-month amounts of the measured NEE, the simulated assimilation exchange and the respiration exchange throughout the year 2002. (b) The weekly accumulated CO_2 amounts throughout the year 2002

soil moisture observations. Also, it must be noted that our soil consists of a heavy clay type, which means that the moisture availability is very limited.

5. CONCLUSIONS

We have quantified the surface annual fluxes of water vapour and CO_2 in a grassland area in the centre of the Netherlands, and we use model calculations to understand better the physiological and biophysical mechanisms that control the exchange mechanism of water vapour and CO_2. The following main conclusions can be drawn from our study:

1. The $A-g_s$ model mimics well the actual measured fluxes for evapotranspiration and the net CO_2. This means that the exchange mechanisms for water vapour and CO_2 are well represented by the model. In addition, it means that gaps in the eddy-covariance measurements can be completed with the evaluated model calculations.
2. The accuracy of the calculated net CO_2 fluxes is lower than the calculated water vapour fluxes. The reason is that the net CO_2 flux consists of two terms of about the same magnitude but with opposite sign: towards the vegetation, the uptake assimilation term; and released from the surface (soil as well as plant), the respiration term.

3. The year analysed followed a more or less ordinary course for the evapotranspiration and precipitation patterns to be expected for the mid-latitudes; during the winter half-year a clear precipitation surplus is found, whereas during summer half-year the opposite is observed. It must be noted that the start of the year and the end of the year were extremely wet.

4. From the detailed model calculations it can be concluded that, nearly the whole year round, the assimilation process dominates the net exchange of CO_2. This result suggests that the grassland area behaves as a net sink term for CO_2. To be sure that this continues in the long-term, however, long-term observations are needed and are planned for this area. There is also a possibility that other processes can occur where the uptake of CO_2 is transferred in, for example, methane. That is why, besides long-term observations, additional measurements are also needed in this area.

5. The depression in the respiration during the mid-summer period in combination with the low water table during this period suggests that respiration is not only dependent on the soil temperature, but that the soil moisture in the root zone can also play an important role. It is recommended to focus attention on observing detailed soil moisture measurements in order to explain this phenomenon.

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