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Discriminating net ecosystem exchange between different vegetation plots in a heterogeneous forest

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Abstract

A model describing the half-hourly evolution of the net ecosystem exchange of a heterogeneous forest was developed. It viewed the forest as a patchwork of three homogeneous vegetation plots whose contribution varied with wind direction. The model was calibrated on eight (1997–2004) years of measurements made at the Vielsalm experimental site in Belgium. The first 6 years were used for model calibration, the last two for validation. The model predicted the eddy flux measured by the system with a degree of performance comparable with those of other models running on the same time scale on homogeneous canopies. The model also allowed the three ecosystem behaviours to be differentiated: the beech characterised by higher carbon sequestration efficiency during the growth period; but also by a shorter growth period, the Douglas fir and the spruce/silver fir characterised by a longer growth period, with the efficiency of the former higher than the latter. The evolution with wind direction of the beech forest contribution (i.e., the relative contribution of the beech plot to the total measured flux) was also obtained and was found to be in very good agreement with footprint predictions on average. However, on a half-hourly scale the agreement between observed and predicted beech forest contributions was not so good. In particular, it was found that the predictions made by footprint models of the variations due to longitudinal footprint changes were not observed by the experimental system.

Keywords: Net ecosystem exchange; Footprint; Eddy covariance; Modelling; Forest ecosystem; Heterogeneity

1. Introduction

The eddy covariance technique has become the most widespread method of measuring carbon dioxide fluxes exchanged between the biosphere and atmosphere at the ecosystem scale (Baldocchi, 2003; Valentini et al., 2000; Valentini, 2003). Strictly, this method is valid only for homogeneous sites (Baldocchi et al., 1988), but the need to develop networks that cover the widest possible spectrum of ecosystem types led to a choice of sites that were not necessarily ideal and, in particular, did not always fulfil the homogeneity conditions (Baldocchi, 2003). In such sites, the climate response and the inter-annual variability of the fluxes are difficult to interpret because the observed variability stems not only from their response to meteorological and phenological changes, but also to changes in sources/sinks following wind direction or stability changes (Lloyd, 1995; Aubinet et al., 2002).

Under these conditions, models could be useful tools for identifying the factors that control the fluxes. Different types of models could be used to address this problem. On one hand, functional models have been

Abbreviations: BFC, beech forest contribution; HVP, homogeneous vegetation plot; LAI, leaf area index; NEE, net ecosystem exchange; PPFD, photosynthetically active photon flux density

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Nomenclature

D_{sat} air saturation deficit (mmol mol^{-1})
f_j, f_1, f_2 HVP weighing factors of the HVP j (1, 2)
f_{laij} function describing the seasonal evolution of the leaf area index
$F_{r,\theta}$ footprint function in polar coordinates (m^{-2})
F_x cross-wind integrated footprint function (m^{-1})
$F_{x,y}$ two-dimensional footprint function (m^{-2})
g_{r,θ_j} proportion of the element dr dα that is covered by the HVP j
G_{pj} gross primary productivity (μmol m^{-2} s^{-1})
G_{pjm} gross primary productivity at light saturation and optimal water deficit (μmol m^{-2} s^{-1})
G_{pjs} gross primary productivity at light saturation (μmol m^{-2} s^{-1})
k von Kármán constant (0.4)
L Obukhov length (m)
n number of measurements
N_e net CO_2 flux measured at a single point by eddy covariance systems (μmol m^{-2} s^{-1})
N_{ej}, N_{e1}, N_{e2} net ecosystem exchange of the HVP j (1, 2) (μmol m^{-2} s^{-1})
Q_0 photosynthetically active photon flux density (mol m^{-2} s^{-1})
r radial coordinate (m)
R correlation coefficient
R_{dj} total respiration (μmol m^{-2} s^{-1})
R_{djm} respiration at 10 °C and non-limiting soil water content (μmol m^{-2} s^{-1})
R_{dj0} respiration at 10 °C (μmol m^{-2} s^{-1})
S_w soil water content (m^3 m^{-3})
T_{air} air temperature (°C)
T_{s2} soil temperature at 2 cm (°C)
u mean wind speed (m s^{-1})
u_* friction velocity (m s^{-1})
x distance upwind of the measuring point (m)
y distance in the cross-wind direction (m)
z_m measuring height (m)

Greek symbols
α_j quantum efficiency (mol mol^{-1})
α_{jm} maximum quantum efficiency at optimal temperature (mol mol^{-1})
ζ hyperbolic transformation of the correlation coefficient
θ polar angle
μ_p normal variable at the p probability level
σ_v standard deviation of the lateral wind component (m s^{-1})
σ_y standard deviation of the lateral wind direction (m)

developed with the aim of describing the net ecosystem exchange response to meteorological driving functions. Several models have been built that describe fluxes at different spatial and temporal scales. At the stand level and on a half-hourly scale, models based on the description of fundamental processes (Farqhuar model) have been developed, notably, by Baldocchi and Wilson (2001), Ogee et al. (2003), van Wijk et al. (2002) and Longdoz et al. (2004). Models based on empirical laws (Monteiro Santos and Heil Costa, 2004) or on neural network analysis (van Wijk et al., 2002; Papale and Valentini, 2003) have also been developed. To date, all these models have been based on the assumption that the ecosystem is homogeneous. The problem of heterogeneity of the source was not addressed.

On the other hand, footprint models can address source heterogeneity. Based on either Lagrangian stochastic simulation (Leclerc and Thurtell, 1990; Rannik et al., 2000) or the advection–diffusion equation (Schuepp et al., 1990; Horst and Weil, 1992; Horst and Weil, 1994; Schmid, 1994), they are used to determine the relative contribution to the measured vertical flux of each element of the upwind surface area. By combining footprint modelling and meteorological measurements, one can characterise the footprint climatology of the measurement sites; i.e., the area from which the flux measured by a given system originates (Amiro, 1998). This concept was developed by Göckede et al. (2003) who combined footprint modelling with quality assessment tools in order to establish the spatial distribution of the quality of fluxes measured by eddy covariance. It was applied by Rebmann et al. (2005) on 18 CARBOEUROFLUX sites. The combination of footprint models with land-use maps could also help in interpreting the long-term flux measurements at heterogeneous sites (Aubinet et al., 2001). Rannik et al. (2000) also used footprint simulation to determine the contribution of different sources and sinks present in the ecosystem. In a recent review, Foken and Leclerc (2004) highlighted that, although footprint models are widely used, they have