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Scaling Energy and CO₂ Fluxes from Leaf to Canopy Using Multilayered Implementation for Natural Canopy-Environment Relations (MINCER)

By

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Summary

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As a tool for compiling individual leaf-scale measurements into a comprehensive representation of canopy-scale fluxes, we developed a stand microclimate model named Multilayered Implementation for Natural Canopy-Environment Relations (MINCER). This model includes all essential processes that affect the fluxes above a plant canopy, that is, biophysical, hydrological and physiological processes functioning differently at various levels inside the canopy. Testing of the model against flux data gathered in a broadleaf deciduous forest in northern Japan indicated the robustness of the model's basic framework for scaling leaf-scale exchanges into canopy-scale fluxes, for both daily and annual time scales. Although there were some cases when the model could not reproduce the measured fluxes consistently, the measured data, rather than the modelled results, were generally found to be problematic in such cases. Because of its mechanistic nature, the model is a reliable tool for gap filling of measured flux data and for investigations of the mechanistic background of long-term and inter-site variations in fluxes.

Introduction

In recent years, long-term tower measurements of energy and CO₂ fluxes have been conducted at numerous forest sites worldwide (e.g., BALDOCCHI & al.

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2001). Thus far, data from these measurements have provided a substantial amount of new phenomenological knowledge on, for example, how annual CO₂ uptake differs among forest types, how seasonal flux patterns differ across climate gradients, and the nature of inter-annual flux variations. Therefore a desirable next step would be to extend our scope towards the mechanisms of long-term and inter-site variations in these fluxes.

The fluxes transferred to and from forests are the output from a complex system where physical, hydrological and biological processes interact with one another. Because of the numerous biotic and abiotic factors that influence fluxes, and the varying importance of each factor with time and space, it is impossible to detect a clear causal mechanism behind the spatial and/or temporal variations unless precise and simultaneous measurements of all relating sub-processes are available at all sites. Needless to say, such measurements are currently beyond our ability. One possible approach is, therefore, to use a model that is mechanistic enough to be able to compile individual measurements of each sub-process into a comprehensive representation of the ecosystem.

In this context, we develop the Multilayered Implementation for Natural Canopy-Environment Relations (MINCER), which includes all essential sub-processes affecting the fluxes above a plant canopy. In addition to biophysical and hydrological components, it also incorporates biochemical and physiological components (FARQUHAR & al. 1980, BALL & al. 1987) to simulate biological responses of plants. In this paper, results of a test simulation using flux data gathered at one of the flux sites in FFPRI FluxNet (OHTANI & al. 2001) are presented.

Material and Methods

Model

The model (MINCER) was designed to simulate the vertical profiles of climate and eddy fluxes within and above a plant canopy by integrating leaf-scale processes (e.g., light absorption, photosynthesis, transpiration) throughout the whole canopy layer. The model is based on one-dimensional multilayered representations of the vertical transfer of momentum (KONDO & AKASHI 1976), heat (KONDO & KAWANAKA 1986) and water vapour (KONDO & WATANABE 1992) within a plant canopy. The rainfall interception was included by WATANABE & MIZUTANI 1996. Recently, this model was completed to include all biophysical and hydrological processes (TAKATA & al. 2003), and was used as part of a model for describing dynamic interactions between the microclimate and plant growth (WATANABE & al. 2004). As a result, the physical processes considered in the present model include (1) transfer of PAR, near-infrared radiation and longwave radiation; (2) turbulent transport of momentum, heat, water vapour and CO₂; (3) energy budgets of a single leaf and the underlying ground surface; (4) rainfall/snowfall interception; (5) snow accumulation/melt on the ground; and (6) soil heat and moisture conduction. Physiological processes were also included: (7) photosynthesis and leaf respiration; (8) stomatal regulation of transpiration and CO₂ uptake; and (9) respiration of nonphotosynthetic organs and soil. For more details, see the paper by WATANABE & al. 2004 and the literature cited therein. In the present simulations, the forest canopy was divided into 30 layers of 1 m thick since the vertical profile of leaf area was available at 1 m interval up to 28 m above the ground.

Site

The testing site was a broadleaf deciduous forest located in Sapporo, northern Japan (42°59'N, 141°23'E, 180mASL). This forest is a mixture of various broadleaf species dominated by *Betula platyphylla*, *Quercus mongolica*, and *Kalopanax pictus*. The mean canopy height is 20m but some tall trees reach about 30 m. The forest floor is covered by dense evergreen *Sasa* bamboo (*Sasa kurilensis* and *Sasa senanensis*), which is generally under a snow pack of about 1m thick during the winter. The annual precipitation is 957 mm and the annual mean temperature is 7.1°C. The eddy fluxes of sensible and latent heat and CO₂ have been continuously measured since late 1999 using a 41m-scaffold tower. Various meteorological and hydrological variables have also been measured simultaneously. For the details of the flux data processing, see the paper by NAKAI & al. 2003. These authors reported the full year results of these measurements for 2000, which indicated that the annual carbon uptake (or NEP) of this forest was 260 gC m⁻² y⁻¹, with GPP and the total ecosystem respiration being 1120 and 860 gC m⁻² y⁻¹, respectively.

Parameterization

In the present model simulations, the most sensitive key parameters were the leaf area index (LAI), maximum catalytic activity of Rubisco (V_{cmax}), and soil respiration rate (R_{soil}). These parameters were evaluated based on *in situ* measurements, in the manner shown below, while other parameters were specified by the model's default values for broadleaf deciduous species, which were imported from SELLERS & al. 1996a,b.

The vertical profile of leaf area density was measured once for each major species using the allometric relationships obtained for several sample trees of each species, and the seasonal variation in total leaf area (LAI) was monitored by the photographic method and by measurements of PAR attenuation across the canopy (UTSUGI & al. 2004). Based on these data, a simple phenological model was prescribed as follows: (1) leaves emerge when the growing degree-day (GDD), defined as the summation of daily mean temperature higher than 5°C (e.g., CANNELL & SMITH 1983), exceeds 95°C-day; (2) LAI reaches its maximum plateau when GDD reaches 250°C-day; (3) leaf fall starts when the 10-day running mean temperature falls below 10°C; and afterwards (4) LAI decreases linearly to be zero one month later. This simple model well fitted to the measured seasonal variation of LAI.

To monitor seasonal variations in the photosynthetic capacity of the dominant species, light-saturated net photosynthetic rates at two different CO₂ concentrations (360 and 1500 ppm) were measured about once per month for several leaves at each of four different heights in the canopy. Measurements were made with a portable open gas exchange measurement system (LI-6400, Li-Cor). From these data, seasonal variations in the vertical profile of V_{cmax} were evaluated for the dominant species (TOBITA & al. 2004). In summary, the value of V_{cmax} for the top-leaves of each species maximized about one month after full leaf expansion, and decreased gradually during the summer until it started a steep decline about one month before leaf fall. The value of V_{cmax} for leaves near the bottom of the canopy was 20–30% of that for the top leaves. Since the factors that control the seasonal variation in V_{cmax} at this site are still unclear, we tentatively approximated the seasonal variation by linear functions of the day of year (DOY) values for each dominant species. For *Betula platyphylla* this was expressed as:

$$V_{cmax0} = \begin{cases} 80 \times (\text{DOY} - 122)/53, & 122 \leq \text{DOY} < 175, \\ 80 - 20 \times (\text{DOY} - 175)/85, & 175 \leq \text{DOY} < 260, \\ 60 - 60 \times (\text{DOY} - 260)/45, & 260 \leq \text{DOY} < 305, \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where V_{cmax0} ($\mu\text{mol m}^{-2} \text{s}^{-1}$) is the V_{cmax} of the top leaves. Although not shown here, similar equations were obtained respectively for the other dominant species. The vertical distribution of V_{cmax} was approximated by the following equation:

$$V_{cmax} = V_{cmax0} \exp(-\alpha L), \quad (2)$$

where α (= 0.3) is a parameter and L is the cumulative leaf area ($L = 0$ at the canopy top).

The soil respiration rates at the testing site were measured once per month by the closed-chamber method (ISHIZUKA & al. Unpublished). Since the measured respiration rates correlated well with soil temperature, they were represented by the following equation:

$$R_{\text{soil}} = R_{s0} \exp(bT_s) \quad (3)$$

where R_{s0} ($= 0.894 \text{ gC m}^{-2} \text{ d}^{-1}$) is the respiration rate at 0°C , b ($= 0.085 \text{ }^\circ\text{C}^{-1}$) is the parameter, and T_s ($^\circ\text{C}$) is the soil temperature at a depth of 5 cm.

Meteorological conditions

The model was driven by meteorological conditions above the forest given every 30 minutes. The given variables include shortwave and longwave radiation, air temperature, humidity, wind speed, CO_2 concentration, atmospheric pressure and precipitation rate. These variables were specified by 30min-averages of instantaneous measurements taken at the flux tower, except for precipitation rate, which was specified by hourly data obtained by the National Agricultural Research Centre for Hokkaido Region (3km NE from the site). Rainfall/snowfall detection was performed using air temperature and humidity according to the method of YAMAZAKI 1998. The model simulation was started at 0 AM on 1 January 2000 and continued for 1 year with a constant time-step of 30 minutes.

Results and Discussion

The present model generally produced consistent results for the diurnal patterns in the energy (Fig. 1) and CO_2 fluxes (Fig. 2) above the forest at least for the daytime, while slight overestimations are observed for the nighttime CO_2 flux. These overestimations are partly due to a difficulty in predicting the soil temperature underneath a dense canopy and partly attributable to an undermeasure of the nighttime flux as discussed later in this paper. Nevertheless, the correlation between modelled and measured results are quite high for the data shown in these figures ($R^2 = 0.9996, 0.894, 0.887$ and 0.975 for the net radiation, sensible heat, latent heat and CO_2 flux, respectively).

In the model, these fluxes were calculated as the sum of fluxes between leaves and the surrounding air within each of 30 layers inside the canopy. These leaf-scale fluxes were determined as a result of interactions among the energy balance of a single leaf, leaf physiology and the microenvironment around a single leaf. The microenvironment also interacted with the turbulent diffusion of momentum, energy and other quantities across the layers. Shortwave radiation in the top-most layers was intense and had both direct and diffuse components (i.e., some leaves were sunlit), whereas diffuse light was dominant in the lower layers. Leaf photosynthetic capacity (V_{cmax}) was set to diminish with depth into the canopy, thereby mimicking the fact that plants tend to allocate more nitrogen to leaves in high light conditions. All these sub-processes are quite consistent with the actual operations of real canopies. The resulting agreement between the modelled and measured fluxes shown in Figs. 1 and 2 confirms the robustness of the basic framework of these mechanistic treatments for scaling leaf-scale fluxes to the canopy scale.

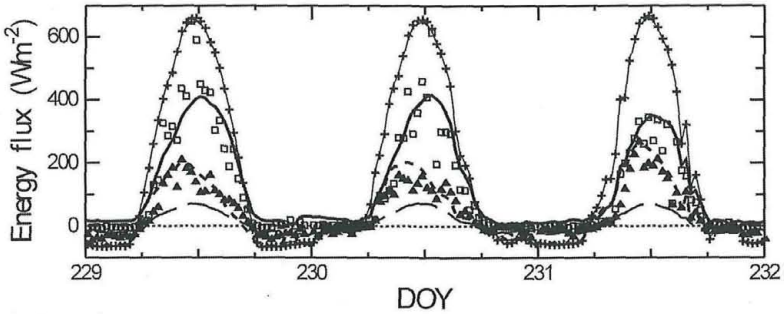


Fig. 1. Temporal variations in the 30min-averaged energy fluxes for three days from 17 August 2000. Lines denote the modelled results (solid: net radiation, solid bold: latent heat, dashed: sensible heat, dashed dot: heat storage) and points represent the actual measurements (cross: net radiation, open square: latent heat, filled triangle: sensible heat).

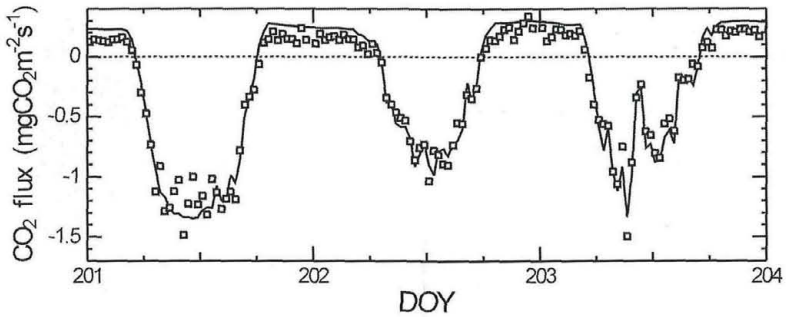


Fig. 2. Temporal variations in the 30min-averaged CO_2 flux for three days from 20 July 2000. Lines and points denote the modelled and measured results, respectively.

The model also showed a reasonable ability to reproduce annual flux variations (Figs. 3 and 4). The daily mean sensible heat flux increased in the early growing season when the snow pack had already disappeared, yet leaves had not fully expanded. The latent heat flux increased after leaf emergence (mid-May) and maximized in mid summer, followed by a gradual decrease until leaf fall. The CO_2 flux had almost constant positive values during the pre-growing season, but abruptly changed its sign when leaves emerged (i.e., when the forest started uptake of CO_2) and negatively peaked about 1.5 months later. The magnitude of the CO_2 flux then gradually decreased during the rest of the growing season. These seasonal trends reflected both the seasonal course of the environmental conditions (e.g., evaporative demand, PAR availability) and that of leaf transpiration/photosynthetic capacity. By incorporating simplified but observation-based phenology models, the present model could track the seasonal patterns of energy and CO_2 fluxes.

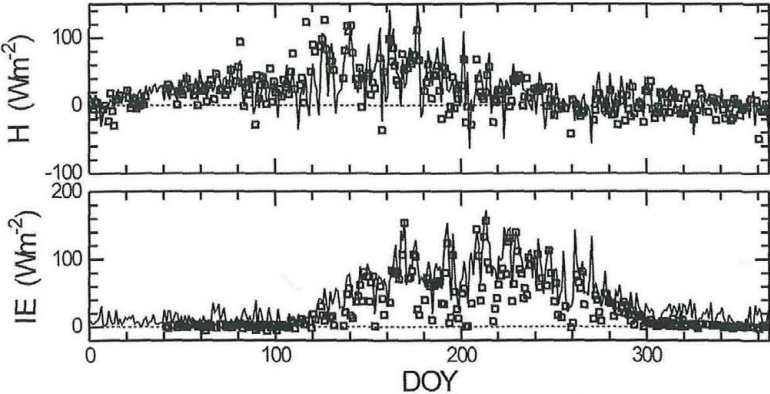


Fig. 3. Annual variations in the daily mean fluxes of sensible (top) and latent heat (bottom) for 2000. Lines and points denote the modelled and measured results, respectively. The latent heat flux of 100 W m^{-2} corresponds to the daily evapotranspiration of 3.5 mm d^{-1} .

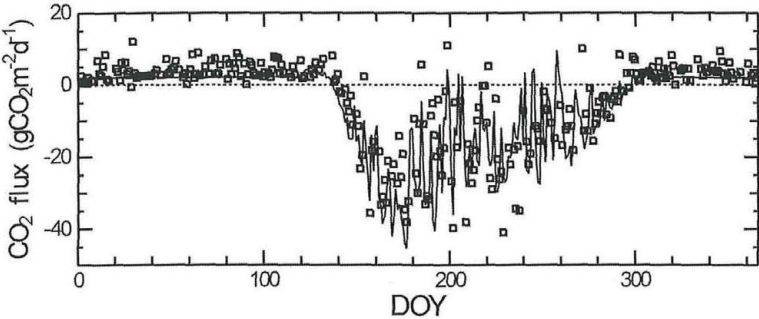


Fig. 4. Annual variation in the daily CO_2 flux for 2000. Lines and points denote the modelled and measured results, respectively.

However, during preliminary simulations, we observed that the magnitude of CO_2 flux was considerably overestimated for the late growing season, if the value of V_{cmax} of each species was kept constant at the seasonal maxima throughout the growing season (data not shown). Therefore the decline in photosynthetic capacity in the late growing season is an important feature of a deciduous forest. The development of more mechanistic phenology models will largely contribute to better representation of the seasonal flux variations in deciduous forests or probably also in other vegetated sites. Contrasting to the overestimation of the nighttime flux seen in Fig. 2, the modelled CO_2 flux in Fig. 4 is slightly lower than the measured flux during the winter. This is because the soil temperature under a snow pack was underestimated by the model. Hence the prediction of soil temperatures may be a next target of consideration. However, for the moment, a better correspondence

would be achieved if measured soil temperatures are used to evaluate the CO₂ efflux.

The above discussions focused mainly on the positive aspects of the present results, but in reality there were some cases when the model could not simulate the diurnal flux variations. However, individual inspections of such cases revealed that measured data rather than modelled results were generally problematic in these cases. One example of this is that the measured sensible and latent eddy fluxes were not balanced with the measured available energy (= net radiation minus heat storage) in some days. In the bottom panel of Fig. 3, some plots indicate that the measured latent heat flux was much smaller than the model predictions. Noting that the sensible heat flux was consistently predicted by the model and that the modelled results were always energy-balanced, it is apparent that the measured fluxes in these cases were not balanced with the available energy since the daily mean heat storage is generally negligible. The lack of energy balance closure is one of the most serious problems commonly met in the flux sites (WILSON & al. 2002). In another discrepancy, we found that the latent heat fluxes seemed to be undermeasured during rainfall events because of the limitation of the instruments, and that the modelled CO₂ flux was generally larger than the measured flux during calm stable nights, probably because the CO₂-rich air beneath the canopy drained out following the gently sloping topography, thereby reducing the flux transferred across the canopy top.

All these problematic cases were easily detected by comparisons between the modelled and measured results. The present model is, therefore, expected to be a good tool for detecting unreliable measurements and deducing reasonable fluxes (the so-called 'gap filling' procedure, BALDOCCHI & al. 2001), since the present model is mechanistic and the predicted fluxes were indeed consistent with the measured fluxes in the non-problematic cases. Furthermore, because of its mechanistic nature, we believe that the present model is feasible for scaling leaf-scale exchanges up to canopy-scale fluxes even under different conditions.

A c k n o w l e d g e m e n t s

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