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Evaluation of the importance of Lagrangian canopy turbulence formulations in a soil–plant–atmosphere model

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Abstract

The suitability of using K-theory to describe turbulent transfer within plant canopies was evaluated with field measurements and simulations of a detailed soil–plant–atmosphere model (Cupid). Simulated results with both K-theory and an analytical Lagrangian theory (L-theory) implemented in Cupid were evaluated against Bowen-ratio energy balance measurements and the temperature profiles in potato canopies. There was no difference between K- and L-theory in terms of simulating E, H and CO_2 fluxes over the canopy. The model slightly underestimated measured E by 3–8%; the comparison of H contained much scatter and the model slightly overestimated CO_2 flux. When the model was tested by simulating temperature and vapor pressure profiles within the canopy, the difference between the K- and L-theory was much smaller than the difference between each theory and the measurements. From simulated temperature profiles, the near-field correction provided by using L-theory seemed to be significant in canopies where the foliage is concentrated in the upper part, but appeared unnecessary for foliage distributed throughout the canopy depth. The major difference between K- and L-theory was in simulations of canopy radiometric temperature; with foliage distributed through out the depth of the canopy, K-theory consistently predicted higher canopy radiometric temperatures than L-theory by 2–8 °C, depending on leaf area index. More systematic study is required to determine if K-theory or L-theory is inadequate for remote sensing of radiometric temperature of canopies.

Keywords: Turbulence; Eddy diffusivity; Bowen-ratio energy balance; L- and K-theory; Radiometric temperature

1. Introduction

Accurate formulation for the turbulent airflow that controls the transfer of various gases to and from plant canopies and the underlying soil is needed to quantify and study exchange processes of energy, mass and momentum between vegetation and the atmosphere. Formulations that describe turbulent transfer in vegetation canopies may serve two important research purposes: (1) improve fundamental understanding of canopy processes by using supporting field measurement efforts to directly quantify fluxes of heat, mass and momentum in and above plant canopies, and (2) provide credible equations to include the influence of the atmosphere on transfer processes in detailed soil–plant–atmosphere models.

Several useful, plant–environment models are based on the K-theory notion that defines the turbulent flux, F_c, of any scalar in a turbulent airflow as a product of the scalar concentration gradient, dC/dz, and eddy diffusivity, K:

$$F_c = -K\frac{dC}{dz}, \qquad (1)$$

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where z is the height aboveground. Recently, the K-theory has come under wide spread criticism for not predicting the counter-gradient fluxes, which have been observed occasionally in vegetative canopies (Denmead and Bradley, 1985, 1987). Denmead and Bradley measured counter-gradient fluxes of heat, water vapor and CO_2 in Australian pine forests of heights 16–20 m with canopies that extended to 8–10 m. Other field and wind tunnel measurements have indicated that turbulent transfer inside the canopy is dominated by large intermittent eddies with length scales comparable to or exceeding the canopy height (Raupach, 1988; Raupach et al., 1996). At issue is the assumption with the K-theory that the length scale of the concentration gradient must be much greater than the size of eddies doing the transfer in order for the predicted flux to move down its existing gradient (Corrsin, 1974). While advanced theories such as the second (or higher)-order closure theory (Meyers and Paw U, 1987; Wilson and Shaw, 1977) and Monte Carlo Lagrangian trajectory theory (Thomson, 1987; Wilson and Sawford, 1996; Wilson et al., 1981) have been developed to deal with this type of complicated process, usually they are too complex and difficult to implement in detailed soil–plant–atmosphere models. For example, the application of advanced Lagrangian trajectory models has required numerical solution of stochastic differential equations (Thomson, 1987). Recently Raupach (1987, 1989a,b) and Warland and Thurtell (2000) have presented analytical Lagrangian theories (L-theory) that may be suitable to include in more detailed soil–plant–atmosphere models.

In this study, a mechanistic, one-dimensional, plant-environment model, called Cupid (Norman, 1979, 1982; Norman and Campbell, 1983; Norman and Arkebauer, 1991), is employed to evaluate the benefits of using Lagrangian theories for predicting turbulent transfer in soil–plant–atmosphere models. Special emphasis is given to the importance of using the analytical Lagrangian theory (L-theory) developed by Raupach (1989a,b) and recently improved upon by Warland and Thurtell (2000). The Cupid model consists of detailed formulations throughout the soil–plant–atmosphere continuum for many variables; for example, the state variables of temperature, vapor pressure, CO_2 concentration, and wind speed; fluxes of canopy sensible heat (H), and evapotranspiration (E); leaf wetness from condensation or rainfall; soil surface heat and water fluxes; and canopy radiometric temperature from remote infrared thermometers. The traditional turbulent transfer calculation in Cupid is based on the K-theory formulation. The L-theory, on the other hand, may be preferable for predicting concentration profiles of scalars, such as heat, water vapor and CO_2 and is attracting much interest as a simple approach to advanced Lagrangian trajectory models.

The L-theory represents an analytical turbulent transfer model for predicting scalar concentration profiles that are produced by a specified canopy source (or sink) distribution with turbulence characteristics defined by empirical equations of the standard deviation of vertical wind velocity (σ_w) and Lagrangian time scale (T_L–the time scale over which the vertical velocity remains correlated to itself due to persistence of turbulent motions (Raupach, 1989a)). Based on the eddy diffusivity (K_c) concept for transport of scalar quantity, c:

$$K_c = \kappa u^* \frac{z-d}{\varphi_c} \tag{2}$$

where u^* is the friction velocity, d the canopy displacement height, z the height of interest, φ_c the Monin–Obukhov stability factor for a scalar (Monin and Obukhov, 1954; Businger et al., 1971), and κ the von Karman's constant of 0.4. For the L-theory, Raupach (1989a) proposed the following:

$$K = \sigma_w^2 T_L \tag{3}$$

with

$$\frac{\sigma_w(z)}{u^*} = \begin{cases} 1.25, & z \geq h \\ 0.75 + 0.5\cos\left(\pi\left(\dfrac{1-z}{h}\right)\right), & 0 < z < h \end{cases} \tag{4}$$

and

$$\frac{T_L(z)u^*}{h} = \max\left[0.3, \frac{\kappa(z-d)}{1.56h}\right] \tag{5}$$

where h is the height of the canopy.

Previous tests of the Raupach L-theory have shown good agreement with more advanced Lagrangian models, and led to the suggestion that the Raupach L-theory is a realistic alternative to the K-theory for describing turbulent transfer within and above flat canopies. Van den Hurk and McNaughton (1995) and McNaughton and Van den Hurk (1995) evaluated the potential for adopting the Raupach L-theory in a two-layer canopy-resistance model but found no significant advantage over the K-theory in its use to determine bulk soil-canopy evaporation. Furthermore, insignificant differences were observed between Raupach L- and K-theory in determining evaporation over sparse millet (Dolman and Wallace, 1991). In addition, when the Raupach L-theory was used to evaluate the microclimate in soybean, it performed well above the canopy but did a poor job of reproducing profiles inside the canopy (Baldocchi, 1992). Another challenge to using L-theory in models is the following: to our knowledge, no tests of the L-theory have been done at nighttime when wind speeds are near zero.

Warland and Thurtell (2000) recently have improved on the Raupach L-theory by proposing an analytical "mixing matrix" theory (Warland L-theory). The Warland L-theory is a square matrix equation that calculates the mean concentration profile continuously from the near- to far-field. It replaces the separate near- and far-field calculations used in the Raupach L-theory. In the Warland model, calculations for both the near- and far-field use turbulent statistics at all heights, unlike in the Raupach L-theory where the near-field calculation uses profiles of turbulent statistics only at the source height. In the early test comparing the Warland L-theory with Raupach L-theory, Warland and Thurtell (2000) found that the Raupach L-theory tends to underestimate the near-field effect inside the canopy; however, the Warland L-theory requires further tests.

Hitherto, evaluations of the L-theory have consisted of simple sensitivity tests conducted with prescribed boundary conditions at the soil surface, and little effort has been directed toward integrating the turbulent transfer processes above the ground with the transport of mass and energy inside the soil to allow studies of the dynamic feedback between the soil and the atmosphere. The Cupid model used in this study is designed to integrate the various mass and energy transport phenomena in the whole soil–plant–atmosphere system within a single detailed mechanistic framework that includes the description of turbulent exchange in and above the canopy. In particular, it allows explicit interactions between the soil and atmosphere by linking the aboveground equations of the turbulent transfer (using K- or L-theory) to equations of soil water transport and heat conduction, so that water and heat fluxes at the soil surface can be calculated variables and not specified as input parameters; as done in previous tests of the L-theory. The specific objectives of this study are as follows: (1) test the performance of L-theory against that of the traditional K-theory by comparing model predictions with Bowen-ratio measurements of fluxes of E, H and CO_2 above potato canopies; (2) explore the use of L-theory at nighttime when wind speeds are near zero; and (3) determine the conditions under which K-theory provides an inadequate description of turbulent exchange in vegetation canopies. Although not originally an objective of this research, simulations with the Cupid model revealed that use of K- and L-theory produce markedly different predictions of remotely-sensed canopy radiometric temperatures, especially under low leaf area index.

2. Methods

2.1. Field experiments

2.1.1. Crop culture

To obtain model inputs and evaluate model predictions, field measurements were made in corn and in commercially grown potatoes (*Solanum tuberosum* cv. Russet Burbank) during the summers of 1993, 1994, and 1996. One set of turbulence statistics measurements in a corn canopy was made at the Rosemount Agricultural Experiment Station of the University of Minnesota where the soil is a Waukegan silt loam (mixed, mesic, typic Hapludoll). The corn crops were in E–W rows, 1 m apart and 1.7–2.5 m high with one-sided leaf area per unit soil area (LAI in $m^2\,m^{-2}$) values in the range of 1.2–3. Another set of turbulence measurements were made in a corn canopy at the West Madison Agricultural Research Station of the University of Wisconsin where the soil is classified as Betavia silt loam (fine-silty, mixed, mesic, Mollic Hapludoll). The corn crops were in N–S rows, 0.75 m apart and 2.6 m high with LAI of 2.8.

Measurements in potato fields were also made at two sites: Arena, Wisconsin and near the Hancock Agricultural Research Station of the University of Wisconsin-Madison. The soil at the Arena site is Sparta sand (mesic, uncoated, Typic Quartzipsamments) and at Hancock is Plainfield loamy sand (sandy, mixed, mesic, Typic Udipsamments). The volume fraction of quartz minerals was taken as 15% for the Sparta sand and 47% for the Plainfield loamy sand, and these nominal values resulted in soil thermal conductivity of 1.5–2.0 $\mathrm{W\,m^{-1}\,K^{-1}}$ in the simulation of soil heat flux. Potato crops were in rows, 0.9 m apart with 7–14 plant stems per meter along the row. In the early growth stage, soil was mounded around stems forming hills about 0.25 m high; the hilltop is taken as the zero height or ground surface. By the end of the aboveground vegetative growth period, potato canopies reached maximum heights between 0.5 and 0.7 m, and then sagged down to 0.25–0.5 m after mid July. At the same time the canopy reached maximum height, total LAI (measured with the LAI-2000, LI-COR, Lincoln, NE)[1] reached 3–5 and then decreased gradually as leaves settled to the ground. Crop management was typical of the overhead sprinkler irrigation systems used to maintain well-watered conditions and the fungicide and insecticide schemes used to control pests in the Central Wisconsin region (Curwen and Massie, 1984; Adams and Stevenson, 1990; Armour et al., 1997).

2.1.2. *Fluxes*

Evapotranspiration (*E*), sensible heat (*H*), and CO_2 fluxes were measured over the potato crops in the Arena area from 9 to 16 July 1993 and in the Hancock area from 19 to 27 August 1993. At the time of the flux measurements, the crops in Arena had reached a height of 0.60 m and LAI of 3.0, while those in Hancock had canopy height of 0.5 m and LAI of 4.0.

2.1.3. *Bowen-ratio(β) flux measurements*

A Bowen-ratio energy balance approach was used to measure energy fluxes above the plant canopies. The Bowen-ratio sensors, which were mounted at 1 and 2 m heights above the ground, were interchanged to reduce the bias errors that can occur with sensors at fixed heights. Bland et al. (1996) have provided detailed descriptions of the Bowen-ratio system that was used here to measure *H*, *E* and CO_2 fluxes over potato canopies.

Bowen-ratio data used in the analysis were obtained during periods when appropriate wind direction existed for good fetch. Net radiation (R_n) above the canopy was measured with a net radiometer (Swissteco Inst., Oberriet, Switzerland); when missing the net radiation measurement, R_n, was estimated from measured solar radiation using a regression of earlier measurements of both solar (LI-COR, Inc., Lincoln, NE), and net radiation at the same site (slope $=0.74$, $R^2=0.89$). Since Bowen-ratio measurements are only reliable when wind speed and scalar concentration gradients are sufficiently large, data were only used during periods of positive net radiation. Occasionally, values of Bowen-ratio were below -1 during early morning or early evening hours and the data were removed from the analysis. Knowing β allowed E to be calculated from the energy budget equation $[E=(R_n-G)/(1+\beta)]$ with H calculated as the product of β and E. The CO_2 flux (F_c) was calculated using $F_c=H/(\rho_a C_p)(\Delta\rho_c/\Delta T)$, where $\rho_a C_p$ is the volumetric heat capacity of air and ρ_c is the concentration of CO_2.

2.1.4. *Supporting measurements*

Wind speed and wind direction (Met One, Grants Pass, OR) were measured on a cross-arm at the same 2 m height as the upper aspirators and the inlet of the sampling tubes for air for the Bowen-ratio measurements. Air temperatures midway in and at the top of the canopy were measured with fine-wire thermocouples (76 μm diameter) shaded from radiation with white-painted, thin aluminum caps, and vapor pressure inlets at the same height sampled air for a cooled-mirror dew point hygrometer (Model Dew 10, General Eastern, Watertown, MA). Soil heat flux (*G*) was measured with Radiation and Energy Balance System (REBS, Inc., Seattle, WA) plates buried 0.05 m below the soil on the hill and in the furrow. Soil temperatures were measured at 0.05, 0.3, and 0.5 m. The soil temperature at the 0.05 m depth was obtained by averaging four thermal couple measurements (two on the hill and two in the furrow) and those at 0.3 and 0.5 m were measured on top of the hill. The soil temperature was not measured within the soil layer above the heat flux plates, so the heat storage adjustment to the heat flux was obtained by using the average soil temperature change within the 0.05 m depth simulated by Cupid. The soil heat storage correction to the soil heat flux measurements was in the range of 30–60% of the measured heat flux from the heat flux plate. The soil heat flux (*G*) was much lower in the furrow

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[1] Mention of a company and/or product does not imply endorsement by the University of Wisconsin-Madison.

than on the hill with the latter exceeding 100 W m^{-2} on clear sky days even though the crop canopy nearly shaded the ground. The soil surface CO_2 flux (Norman et al., 1992) and leaf photosynthetic rates (McDermitt et al., 1989) were measured using chambers. A 21× data logger (Campbell Scientific Inc., Logan, UT) was used to run all the electronic sensors, with data sampled every 5 s and averaged over 20 min. Gravimetric measurements of soil moisture made during the experiment indicated a well-watered crop of soil volumetric water content between 11 and 15%. Other variables measured in potatoes as part of this study consisted of dew accumulation and evaporation (Wilson et al., 1999).

2.1.5. Turbulence measurements

Measurements of the standard deviation of the vertical wind velocity (σ_w) were made in and above potato and corn crops during the summer of 1993 and 1994. A one-dimensional sonic anemometer (Model CA27, Campbell, Scientific Inc., Logan, UT) was used for measurements above the canopy and two three-dimensional drag anemometers (Norman et al., 1976) used in and above the canopy. The anemometers were sampled at 10 Hz using a data logger (21×, Campbell Scientific Inc., Logan, UT), stored directly in a storage module for runs of 20 min, and then processed off-line to compute σ_w. Friction velocity was measured from wind speed profiles based on four previously matched cup anemometers over potatoes and no u^* measurements were made over corn. On each day of measurements, locations of instruments were changed several times to make the data closely representative of healthy, undisturbed potato crop stands. In addition, on 29–31 August 1996 (days 242–244), both daytime and nighttime values of σ_w were measured using the one-dimensional sonic anemometer 1 m above and a three-dimensional sonic anemometer (Model SATCA3, Campbell Scientific, Logan, UT) within a 2.4 m corn canopy at the West Madison Agriculture Research Station of the University of Wisconsin-Madison.

2.2. A brief description of the Cupid model

Cupid is a comprehensive, mechanistic soil–plant–environment model that divides the soil, canopy air space and the overlying atmosphere into stacks of horizontal layers to simulate the vertical distributions of state variables and fluxes. The number of layers in the soil and the atmosphere immediately above the canopy are specified and those within the canopy region are calculated as a function of the leaf area density distribution, which depends on the LAI. The leaves within each canopy layer are divided into leaf-angle classes (here 10° each). The aboveground calculations in the model are linked to equations of water transport and heat conduction in the soil so that the equations of heat and water transport throughout the system are solved simultaneously using only inputs of easily obtained weather conditions above the canopy and soil conditions at the lower boundary of the root zone. An important advantage of this arrangement is that the evaporation and heat fluxes from the soil surface to the first canopy layer are calculated rather than specified as input variables. Profiles of the aboveground vapor pressure and air temperature are linked with profiles of soil water content and temperature, using the soil surface water vapor and heat transfer coefficients derived by Sauer and Norman (1995) and Sauer et al. (1995) and simplified by Kustas and Norman (1999).

The canopy sources/sinks of H and E are based on calculations of the collective effect of the energy balances for the individual leaves within the canopy. Starting in the top canopy layer, the absorption, reflection and transmission of direct visible, direct near-infrared, diffuse visible and diffuse near-infrared radiation and thermal radiation are calculated based on measured values of the global solar radiation and thermal irradiance above the canopy. The fluxes of H and E in each canopy layer are then calculated by coupling equations of temperature and vapor pressure in the canopy air space with the leaf surface temperature and vapor pressure through the leaf energy balance. The calculation of the leaf energy balance in each layer is based on several factors, including the temperature difference between the leaf and the air, net radiation absorbed in all wavelength bands (VIS, NIR and thermal IR), vapor pressure of the air, eddy diffusivity (K), and the total leaf diffusion resistance (r_l) (the sum of stomatal resistance (r_s) and leaf boundary layer resistance (r_a)). The r_a is calculated as a function of the wind speed (u) near the leaf and leaf size; the profile of K is also based on the wind speed profile; r_s is calculated according to Norman and Polley (1989). Diabatic correction for

u and K is only applied above the canopy using the Monin–Obukhov scaling length (L).

The Cupid model has a detailed equation set to calculate radiometric temperature (See Norman and Becker, 1995 for definition of radiometric temperature) that would be sensed by a remote infrared thermometer or radiometer. The reflected and emitted thermal radiation of leaves in various layers and the soil are weighted by their respective contributions to the radiometer view to derive a radiometric temperature and emissivity of the entire soil/canopy system.

2.2.1. K-theory formulation in Cupid

With K-theory, the heat and water transport equations for the soil–plant–atmosphere system are solved simultaneously using implicit finite difference equations balancing the net flux into and out of each layer with changing storage within the layer. Implicit finite difference equations are solved iteratively using a Newton–Raphson procedure for non-linear equations (Campbell, 1985). The aboveground temperature and vapor pressure profiles are combined with equations for temperature and water in the soil to balance iteratively the soil surface energy budget, where the surface temperature simultaneously satisfies the surface evaporation, sensible heat, net radiation and soil heat conduction.

2.2.2. L-theory formulation in Cupid

In this study, the traditional routine in the Cupid code for describing turbulent transfer was slightly modified in order to implement the L-theory. The modification was necessary because, unlike the K-theory, the L-theory requires fluxes at the soil surface as input; however, Cupid is designed to calculate the soil surface fluxes as output variables. Therefore, we have used the K-theory to provide the initial values of surface water vapor and heat fluxes to start the L-theory on the first hour of the first day of simulations. For subsequent time steps (usually hourly), the initial calculations of temperature and vapor pressure by L-theory are based on soil surface evaporation and heat fluxes from the previous time step. Then surface flux values are changed by 20% and the L-theory equations used again to obtain a second set of temperature (and vapor pressure) profiles. These two conditions permit the calculation of a slope relating sensible heat flux (and evaporation) from the soil surface to near-surface air temperature (and vapor pressure). Ratios of the changes in the surface sensible heat (and evaporation) to the changes in the temperature (and vapor pressure) at the first air layer above the soil are combined with the surface transfer coefficients for heat and water vapor (Sauer and Norman, 1995; Sauer et al., 1995) to calculate the surface temperature (and vapor pressure) values that link to profiles of soil temperature and soil water content. In each time step, convergence is achieved by iterating between the L-theory and the soil heat and water conduction equations assuming a linear relationship between scalar concentration and flux for the small hour-to-hour change in conditions.

3. Results and discussion

This section starts by presenting the turbulence statistics that were measured in potato and corn crops to examine the Raupach (1989a) empirical scheme for estimating σ_w. Then the fluxes of CO_2, energy balance components, and temperature profiles in potato canopies at two sites in Central Wisconsin are presented: Arena during 9–16 July (days 190–197) and Hancock during 19–27 August (days 231–239) of 1993. The relevant weather conditions during this period are summarized in Table 1. Finally, we present an evaluation of the effects of the near-field, counter-gradient process on temperature profiles within plant canopies and the effect of K-theory versus L-theory on simulating canopy radiometric temperature.

3.1. Turbulence statistics

Measurements of σ_w/u^* often show a considerable scatter, but most commonly used empirical formulations estimate it as a linear function of height (z) inside the canopy and a stability-dependent quantity above the canopy that has a value of 1.25 under neutral conditions (Raupach, 1988). Here, our measurements of σ_w/u^* were clustered about mean values that vary daily with respect to locations in the field. On a given day σ_w/u^* did not always monotonically increase with height. Instead, maximum values of σ_w/u^* were sometimes observed at $z = h$, a behavior that may have been due to the mean wind direction in relation

Table 1
Daily weather conditions measured in potatoes

Date	Solar ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)	Wind ($\mathrm{m\,s^{-1}}$)	$T_{\max}$ (C)	$T_{\min}$ (C)	$e_{\max}$ (mb)	$e_{\min}$ (mb)	$\mathrm{Rh}_{\max}$ (%)	$\mathrm{Rh}_{\min}$ (%)	Pcp/Irrig. (mm)
Arena									
190	22.2	3.2	27	17	25.5	15.6	100	89.2	11.9
191	21.5	1.9	27.8	15.4	25.5	14.3	100	84.5	17.8
192	19	2.5	25.1	16.1	25.1	14.1	100	87.2	9.6
193	30.1	2.5	22.5	12.7	18.4	11.2	100	68.7	0
194	8.5	2.1	20.6	12.7	20.8	10.6	100	80	9.2
195	24.6	1.7	25.2	15	21.6	13.4	100	83.2	0
196	26.3	1.9	25.2	14	21.5	12.3	100	76.6	0
197	19.2	2	26.1	11	24.1	10.9	100	84.1	0
Hancock									
231	20.5	2.5	27.3	18.2	23.8	15.8	98	62	0.5
232	15.7	2.5	23.1	14.9	18.2	12	95	57	0
233	25.3	1.5	24.4	10.4	14.3	9.9	97	43	0
234	11	3.1	23.2	13.6	22	9.6	98	59	10.2
236	23.3	3.2	29.2	17.7	23.1	15.2	94	50	0
237	21.9	2.2	30.6	16.4	25.9	14.1	93	52	0
238	16.6	2	29.5	19.9	29.3	16.2	99	67	0
239	17.1	3.8	26.9	16	26.9	15	95	64	4.1

to the rough canopy structure and/or atmospheric conditions. However, stability corrections to the data in Table 2 for u^* were quite small (less than 5%). The values of σ_w/u^* in Table 3 are larger than expected. This may have arisen because of the relatively rough nature of potato canopies, which are planted at a wide-row spacing. Above-canopy, σ_w was measured with two anemometers that operate on different principles (drag and sonic), which were independently calibrated, and both anemometers agreed and gave larger values of σ_w than might be expected. With both turbulence anemometers mounted at the same height, the slope of σ_w/u^* of drag versus sonic was 1.01, R^2 was 0.99, and the root mean square difference was 0.13.

When the wind speed is relatively low so that free convective transport within the canopy becomes decoupled from transport processes above the canopy, values of σ_w may not be a unique function of u^* as proposed by Raupach (1988, 1989a). Such calm conditions can limit the use of both L- and K-theory particularly during nighttime circumstances of dew formation on and evaporation from plant canopies. The main difficulty is that formulations of the eddy diffusivity (K), which are required by L- and K-theory, are based on momentum transfer processes and work only when the winds are not calm and u^* not zero. For L-theory to be useful in soil–plant–atmosphere models, a parameterization for

Table 2
The ratio of standard deviation of vertical wind velocity to the above-canopy friction velocity measured at three heights in potato crops in 1993 in Hancock, WI (potato, 1993)

Day of year	Hour	$\sigma_w/u^* \pm$ S.D.		
		At $z/h = 0.5$	At $z/h = 1$	At $z/h = 3.3$
172	1400–1735	–	1.33 ± 0.12	1.58 ± 0.14
178	1250–1456	–	1.04 ± 0.07	1.39 ± 0.05
199	1455–1856	0.71 ± 0.06	1.54 ± 0.28	1.72 ± 0.16
208	930–1245	0.44 ± 0.08	0.94 ± 0.10	1.55 ± 0.10
237	1417–1736	1.40 ± 0.33	–	1.65 ± 0.11
238	1437–1706	1.01 ± 0.13	–	1.78 ± 0.15

Table 3
The nighttime/daytime standard deviation of vertical wind velocity measured at two heights in corn crops in 1996 in West Madison, WI (corn, 1996)

Day of year	Hour	$\sigma_w \pm$ S.D. (m s^{-1})	
		At $z/h = 0.125$	At $z/h = 1.4$
243	100–400	0.037 ± 0.004	0.047 ± 0.008
243	500–800	0.035 ± 0.005	0.08 ± 0.038
243	900–1200	0.083 ± 0.012	0.259 ± 0.043
243	1300–1600	0.079 ± 0.027	0.288 ± 0.042
243	1700–2000	0.031 ± 0.009	0.187 ± 0.062
244	2300–2400	0.03 ± 0.002	0.169 ± 0.066
244	100–400	0.03 ± 0.001	0.157 ± 0.012
244	500–800	0.03 ± 0.005	0.154 ± 0.038
244	900–1200	0.037 ± 0.013	0.221 ± 0.059
244	1300–1600	0.059 ± 0.005	0.341 ± 0.023

σ_w must be obtained for calm conditions. Nighttime measurements of σ_w in a corn canopy were used here as guide in specifying K during low-wind conditions. We found that σ_w approaches minimum values of about 0.03–0.06 m s^{-1} throughout the corn canopy during moderately low-wind, nighttime conditions. Based on a wind speed sensitivity test we conducted with the L-theory, a constant σ_w value of 0.05 m s^{-1} within the canopy and minimum wind speed of $u = 0.2$ m s^{-1} above the canopy were considered appropriate for calm conditions, which occurred mostly at night. Generally, the nocturnal behavior of turbulence within the canopy under low-wind conditions is associated with radiative cooling at the canopy top and heat flux from the underlying soil that stays relatively warm at night. In contrast, strong surface heating and strong winds during the daytime couple air movements within and above the canopy.

3.2. CO_2 flux

Fig. 1 shows 3 days (20, 21, 27 August 1993) of simulated CO_2 flux (F_c) and measurements above the potato canopy at Hancock, WI. The model simulations tend to be about 20% larger than the measurements, on average, with the mid-afternoon (1400 h) maximum values slightly over 30 μmol m^{-2} s^{-1}. Considering that all the parameters in the leaf physiology routines in Cupid were measured independently with leaf chambers so no calibration of the Cupid model was done to improve agreement with measured fluxes, this agreement is not atypical of other studies. In fact comparisons of fluxes measured with various eddy correlation or Bowen-ratio flux systems often result in disagreements of 20% or more as well (see Twine et al., 2000 or Norman et al., 1995 for discussions of flux errors and Zhan et al., 1996 for typical model errors). Leaf chamber (McDermitt et al., 1989) measurements indicated that the midday maximum CO_2 uptake by the potato leaves was about 24 μmol m^{-2} s^{-1} for leaves exposed to full natural light. The soil surface F_c measured with a soil surface CO_2 chamber (Norman et al., 1992) averaged −2.0 μmol m^{-2} s^{-1} during midday hours compared with a simulated value of about −1.6 μmol m^{-2} s^{-1}. As expected the daily course of the canopy F_c also followed the radiation pattern. The simulated CO_2 flux used a value for the maximum rate of carboxylation (V_{max}) of 85 μmol m^{-2} s^{-1} based on leaf chamber measurements; this is close but somewhat less than the 100 μmol m^{-2} s^{-1} normally used in Cupid to simulate soybean photosynthesis. This adjustment resulted in-canopy stomatal resistance values that range from 60 to 248 s m^{-1} in the simulation of F_c in potatoes.

3.3. Measurements of the energy balance components

The daytime hourly measurements of R_n, E and H over the potato canopy and G at the ground closely followed the distribution of daytime solar radiation (R_s) as expected for well-watered crops in central Wisconsin during the summer growing season. For example, at the Hancock site during 21 August 1993 (day 233), the R_n, E and R_s peaked between 1200 and 1300 h and H and G peaked between 1100 and 1200 h, with average values of $R_s = 860$ W m^{-2}, $R_n = 590$ W m^{-2}, $E = 380$ W m^{-2}, $H = 115$ W m^{-2}, and $G = 95$ W m^{-2}. Average values of E during these periods were about 77% of the available energy ($R_n - G$) compared with 23% for H. Nighttime dew formation may have contributed to evaporation of free water on the plant leaves until 0800 h. During this period, E was equal to R_n as the available radiant energy was used to evaporate free water on the plant leaves. The E then dropped below R_n after 0800 h as the canopy became dry. The component of H was much larger during the morning hours than in the afternoon and the large values of H corresponded to a reduction in E.

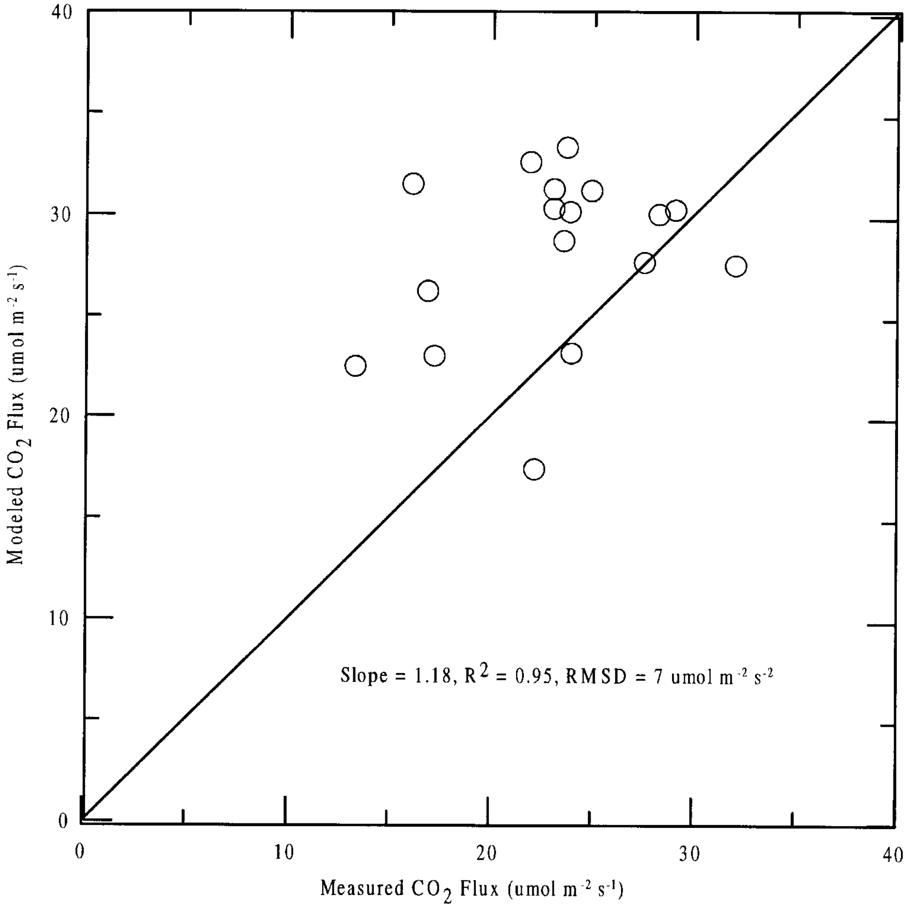

Fig. 1. Measured and simulated CO_2 flux over potato canopies at Hancock, Wisconsin during the daytime on 20, 21 and 26 August 1993. Model simulations exceeded measurements by 19%.

The validity of the flux measurements is supported by the good agreement with potential E (E_p) estimated by the simple Priestley and Taylor (1972) equation (PT), given as $E_p = \alpha(s/(s+\gamma))(R_n - G)$, where s is the slope of the saturated vapor pressure curve versus temperature, γ (66 Pa K^{-1}) the psychrometric constant, and α the Priestley–Taylor coefficient (1.26) for daily E_p calculations (Table 4). The PT equation for E_p is known to work well in temperate regions (Priestley and Taylor, 1972), particularly in Wisconsin (Tanner and Jury, 1976). A comparison of 30 min measured evaporation fluxes with the PT equation over 8 days in July 1993 at Arena, WI, yielded a RMSD of 26 W m^{-2} ($R^2 = 0.99$) with values that varied between 0 and 500 W m^{-2}. A similar comparison of 8 days in August 1993 at Hancock, WI, produced a RMSD of 33 W m^{-2} ($R^2 = 0.99$) over as similar range of values.

3.4. Comparison of the energy balance components

The simulated energy balance components by Cupid in the potato canopy were consistent with the measurements at the Hancock site; for example, during 21 August 1993 (day 233), at 1300 h, $R_{n,\mathrm{Cupid}} = 578$ W m^{-2}, $R_{n,\mathrm{meas}} = 592$ W m^{-2}, $E_{\mathrm{Cupid}} = 378$ W m^{-2}, $E_{\mathrm{meas}} = 405$ W m^{-2}, $H_{\mathrm{Cupid}} = 113$ W m^{-2},

Table 4
Total daily water loss to evapotranspiration measured and simulated in potatoes

Day	Measured (mm day^{-1})	Raupach L-theory (mm day^{-1})	Warland L-theory (mm day^{-1})	K-theory (mm day^{-1})	ET_{eq} (mm day^{-1})	Et_p (mm day^{-1})
Arena						
190	3.77	3.37	3.90	3.70	3.13	3.95
191	3.84	3.81	3.94	3.77	3.13	3.94
192	3.14	3.14	3.2	3.08	2.63	3.31
193	5.59	4.96	5.18	4.95	4.51	5.69
194	0.82	0.92	0.92	0.93	0.57	0.71
195	4.01	3.98	4.14	3.97	3.44	4.33
196	4.39	4.25	4.40	4.23	3.72	4.69
197	3.24	3.11	3.22	3.12	2.60	3.27
Hancock						
231	4.24	3.60	3.68	3.53	3.38	4.25
232	2.61	2.55	2.63	2.46	2.11	2.66
233	4.44	3.90	3.91	3.94	3.81	4.80
234	1.71	1.68	1.68	1.72	1.16	1.46
236	4.52	3.84	3.93	3.83	3.62	4.56
237	3.82	3.90	3.97	3.74	3.16	3.99
238	2.06	1.79	1.83	1.83	1.81	2.29
239	2.99	2.69	2.77	2.58	2.38	3.00

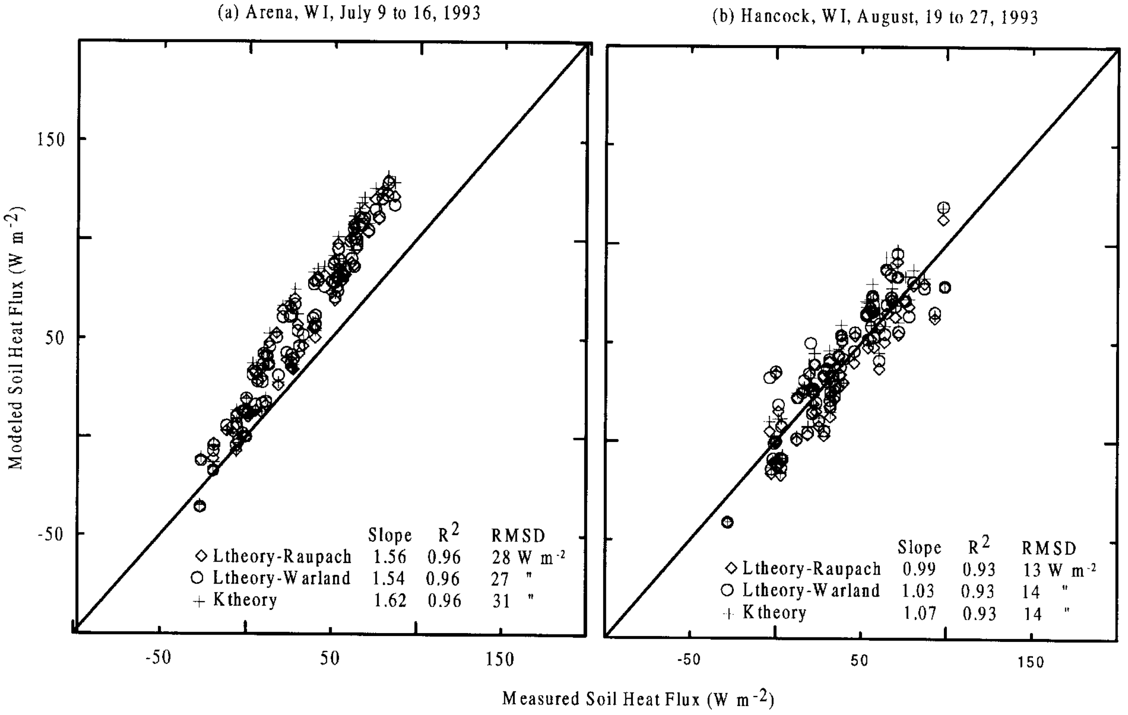

Fig. 2. Soil heat flux underneath potato canopies at Arena (a) and Hancock (b). There was no difference between K-theory (open circle) and L-theory (diamond and plus symbols), but model overestimated the measurements with considerable scatter in the comparison.

$H_{\mathrm{meas}} = 100\,\mathrm{W\,m^{-2}}$, $G_{\mathrm{Cupid}} = 80\,\mathrm{W\,m^{-2}}$, and $G_{\mathrm{meas}} = 87\,\mathrm{W\,m^{-2}}$; at the soil surface only simulated results yield, $R_{\mathrm{n,sfc}} = 132\,\mathrm{W\,m^{-2}}$, $E_{\mathrm{sfc}} = 67\,\mathrm{W\,m^{-2}}$, $H_{\mathrm{sfc}} = -15\,\mathrm{W\,m^{-2}}$. No significant differences were observed between the K- and L-theory.

The daytime hourly R_{n} simulated by Cupid over the potato canopy at both the Arena and Hancock sites compared quite well with values of net radiation derived from measured solar radiation, shown by the excellent 1:1 relationship, with RMSD $= 21\,\mathrm{W\,m^{-2}}$, slope $= 1.02$ and $R^2 = 0.99$. The following radiation properties were used for the potato leaves in the model simulation: 42% near-infrared reflectance and transmittance, 10 and 8% visible reflectance and transmittance, and 4 and 0% thermal reflectance and transmittance, respectively. These nominal values corresponded to an estimated daily albedo of about 20% for cloudless conditions, where hourly values varied from 16% at midday to 32% at solar zenith angle of 74° (or 1800 h). Values of the albedo for a potato canopy in temperate regions often range from 10 to 26% related to increasing LAI (Brown, 1976; Szeicz et al., 1969).

Values of G simulated by Cupid were essentially the same based on both the K- and L-theory, with simulations comparable to the measurements at the Hancock site but exceeding the measurements at the Arena site (Fig. 2). The larger values of G at Arena may have resulted from the smaller LAI of 3 (compared to LAI of 4 for crops at Hancock). In general, the measurements of G on the hilltop were greater than those in the furrow (Fig. 3). Although soil heat flux simulations agreed somewhat better with measurements on the hilltop, differences were generally minor and demonstrated that the relatively deep furrows typical of potato canopies could be reasonably simulated with one-dimensional heat conduction equations.

The Cupid simulations of E based on both the K- and L-theory show reasonable agreement with the Bowen-ratio measurements (Fig. 4). Values of

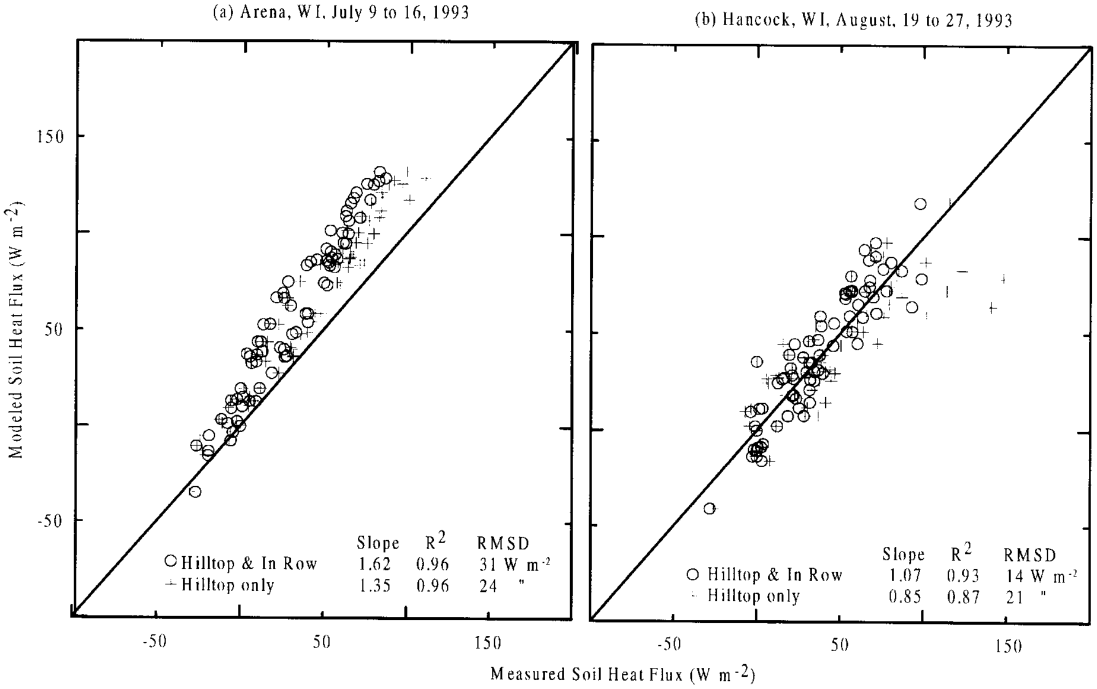

Fig. 3. Soil heat flux underneath potato canopies at Arena (a) and Hancock (b). Model simulations show reasonable agreement with measurements on the hilltop.

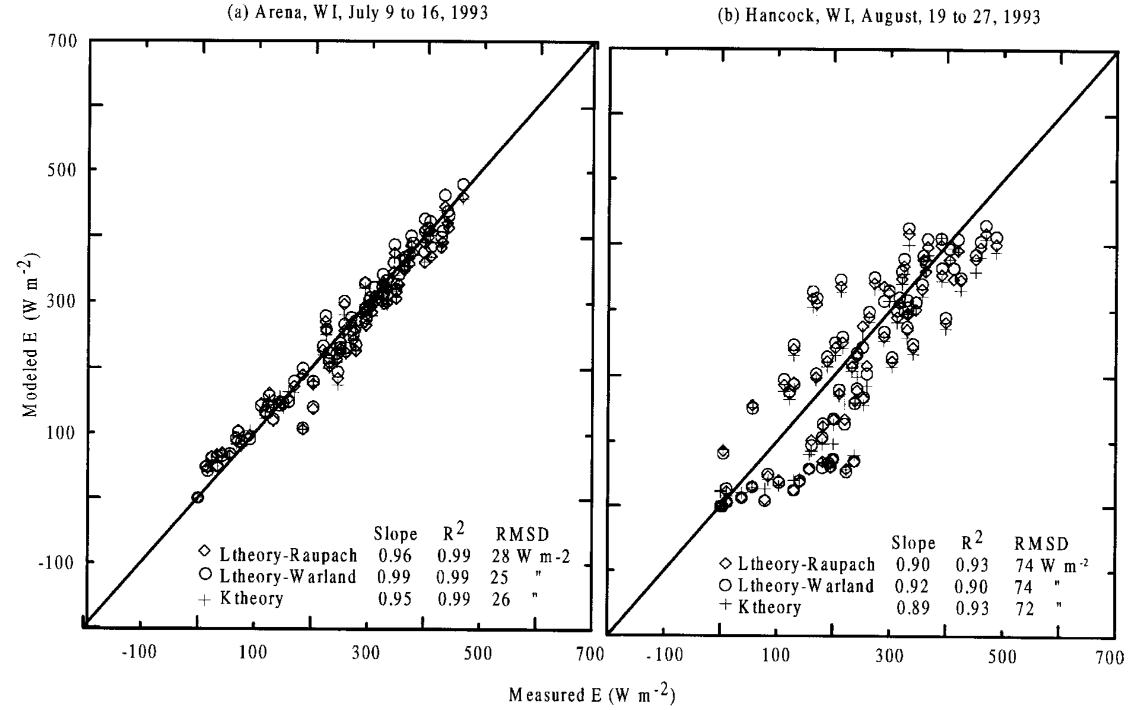

Fig. 4. Evapotranspiration measurements compared with model simulations over potato canopies at Arena (a) and Hancock (b). The K-theory (open circle) and L-theory (diamond symbol) simulations were equal but they underestimated the measurements by 3–8%.

H above the canopy at Hancock showed the largest scatter between Cupid simulations and measurements (Fig. 5), but the RMS error of 41 W m^{-2} is reasonable agreement even for comparisons between measurement techniques (Twine et al., 2000). Clearly surface flux measurements have uncertainties, and comparisons among eddy covariance, lysimeters and Bowen-ratio methods have produced discrepancies of up to 25% (Blad and Rosenberg, 1974; Prueger et al., 1997; Twine et al., 2000).

The minor differences that arise in the comparison of K- and L-theory reported here are consistent with other findings in the literature, as discussed in Section 1.

3.5. Dew accumulation

The nighttime hourly dew accumulation (in gram water per square meter of ground area) depends on a supply of water from the atmosphere and, if the soil is moist, an equally or more important supply from the soil. Therefore, under moist soil conditions, a comparison of simulated and measured dew accumulation provides a test of in-canopy transport formulations. The total dew accumulation simulated by the Cupid model assuming random canopy leaf orientation underestimated field measurements (Fig. 6), with the model performing better in the upper canopy than in the lower portion of the canopy for high soil moisture situations (Wilson et al., 1999). We measured a total dew accumulation of 450 g m^{-2} during 29–30 July 1992 and 26–27 July 1994, 470 g m^{-2} during 16–17 August 1994, and 100 g m^{-2} during 21–22 August 1992. The greater amount of dew was recorded in dense canopies with an underlying wet soil (29–30 July 1992 and 26–27 July and 16–17 August 1994) than in the less dense canopy with dry soil (21–22 August 1992). For all four nights, condensation started well before the air at 2 m reached saturation. The dew accumulation increased gradually to maximum values

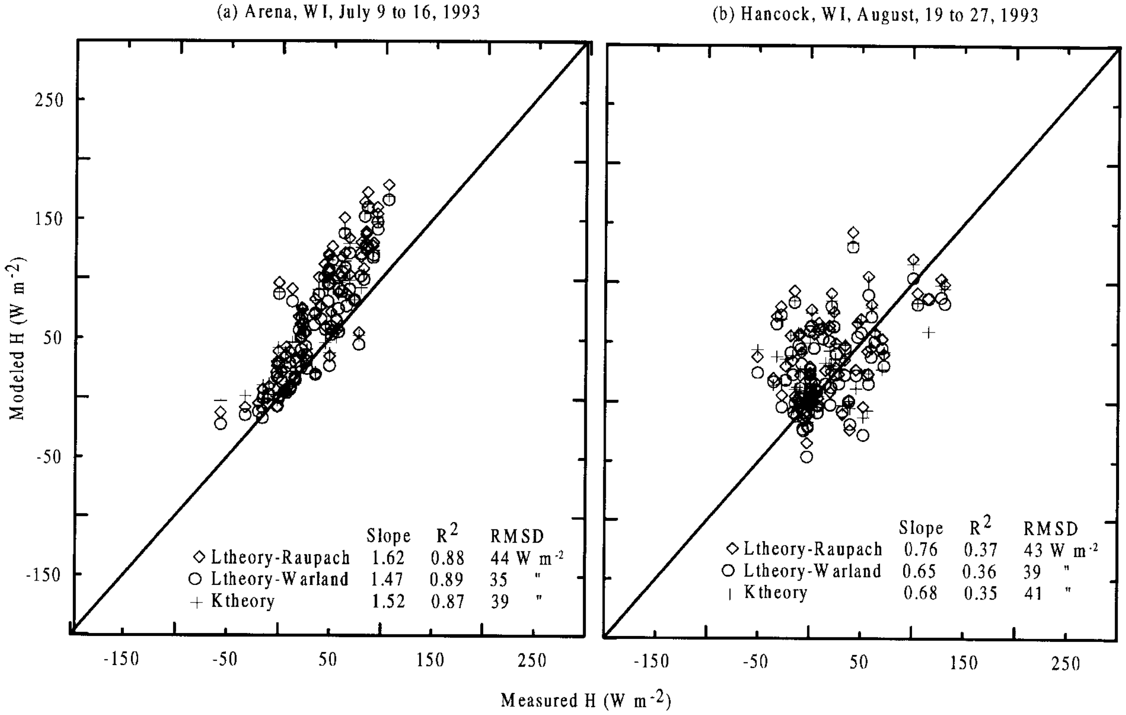

Fig. 5. Sensible heat over potato canopies at Arena (a) and Hancock (b). The K-theory (open circle) and L-theory (diamond and plus symbols) were the same, but model comparison with measurements showed considerable scatter.

during the night and then quickly dried off throughout the whole canopy following sunrise in the morning. Under moist soil conditions, 50–80% of the dew deposited on the leaves was predicted by the Cupid model to have arisen from the soil; supporting the idea that dew accumulation is a way to test in-canopy transport formulations.

The model predictions of total dew accumulation only reached 300–360 $g\,m^{-2}$ during the nights when the soil was wet. During the dry soil situation (21–22 August 1992), the model predictions were 105 $g\,m^{-2}$, in good agreement with the field measurements. On average, Fig. 6 reveals no serious difference between the K- and L-theory as both theories consistently underestimated dew formation in the potato canopies. Considering that dew supplied through distillation of soil water is one of the most difficult quantities to predict and few attempts are available in the literature (Norman and Campbell, 1983), these results suggest a reasonable agreement between model and measurement and generally support the use of K- or L-theory with $\sigma_w = 0.05\,m\,s^{-1}$ under calm conditions.

3.6. Daytime temperature profiles in potato canopies

Figs. 7 and 8 show measurements of the temperature at several points in potato canopies compared with predictions of the Cupid model during the daytime hours of 1000, 1200 and 1400 for 3 days (22 August 1993, 27 July and 17 August 1994). The largest disagreement between measured and predicted temperature profiles occurs on 21–22 August 1993. The simulated temperature profiles indicate good agreement between the K- and L-theory, but both simulations show only a reasonable agreement with measurements inside the canopy. In general, the difference among model predictions is much smaller

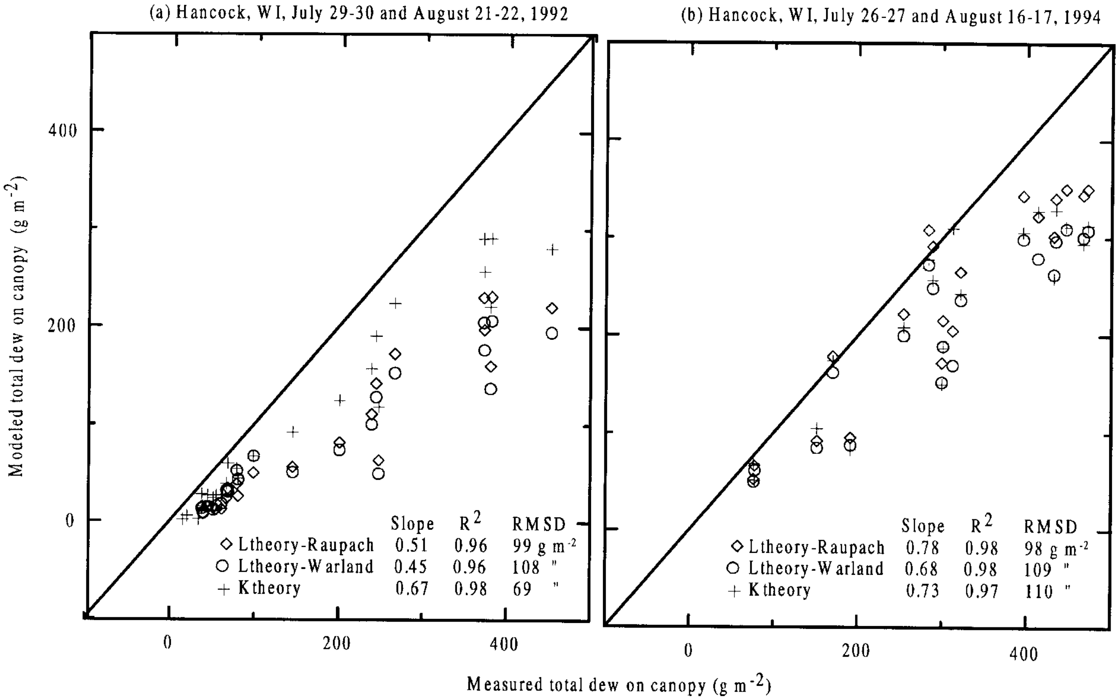

Fig. 6. Total dew liquid water simulated and measured on potato canopies. The K-theory (open circle) and L-theory (diamond and plus symbols) were the same, but model comparison with measurements showed considerable scatter.

than the difference between each model prediction and the measurements. For example, at 1400 h during 27 July 1994, at mid-canopy height, the K-theory, Raupach L- and Warland L-theory overestimated the measurement of temperature by 1.82, 2.2 and 1.75 °C, respectively, with a difference of 0.07 °C between the Raupach L- and K-theory and 0.38 °C between the Warland L- and K-theory. These results illustrate that the K- and L-theory have about the same capability in simulating turbulent transfer in potato canopies.

Our findings are consistent with studies in the literature. Baldocchi (1992) reported that inside a soybean canopy a one-dimensional L-theory model underestimated measurements of temperature and vapor pressure by 2 °C and 0.25 kPa, respectively, and overestimated CO_2 by up to 40 ppm. Similarly, Meyers and Paw U (1987) reported that a higher order closure model underestimated measurements of temperature by 1 °C inside a water-stressed soybean canopy. Both these studies and ours suggest that counter-gradient effects may not have as important an impact on the concentration profiles as did the soil and heterogeneous canopy characteristics. Our results suggest that the K- and L-theory, in one-dimensional modeling framework, have about the same limitation in short canopies, such as potatoes.

3.7. Near-field effects on temperature profiles

We simulated the mid-afternoon (1400) temperature profile in a 3 m tall canopy with different LAI and canopy foliage distributions using the L-theory. The aim was to assess the possible role of canopy structure on counter-gradient effects in terms of simulating scalar concentration profiles in plant canopies. When a canopy with maximum leaf area density at $z = 0.5\,h$ and the lowest leaves close to the ground at $z = 0.1\,h$ was used, the inversion (counter-gradient) in our simulated temperature profiles within the canopy was very small for the simulation with the Warland L-theory

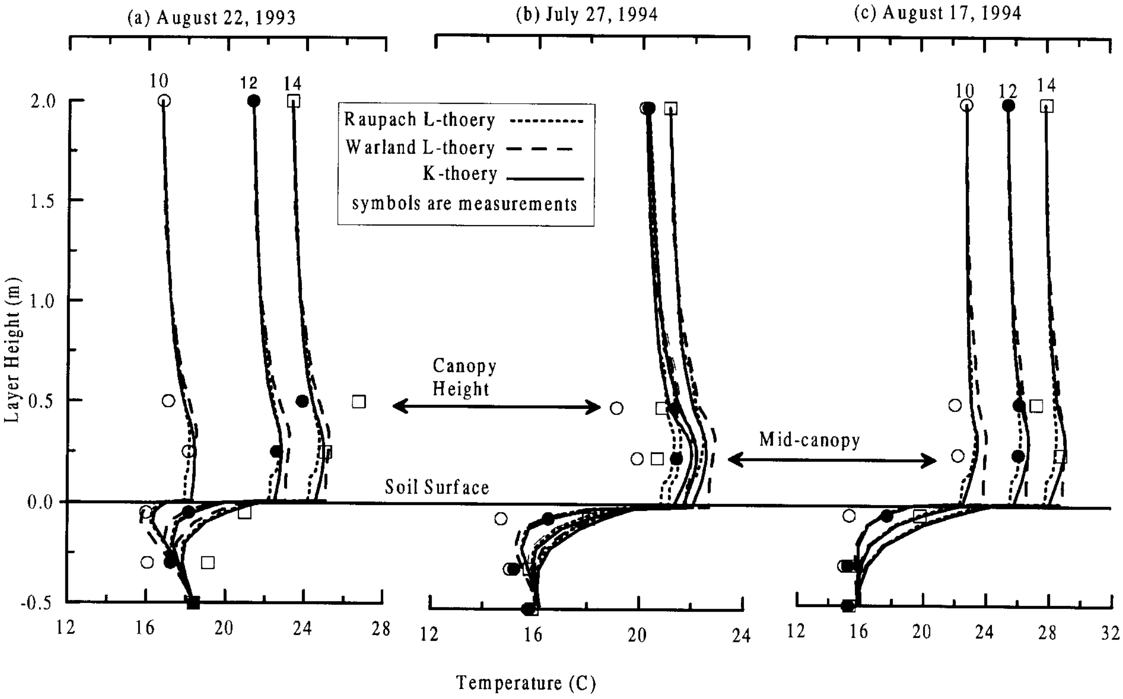

Fig. 7. Measurements (symbols) of temperature profiles in potato canopies compared with simulations using (solid lines) and L-theory (dash lines).

and completely absent for that with the Raupach L-theory (Fig. 8a and b), indicating an upward sensible heat flux (or positive) throughout the canopy. The inversion in our simulated temperature profiles was much stronger within the canopy in which maximum leaf area density at $z = 0.8\,h$ and the lowest leaves far above the ground at $z = 0.7\,h$ (Fig. 8c and d). For both canopy distributions, however, the inversion was nearly absent for the temperature profiles within canopies with LAI = 2. Thus, the near-field correction provided by L-theory seems important in canopies where the foliage is elevated considerably above the ground but may be unnecessary in those canopies with their foliage distributed throughout the canopy depth.

Our simulations also show that magnitudes of the temperature are very large at the soil surface underneath the plant canopy and the surface temperature can exceed air temperature by 3–12 °C. Mass and energy exchange at the soil surface of plant canopies is known to depend on many factors, including soil organic matter content, texture, bulk density, water content, the absence or presence of litter, albedo, wind speed, temperature, and humidity (Campbell, 1985). Because of the low-wind speed, small vertical gradients, roughness, obstructions from plants, and spatial variability at the soil surface, obtaining boundary conditions for a model from direct measurements of CO_2, water vapor and sensible heat fluxes and exchange coefficients at the soil–atmosphere interface is virtually impossible (Baldocchi et al., 2000). As our results demonstrate, transfer coefficient formulations are a robust method for specifying mass and energy exchange at the soil surface in soil–plant–atmosphere models (Sauer et al., 1995; Kustas and Norman, 1999).

The radiometric temperature of the vegetation/soil system depends on a combination of soil and vegetation temperatures. With high LAI and full vegetative cover, the vegetation is most important in determining radiometric temperature and K- and L-theory both

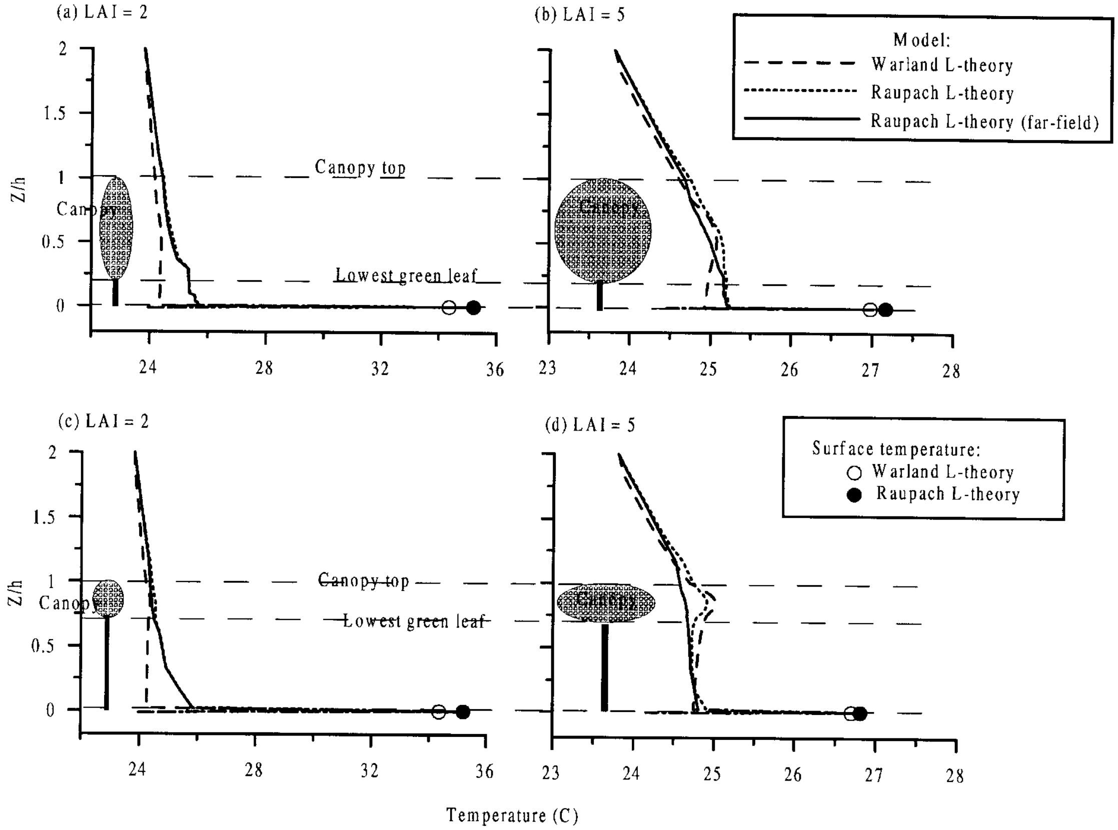

Fig. 8. Simulated temperature profiles evaluating the near-field effects within plant canopies. For all simulations $R_n = 503\,\mathrm{W\,m^{-2}}$, relative humidity = 51%, wind speed = $5\,\mathrm{m\,s^{-1}}$ above the canopy and leaf physiological properties are similar to potato. For (a) and (c), the soil sensible heat source is $98\,\mathrm{W\,m^{-2}}$ and the vegetation heat source is $177\,\mathrm{W\,m^{-2}}$. For (b) and (d), the soil sensible heat source is $13\,\mathrm{W\,m^{-2}}$ and the vegetation heat source is $316\,\mathrm{W\,m^{-2}}$ vegetation heat source is $316\,\mathrm{W\,m^{-2}}$.

give similar results. With low LAI, the lowered wind speed and high soil radiation loads create high soil temperatures that cause greater differences between K- and L-theory. The results in Table 5 show that K- and L-theory formulations in the canopy result in substantial radiometric temperature differences even for canopies with LAI = 5. For LAI = 0.5, the differences in K- and L-theory predictions of radiometric temperature approach 8 °C. When all the vegetation is concentrated in the upper portion of the canopy, predictions of radiometric temperature using K- and L-theory usually agree within 1 °C with extreme differences being 2 °C.

Table 5
Radiometric temperature of various vegetation covers (LAI) using the K- and L-theory formulations with leaf area distributed over the entire depth of the canopy (see Fig. 8a and b)

	Radiometric temperature (°C)			
	LAI = 0.5	LAI = 1	LAI = 2	LAI = 5
K-theory	46.2	36.0	30.8	28.0
Raupach L-theory	37.5	33.7	29.2	25.9
Warland L-theory	34.6	32.6	28.7	25.8

In this simulation, the soil surface was dry and the vegetation unstressed with Cupid input conditions are the same as for Fig. 8.

The discrepancy between K- and L-theory arises because L-theory predicts lower soil surface temperatures and lower leaf temperatures in the lower regions of the canopy. Because predictions with K-theory have yielded reasonable agreement with soil surface temperature measurements (Anderson et al., 2000), more research remains to be done to determine whether K- or L-theory are more suitable for remote sensing applications of radiometric temperature.

4. Conclusions

Two important conclusions can be drawn from this study. First, the L-theory can be used in a detailed, mechanistic soil–plant–atmosphere model to describe some of the observed features of H, E and CO_2 transfer within and above a plant canopy. Furthermore, simulating the nighttime portion of the diurnal cycle, which is essential if L-theory is to be used in soil–plant–atmosphere models, can be reasonable accomplished by using $\sigma_w = 0.05\,\mathrm{m\,s^{-1}}$ throughout the canopy under low-wind speed conditions. However, L-theory did not out perform the K-theory in simulating the microclimate conditions within the potato canopy. Both theories performed equally in estimating surface energy balance components in and over the potato canopy, but sometimes failed to simulate the temperature and vapor pressure profiles observed within the canopy. Their poor performance within the canopy may have been partly because one-dimensional models treat the soil–plant system as a horizontally homogeneous medium and such a condition may not have existed in the somewhat heterogeneous potato canopy. This work supports the conclusion by Leuning (2000) and Raupach (2001) that the most important application of Lagrangian turbulent transfer theories in vegetation canopies is the inverse problem of inferring source/sink distributions from concentration profiles.

A second conclusion of this paper is that the near-field corrections provided by the L-theory are more important in canopies with large foliage densities concentrated in the upper part of the canopy than in those with low leaf area densities or foliage distributed throughout the canopy depth. Because simulating transport in plant canopies is simpler with K-theory than with L-theory, K-theory can continue to be used in one-dimensional models with little error except for some unusual canopies.

A third result identifies the possibility that K-theory may systematically overestimate vegetation/soil radiometric temperature, particularly for canopies that have their leaf area distributed vertically over the entire depth of the canopy. However, further research needs to be done to prove this.

Acknowledgements

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