Identifying sources and sinks of scalars in a corn canopy with inverse Lagrangian dispersion analysis I. Heat

O.T. Denmead [a,*], L.A. Harper [b], R.R. Sharpe [b]

[a] *CSIRO Land and Water, F.C. Pye Laboratory, GPO Box 1666, Canberra, ACT 2601, Australia*
[b] *Southern Piedmont Conservation Research Center, USDA-ARS, 1420 Experiment Station Road, Watkinsville, GA 30677, USA*

Abstract

Sources and sinks of heat in the canopy of a dense corn crop (LAI~5) were inferred through an inverse Lagrangian dispersion analysis. Input data were the profiles of air temperature and turbulence above and within the canopy. The analysis was verified in part by comparing its predictions of the net exchanges of sensible heat between canopy and air with direct measurements of the sensible heat flux above the crop made by eddy correlation.

Almost all the heat exchange occurred in the top half of the canopy, which was a strong heat source. The bottom half was a weak sink, virtually neutral in the overall heat exchange. The net exchanges of heat predicted by the analysis were, on average, 21% higher than the eddy correlation heat fluxes, but exhibited identical time trends. It is concluded that the inverse Lagrangian technique leads to robust and qualitatively correct predictions of the heat flux and that the analysis scheme employed offers a relatively simple means for calculating scalar fluxes in plant canopies. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Many investigations of the exchange of scalars such as heat, water vapour and trace gases, between plant communities and the atmosphere require information on the distribution of sources and sinks within the canopy space. Evapotranspiration and CO_2 assimilation are good examples of relevant exchange processes. Understanding each requires knowledge of the separate contributions to the net exchange by plants and soil. Seminal contributions in these fields include analyses of the relative importance of soil and plant evaporation in the overall water loss from crops by John Monteith and his mentor, Howard Penman (Penman and Long, 1960; Monteith, 1965), Monteith's investigations of the role of soil respiration and plant assimilation in the CO_2 exchange of crops (Monteith, 1962; Monteith et al., 1964) and of course, Monteith's introduction of the concept of crop and canopy resistances to examine gas exchange in plant communities (Monteith, 1963).

Emission of ammonia following application of nitrogen fertiliser is another instance where information on canopy sources and sinks is necessary. In this case, NH_3 can be emitted from the soil and absorbed or emitted from the foliage. Formulation of effective emission control measures will depend on

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* Corresponding author. Fax: +61-2-6246-5560.
E-mail address: tom.denmead@cbr.clw.csiro.au (O.T. Denmead)

the relative importance of the soil and plant sources (or sinks). In a companion paper, we examine source and sink distributions of NH_3 within the canopy of a corn crop irrigated with dairy effluent (Harper et al., 2000).

Early attempts at identifying sources and sinks of scalars in plant canopies used gradient-diffusion approaches in which the scalar was assumed to be transported by turbulent diffusion along its concentration gradient from regions of high to low concentration. Formally, such transport is described by

$$F_S(z) = -K(z)\frac{\partial C}{\partial z} \qquad (1)$$

where F_S represents the flux of the scalar at height z, K is a height-dependent eddy diffusivity and C is the scalar concentration. It has been demonstrated, however, that such a description can give quite misleading pictures of transport within the canopy space (Denmead and Bradley, 1985, 1987). Apparent counter-gradient flows occur commonly in plant canopies, i.e. the transport is in an opposite direction to that indicated by the sign of the concentration gradient. Alternative descriptions have been developed in consequence. These include higher-order closure models (Wilson and Shaw, 1977; Finnigan and Raupach, 1987), large-eddy simulation (Shaw and Schumann, 1992), wavelet analysis (Collineau and Brunet, 1993) and Lagrangian dispersion models (Raupach, 1989a,b,c; Raupach et al., 1992; Denmead, 1995). The first three approaches require rapid measurement of instantaneous scalar concentrations. The inverse Lagrangian dispersion model developed by Raupach (1989b), however, permits the identification of scalar sources and sinks in the canopy space from measurements of mean concentration profiles which are usually much easier to obtain.

The present paper validates inverse Lagrangian dispersion analysis in a corn canopy by examining the transport of heat. The net exchanges of sensible heat between canopy and atmosphere predicted by the analysis are compared with direct measurements made by eddy correlation. A companion paper by Harper et al. (2000) applies the model to an examination of NH_3 exchange between soil, plants and atmosphere.

2. The inverse Lagrangian dispersion model

The model is based on theoretical developments by Raupach (1989a,b,c). Here, we give only a brief qualitative description of its theoretical basis.

The model considers dispersion in regions near to and far from canopy source elements (the foliage and the ground). Scalar concentrations within and above the canopy result from contributions from the near field and the far field

$$C(z) = C_n(z) + C_f(z) \qquad (2)$$

where the subscripts n and f refer to the near and far fields, respectively. In the near field which extends about one canopy height downwind of a particular source, dispersion is dominated by the local coherence of eddy motions. In the far field, dispersion is dominated by the randomness of the turbulence and dispersion there can be described by gradient-diffusion following Eq. (1), viz.

$$F(z) = -K_f(z)\frac{\partial C_f}{\partial z} \qquad (3)$$

The near field concentration C_n is obtained from knowledge of the source strength S and the turbulence. The latter is characterised by σ_w, the standard deviation of the vertical wind speed w, and T_L, the Lagrangian time scale for vertical velocity, which is a measure of the average coherence time of eddies. Calculation of C_n follows the model of Raupach (1989a). In practical applications, the profile of σ_w above and within the canopy is a model input based on ensemble averaged measurements for that canopy. T_L is obtained empirically from the canopy height h and the friction velocity u_* above the canopy, both of which are also model inputs.

The far field concentration C_f is obtained by solving Eq. (3) with

$$K_f(z) = \sigma_w^2(z)T_L(z) \qquad (4)$$

Through these equations, Raupach (1989b) relates concentrations at any level i ($i=1–n$) to the source strengths at levels j within the canopy ($j=1–m$) using a dispersion matrix D with coefficients D_{ij}.

$$C_i - C_R = \sum_j D_{ij} S_j \Delta z_j \qquad (5)$$

where C_R is the concentration at a reference level above the canopy, m represents the number of discrete layers in the canopy for which solutions are required, each layer having strength S_j and depth Δz_j. Raupach (1989a,b) gives procedures for calculating the coefficients D_{ij} from u_*, σ_w and T_L.

Eq. (5) is the solution to the forward Lagrangian dispersion problem, i.e. that of predicting the concentration profiles generated by a given source–sink distribution. Raupach (1989b) shows how to extend the dispersion analysis to the inverse problem: determining source strengths from mean concentration profiles. Once the input data are assembled, the analysis can be performed on a personal computer in a matter of seconds. One practical requirement of the procedure is that the number of source layers be less than the number of heights for which concentration data are available. We note that the net flux of the scalar from the canopy is given by

$$F_S(h) = \sum_j S_j \Delta z_j \tag{6}$$

Examples of the use of inverse Lagrangian dispersion analysis are given by Raupach (1989b) for studying the dispersion of heat from an elevated plane source in a model canopy in a wind-tunnel, by Denmead and Raupach (1993) and Denmead (1995, 1996) for determining source- and sink-strengths for heat, water vapour and CO_2 in crops of wheat and sugar cane and by Harper et al. (2000) for investigating pathways of NH_3 loss within a corn canopy.

3. Materials and methods

3.1. Crop

The research was conducted in a crop of irrigated corn (*Zea mays* L.) grown for silage at Montezuma, GA, USA. The study was conducted during a period of 20 days after anthesis, from 13 June to 2 July 1993. The corn was planted at a density of 77,000 plants ha^{-1} with starter fertilizer nitrogen (N) applied at 27 kg N ha^{-1}. During the growing season, further N was supplied by regular sprinkler application of dairy waste effluent. At the commencement of the study, the crop had a leaf area index (LAI) of 4.95 and was 2.7 m

high. At the end of the study, the LAI was 5.3 and crop height was 3.3 m. LAI was determined by measuring the areas of all leaves on each of 10 plants selected randomly, and dividing that area by the ground area occupied by the plants. The height interval occupied by each leaf was also recorded in order to calculate the LAI in each of four canopy layers employed for the inverse Lagrangian analysis (Section 3.2.1).

3.2. Micrometeorological

As indicated above, the net heat fluxes from the canopy calculated by the inverse Lagrangian analysis were compared with heat fluxes above the crop measured by eddy correlation. Input data for the analysis were temperature profiles within the canopy and above it.

3.2.1. Temperature

In this study, source densities for heat were calculated for four layers of equal depth in the canopy using measurements of air temperature at eight levels, viz. 0.45, 0.9, 1.35, 1.8, 2.25, 2.7, 3.3 and 4.3 m above the ground on 13 June and 0.55, 1.10, 1.65, 2.2, 2.75, 3.3, 3.9 and 4.9 m for observations made on 29 June, 30 June, 1 July, and 2 July. The sixth measurement in each list was at h, while the seventh and eighth were above the canopy. The thermometers were aspirated, double radiation-shielded, three-junction, copper/constantan thermocouples. The fans were of the squirrel-cage type and were designed to give an airspeed of 3 m s^{-1} over the thermocouples. The sensors were cross-calibrated with measurements at the same point and in profile mode. Electronic noise was about 0.01°C.

3.2.2. Turbulence measurements

σ_w and u_* were measured 5 m above the ground with a Dobbie three-dimensional sonic anemometer with a 0.1 m path length (Coppin and Taylor, 1983).

$$u_* = -\overline{w'u'}^{1/2} \tag{7}$$

where u is horizontal velocity, the primes denote deviations from the means and the overbar represents a time average.

Turbulence profiles within the canopy were estimated from LAI (cumulated from the top of the

canopy) using published data of Wilson et al. (1982). Their data for corn indicate that

$$\frac{z}{h} \geq 1, \qquad \text{LAI} = 0, \qquad \sigma_w = \sigma_w(h),$$

$$\frac{z}{h} < 1, \qquad 0 < \text{LAI} \leq 3,$$
$$\sigma_w = (1 - 0.283\text{LAI})\sigma_w(h), \qquad (8)$$

$$\frac{z}{h} < 1, \qquad \text{LAI} > 3, \qquad \sigma_w = 0.15\sigma_w(h)$$

The correlation between $\sigma_w/\sigma_w(h)$ and LAI in the data of Wilson et al. (1982) is very strong, with $r^2=0.996$. The $\sigma_w/\sigma_w(h)$ relationship for LAI>3 is an extrapolation of those data. In order to perform the inverse Lagrangian analysis, it was necessary to express Eq. (8) in terms of z rather than LAI. This was accomplished by fitting a third-order polynomial to measurements of the distribution of LAI with z, for which $r^2=0.996$ also. The final form of the dependence of σ_w on z used in the analysis is shown in Fig. 1.

3.2.3. Eddy correlation measurements

The sonic anemometer measurements were combined with measurements of temperature T at 5 m made with a fast-response, fine-wire, resistance thermometer in order to obtain the sensible heat flux H.
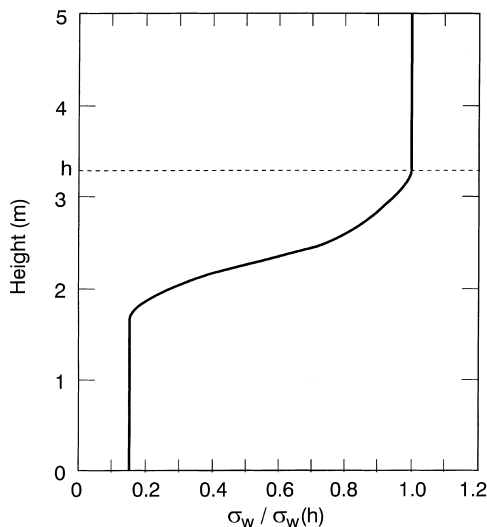
$$H = \rho c_p \overline{w'T'} \qquad (9)$$

where ρ is air density and c_p is the specific heat of air at constant pressure.

A cross comparison between the mean temperatures indicated by the resistance thermometer at 5 m and the thermocouple thermometer at 4.9 m showed a difference of 6% between the two, which was fed into the calculation of the eddy correlation H. That calculation also applied corrections of approximately 10% to the apparent H to account for different averaging paths for the wind and temperature sensors and for sensor separation (Moore, 1986).

3.2.4. Sampling periods

The micrometeorological data were collected in successive 0.5 h runs. Data collection periods varied from 4.5 h on 29 June to 9.5 h on 1 July.

4. Results and discussion

4.1. Heat fluxes from inverse Lagrangian dispersion analysis

4.1.1. Temperature profiles

Fig. 2 shows representative temperature profiles for one day in the study, 2 July. A notable feature in all

Fig. 1. Assumed profile of normalised σ_w above and within the corn canopy following Wilson et al. (1982). h denotes canopy height.
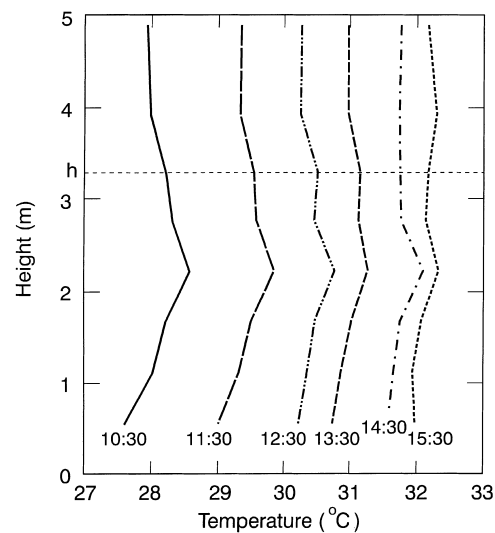

Fig. 2. Representative profiles of air temperature above and within the corn canopy, measured on 2 July.
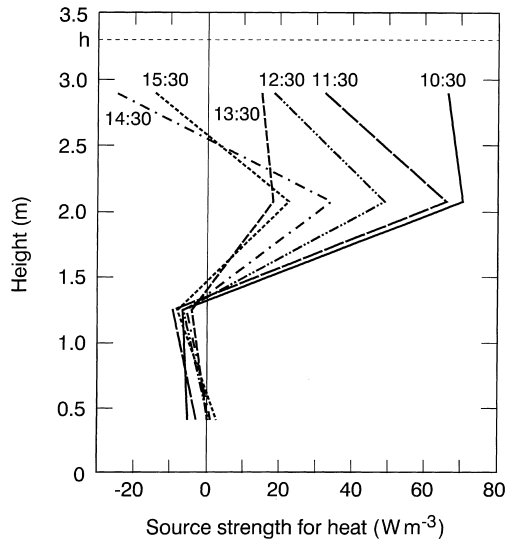
Fig. 3. Source strengths for sensible heat calculated by the inverse Lagrangian analysis for the temperature profiles in Fig. 2.

Fig. 4. Average cumulative heat fluxes in the canopy calculated by the inverse Lagrangian analysis for 5 days of measurement.

profiles is the existence of a 'hot spot' at about 2/3 canopy height during the daytime, which indicates a region of strong heat production there. The same feature was present during high radiation periods on all days during the study.

4.1.2. Source–sink distributions within the canopy

Fig. 3 shows the distribution of heat sources in the canopy, calculated by the inverse Lagrangian dispersion analysis, for the temperature profiles in Fig. 2. It is evident that the canopy was a net heat source for most of the day, with strong heat production around the 'hot spot'. Foliage in the top layer changed from a heat source in the morning to a heat sink in the afternoon, while the bottom foliage and the soil constituted weak heat sinks for most of the day. Very much the same source distribution was observed on each day of measurement, as can be seen in Fig. 4 which shows the average cumulative heat flux through the canopy for each day.

4.2. Comparison with conventional micrometeorological measurements

While it was not possible to test the predictions of the analysis layer by layer, it was possible to com-
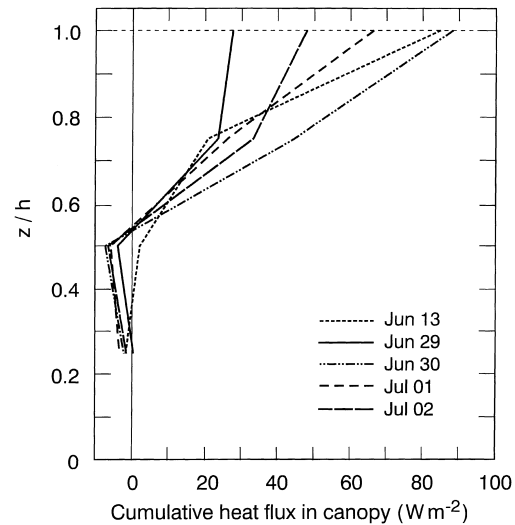
pare its predictions of the net exchanges of heat for the canopy, i.e. the cumulative heat flux at the canopy top, with the independent eddy correlation measurements of H at 5 m. Fig. 5 shows both heat fluxes on 3 days: the example day of 2 July and two previous days, 30 June and 1 July. The time courses of the inverse Lagrangian fluxes closely followed those of the eddy correlation measurements, but the magnitude of the former was often somewhat higher. Fig. 6 compares all the inverse Lagrangian estimates of the net canopy heat flux with the directly-measured eddy correlation fluxes. As noted already, the qualitative agreement between the two was good ($r^2=0.710$), but the inverse Lagrangian fluxes were 21% higher.

The reasons for the apparent overestimation of the heat flux by the inverse Lagrangian analysis are not clear. As we indicated earlier, the eddy correlation fluxes of heat were increased by 10% to account for losses due to instrument separation and different averaging paths, following the procedures of Moore (1986). Eddy correlation measurements by other researchers suggest that corrections for flux loss are unlikely to exceed 10% for measurements over agricultural crops, e.g. Anderson et al. (1984), Baldocchi (1994), so flux loss does not seem to be the cause of the discrepancy. Leuning (2000) has shown that atmospheric stability can influence the results of
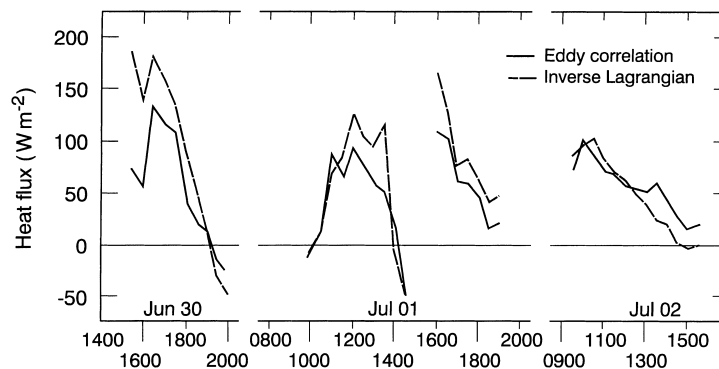
Fig. 5. Net exchanges of heat between canopy and air inferred by inverse Lagrangian analysis and measured by eddy correlation.

inverse Lagrangian dispersion analyses. In most of the analyses in the present study, conditions were moderately unstable. From the work of Leuning (2000), this would have resulted in negligibly small corrections that, in any case, would have made the inverse Lagrangian predictions of the heat flux marginally higher. It is possible that the discrepancy resulted from small, systematic errors in the temperature measurements. Achieving a perfect match between eight thermometers is very difficult. As illustrated in Fig. 2, the temperature variation over the whole profile was usually less than 1°C, so that small errors in thermometer readings or calibrations could produce relatively large errors in the overall estimate of the heat flux. Whatever the cause, it is still the case that

the inverse Lagrangian technique provided a robust and qualitatively correct estimate of the net heat flux from the canopy, in reasonably close agreement with independent measurements. This gives confidence in the analysis of sources and sinks of ammonia in the canopy presented by Harper et al. (2000), which relies on the same general approach.

5. Conclusions

The inverse Lagrangian dispersion analysis outlined here provided stable, qualitatively correct estimates of the net exchange of heat between canopy and atmosphere. The estimates were 21% higher than direct measurements of heat flux by eddy correlation, perhaps due to small systematic measurement or calibration errors in the thermometer array used to define the within-canopy temperature profiles. Both heat flux measurements showed the same diurnal trends and the correlation coefficient between them was 0.84.

Almost all the heat exchange between foliage and air occurred in the top half of the dense corn canopy which, overall, constituted a strong heat source. The bottom half was a very weak heat sink, virtually neutral in terms of the overall heat exchange. We conclude that Raupach's (1989b) analysis offers a robust and relatively simple measurement scheme for calculating scalar fluxes within plant canopies.

Fig. 6. Comparison of inverse Lagrangian and eddy correlation heat fluxes for all available data.

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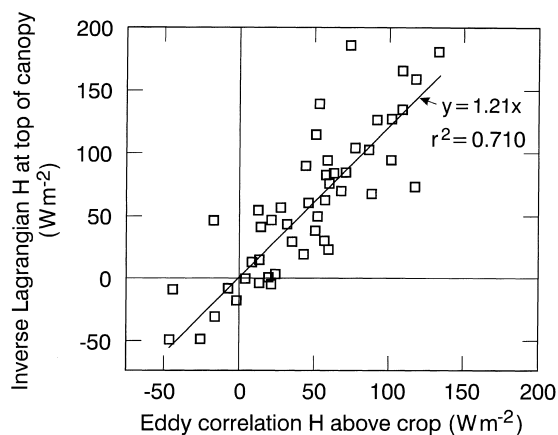inverse Lagrangian analysis. The senior author wishes to thank USDA-ARS and the Southern Piedmont Conservation Research Center, Watkinsville, GA, for hosting him during the study.

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