Turbulent diffusion within a wheat canopy:

II. Results and interpretation

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SUMMARY

The coefficient of turbulent diffusion was measured in a 1.25m tall wheat canopy using a uniform release of nitrous oxide, the energy and momentum balance methods, and the humidity profile. The nitrous oxide profile gave the most accurate values, $K_N$, in the lower two thirds of the canopy, and a regression of the energy balance estimates, $K_E$, against $K_N$ had a slope of $1.17 \pm 0.10$ with a non-significant intercept of $17 \text{cm}^2\text{s}^{-1}$.

The mean day time profile of $K_N$ was exponential, $K_N(z) = K(0) \exp(-y(1 - z/h))$ with $y = 3.9$ when $u(h) < 1.2 \text{m s}^{-1}$ increasing to 5.3 when $u(h) > 1.2 \text{m s}^{-1}$. But analysis of $K_N$ for the height interval 0.3 to 0.8m shows the importance of thermal stability, and the results are related to the non-dimensional stability parameter $2 \left( \frac{\Delta T/\Delta z}{(u(h)/h)^2} \right)$ where $\Delta T/\Delta z$ is the temperature gradient and $u(h)$ is the windspeed at crop height, $h$.

The large scatter in the results was attributed to the heterogeneity of the crop. Also the wind profile was frequently S-shaped defying a simple one-dimensional analysis and causing the momentum balance to give nonsensical results. Hence it seems unlikely that one-dimensional analysis of transfer can give values of $K$ allowing an accurate estimate of the source and sink distributions within a dense crop canopy.

1. INTRODUCTION

Air flow within and above crop canopies is three dimensional, but above crop surfaces it is often possible to assume horizontal uniformity and study the vertical transport of momentum, heat and water vapour in one dimension only (Deacon 1973). The assumption of horizontal uniformity is less likely to be valid within crops, but it has frequently been made so that the vertical distribution of the fluxes of water vapour, heat and carbon dioxide could be estimated. In all these studies the existence of a vertical coefficient of turbulent diffusion, $K$, is implied, and is commonly assumed to have the same numerical value for different entities. This simplification allows the transfer processes within the canopy to be considered one dimensionally, and provides a theoretical framework that can be applied to the movement of any gas or of small particles. Hence it is of value in studies of the energy balance and CO$_2$ uptake, and also of the movement and subsequent deposition of pollutants and airborne pathogens.

In this study $K$ is estimated by four different methods, including the release of nitrous oxide described in the first paper, and the most accurate results are used to explore the relationship between $K$ and the wind speed and thermal stability. Then the assumption of horizontal uniformity is checked by calculating the flux divergence of N$_2$O and CO$_2$ from the measured horizontal variations in concentration.

2. METHODS OF MEASURING THE COEFFICIENTS OF TURBULENT DIFFUSION

The profiles of eddy diffusivity were estimated simultaneously from the wind profile, the energy balance, the nitrous oxide profile and the water vapour profile (Figs. 1 and 2). Each value of $T$, $T_o$, and $Rn$ was an average of 11 readings, and each value of nitrous oxide concentration an average of 5 readings; one of the main sources of inaccuracy was the
Figure 1. Profiles measured on (a) 16 July 1969 10–11h and (b) 18 July 04–05h. a, foliage area density; $T$, air temperature; $e$, air humidity; $T_{eq}$, equivalent temperature ($T + e/e_0$); $R_n$, net radiation; $G$, soil heat flux; $c$, N$_2$O concentration; $u$, wind speed; $\tau$, shearing stress; $K$, turbulent diffusivity derived from the N$_2$O profile (O); energy balance ($\Delta$); momentum balance (+) and the Penman equation ($\theta$).

Figure 2. Profiles of $K$ for, (a) 10 July 1969 09–10h; (b) 13 July 13–14h; (c) 24 July 10–11h; (d) 17 July 23–24h; calculated from nitrous oxide profile (O), energy balance ($\Delta$), momentum balance (+) and Penman equation ($\theta$).
standard error of these means. It was always found that a smooth profile could be drawn
by eye within the error limits, so the slopes of the smooth curves were used for calculating $K$.
Estimates of error were made throughout, based on the accuracy of individual measurements.
For clarity the possible errors are not shown in Figs. 1 and 2, but are indicated in the
discussion. Some of the instruments were separated horizontally by as much as 30m, so
some differences in $K$ values may be caused by variation in crop density rather than by
instrumental or sampling errors. The accuracy depended on the height of measurement and
on the mean weather conditions, both of which are discussed for each method.

(a) Wind profile

The derivation of $K_M$ from the momentum balance was described by Uchijima and
Wright (1964) and Lemon and Wright (1969) who obtained the equation

$$K_M(z) = \frac{\tau(z)}{\rho u/dz} = \frac{\tau(h) - \int_z^h C_D a(z) u^2 dz}{\rho u/dz}$$

$$= \frac{\tau(h)}{\rho u/dz} \left(1 - \frac{\int_z^h a(z) u^2 dz}{\int_0^h a(z) u^2 dz}\right)$$

The main assumptions here are that the drag coefficients for leaves and stems are independent
of both wind speed and height. Thom (1971) avoided these assumptions by measuring the
drag coefficient of an artificial bean leaf at a variety of wind speeds and orientations in a
wind tunnel, then using these values in Eq. (1). For a bean canopy the leaf angle is almost
constant except at the top of the canopy, so Thom was able to assume a leaf angle of 23°
at all heights with some justification. Wheat would be more difficult as there are leaves at
all angles, and the leaf angles change with wind speed. For this study it was simply assumed
that $C_D$ was constant and Eq. (2) was used.

Before calculating $K_M$ within the canopy it is necessary to know the shearing stress
at the top of the canopy, and this was found from the wind profile. The form of the wind
profile above rough surfaces is well established (Deacon 1973) and for the daytime profiles
$u_*$ was derived from the log-linear approximation with $\phi_M = 1 + \alpha(z - d)/L$ where $\alpha = 2.5$,
and it was assumed that $K_M = K_H$ close to the crop surface (Swinbank and Dyer 1967).
The choice of $\alpha = 2.5$ makes $\phi_M$ agree to within 0.1 with the forms suggested by Dyer
and Hicks (1970) and Pruitt et al. (1973) for the range $0 \geq z/L \geq -0.2$. Putting $\alpha$ equal to
4.5, as suggested by Webb (1970), gives excellent agreement with the results of Pruitt et al.
for $0 \geq z/L \geq -0.04$ but differs greatly for $z/L \leq -0.06$.

The best values of $d$, $z_0$ and $u_*$ were found by an iterative procedure that minimized
the value of $(u(\text{observed}) - u(\text{fitted}))^2$. The values of $d$ and $z_0$ for 41 hours (Fig. 3) were all
obtained after the crop had reached its full height of 1.25m and show no dependence on
the wind speed. This is not surprising because the wheat stems were quite rigid, and although
the top leaves did stream in the wind their height was changed very little. There was,
however, an exceptionally close correlation between the fitted values of $d$ and $z_0$ (Fig. 4(a))
which indicates that the computer technique could usually adjust $d$ and $z_0$ to give a spuriously
good fitted profile. It was therefore decided to refit the profiles with $d$ fixed at its mean value
of 0.7m, and the resulting $z_0$ values (Fig. 4(b)) show a very slight decrease with increasing wind
speed.

The value of $d/h = 0.56$ is smaller than those found by many other workers, for
Figure 3. Zero plane displacement and roughness length as a function of wind speed in near neutral (○); stable (+, |L| < 33 m); and unstable (−, |L| < 33 m) conditions. With an east wind (△) there was only 30 m fetch.

Figure 4. (a) Computer fitted values of roughness length versus fitted values of zero plane displacement. (b) Computer fitted values of roughness length versus wind speed at crop height with d fixed at 0.70 m.

example 0.77 over beans and 0.60 over mature wheat (Monteith 1963); 0.66 to 0.90 over rice (Isobe 1964); 0.58 to 0.90 over maize (Maki 1969) and 0.76 over beans (Thom 1971). These wide differences are most probably related to the differing morphology, and a low value would be expected for wheat which has 0.3 m of thin stems and heads above the highest leaves at 0.95 m.

The value of \(z_0\) was 0.175 m, and \(z_0/h = 0.14\) is very close to 0.13 obtained by Tanner and Pelton (1960) from a survey of many different crops. Thom (1971) suggested that it is more realistic to represent the variation of \(z_0\) by \(z_0 = \lambda (h - d)\), and the value of \(\lambda\) of 0.31 found here for wheat is quite close to 0.36 found by Thom for beans.

Having found \(u_w, K_M\) can be calculated from \(k u_w (z - d)/(1 + a(z - d)/L)\) where the accuracy of \(K_M\) depends critically on the correct choice of \(d\). If \(d\) were wrong by only 0.2 m it would cause an error in \(u_w\), and \(K_M\) just above the crop would be wrong by 40%.

In very stable conditions the differential form of the wind profile was used with the stability parameter found by Pruitt et al. (1973)
\[ \phi_M = (1 + 16Ri)^{0.33} \quad Ri \leq 0.3 \]
\[ \phi_M = 1.8 \quad Ri > 0.3 \]

With very low wind speeds at night it was not possible to estimate \( d \) and the daytime value of \( d = 0.7 \) m was used.

![Graphs showing wind speed within the wheat canopy.](image)

**Figure 5.** Wind speed within the wheat canopy. (a) to (e) wind speed at 0.1, 0.3, 0.5, 0.75 and 1.00 m versus wind speed at crop height of 1.25 m. (f) Normalized wind profile.

Before calculating \( K_M \) within the canopy it is instructive to look at the shape of the wind profiles. Graphs of the wind speed at several heights within the canopy against the speed at the top of the crop (Fig. 5) show no systematic curvature, and there is no evidence of the canopy scaling at the top at high wind speeds as shown by Penman and Long (1960) for young wheat. Hence a normalized wind profile can be drawn (Fig. 5(f)), and it shows a rapid decrease in the upper half of the canopy and then a slight increase below this. This effect has also been reported by Oliver (1971) in a forest and Allen (1968) in a larch plantation. Wind profiles in maize that are almost constant with height in the lower half of the canopy have also been measured by Uchijima and Wright (1964), Lemon and Wright (1969) and A. Perrier (1967), though the last two papers show smoothed or theoretical profiles that miss the lowest measured value. E. R. Perrier *et al.* (1970) analysed wind measurements within a soybean canopy by a null hypothesis technique and found no difference in the fluid motion between adjacent heights.

One possible explanation of this is that wind blows through from the edge of the canopy. This may be true for forest stands with a small fetch, but the calculated pressure gradient required to maintain a wind speed of 0.1 to 0.2 m s\(^{-1}\) through a 100 m stand of wheat is more than an order of magnitude larger than could be caused by either the wind at the edge of the stand, or synoptic pressure gradients. It is also possible (Allen 1968)
that thin patches in the canopy allow a pressure pulse or a gust of wind to penetrate directly to the bottom of the canopy where momentum would be absorbed slowly because of the small leaf area density. Even without thin patches it is possible that occasional large eddies transfer momentum directly from the air above the canopy to the less dense zone near the bottom, and some of this momentum is then transported upwards and absorbed in the dense upper parts of the canopy. Some support for this comes from Isobe's (1972) measurements of the phase lag between wind fluctuations at two heights within a maize canopy. He found evidence that although very low frequency components (<0.04 Hz) were propagated downwards, frequencies between 0.04 and 0.2 Hz were propagated upwards.

There is need for more information about the mechanism of momentum transfer within dense canopies, but the theory that momentum is passed vertically downwards by small eddies is not always tenable. However Eq. (2) is based on this assumption, and as no other theory is available it was used to give $K_M$ within the canopy (Figs. 1 and 2). The values of $K_M$ above the crop were accurate within ±20%, most of the uncertainty being in the value of $d$. At night the possible errors were much larger because the wind speeds were low and the stability correction very large. In the upper third of the canopy $K_M$ decreases rapidly with depth, but it then apparently increases as the wind shear decreases to zero. For three of the daytime hours the $K_M$ profile in the upper third of the crop agrees well with estimates from the nitrous oxide profile and energy balance, but between 13 and 14h on 13 July the $K_M$ values were much smaller. Wind speeds were also very low in this hour (only 0.08 m s⁻¹ in the lower half of the canopy) so large errors may have been incurred by assuming that $C_p$ was constant with height.

(b) Energy balance

The energy balance was used to obtain $K_e$ within plant canopies by Uchijima (1962), Denmead (1964), Brown and Covey (1966), Inoue et al. (1968) and Impens (1970) who all used the equation

$$K_e = \frac{R_n - G - dB/dt}{\rho C_p (d(T + e/\gamma_0)/dz)} \quad (3)$$

where $dB/dt$ is the rate of change of energy stored in the air and plants below height $z$. Impens made an allowance for photosynthetic energy but this was not done in the present study. The energy storage term was important only at night, and the values of $(R_n - dB/dt)$ are shown by open circles (Fig. 1(b)). This method was subject to error near the top of the canopy where the slope of $T + e/\gamma_0$ was small and where there was frequently a lot of scatter (Fig. 1(a)), and also low down in the canopy where $(R_n - G)$ was small or negative.

When $(R_n - G - dB/dt)$ is zero Eq. (3) gives zero values for $K_e$ unless the equivalent temperature has a zero slope at the same height, and it is interesting to notice that this is almost true for both the day and night-time profiles. At night the uncertainty in $G$, which had values differing by 50% at two places in the field, makes accurate calculation of $K_e$ impossible. A careful assessment of the possible errors in $K_e$ during the day, however, showed that an accuracy of ±30% could usually be attained between heights of 0.5 and 1.0 m, and better was possible in ideal conditions of large $R_n$ and low wind speed.

(c) Nitrous oxide

The nitrous oxide method for calculating the turbulent diffusion coefficient is discussed fully in the first paper. It was shown that any decrease with height of $N_2O$ flux caused by inadequate fetch would give erroneously high values for $K_N$. However, there is no evidence
that this happened below 1.25 m (Figs. 1 and 2), and at this height the \( N_2O \) concentration was almost too small to measure. On most occasions the concentration profiles were very smooth making it possible to determine \( K_W \) within \( \pm 25\% \) in the lower half of the canopy increasing to \( \pm 30 \) to \( 40\% \) at 1.0 m. In very steady conditions the probable error was less than \( \pm 15\% \).

On no occasion was \( K_W \) observed to have a maximum value within the canopy during the day, although more than 80 profiles were examined. This is in contrast to the results of Druilhet et al. (1971) who found S-shaped profiles in maize by measuring the profile of thoron concentration, of Stewart and Lemon (1969) who found the same using the energy balance, and of Thom (1971) who found \( K_W \) to be almost constant with height in the upper half of a bean canopy. There is no doubt that such maxima could occur, and they were frequently found at night in this wheat crop (Figs. 1(b) and 2(d)), but these were in a layer that was thermally unstable beneath a very stable layer. Such extreme conditions rarely occur during the day. Druilhet published temperature profiles for the same hours as the \( K \) profiles, but the heights of the maxima do not appear to correlate well with levels of instability. Thom (1971) attributes the large \( K \) values within a bean canopy to the turbulence generated in the wakes of leaves. For small leaved crops wake turbulence would have too small an eddy size to have a major influence on \( K \), but it could be important in large leaved crops such as maize.

Gillespie and King (1971) measured S-shaped \( K \) profiles in a maize canopy at night by blotting the dew from leaves and estimating \( K_W \) from the water vapour fluxes and vapour pressure gradients; their results show the maxima and minima to coincide with unstable and stable layers. Gillespie (1971) measured the \( CO_2 \) profiles within the canopy at night and these also indicated large values of diffusivity in the lower half of the crop. In this experiment it was found that the \( CO_2 \) and \( N_2O \) profiles were the same shape at night confirming that the \( N_2O \) profile was not caused by an irregular distribution. It is unfortunate that the energy balance method was not more accurate at night, but there is a suggestion of a maximum value of \( K_E \) at 0.6 m for 04-05h 18 July (Fig. 1(b)).

\[(d) \ \text{Water vapour profile}\]

It is possible to calculate the transpiration from each layer of a canopy by using Monteith’s (1964) version of Penman’s combination formula (1948)

\[
E = \frac{\Delta (Rn(z_2) - Rn(z_1) - d(B(z_2) - B(z_1))dt)}{z_2 - z_1} + \frac{\rho C_p a(z)(e_s(T) - e)}{r_a \gamma_0 (1 + r_s/r_a)}
\]

(4)

By estimating the evaporation from the soil surface the water vapour flux can then be calculated for each height within the canopy, and \( K_W \) can be derived by dividing the flux by the vapour pressure gradient. Unfortunately no porometer was available so \( r_a \) had to be inferred from laboratory measurements of \( r_a \) as a function of light intensity.

It was found that \( E \) was not at all sensitive to the values of \( r_a \) so no measurements were made, instead Thom’s (1968) equation \( r_a = 1.84 (d^{-1} (\kappa D)^{-1/2}) \) was used with \( \kappa \) or \( D \) for heat or water vapour. For the hours shown (Figs. 1(a) and 2) \( E \) was changed by less than 10% if \( r_a \) was halved or doubled.

On a few occasions the vapour pressure had a maximum value at about 0.35 m above the soil surface (Fig. 1(a)) so the calculation was simplified by assuming the vapour flux to be zero at that height. The downward flux of water vapour into the soil was caused
by the temperature of the soil surface being below the dew point of the air in the canopy.

This method could not be used at night because the net radiation was too small, nor could it be used when the vapour pressure gradient was very small (e.g. 10–11h 24 July). For 10–11h 16 July $K_w$ agreed well with $K_e$, but for 9–10h 10 July and 13–14h 13 July the values of $K_w$ are too small. This was attributed to an underestimate of the evaporation near to the ground, and possibly to erroneous values of $r_s$. However, with a porometer this method could be improved to give accurate estimates of $K_w$, and would be even more valuable by indicating directly the vertical distribution of transpiration.

3. COMPARISON OF TURBULENT DIFFUSION OF NITROUS OXIDE AND ENERGY

Of the four methods of measuring $K$ that were discussed in section 2 only those from the energy balance and the nitrous oxide flux were reliable within the canopy, and so estimates from these two methods were compared. The night-time values were not used because the energy balance was very inaccurate. Initially 49 hours were chosen between 2 July when the crop had almost grown to its full height of 1.25m and 7 August when the leaves were drying. These hours were selected because:

(i) the nitrous oxide profiles were steady – sudden changes of wind speed produced irregular profiles and as the hourly means were an average of only five measurements these were rejected;

(ii) the net radiation above the crop was steady – large changes in net radiation caused scatter in the temperature and humidity profiles;

(iii) they included the widest possible ranges of radiation and wind speed. Unfortunately the energy balance was liable to have large errors when the slope of the equivalent temperature was small, and as $T_{eq}$ is closely linked with the wet bulb temperature a further 20 hours were rejected in which the wet bulb temperature changed by less than 2 deg C between 0.1 and 3.0m. For the remaining 29 hours $K$ was calculated by both methods for the heights of 0.6, 0.8 and 1.0m, the heights for which both were considered to be reliable (Fig. 6). The height of 0.4m could not be included because although $K_N$ was obtainable $K_e$ was frequently indeterminate and sometimes negative.

The line of best fit of $K_e$ against $K_N$ taking all the results together has a slope of 1.17 ±

![Figure 6. Comparison of $K$ measured from the nitrous oxide profile with values from the energy balance at heights of 0.6 (○) 0.8 (+) and 1.00m (○). Crop height was 1.25m.](image-url)
0.10 and a non-significant intercept of 17 cm² s⁻¹. This departure from unit slope is small compared with the scatter, and remarkably good considering that $K_E$ and $K_N$ contain independent errors of ±30%, and were measured at sites separated by 15 m.

However, the agreement between $K_E$ and $K_N$ was very much better at heights of 0.6 and 0.8 m, than at 1.0 m where the mean value of $K_E$ was 30% greater than the mean value of $K_N$, with $K_E$ sometimes more than double $K_N$. It seems very unlikely that $K_N$ could be too small, because any decrease of flux with height causes an overestimate. If the two diffusion coefficients are different it is probable that the ratio would be related to thermal stability as it is for momentum and heat above a crop, but no correlation could be found with the local Richardson number. Also an effect of stability should have been greater at 0.8 m where the wind shear was smaller, but this was not found. It is possible that the difference was caused by a variation in crop density between the two sites, but there is no direct evidence for this.

There have been very few attempts by other workers to compare the turbulent diffusion coefficients for different properties within crop canopies. Wright and Brown (1967) measured $K$ by both the momentum and energy balance methods and found that $K_E/K_N$ at the top of the canopy exceeded 2.0 for high wind speeds; they attributed this to experimental error. There are still no comparisons of any two $K$ values that show how differences might be related to the variations in stability or distribution of sources and sinks with height. Until this has been done $K$ profiles should not be used to estimate the distribution of photosynthesis within canopies.

4. The profile of the turbulent diffusion coefficient

The energy balance has been used to give $K_E$ in plant canopies of very different kinds –

![Figure 7](image_url)

Figure 7. (a) Mean values of $K_E$ within the canopy versus height; (b) Mean values of $K_{E,(z,a)}(z)/u(h)$ versus cumulative leaf area index for $u(h) < 0.8$ m s⁻¹ (+); 0.8 to 1.0 m s⁻¹ (○); 1.0 to 1.2 m s⁻¹ (△); and $> 1.2$ m s⁻¹ (□).
10 year old pinus radiata, height 5·5m (Denmead 1964); maize, height 2·5m (Uchijima et al. 1970; Brown and Covey 1966); sunflowers, height 2·3m (Impens 1970); and red clover, height 0·5m (Lemon 1965). All these workers found \( K \) to decrease rapidly with depth in the top of the canopy, and Lemon, Brown and Covey, and Uchijima et al. expressed \( K(z)/K(h) \) as an exponential function of \( z/h \) with an extinction coefficient, \( \gamma \), between 2·5 and 2·7. However, the results of Uchijima et al. show a scatter of approximately \( \pm 50\% \) and those of Lemon and Brown and Covey show a scatter of more than 100\% in the lower half of the canopy, so the exponential form has not been verified accurately.

For comparison the nitrous oxide results were divided into four groups with the wind speed at the top of the crop (a) \( < 0·8 \text{ m s}^{-1} \), (b) 0·8 to 1·0 m s\(^{-1}\), (c) 1·0 to 1·2 m s\(^{-1}\), and (d) \( > 1·2 \text{ m s}^{-1} \). Each profile was normalized with respect to \( K_M(h) \) derived from the wind profile above the crop. The profiles were approximately exponential (Fig. 7(a)) with an extinction coefficient of 3·9 for groups (a), (b) and (c) \( (u(h) < 1·2 \text{ m s}^{-1} ) \) and 5·3 for group (d) \( (u(h) \geq 1·2 \text{ m s}^{-1} ) \). These values are larger than those obtained by other workers, probably because of the large leaf area index of 5·6 compared with 2·7 to 4·9 for the maize canopy of Uchijima et al. and 3·7 for the maize canopy of Brown and Covey.

There have been several attempts to predict the shape of the \( K_M \) profile for idealized canopies; the leaf area density was assumed to be constant with height by Cionco (1965) and Cowan (1968), and both predicted exponential profiles. The leaf area density of our wheat crop was not constant with height, so these will not be considered here. One theory, however, changes the dependent variable from height, \( z \), to \( A \), the cumulative leaf area index measured downwards from the top of the canopy. Stewart and Lemon (1969) assume that \( u_A/u_A \equiv B \), is a constant with height, and so the momentum balance equation can be integrated giving

\[
u = u(h) \exp(-\gamma A)
\]

and

\[
K = \frac{B^2 u(h) \exp(-\gamma A)}{\gamma a(z)}
\]

where

\[
\gamma = C_D/2B^2
\]

Perrier (1967) obtained the same result by using a mixing length hypothesis with \( l = k'/a(z) \). It can easily be shown that this is the same as Stewart and Lemon’s assumption with \( k' = 2B^2/C_D \).

If this theory is valid \( \ln (Ka(z)/u(h)) \) should be a linear function of \( A \). This was certainly not true above 0·8m (Fig. 7(b)), and below 0·8m the wind profiles do not decrease exponentially with \( A \) so the theory is not valid at any height within this wheat canopy. This shows that the mixing length was not controlled by the leaf spacing alone.

Despite the unrealistic assumptions made by Cionco and by Cowan, the exponential equation gives the best fit for the mean \( K \) profiles. However, they ignore the wide variation between individual profiles caused by differing thermal stability.

5. Dependence of turbulent diffusion on wind speed and thermal stability

In section 4 the profile of \( K \) was considered to be a function of wind speed and foliage density or height only. However, it is well established that above rough surfaces \( K \) also depends on thermal stability, and it is very likely to be affected by stability within the canopy where the Richardson number can be very large.

If it is assumed that \( K \) can be expressed as a function of the energy dissipation rate
per unit mass of air, \( \varepsilon \), and a mixing length, \( l \), then dimensional analysis leads to the relation

\[
K^3 = \alpha l^4 \varepsilon
\]  

(7)

where \( \alpha \) is a dimensionless constant. For shear-engendered turbulence \( \varepsilon = \frac{1}{\rho} \frac{d(\tau u)}{dz} \) and when \( \tau \) is constant with height this gives \( K = \alpha l u^* \), the familiar equation for \( K \) above a rough surface in neutral stability. The constant \( \alpha l \) can be identified with \( k z \) where \( k \) is von Kármán's constant. Within a crop canopy the energy dissipation rate has an additional term caused by the turbulent wakes of the foliage and

\[
\varepsilon = \frac{1}{\rho} \frac{d(\tau u)}{dz} = \frac{\tau}{\rho} \frac{du}{dz} + \frac{u}{\rho} \frac{dz}{dz}.
\]  

(8)

These terms must be taken individually before substituting in Eq. (7) because they are likely to be associated with different mixing lengths. The first, \( \frac{\tau}{\rho} \frac{du}{dz} \), is caused by wind shear and gives \( \varepsilon = K \left( \frac{du}{dz} \right)^2 \) and hence \( K = \alpha_1 l_1^2 \frac{du}{dz} \). It was shown (Fig. 5) that the shape of the wind profile was independent of the wind speed, and so \( \frac{du}{dz} = \beta(z)u \) and \( K = \alpha_1 l_1 \beta(z) \). The second term, \( \frac{u}{\rho} \frac{dz}{dz} \), is caused by turbulent wakes and assuming a constant drag coefficient gives \( \varepsilon = C_d a(z) u^3 \) and hence \( K = \alpha_3 (C_d a(z))^2 l_2^4 u \). Assuming that the mixing lengths are independent of wind speed, both expressions for \( K \) can be written as \( K = \alpha l u \) where \( l \) has the dimensions of length and is likely to depend on both height and foliage density.

Above rough surfaces buoyancy effects are usually included by writing \( K = ku^* z/\phi \), where \( \phi \) is a function of the Richardson number. Within the canopy the Richardson number should include in the denominator the turbulent energy contributed by wake turbulence. However, the turbulent energy associated with both wind shear and wakes is approximately proportional to \( u^2 \), so the normal gradient Richardson number still applies, though perhaps with a different constant within \( \phi \).

To examine the relationship between \( K \) and the wind speed and temperature gradient the results for nitrous oxide were used. These were considered to be more accurate than those from the energy balance, especially low down in the canopy, and were also completely independent of \( u \) and \( dT/dz \), so there could be no spurious correlations. Of the 49 daytime hours used in section 3 the first 8 were rejected because the crop had not grown to its full height of 1.25m. For the remaining 41 hours it was found, fortuitously, that there was no correlation (at 5% level) between the temperature gradient at any height and the wind speed. The results showed that \( K \) at 1.0m was correlated (1% level) with the wind speed at the same height, but \( K \) at 0.8, 0.6 and 0.4m was not. The absence of any correlation between \( K \) and wind speed in the lower half of the canopy was unexpected, and as the 41 hours contained wind speeds varying by more than a factor of four the results do show that the wind speed is not the major factor affecting \( K \). However, at all heights \( K \) was negatively correlated with the temperature gradient at the same height (1% level at heights of 1.0, 0.8 and 0.6m, and 5% level at 0.4m), and this demonstrates the importance of buoyancy on turbulent mixing.

These correlations and a few simple regressions showed that there was still much scatter in \( K \) that could not be explained at all. This was probably caused, in part, by the horizontal heterogeneity of the crop, but also because the derivation of \( K \) from the slope is not very
Figure 8. Four different shapes of air temperature profile. (A) 18 July 1969 04-05h, unstable within canopy and stable above; (B) 16 July 16-17h, stable within and above canopy; (C) 14 July 08-09h, stable within canopy and unstable above; (D) 21 July 12-13h, unstable within and above canopy.

accurate, and because the temperature gradient often changed rapidly with height so that $dT/dz$ at one height was unlikely to be very meaningful. To improve this, an average value of $K_N$ was calculated for the height interval 0-3 to 0-8 m, and all hours in which the temperature gradient changed sign within this height interval were rejected. This left only 21 daytime hours, but 17 night hours were also included. As it was thought likely that the shape of the complete temperature profile might influence the turbulent mixing the hours were divided into four groups (Fig. 8) with temperature:

(A) having a minimum in the canopy but above 0-8 m;
(B) increasing steadily above 0-3 m and above the canopy;
(C) having a maximum within the canopy but above 0-8 m and
(D) decreasing steadily above 0-3 m and above the canopy.

Figure 9. Coefficient of turbulent diffusion measured with nitrous oxide for the height interval 0-3 to 0-8 m, in a wheat canopy 1-25 m tall, versus wind speed at the top of the canopy. A, B, C and D indicate the shape of the temperature profiles as defined in Fig. 8. Line drawn by eye.
The average $K_N$ values still show very little dependence on wind speed (Fig. 9), but if a line is drawn through the lower points it can be seen that the major departures from the line are group A at very low wind speeds and group D for higher wind speeds. The A group comes from clear nights with a temperature minimum near the top of the canopy and very unstable air within, and the D group come from daytime hours with instability throughout the canopy and above it – ideal conditions for large convective eddies.

It is required to find a stability correction corresponding to $\phi$ in the equation $K = K_{\text{neutral}}/\phi(R_i)$ for turbulent transport above the canopy. It was shown that for turbulence caused by wind shear and wakes $K$ is likely to have the form $K = \alpha u$ and, as $u(z)$ is linearly dependent on $u(h)$, this gives $K = \alpha u(h)/\phi(R_i)$. The gradient Richardson number is defined above rough surfaces as $R_i = \frac{g}{T} \frac{dT}{dz} \left( \frac{du}{dz} \right)^2$. In the lower half of the wheat canopy $du/dz$ is virtually zero so $u(h)/h$ was used instead, and for the height interval 0.3 to 0.8m $R_i$ was estimated from $R_{i*} = \frac{g(\Delta T/\Delta z)}{T(u(h)/h)^{2}}$. As $\phi$ is defined to be unity when $R_i = 0$ a graph of $u(h)/K_N$ against $R_i$ (Fig. 10) has an intercept of $1/\alpha l$ and a shape determined by $\phi(R_i)$. The dependence of $u(h)/K_N$ on stability is very obvious for the hours with a temperature profile of type A, and is also shown for the D profiles. Unfortunately there are insufficient hours to give $\phi_N$ in stable conditions, but the values are noticeably larger than $\phi_N$ for negative $R_i$, as would be expected.

The results for $R_i < 0$ are well fitted by the equation $u(h)/K_N(z) = \phi_N/(\alpha l) = (1 - \beta R_{i*}^\eta)/(\alpha l)$ with $\alpha l = 5-2$mm, $\beta = 0-9$ and $\eta = -2-9$. For comparison the functions $\phi_N$ obtained above rough surfaces for unstable conditions (Dyer and Hicks 1970) and $\phi_N$ for stable conditions (Pruitt et al. 1973) are also shown with the value of $u/K = 1-93$ when $R_i = 0$. The fact that $\phi_N$ is smaller than $\phi_N$ for large negative $R_i$ may be caused by the

![Figure 10. Stability function for turbulent transfer within the canopy with $R_{i*}$ defined as $g(\Delta T/\Delta z) / T(u(h)/h)^2$.

A, B, C, D and E indicate the shape of the temperature profile as defined in Fig. 8.](image)
difference in definition of $Ri$. It is known that $u(h)/h$ used here was larger than the almost zero values of $du/dz$ between 0.3 and 0.8 m, so $Ri^*$ was always an underestimate. Even in a more open canopy in which $du/dz$ can be measured accurately, however, $Ri$ would not correspond to values above the crop unless the mechanical energy input from wake turbulence were included in the denominator, and this could only be done if reliable estimates of the drag coefficients of individual leaves within the canopy were available.

The stability correction $\phi_u$ is smaller for the hours when the air was unstable both within and above the canopy, D, than when the unstable layer was beneath a stable layer, A. This demonstrates that $K$ is not determined only by the wind speed and temperature gradient at a single level, but also by the conditions at other heights. It may be that, for a profile of type D, turbulent energy is transferred downwards from the top of the canopy, or that a stable layer above an unstable layer (profile of type A) limits the size of buoyant eddies and decreases the effective mixing length. It is probable that an expression for $K(z)$ could be improved by using $K(h)$ rather than $u(h)$. This was not done because of the difficulty in estimating $K(h)$ on calm nights. For very unstable conditions the equation $K = a u(h) (1 - 0.9 R_i)^{2+\gamma}$ shows that $K$ decreases with increasing wind speed. This is demonstrated by the temperature profile of type A where the temperature gradient varied little from hour to hour but for very low wind speeds $K$ increased as $u$ decreased (Fig. 9). This is possible when the major cause of vertical transport is convection by large eddies which can be broken up by mechanical turbulence. A similar effect is found for some hot wire anemometers for wind speeds below 0.05 m s$^{-1}$ (Simmons 1949).

Combining the results from this section with the profile results of section 4 gives

$$K(z) = K(h) \exp(-\gamma(1- z/h)/(1- \beta R_i^*)^{\gamma}).$$

Further experiments are needed before this equation can be extended to allow for the effects of leaf area density, though it is possible that they could be included by making $\gamma$ a function of $a(z)$.

6. ERRORS CAUSED BY HETEROGENEITY OF THE CANOPY

In paper I it was shown that the flux of nitrous oxide at a height $z$ is given by the equation

$$F(z) = F(0) - z \left[ \frac{dc}{dt} + u \frac{\partial c}{\partial x} \right]$$

and so far both the terms in the brackets have been neglected. The first, $dc/dt$, represents the change with time of the amount of gas in the profile. Hourly averages have been used throughout, and it was found that $z dc/dt$ was always less than 0.01 of $F(0)$ for daytime hours, and 0.03 of $F(0)$ for night hours. The second term is caused by horizontal advection, and non-zero values of $\partial c/\partial x$ could be caused either by the finite size of the $N_2O$ distribution network, or by horizontal variations in crop density. Horizontal variations in crop density would also affect the wind flow causing non-zero values of vertical wind speed and $\partial u/\partial x$, but these were not investigated. The values of $\partial c/\partial x$ were measured, however, by placing five sampling tubes at a height of 0.7 m and separated horizontally by 2.5 m in an east-west direction.

For five days, 27 June to 1 July, the wind direction was almost always between 240° and 300°, and $N_2O$ was distributed from an area of 12 m radius, so the five samplers were distant 7.0, 9.5, 12, 14.5 and 17 m downwind from the start of the distribution area. In each of the 10 daytime and 8 night-time hours analysed the flux of nitrous oxide was $21 \times 10^{-8}$ m s$^{-1}$. 


It was found that there was no systematic increase in concentration with distance downwind (Fig. 11) showing that the N₂O profile had reached equilibrium to a height of 0·7m in a fetch of less than 7m. However, the sampler at 14·5m downwind measured significantly smaller concentrations than the others both in the day and at night. The error bars shown are the standard errors for the deviation of each concentration from the mean concentration at all five samplers. This irregularity could not have been caused by a non-uniform distribution of N₂O because the same effect is shown by the night-time CO₂ profiles (Fig. 11(c)). Nor was it caused by a faulty sampling line as the sampling tubes for 14·5 and 17·0 fetch were exchanged for 24 hours and the effect persisted. It is concluded that this variation was caused by the heterogeneity of the crop.

By applying the continuity equation, assuming \( \partial u / \partial x = \partial u / \partial y = \bar{w} = 0 \), it is possible to calculate the flux divergence. This was done for all the hours shown. For each hour four values of \( \partial c / \partial x \) were obtained from adjacent masts, and the mean of these was used with the mean horizontal wind speed to give the rate of change of vertical flux with height.

TABLE 1. Changes in the vertical fluxes of N₂O and CO₂ at a height of 0·7m caused by crop inhomogeneities

<table>
<thead>
<tr>
<th>Gas</th>
<th>Time</th>
<th>( \frac{\partial c}{\partial x} ) (vpm m⁻¹)</th>
<th>( u(70) ) (m s⁻¹)</th>
<th>( \partial (F(z))/\partial z ) (s⁻¹)</th>
<th>( F(z) ) (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O</td>
<td>Day</td>
<td>1·44</td>
<td>0·16</td>
<td>( 24 \times 10^{-8} )</td>
<td>( 21 \times 10^{-8} )</td>
</tr>
<tr>
<td>N₂O</td>
<td>Night</td>
<td>2·04</td>
<td>0·04</td>
<td>( 9 \times 10^{-8} )</td>
<td>( 21 \times 10^{-8} )</td>
</tr>
<tr>
<td>CO₂</td>
<td>Night</td>
<td>1·52</td>
<td>0·04</td>
<td>( 7 \times 10^{-8} )</td>
<td>( 11 \times 10^{-8} )</td>
</tr>
</tbody>
</table>
(Table 1). If this flux divergence exists at all heights in the crop any assumption of constant flux or one dimensional vertical transport is clearly invalid. However, it is possible that these values of flux divergence may be exaggerated. The divergence should be the mean of \( \nabla \cdot (cv) \) where \( c \) and \( v \) are instantaneous values. However, it is probable that \( c \) and \( v \) are negatively correlated, and using the mean scalar wind rather than the mean vector wind probably causes a further overestimate; also there is no evidence that such large horizontal variations of concentration exist at other heights in the canopy.

An estimate of the variation of crop density was obtained by collecting samples from 5 areas of 0.09 m\(^2\) (\( \sim 50 \) whole plants) selected at random. This was done on seven occasions, and the variation of fresh weight of the samples was found to be 22% whereas variation in crop height was only a few centimetres. It is unfortunate that the crop density was not measured in detail close to the five horizontally spaced samplers, but the canopy did appear a little less dense at a fetch of about 14 m and this was consistent with the lower concentrations measured there. It should be emphasized, however, that the canopy was exceptionally uniform by most agricultural standards, and in any future measurements of fluxes within canopies the possibility of horizontal divergence should not be ignored.

7. Conclusion

The results of this study cast serious doubts on the usefulness of the one-dimensional approach to turbulent transport within canopies. Measurements of the horizontal variation of CO\(_2\) and N\(_2\)O concentrations showed large heterogeneities, but were not conclusive as they were made at one height only, and it was not possible to measure the mean vector wind speed. Further experiments are essential to show how much variation in crop density is permissible before the horizontal flux divergence is comparable with the vertical flux.

Further doubts arise from the S-shaped or near constant wind profiles within the crop causing the momentum balance to give nonsensical results. A possible explanation is that some momentum is transferred directly to the bottom of the crop by occasional large eddies rather than being passed down by a succession of small ones. Because there are few leaves low down in the crop the momentum is absorbed slowly and some is transferred upwards to the denser part of the canopy. If large eddies are important the vertical transport of any property can no longer be specified as the product of a diffusion parameter \( K \) that depends only on the wind movement and the concentration gradient at one height, but must also depend on the shape of the concentration profile at other heights and on the distribution of sources and sinks. This effect would only be expected when the concentration gradient changes appreciably within the mixing length, so that \( \frac{dc}{dz} \lesssim l \).

In practice it was found that \( K \) measured independently for energy and nitrous oxide within the canopy agreed within about 40% and fluxes calculated from measured \( K \) values would not be more accurate. This is not accurate enough to allow the source and sink distributions to be derived by differentiating the flux profile, but may be useful in other studies.

The attempt to relate \( K \) within the canopy to the wind speed and temperature gradient shows the great importance of thermal stability; but there was much scatter about the fitted curve so equations for \( K \) must be used with caution.

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