植物群落内における運動量流束の消衰と光強度の消衰の関係

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A Study of the Extinction of Momentum Flux within Plant Communities from the Point of View of the Light Extinction*

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Abstract

Measurements of momentum flux in a wheat field have shown exponential profiles of the flux with depth from the top of the crop. The extinction coefficients of momentum flux have exceeded that of the isotropic scattered light. The results suggest that the extinction of momentum flux is rather closely related to a vertical projection area of the plant than to a horizontal projection area which accounts for the most part of the extinction coefficient of light. With introduction of the angle of attack of the momentum transport in place of the angle of incidence of light, the expression for the extinction coefficient of light is applied to the extinction of momentum flux. On this occasion an assumption is made that every part of the plant is a complete absorber of the momentum encountered. The local drag coefficient in plant communities is shown to be estimated from the extinction coefficient and the angle of attack. For the vertical leaf arrangement the local drag coefficient is independent of the angle of attack, while for the horizontal leaf arrangement the extinction coefficient is the case. The general trend is that the local drag coefficient decreases with the angle of attack, which is thought to be decreasing with turbulence intensity. For deformation of the plant in wind, presented is a simple modification of the expression of the coefficients, which gives results in fair agreement with those of the field experiment.

1. Introduction

In recent years there has been some interest in the way that the statistical properties of turbulence and the mean windspeed vary with height in plant communities. The interest has arisen from the meteorological inquiry to extend the profile study to the realistic circumstances. On the other hand, the study could contribute much to the matter production problem of plants in the real field. To date the approach to the problem by plant scientists has been to integrate their studies of individual leaves into production studies by plants. In their study of transfer of the matters related to production the boundary layer of an individual leaf is constructed in the same manner as in the aerodynamics of engineering problems. However, little attention has been given to interaction

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between the boundary layer of an individual leaf and the flow pattern of the surrounding air.

From the viewpoint of the build up of profiles above plant communities, which has been fairly extensively studied, the underlying plant layer produces only parameters that describe boundary conditions to the air flow. In this respect the profile study has stood aloof from an adequate understanding of the layers occupied by plants. Extension of the profile study to underlying plant communities has been first made on the mean windspeed. Some quantities have been introduced to express local characteristics of the plant layer, but they are yet to be qualified in the future physical works.

Apart from the well known bulk parameters, zero-plane displacement d and roughness parameter z_0, the surface drag coefficient is supposed to be first introduced in the plant layers. It describes the underlying plant layer on the whole. Some attempts were made on the variation of the coefficient with little reference to the underlying plant communities (Inoue 1955). The surface drag coefficient has not been effectively used since.

Application of energy balance technique has put forward a possibility to draw the profile of the apparent diffusivity in plant communities. The apparent diffusivity has also been studied with diffusion experiments. The results indicate that the diffusivity will be of wide application to the study of the layers occupied by plants. Some applications have already been made to estimate the vertical transfer of momentum, water vapour and carbon dioxide, which is of agronomic importance.

The geometrical study of plant communities was first initiated by ecologists. Their interest has been in the light-matter production relationship in plants. The vertical variation of light intensity in plant communities is fairly well studied and fitted in an exponential expression with leaf area index. The extinction coefficient in the exponential expression was studied mathematically in relation to the geometry of leaf arrangement (Isobe 1962 a, b and c). Since the light-leaf interaction is fairly clear-cut and tractable, the relation between geometry and light intensity is straightforward. On the contrary, the interaction between air motion and plants is the least known of the least understood turbulent motion. This has long provided consolation for frustrating analysis of the observational data on wind and relevant quantities. However, the recent inquiries, mostly observational, on the nature of transfer of matter and of its conversion in the plant communities have accumulated some information and brought about clues for solving the problem. The data are often divergent and conflicting with each other, but there is an observational evidence that appears to be convergent. It is that the exponential profile with the depth from the top of plant seems to be applicable to a quantity related to wind. As a matter of course the extinction coefficient of the exponential profile varies with many phases of plant environments on the whole. The present study is prompted by the observational evidence of Isobe (1965) that the momentum flux in a wheat vegetation is fairly well fitted to an exponential profile. Recent studies in wind tunnel, by comparison, appears to indicate that the windspeed in plant communities is deviated from the simple exponential profile, towards which the available theoretical study is directed. In the present paper analysis will be given principally on the extinction coefficient of momentum flux in plant commuities because in this matter one is more directly concerned with geometry and can take full advantage of the analysis of light extinction.

Before the analysis of wind proper is started, it may be as well to review briefly the formulation of the light extinction problem in considering its essential role in the present study. In order to simplify the problem one restricts consideration in the arrangement of leaves with a fixed angle to the vertical and vertical stems of perfect absorber of light. In the case the problem is reduced purely to the geometrical one. The following equation can be derived (Isobe 1962 a and b) for infinitesimal change, because of the presence of an element of LAI (dA) and of stem (dB), in the averaged light intensity transported in the direction (l, m, n)

$$|n|\ dI_{lmn}=-I_{lmn}\left[\int dA\ P_{zA}(\mathrm{a},\mathrm{b},\mathrm{c})\,|l\mathrm{a}+m\mathrm{b}+n\mathrm{c}|\,d\Omega\right.$$
$$\left.+\int dB\ P_{zB}(\alpha,\beta,\gamma)\{1-(\alpha l+\beta m+\gamma n)^2\}^{1/2}\ d\Omega\right], \qquad (1.1)$$

where l, m and n are direction cosines of transportation, P_{zA} (a, b, c) and P_{zB} (α, β, γ) are the probability desnsity functions of the distribution of leaves and stems on a plane at z, respectively. (a, b, c) and (α, β, γ) are vectors specifying the normal to the leaf and the axis of the stem, respectively. In consideration of the manner of the distribution of leaves and stems in the real field one can further simplify equation (1.1) by introducing the following distribution functions,

$$P_{zA}(\mathrm{a},\mathrm{b},\mathrm{c})=\frac{1}{2\pi}\delta(\mathrm{c}-\mathrm{c}_0) \qquad (1.2)$$

and

$$P_{zB}(\alpha,\beta,\gamma)=\delta(\gamma-1). \qquad (1.3)$$

Equations (1.2) and (1.3) reflect simply the fact that the stems are vertical and one is concerned with leaves of a fixed angle (c_0) with the vertical and symmetrical with respect to the axis of the stem. This model can simulate some types of plant communities, as shown in previous papers (Isobe 1962 a, b and c). Putting equations (1.2) and (1.3) into equation (1.1) and conducting integration with respect to Ω, one has

$$dI_{lmn}=-I_{lmn}\{dA\ K(\mathrm{c}_0,\Theta)+dB\tan\Theta\}, \qquad (1.4)$$

where

$$K(\mathrm{c}_0,\Theta)=\frac{2}{\pi}\{(\xi-\frac{\pi}{2})\cos\theta_0+\sin\xi\sin\theta_0\tan\Theta\}. \qquad (1.5)$$

And ξ satisfies the condition

$$\frac{\pi}{2}\leq\xi\leq\pi,$$
$$\cos\xi=-\cot\Theta\cot\theta_0.$$

In deriving these equations the random distribution of stems and leaves has been assumed both vertically and horizontally. Validity of the expression (1.4) is well verified in the study of the light extinction of natural plant communities. In previous papers (Isobe 1962 a, b and c), $K(\mathrm{c}_0,\Theta)$ has been extensively studied. However, little has been done on the second term in the brackets of (1.4), For later convenience some manipulation of (1. 4) is needed at this point. Introducing half of the surface area of a cylinder, B^*, one has

$$\frac{2}{\pi}B^*=B.$$

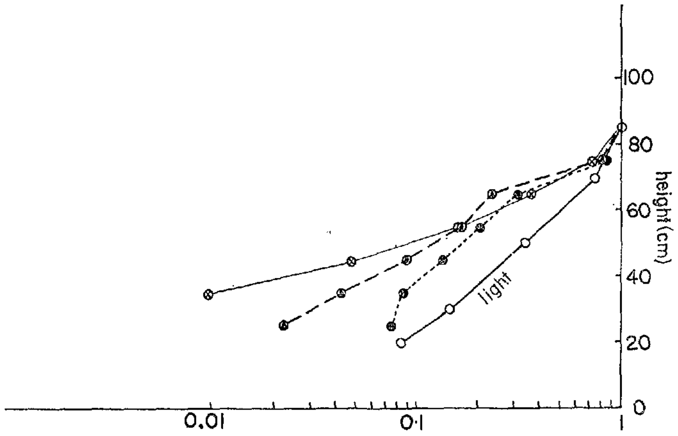
Thus (1. 4) can be rearranged in a more symmetrical form

$$dI_{lmn}=-I_{lmn}\{dA\,K(c_0,\Theta)+\frac{2}{\pi}dB^*\tan\Theta\}. \qquad (1.6)$$

For the incidence of the isotropic radiation, the apparent extinction coefficient is calculated by integration of equation (1. 6) and has been shown in Fig. 1 of Isobe (1962 c). The result has indicated that the apparent extinction coefficient decreases with leaf angle with unity for the leaves of horizontal habit.

2. A simple example of momentum extinction

In this section one shall demonstrate by detailed consideration of a relatively simple but general example that the vertical flux of momentum can be expressed in an exponential profile. First, observational examples of the exponential variation with the depth from the top of plants are presented in Fig. 1. The flux has been obtained by mutiplying the gradient of the mean windspeed by the diffusivity of water vapour. Each was averaged over ten minutes. They have been obtained in a wheat field with heads. Comparison of the vertical profiles of the normalized momentum fluxes and that of isotropically scattered light, which is calculated from equation (1. 4), readily submits the larger extinction coefficients for momentum flux than that for light. Since the horizontal intensity of light is a weighted mean of (1. 4) with cos Θ, the apparent extinction



Fig, 1 Profiles of normalized flux of momentum in a wheat field, compared with the profile of light intensity calulated for the isotropic scattered radiation.

coefficient is nearly in proportion to the horizontal projection area of plants. From equation (1.4) a conclusion follows that a very large extinction coefficient could result for light beams with a selected range of angles of incidence. Bearing this in mind one is drawn to investigation of the interaction of wind with plants. On average, the momentum of wind in plant communities is horizontal and parallel to the mean wind direction, so that one is tempted to think the absorption of momentum is in proportion to the vertical projection area. To show that this is almost the case, some relevant quantities are to be defined. It is highly plausible on the basis of diffusivities hitherto obtained that the air movement in plant communities is always turbulent so that the local velocity vector has the non-vanishing vertical component. A further discussion of the daunting difficult question how big space a vector represents is not atttempted at the present stage. However, one assumes simply the existence of a significantly large mass of air which can be represented by a velocity vector. The momentum of air motion in a unit volume ($\boldsymbol{p}$) is represented in the two dimensional space

$$\boldsymbol{p}=\rho(U+u', w'), \qquad (2.1)$$

where $U+u'$ and w' are the horizontal and the vertical velocity, respectively. The instanteneous vertical transfer τ_p of the horizontal momentum leads to

$$\tau_p=\rho(U+u')w'. \qquad (2.2)$$

One looks into the absorption of the momentum of the form (2.1) by a plane leaf expressed in dA (a, c). Since the momemtum density is expressed by $\boldsymbol{p}=\rho\boldsymbol{u}$ and the transfer velocity is $\boldsymbol{u}$, the transfer rate of momentum across unit surface area perpendicular to the direction of transportation is $(\boldsymbol{p}.\ \boldsymbol{u})$, where the round brackets denote the scaler product between two vectors. In terms of vector notation τ_p can be expressed by

$$\tau_p=(\boldsymbol{p}\cdot\boldsymbol{u})\boldsymbol{n}_p, \qquad (2.3)$$

where $\boldsymbol{n}_p$ denotes the unit vector parallel to $\boldsymbol{u}$. Provided that the leaf is a perfect absorber of the momentum of air movement, one can take advantage of the way of reasoning of the light extinction. It is to put (2.3) in equatipn (1.1) in place of I_{lmn}. Therefore, the extinction coefficient of τ_p is the same as that of light. On this occasion, it is noted that the definition of the extinction coefficient for the momentum flux (k_m) is somewhat different from that of light (K). Namely,

$$\frac{d\tau}{dz}=-k_m\,\tau \text{ for vertical momentum flux,}$$

and

$$\frac{dI}{dA}=-KI \text{ for light.}$$

However, on the ordinary occasion introduction of the density of LAI, $\frac{dA}{dz}$, is acceptable. One recalls that the problem of the light extinction has been dealt with under the condition that $\frac{dA}{dz}$ is bounded. Thus, it establishes a relationship

$$k_m=K\frac{dA}{dz}. \qquad (2.4)$$

The local drag coefficient c is defined in a similar manner to the resistance coefficient of the previous paper (Isobe 1965)

$$\frac{d\tau}{dz}=-\rho c\frac{dA}{dz}U^2. \tag{2.5}$$

Hence there is a relationship between the extinction coefficient and the local drag coefficient. For simplicity one is concerned for the time being with the case $U\gg u'$. Since the angle of incidence of light Θ corresponds to Θ_m defined by

$$\tan\Theta_m=\frac{U+u'}{w'},$$

it leads to

$$\tan\Theta_m\fallingdotseq\frac{U}{w'}. \tag{2.6}$$

Hereafter Θ_m is referred to as angle of attack in the paper. In contrast to angle of incidence of light, the angle of attack is a locally defined quantity. In the study of the light extinction one was able to trace the straight line of transportation, which enabled to replace the locally defined Θ by the angle of incidence on the crop surface. In the case of momentum transfer, however, the trajectory of an eddy is hardly found over a sufficient distance in the direction of transport, so that no attempt will be made to replace the local quantity by the one at the crop surface. With the aid of the angle of attack the relationship between the two coefficients is obtained: (2.2) and (2.6) lead to

$$\tau=\rho U^2\cot\Theta_m.$$

Using the equation defining k_m,

$$\rho k_m U^2\cot\Theta_m=\rho c\frac{dA}{dz}U^2.$$

Thus

$$k_m\cot\Theta_m=c\frac{dA}{dz}. \tag{2.7}$$

Some expressions of c are given for clearly defined arrangement of leaves. For the horizontal leaves $K=1$ so that $c=\cot\Theta_m$ and for the vertical leaves $K=\frac{2}{\pi}\tan\Theta$ so that $c=\frac{2}{\pi}$. In Fig. 2, $k_m\Big/\frac{dA}{dz}$ is illustrated and the figure is reproduced from the calculated results in previous papers (Isobe 1962 a, b and c). Equation (2.7) enables one to calculate the local drag coefficient from Fig. 2 and the result is illustrated in Fig. 3. In both the figures the contribution of the stem is neglected, since it does not have an essential influence on the results. A marked difference between the two figures is that the trends of variation of the coefficients with angle of attack are perfectly contrary to each other. Thus the smaller extinction coefficient yield the larger local drag coefficient and vice versa. What is the physical significance of this result ? The vertical flux of momentum with a large extinction coefficient cannot be transported over a long distance so that one may take that the situation under the condition in which large extinction coefficient prevails is essentially local and that the flow pattern is such that the local drag coefficient is as small as possible. The reverse case is that the extinction coefficient is small while the local drag coefficient is large. The flow pattern is therefore not determined locally. The consideration invokes a conclusion that locally determined flow in the plant commnity

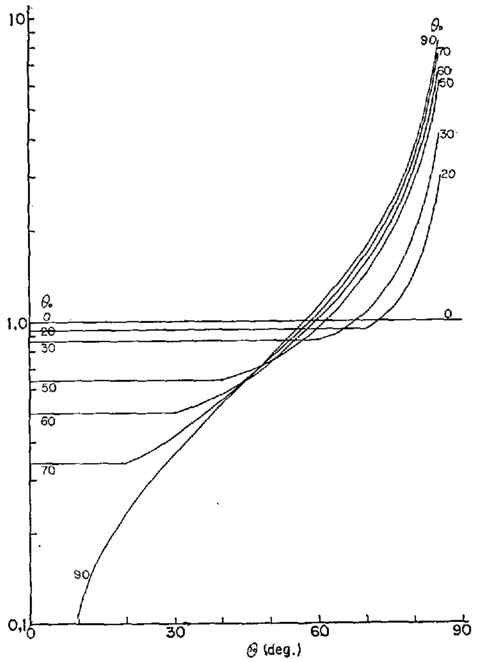


Fig. 2 Extinction coefficient as a function of angle of incidence Θ and of leaf angle θ_0

has a local drag caefficient as small as possible. Increase in the angle of attack towards 90° implies decrease in the vertical compoment of velocity in relation to the horizontal component. Hence the conclusion mentioned may almost be equal to that the local flow pattern retains its turbulence intensity as low as possible. Decreasing turbulence intensity with depth has been found in many types of crop field. The flow, in the light of the present investigation, may be approaching a locally determined flow. A constant mixing length with height has been the starting point of theoretical studies of turbulence in plant canopy (Inoue 1963 and Cionco 1965). This picture of the mixing length will be discussed, though briefly, in a later section.

So far, the formulation of the problem has been based on a plant commuity of rigid material. Moreover, little has been

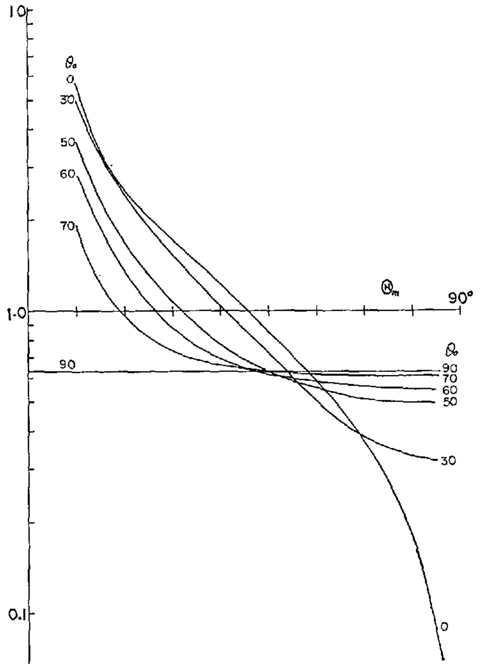


Fig. 3 Local drag coefficient as a function of angle of attack and of leaf angle.

done on the determination of Θ_m, which describes the turbulence characteristics of air motion. On this point any theoretical attempt is not pertinent to practical application. Therefore, one investigates the experimental results in the sequel.

First, one looks into the turbulence intensity in the light of the extinction and the local drag coefficient. To date there have appeared two categories of the manner in which the vertical distribution of the turbulence intensity is expressed. Nakagawa (1956) has provided an experimental evidence of the turbulence intensity constant with the depth of a rice field. Some theoretical inquiries have been followed with a view to supporting the result (Inoue 1963 and Cionco 1965). In these theoretical studies the main concern appears to describe turbulent state of the air movement in plant canopies with the use of a mixing length which is essentially constant with depth in a plant canopy with a uniform vertical leaf area density. They aimed directly at supplying the exponential expression of the mean windspeed in plant canopy so that the methods of reasoning were rather ad hoc. and the problem is still open to question. Uchijima and Wright (1963) has obtained a series of data showing a decreasing trend of the turbulence intensity with depth in a community of corn plants. There is a third possibility that the turbulence intensity increases with depth. This is often observed in real plant cammunities because of varying plant geometry with height.

In the reports referred to, the study of the geometrical structure of the plant communities concerned was not feasible to the workers. There are a few papers deailng with the method of specifying the geometry of natural plant communities (Isobe 1962 a and c, Philip 1965, Warren Wilson 1959, 1963 and 1965). However, the problem has much to be developed towards general use. At the present stage, one is restricted in a rather qualitative discussion. In Fig. 3, a constant local drag coefficient throughout the angle of attack is found for the leaves of vertical habit. On this occasion the turbulence intensity, which reflects the angle of attack, may not be related to variation of the local drag coefficient. On the other hand, the coefficient in the leaf arrangement of horizontal habit decreases rapidly with angle of attack, which could be related to decrease in the turbulence intensity. From the measurement of the velocity components and the diffusivity assessment, one is convinced that the air motion in plant communities is always turbulent. This leads to the time variation of the angle of attack. Since the flux means an averaged value over a sufficient long period, the practical and convenient way is to obtain an averaged value of Θ_m. On the way of a complete discussion of the problem there stands a question of daunting difficulty. This is to understond the complete properties of the turbulence in the plant canopy. Little knowledge has so far been provided on the turbulent properties in the plant canopy. Accodingly, one has to be confined in a rather intuitive discussion. In the case under discussion the downward transportation of momentum is under way on average so that averaged Θ_m is confined in $0 \leq \Theta_m \leq \frac{2}{\pi}$ A further discussion, including the case of flexible plants, will be given in the following section.

3. Momentum extinction in a flexible plant community

So far, one has been conerned with the plant community of rigid material. Natural plant communities are more or less flexible so that it is of importance to take the flexibility into account. The simplest way to do it is to introduce the velocity of the movement of plants. For the sake of simplicity, the horizontal velocity of plant displacement alone is considered. The relative velocity of wind to the moving plant is $\boldsymbol{u}-\boldsymbol{u}_p$, where u_p is the displacement velocity of the plant. Hence the absorption of momentum by plants is proportional to

$$(\boldsymbol{p}\cdot(\boldsymbol{u}-\boldsymbol{u}_p)). \tag{3.1}$$

The angle of attack Θ_{mp} is expressed by

$$\tan\Theta_{mp}=\frac{U+u'-u_p}{w'}. \tag{3.2}$$

Thus, one obtains a following relationship corresponding to (2.8)

$$k_{mp}\cot\Theta_m=c_p\frac{dA}{dz}\ , \tag{3.3}$$

where the symbols with suffix p denote that they are for flexible plant communities. Other relations are similarly modified

$$c_p=\cot\Theta_{mp} \text{ for the horizontal leaves,}$$
$$k_{mp}=\frac{2}{\pi}\tan\Theta_{mp}\frac{dA}{dz} \text{ for the vertical leaves.}$$

On usual occasions, when plant is displaced by the force of wind, $\boldsymbol{u}$ and $\boldsymbol{u}_p$ are in the same direction. If the turbulence is not affected by the movement of plant, decrease in the extinction coefficient and increase in the local drag coefficient result. However on special occasions, in which a sort of resonance occur, inverse phenomana could occur.

It should be noted here that the effect of displacement velocity of the plant on the pattern of extinction and local drag coefficients is to deviate them markedly from those of the rigid plant community. Even for the vertical leaves the local drag coefficient is variable with the displacement velocity. For the rigid vertical leaves the local drag coefficient has been independent of angle of attack. It is also important to notice that for the plant community whose relative geometry is retained as it is in the calm condition, the extinction and the local drag coefficients show a large variation with the displacement velocity.

For later convenience, an expression is given on the variation of the local drag coefficient for the vertical leaves. By use of equation (3.3), one has

$$c_p/c_0=1-\frac{u_p}{U},$$

where c_0 is the local drag coefficient for the rigid plants. One notices that equation (2.7) does not change its form and that Θ_m can be evaluated, provided that the extinction and the local drag coefficient are obtained experimentally. Naturally the angle of attack thus obtained is an average of the angles of various eddies. However, the averaged angle of attack could give a trend of variation of turbulence pattern with the depth.

4. Some experimental evidences

Comparisons of the formulation described with experimental results are made in the section. For the detailed procedure of the measurement reference should be made to a previous paper (Isobe 1965). Fig. 4 shows extinction coefficients of momentum flux in a wheat field against the flux at the top of the crop. A schematic illustration of an averaged wheat plant in Fig. 5 gives the geometrical structure of the field. The head has been of vertical cylinder with diameter of 9.8 mm and about 10cm long and awns of a few centimeters have extended upward. Planting density has been 0.06 per unit square centimeter. So that one has

$$\frac{dA}{dz}=60\times10^{-3}\mathrm{cm}^{-1}$$

The variation of $c\frac{dA}{dz}$, which was referred to as resistance coefficient in a previous paper, is reproduced in Fig. 6 from Isobe (1965). As can be seen in the figure, the coefficients change with the incident flux, which implies at the same time their variation with wind speed. Applying (2.7) to the head one has a resistance coefficient

$$36\times10^{-3}\mathrm{cm}^{-1}.$$

This value appears to be in fair agreement with that at h=70cm on the larger end of incident flux. The values are all smaller than that predicted in this manner. The reason is most probably that the plant is not a complete absorber of the momentum. This has been the case also in the light extinction. Comparison between Fig. 4 and 6 indicates existence of the vertical variation of turbulence structure with the depth and with the incident flux. Using relationships (3.2) and (3.3), preliminary attempts are made to evaluate vertical variations of turbulence structure in terms of angle of attack. Since equation (3.3) relates k_m to c with the help of Θ_m which is defined through turbulent

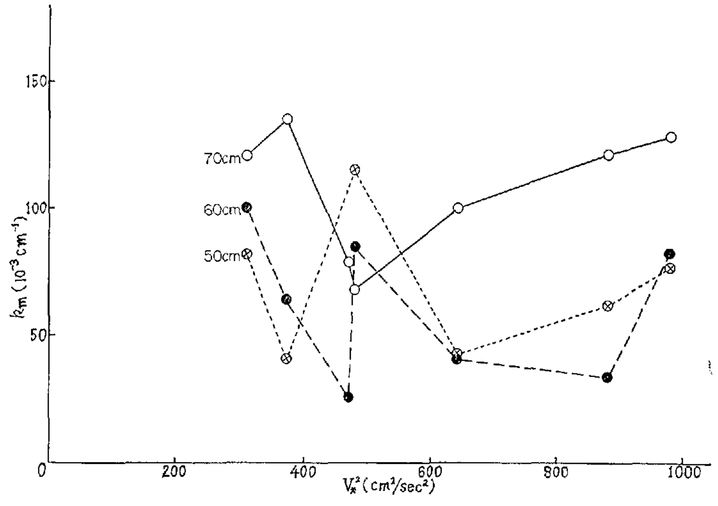


Fig. 4 Variation of extinction coefficients of momentum flux with V^2_*

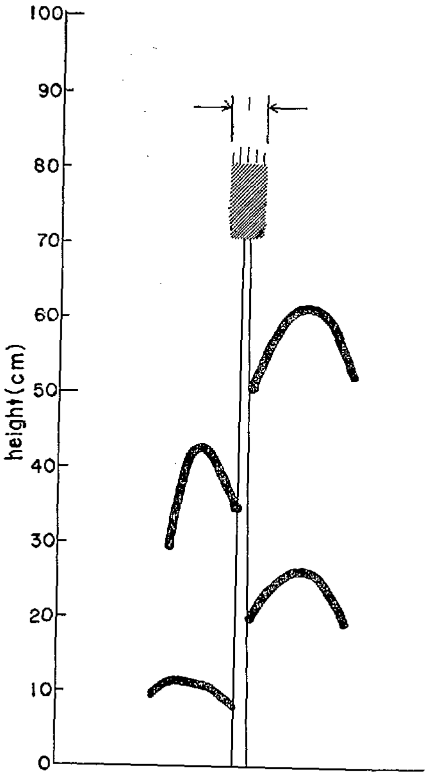


Fig. 5 Shematic illustration of an averaged plant from the wheat field.

fluctuation of veloicty, one is able to obtain an information of the turbulence in plant communities. Figs. 7 and 8 show some examples of the vertical profile of k_m/c. From these profiles it may be safe to conclude that turbulence intensity is decreasing with the depth in the wheat under study. This conclusion does not accord with those of Nakagawa (1956), Inoue (1963) and Cionco (1965), but with that of corn canopy by Uchijima and Wright (1963). The similar trend of the vertical variation of the turbulence intensity has been found in a lucerne stand, which will be published elsewhere. As has been mentioned in a former section this leads to a decreasing local drag coefficient with the depth. However, it is yet to be seen whether or not the results imply existence of a unique turbulence pattern, which determines a unique local drag coefficient. At this stage detailed discussion of the coefficient for the lower height will not be undertaken because specification of the leaf arrangement especially of the leaf angle is rather difficult and this makes evaluation too complicated.

With the aid of Fig. 6, some numerical examples of the plant displacement speed u_p are tabulated in table 4. 1. The values of table 4. 1 suggest, when one considers the mean

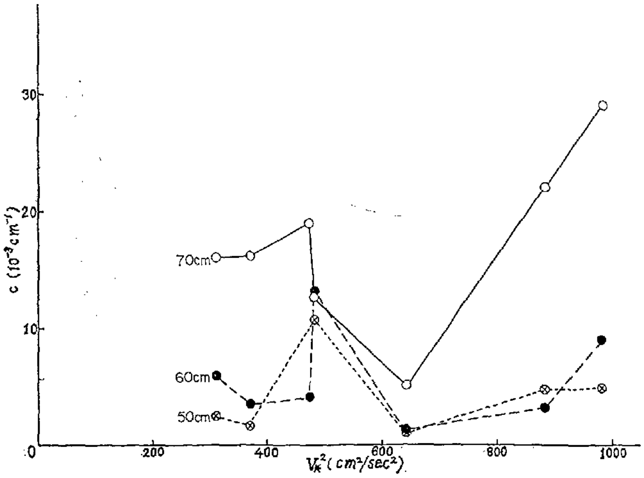


Fig. 6 Plot of $c\dfrac{dA}{dz}$ against V^2_*.

Table 4.1 Estimates of the displacement velocity of wheat heads

$\frac{\tau}{\rho}$ cm²/sec²	U cm/sec	u_p cm/sec
480	48	31
640	83	71
980	49	9

wind velocity, that the deformation does not depend exclusively on the mean wind velocity. This is suggestive that there could be effects of resonance of the plants. The wind tunnel study of vibration of rice plant by Hitaka, which will be published elsewhere, has confirmed the existence of resonance frequencies of vibration.

In the present context the study of transport of a physical entity in simple artificial plant communities is most desirable and one can take advantage of results of Chamberlain (1966) to assist the present method of analysis. Fig. 9 has been drawn from Table 8 of Chamberlain. The extinction coefficient of Thorium-B deposit with height is about 200×10^{-3}cm^{-1}. On the other hand, from the artificial grass arrangement made from PVC

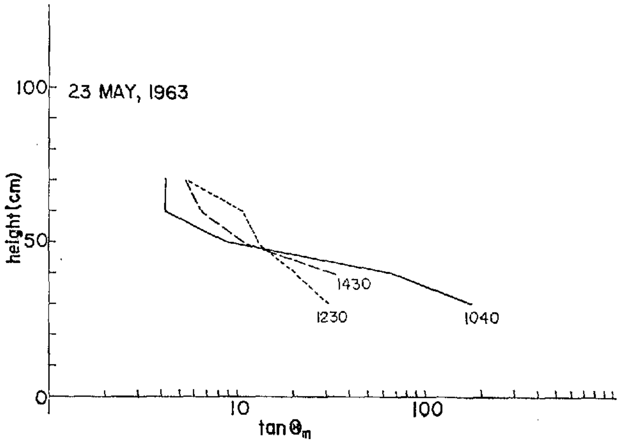


Fig. 7 Profiles of tan θ_m

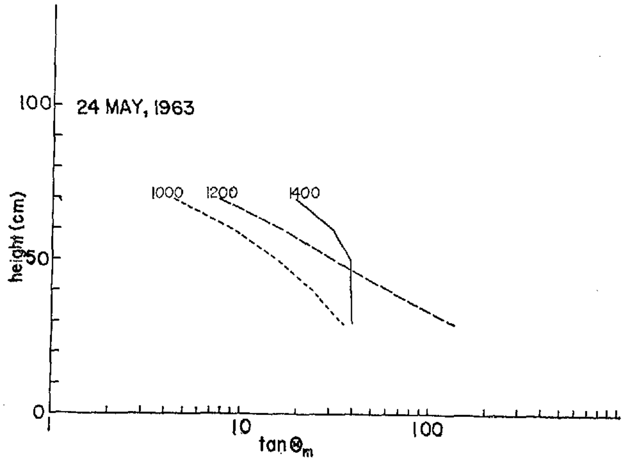


Fig. 8 Profiles of tan θ_m

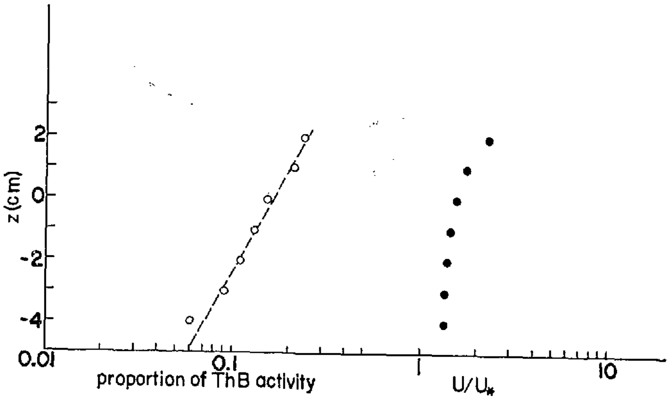


Fig. 9 Wind speed, and active deposit, as a function of height (above zero plane) within stand of artificial grass (Chamberlain 1966).

strips (oriented edge on, face on and in each of the directions making 45° to the direction of wind flow, on average one strip per 1.8cm^2 of substrate), one obtains an extinction coefficient

$$k_m=200\times10^{-3}\tan\Theta_m$$

So that one has $\Theta_m=\frac{\pi}{4}$ throughout the depth. The PVC strips fluttered rather vigorously in the wind, which might couterbalance the increase in Θ_m with the depth. From the figure it is understood that the profile of the mean wind speed is not a simple exponential.

5. Discussion

In the present study any conventional investigation of turbulence has not been attempted. To those familiar with the experimental literature on turbulent flow it may be convenient to look into the relation of the turbulence study in plant canopy to the present approach.

Studies of air flow in vegetation have been mainly concerned with the mean windspeed profile, which seems to converge upon a simple exponential expression. The direction of the studies has been towards obtaining relationships between extinction coefficient in the exponential expression, mixing length and friction coefficient. However, recent data of the wind profile in modelled study of wind in vegetation by Chamberlain (1966) and Plate and Quraishi (1965) have witnessed that there is deviation from a simple exponential profile with depth even in the well defined geometry of model grasses. They imply that the exponent in the wind profile expression is decreasing with depth. This is probably associated with the vertical varition of the turbulence pattern, which may be conflicting with the basic physical pictures of the theoretical studies.

Dissipation of kinetic energy of wind in the wheat field has been mainly due to interaction with plants (Isobe 1965). The mixing length may be connected with the extinction coefficient. Smaller extinction coefficient corresponds to longer mixing length. From the context of the present study the mixing length constant throughout the depth of a plant community is established for a turbulence structure constant with depth. This type of turbulence pattern is not favoured in the light of the local drag coefficient studied. However, the problem of a specific turbulence pattern in plant communities is left to be done in future works.

Most of the relationships in section 3 have been derived on the assumtion $U \gg u'$. This is often not the case in the field condition. In the formulation described this neglect could lead to underestimation of the local drag coefficient. The underestimation could be counterbalanced by the overestimation resulting from the assumption of complete absorption of momentum by plants. However, it is not known to what extent this counterbalancing effect works.

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植物群落内における運動量流束の消衰と光強度の消衰の関係

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麦畑内部の拡散係数と風速の垂直分布の測定から運動量流束の垂直分布が求められた。この分布は高さについて指数曲線となることがわかった。この曲線の消衰係数は葉の分布から計算される等方的散乱光強度の消衰係数よりもはるかに大きいことが示された。散乱光の消衰係数はほぼ植物体の水平面射影面積に比例する。光消衰の研究から垂直な葉に入射角の大きな光が入射する場合の消衰係数は極めて大きなものになることがわかっている。この場合消衰係数は植物体の垂直射影面積に比例する。

植物群落内の風は平均として水平に吹くから風については植物体の垂直な射影面積が関係するということが考えられる。この場合当然消衰係数は水平射影面積に関係する光の消衰係数よりも大きくなる。上に述べた測定結果はこの様な性質をもっている。従って光消衰の方法を運動量の流束に適用することを考える。最も簡単な方法は瞬間的な運動量流束を光の光線と同様に考えることである。こうすると運動量流束の消衰係数は光のそれと同様に計算することが出来る。当然光の入射角に対応して運動量の衝突角が定義される。一般には運動量衝突角の分布は水平方向に大きいので消衰係数は光よりも大きくなる。

今まで群落内の風の問題には抵抗係数で取扱われて来たので，局所的な抵抗係数を定義すればこれは消衰係数から計算によって求められることが得られた。消衰係数と抵抗係数とを比較してみると衝突角に対する変化がちょうど反対になっている。すなわち抵抗係数は角度とともに減少するのに対して，消衰係数は角度が大きいほど大きい，例外は水平な葉に対する消衰係数及び垂直な葉に対する抵抗係数で角度によらず一定である。この2つの係数が角度に対して正反対に動くということはつぎのように解釈される。すなわち，消衰係数が大きければ上下の流れは小さくなるので群落の各部分の風はかなり独立になって来る。このとき抵抗係数は小さくなる。逆に消衰係数が小さいと各部分の風は互に関係し大きな抵抗係数を生ずる。このような観点から現在までの乱れの強度の測定結果が論ぜられた。

以上のことは風が当っても動かない剛体の群落を考えたが，風が当って変形する場合には上の方法を若干修正する必要がある。最も簡単に植物体が風によってその方向に速度をもつ場合を考えた。結果は剛体の場合に角度によらず一定な抵抗係数をもつ垂直な葉でも風との相対速度によって抵抗係数が変化する。これらの結論を麦畑で得られた測定値に適用してよい一致が得られた。麦が光消衰の場合のように完全な運動量の吸収体ではないことも示された。