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The Physics of Application

From p173

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DEPOSITION AND PENETRATION OF SPRAYS

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INTRODUCTION

Considering the fact that only a small part of the spray chemical reaches the target and contributes to the biological effect, every effort should be made to develop and adopt application techniques in order to increase the percentage of the chemical which is collected on the biological target. Because of considerable differences in the structure of plants, the properties of the chemical and the application method, more knowledge is needed of the behaviour of droplets when penetrating through crop canopies and settling on the target. Much has been investigated in the past but still more information will become necessary, to give recommendations for optimized procedures considering the different conditions for field and orchard applications.

Such an optimization should enable one to reduce the amount of chemical applied per unit area, and that would mean lower costs and fewer unwanted side effects like drift or ground contamination. The considerable progress which has been made in the development of spraying machines during recent years, particular in the accuracy of the distribution has led to expectations for a better efficiency of spraying procedures. Such efficiency could be defined either as a reduction in the time needed for an application, or as a reduction in the amount of chemical necessary for an operation. The following considerations deal with the latter point, and will contribute to a better understanding of the settlement and penetration of sprays.

CONSIDERATIONS ON DISTRIBUTION

Generally speaking, the biological success of a chemical applied for plant protection purposes depends on the degree and accuracy of the coverage of the biological target.

In principle, there are two possible ways to improve or increase the probability of achieving the desired deposition, redistribution and penetration of sprays:

1. Uniform mass distribution of the approaching spray before reaching the target itself.

2. Specific adjustments of the spray characteristics according to the nature of the target and of the pest or disease itself.

A more uniform distribution can be realised by various technical means like nozzle function, pressure control, constant concentration of the chemical in the spray, correct nozzle distance to the target etc. Specific adjustments of the spray properties mean the adaptation of the spray characteristics according to the biological target i.e. droplet size, droplet movement and direction of the movement, droplet guidance etc. Such a specific adjustment could also lead to the reduction of losses by drift and losses on the ground.

DROPLET SIZE

Some fundamental concepts may be demonstrated by the following graphs. Fig. 1 shows the correlation between droplet size and retention on two different plants according to Bengtsson (1961). Principally smaller droplets will increase the retention particularly on cereals, using water solutions. The correlation will differ if oil is used instead of water as a carrier.

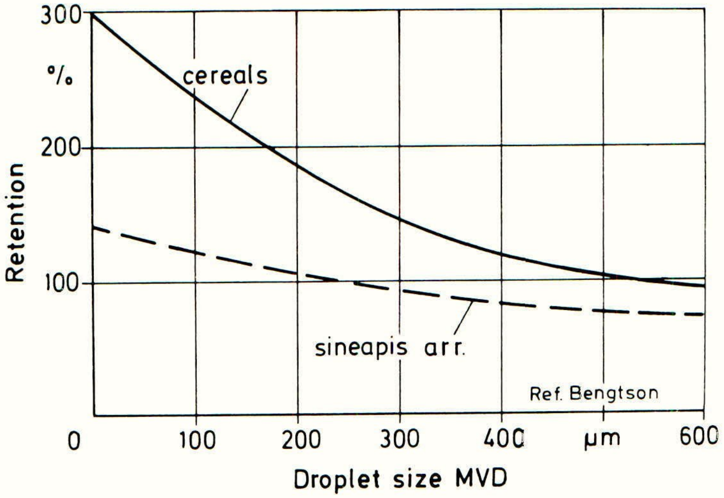

Fig. 1 The dependence of retention on the droplet size (Water solution)

Other investigations on Kohlrabi and cucumber plants showed an increase in coverage of up to 200% with 32 l/ha and an average droplet size of 100 µm compared to 320 l/ha. with an average droplet size of 100 µm (Bau, 1980).

The influence of droplet size generally becomes still more important when the biological target is on the underside of a leaf. Fig. 2 shows a general relationship between coverage on the undersides of leaves and droplet size, and demonstrates in particular that droplets below 100 µm are able to reach such targets.

Another general observation is the change of the average droplet size of a spray cloud whilst penetrating through a plant canopy such as cereals or maize. The tendency of such an effect in cereals is shown in Fig. 3. The bigger droplets settle mainly at the upper part of a plant structure. This effect becomes still more pronounced when using an additional air carrier stream.

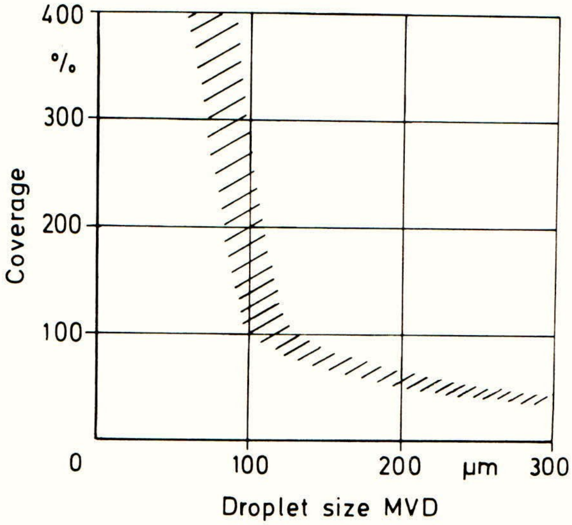

Fig. 2. The dependence of coverage on the undersides of leaves on the droplet size

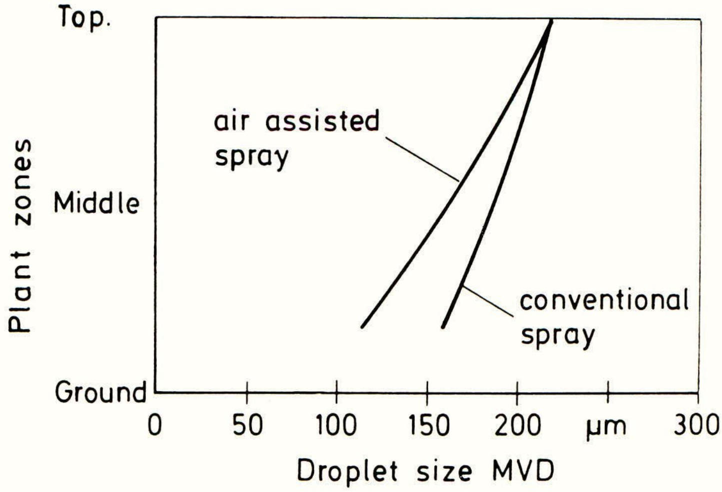

Fig. 3. The change of droplet size with the penetration depth

Another recent measurement shows the change of the average droplet size of a spray above a cereal plant compared with the penetrated and settled spray close to the ground (Fig. 4).

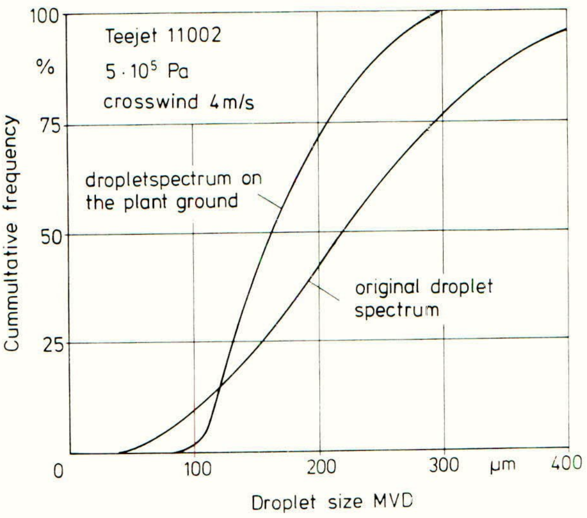

Fig. 4. Cumulative frequency of a droplet spectrum versus average droplet size for a measurement above and on the ground beneath a cereal plant (artificial plants)

Factors influencing the droplet size at the nozzle itself are not a point of discussion in this paper, but one observation should be mentioned briefly, namely the change of droplet size by evaporation during movement through the air. Fig. 5 shows the cumulative frequency as a function of the droplet size for different temperatures, relative humidities and dropfalls. The curves show a reduction of droplet size during a 2 m fall from 80 µm MVD to 35 µm MVD when the temperature is 25°C and the relative humidity is 45% (Göhlich, 1983).

COVERAGE

The degree of coverage of the target by the spray normally decreases with the depth of the penetration in a crop. Fig. 6 compares qualitatively the coverage of a conventional spray with that of an electrostatic charged spray. Electrostatic charging results primarily in a greater deposition of the droplets on the upper layer of the plants. Consequently the lower layer shows less deposit compared to uncharged application.

Similar results are obtained when the spray is assisted by air and guided towards the plant structure, for instance by an air foil. Fig. 7 shows the principle and design of an air foil boom with a double profile. The difference of the coverage in the upper layer is mainly caused by the acceleration of smaller droplets, Fig. 8. The difference becomes more obvious when a crosswind is influencing the spray. Fig. 9 demonstrates the effect of a crosswind on the penetration of a spray.

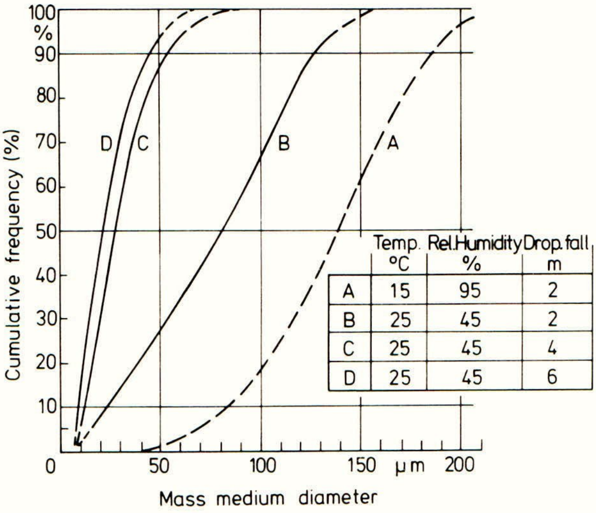

Fig. 5. The change in droplet size distribution due to evaporation, measured under different climatic conditions. Droplet generation by means of a spinning disc

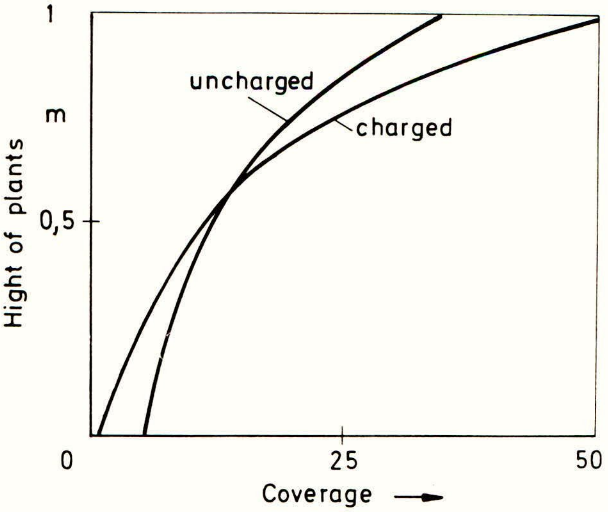

Fig. 6. The effectiveness of electrostatic charged spray on the coverage in field crops

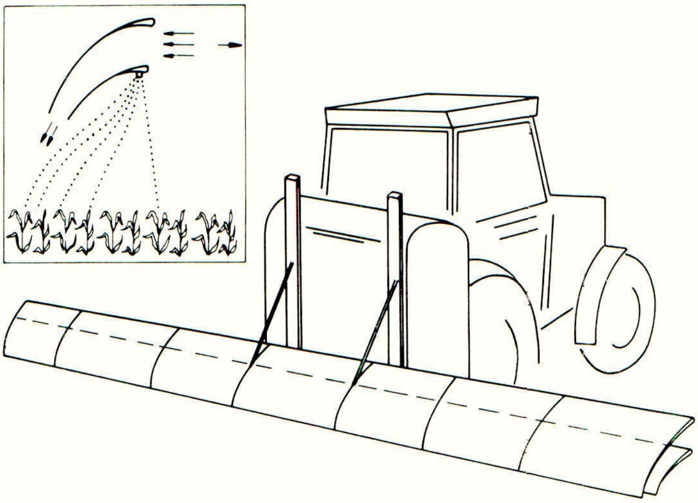

Fig. 7. Principle and design of an air foil boom

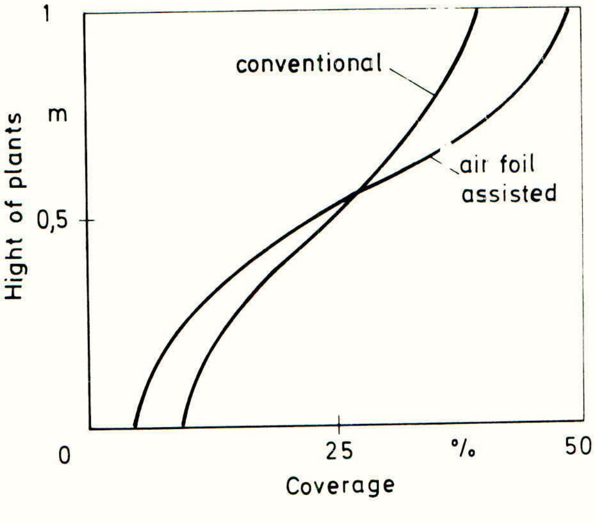

Fig. 8. The effectiveness of air foil assisted sprays on the coverage in field crops (2 m/s crosswind)

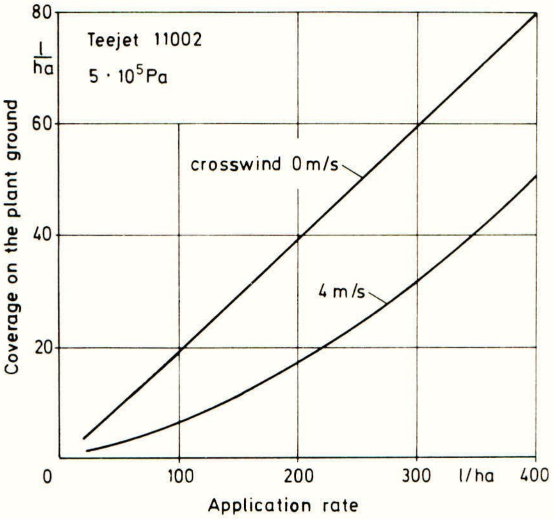

Fig. 9. Effect of crosswind on the penetration (artificial plants)

The effect of an air foil boom is once more given in Fig. 10. The coverage on the ground beneath a crop is less than that obtained without using the air foil assistance, because the retention of the droplets on the plants is increased by the additional air turbulence, created by the air foil.

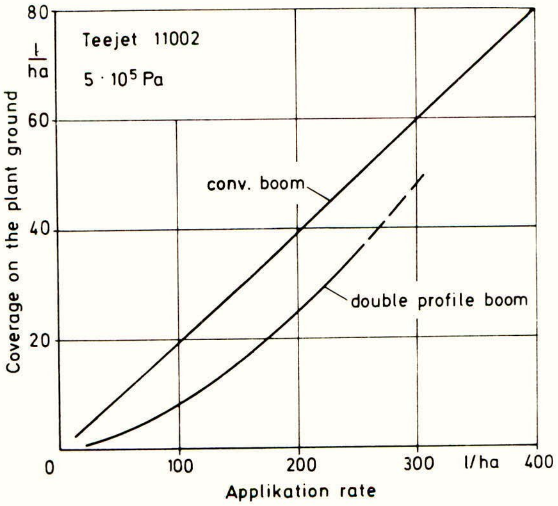

Fig. 10. Effect of air foil boom on the ground coverage (artificial plants)

DRIFT

Drift arises primarily when airborne droplets are influenced by the natural wind. Fig. 11 gives an impression of how airborne droplets react behind the spray boom. It compares the spray haze development when the spraying nozzle is driven at different forward speeds. The measurements were made at a laboratory test stand. The visible length and density of the spray cloud are approximately proportional to the forward speed. Fig. 12 shows the upper boundary layer of the spray haze at different speeds. From the increasing length of spray cloud one can easily recognise the growing drift hazard (Göhlich and Selcan, 1982).

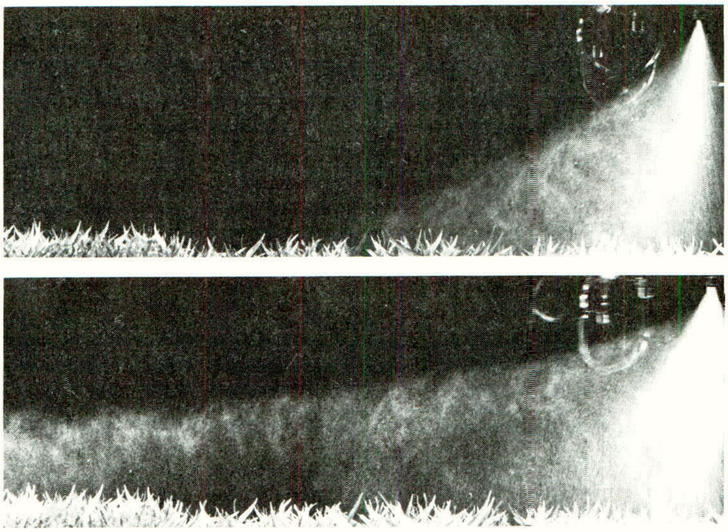

Fig. 11 Spray haze from a flat-jet nozzle when operating with 5 km/h (above) or 10 km/h (below)

The drift effect represents another criterion of the effectiveness of an air foil. Fig. 13 shows the difference in the spray deposit one meter beside the original spray path, when using an air foil device. These results are quite remarkable because the shifted spray is almost 3 times as much compared to a double profile boom when applying a crosswind of 4 m/s. Fig. 13 also demonstrates the relative inefficiency of a single profile boom. Aerodynamic investigations have proved that only a double profile is able to create a sufficient assistance in penetration of a spray.

Drift represents a loss of chemical and implies the danger of air pollution. The most critical problems in that way are created by the various blower sprayers, such as spraying machines for orchard and similar crops (Göhlich, 1979). It is not the topic of this paper to deal with drift problems. However, one remark may be given on the design of blower sprayers. The guidance of air is one important way to reduce drift, particular of blower sprayers. Two new blower designs have been found capable of reducing drift to a considerable extent, and simultaneously improving the effective deposit. Fig. 14 gives results of deposit measurements in vineyards, using a blower sprayer with a special air guidance. The results show the best deposit of sprays in vineyards when directing the air stream 45° backwards and when applying a terminal air speed of 6-8 m/s.

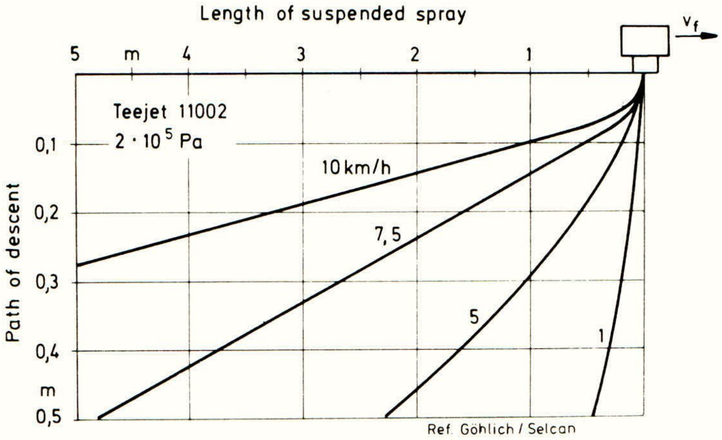

Fig. 12. Distribution of droplets in a spray cloud when sprayer is operated at different driving speeds

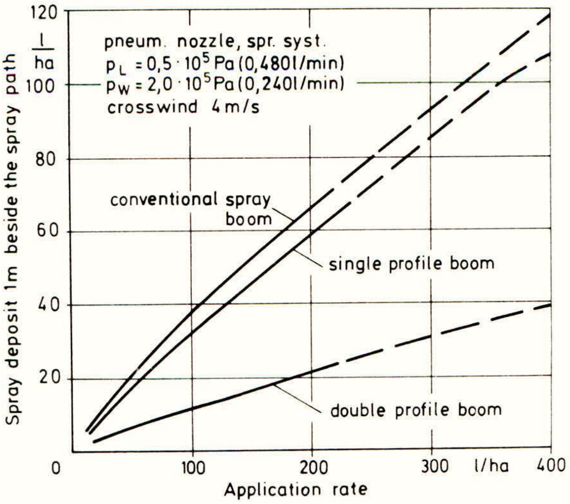

Fig. 13. The effect of an air foil boom on the drift

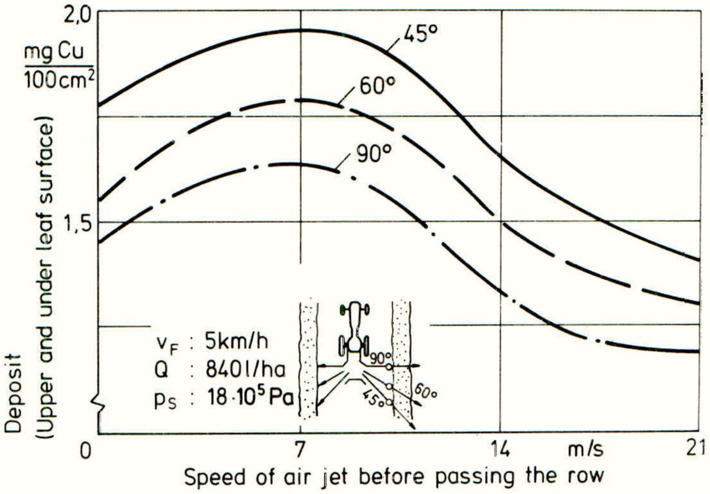

Fig. 14. Effectiveness of blower speed on the deposit of a chemical applied in grape vines

CONCLUSIONS

Deposit, retention and penetration of spray droplets represent a complex system with numerous unknown parameters involved. More research is needed to learn more details and their influence on the whole system. However the present state of knowledge already allows more specific developments and adjustments for improved techniques in plant protection.

Such developments may be primarily directed towards a reduction of chemical applied per unit area and toward a reduction of losses of chemicals, which includes drift as well as losses on the ground. New techniques which contribute in producing efficient droplet spectra as well as in better droplet guidance on their way to the biological target may be helpful approaches toward a better application and biological efficiency of chemicals.

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PREDICTION AND ANALYSIS OF SPRAY PENETRATION INTO PLANT CANOPIES

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ABSTRACT

A simple, but theoretically rigorous mathematical model, based on solutions of the mass transport equations is described - this allowing estimates to be made of the vertical distribution of sprays into plant canopies. The calculation scheme, which can be applied to a programmable calculator with a limited memory capacity, is illustrated by a design example. Discussion is presented on the general difficulties which are faced in forecasting and analysing the vertical distribution of spray.

INTRODUCTION

Of the many operational requirements in crop protection, the specification of the dosage is particularily important. Though doses are commonly quoted on an area base e.g. ι/ha (ground area), they are also quoted in terms of deposition on biological targets within the crop e.g. droplets/ cm^2 (foliage area). The relationship between the two depends on the location of the biological target and on vertical distribution of the spray cloud within the crop.

Though there have been many experimental studies examining the canopy penetration of sprays e.g. Smith and Burt (1970), there has been little effort to relate the findings to theory. From a theoretical viewpoint, the problem of predicting or analysing the vertical distribution of spray droplets is exceedingly complex and to some extent intractable. A simplified approach was proposed by Bache and Uk (1975) and developed by Bache (1979a, 1979b). These studies provide an analytical framework for obtaining rough estimates of the deposition pattern. Further progress (Bache, 1984) allows the mathematical procedures developed in previous analysis to be adapted to a programmable calculator with limited memory capacity; accuracy is retained-in so far as it exists!

The present paper outlines the analytical scheme and demonstrates its use for predicting or analysing the vertical distribution within the canopy; it also identifies some of the basic difficulties raised by this form of analysis.

ANALYTICAL SCHEME

Consider a uniform horizontal distribution of droplets drifting with the wind and transported downwards by turbulent diffusion and sedimentation. On coming into contact with the foliage canopy, droplets are trapped, filtered out and the airborne concentration reduced. The resultant vertical distribution - such as shown in Fig. 1 - depends on a balance between the rate at which material is trapped and the rate of vertical transport.

Vertical transport if often specified by the bulk deposition velocity, v_g, which when mutliplied by the local airborne concentration c i.e. $v_g c$ specifies the mass flux per unit area.

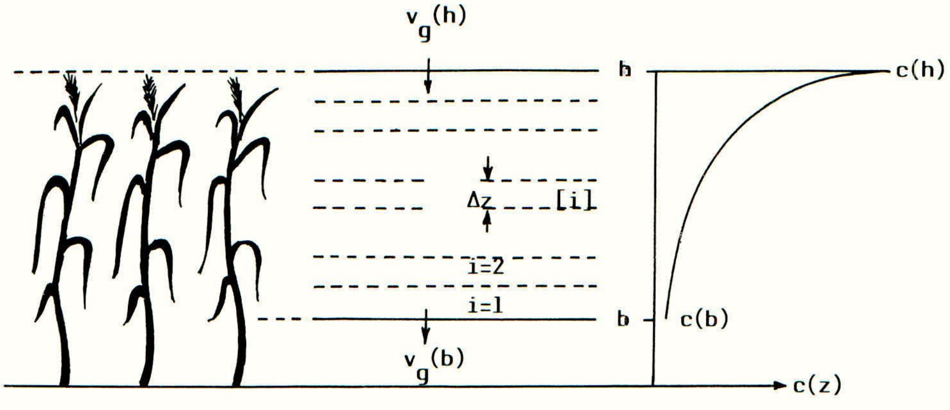

Fig. 1. Schematic representation of an absorbing region and the airborne concentration distribution c(z) in the height interval (b,h), subdivided into segments of width Δz for use in iterative scheme shown in Fig. 2. Terms $v_g(h)$ and $v_g(b)$ scale the vertical flux at heights h and b respectively.

Material is trapped by a number of mechanisms of which sedimentation and inertial impaction are generally the most important. Their effect was reviewed by Bache (1980) and can be specified by an absorption coefficient, β, which indicates the loss of airborne concentration per unit distance. When sedimentation is dominant $\beta = f_x\rho$ where ρ is the foliage area per unit volume (the trapping surface) and f_x a structure coefficient indicating the proportion of the foliage facing upwards. When sedimentation is negligible and the cloud of droplets is blown horizontally the amount of material trapped is specified by $\beta = E_i\ f_z\rho$ where f_z is structural coefficient giving the vertical projection of the foliage area. E_i is the impaction coefficient whose magnitude lies in the range 0 → 1 and can be roughly specified by

$$E_i = S^2/(S + 0.6)^2 \qquad (1)$$

where

$$S = \rho_p u d_p^{\,2}/(18\rho_a \nu\lambda) \qquad (2)$$

In Eq. 2 ρ_p and ρ_a are the density of the particle and air respectively, d_p is the particle diameter, u is the wind speed and λ, a characteristic dimension taken as the smallest dimension of a single leaf (or stem) when projected on a plane normal to the wind direction.

When both impaction and sedimentation are significant Bache (1979a) suggested that β might be evaluated by

$$\beta = f_x\rho \sin\vartheta + E_i\ f_z\rho \cos\vartheta \qquad (3)$$

where $\tan\vartheta = v_s/\bar{u}$ defines the potential angular trajectory in conditions of low wind speed, v_s referring to the sedimentation velocity.

Using these concepts Bache (1979b) showed that the vertical flux across the absorbing layer can be specified by the expression:

$$v_h = \frac{(m^2 - \delta^2)\tanh m(h - b) + v_b\ (m - \delta \tanh m(h - b))}{(v_b + \delta)\tanh m(h - b) + m} \qquad (4)$$

and the concentration variation with height is given by

$$c(z)/c(b) = e^{-\delta(z-b)} \{\cosh m(z-b) + ((v_b + \delta)/m) \sinh m(z-b)\} \qquad (5)$$

in these expressions

$$v_h = (v_g(h) - v_s)/K(h) \qquad v_b = (v_g(b) - v_s)/K(b) \qquad (6a,\ 6b)$$

$$m = \sqrt{(\delta^2 - g_R)} \qquad \delta = f_R/2 \qquad (6c,\ 6d)$$

$$\text{where } f_R = \frac{v_s}{K_R} + \frac{1}{K_R}\left(\frac{dK}{dz}\right)_R - \beta_R \sin \vartheta \qquad (7)$$

$$\text{and} \quad g = -\frac{\beta_R}{K_R}\sqrt{(u_R{}^2 + v_s{}^2)} \qquad (8)$$

The subscript 'R' refers to a representative position in the interval (b,h) at which the respective parameters are evaluated. If the layer is sufficiently shallow then it is reasonable to select the representative position as the mid-point of the absorbing zone i.e. $z_R = (h + b)/2$. The term β is defined by Eq. (3), and the only parameters requiring further definition are u and K. Wind speeds may be specified by

$$u(z) = (u_*/k) \ln((z-d)/z_0)) \text{ for } z \geqslant h \qquad (9)$$

$$\text{and } u(z) = u(h) \exp(-\alpha\ (1-z/h)) \text{ for } z \leqslant h \qquad (10)$$

In Eq. 9, u_* is the friction velocity (roughly 1/10x wind speed above the crop); k is von Karman's constant (= 0.4); d is the zero plane displacement and z_0 the roughness length. In Eq. 10, α is a velocity attenuation coefficient (dependent on the foliage density) and h refers to the canopy height.

In a canopy in which foliage is uniformly distributed with height, the diffusivity can be roughly specified by

$$K(z) = K(h) \exp(-\alpha\ (1-z/h)) \text{ for } z \leqslant h \qquad (11)$$

$$\text{where } K(h) = ku_*\ (h - d) \qquad (12)$$

With the above definition of K, Eq. (7) can be written

$$f_R = v_s/K_R + \alpha/h - \beta_R \sin \vartheta \qquad (13)$$

To use this model, the canopy is divided into a number of shallow layers within which Eqs. (4)-(5) may be applied. To predict the concentration profile through the canopy we first evaluate Eqs (4)-(5) at the lower boundary and proceed iteratively to $b + \Delta z$, $b + 2\Delta z$ and so on until we reach h and obtain the value c(h). The iterative scheme is summarised in Fig. 2. To start the procedure, values c(b) and v_b must be specified in advance. In most instances it is convenient to select $v_b = 0$; the reasons are discussed by Bache (1979b). The value c(b) = 1 is arbitrary, but is also convenient since which $c(h) \propto c(b)$ (see Bache, 1984). If we want c(h) to take some specified value e.g. c_0 we simple multiply all the concentration values (including c(b) = 1) by $c_0/c(h)$.

WORKED EXAMPLES

To illustrate use of the iterative scheme, analysis will be based on data collected in a dense cotton canopy whose aerodynamic behaviour was described by Bache and Unsworth (1977). Analysis will focus on the vertical

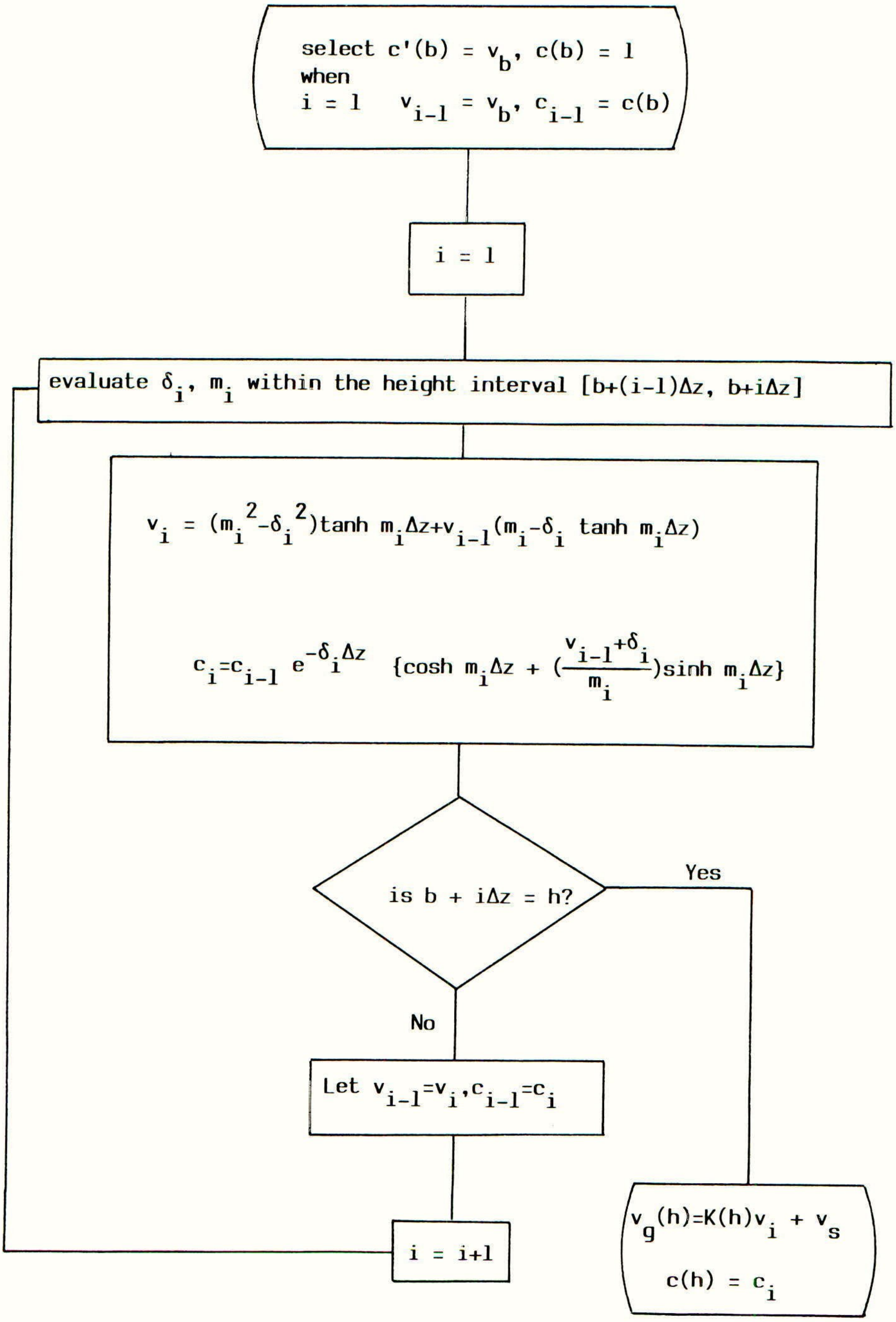

Fig. 2. Solution procedure based on Eqs (4)-(8) for evaluating the deposition velocity and concentration profile across an absorbing layer.

distribution of droplets having diameter d_p = 80 µm, as described by Bache and Uk (1975). Representative input data may be listed as follows:

Aerodynamic parameters: $u_* = 0.3$ ms^{-1}; $d/h = 0.75$; $z_o/h = 0.05$; $\alpha = 5.7$

Crop structure: $h = 1.2$ m; $b = 0.2$ m (canopy base); $\rho = 6.4$ m^2 m^{-3};

$f_z = 0.32$; $f_x = 0.85$; $\lambda = 0.05$ m

Droplets: $d_p = 80$ µm; $\rho_p = 1000$ kg m^{-3}; $v_s = 0.165$ m s^{-1}

Air properties: $\rho_a = 1.2$ kg m^{-3}; $\nu = 0.151 \times 10^{-4}$ m^2 s^{-1}

Iterative scheme: 5 layer; $\Delta z = 0.2$ m; $v_b = 0$; $c(b) = 1$; (K and u values are determined by Eqs. (9)-(10) respectively at the mid-height of successive layers)

TABLE 1

Value of key parameters during iteration for d_p = 80 µm, u_* = 0.3 m s^{-1} and data cited in the text

z (m) (1)	v_i (m^{-1}) (2)	c_i (3)	$v_g(z)$ (ms^{-1}) (4)	$c(z)/c(h)$ (5)	$\frac{v_g(z)\,c(z)}{v_g(h)\,c(h)}$ (6)
1.2	3.19	98.2	0.280	1.00	1.00
1.0	3.99	49.9	0.221	0.51	0.40
0.8	4.86	21.9	0.191	0.22	0.15
0.6	5.24	8.2	0.176	0.08	0.05
0.4	5.36	2.9	0.169	0.03	0.02
0.2	0.00	1.0	0.165	0.01	0.01

Table 1 shows the variation of the key parameters v_i and c_i during iteration, the subscript (i) referring to height z. The term $v_g(z)$ is of the same form as Eqs 6(a) and 6(b) i.e. $v_g(z) = K(z)\, v_i + v_s$. Column (5) of Table 1 shows the variation of the concentration ratio $c(z)/c(h)$ throughout the canopy. It is seen that the airborne concentration is rapidly reduced in the upper layers and penetration is difficult. Data within the upper 0.8 m of the canopy can be roughly fitted by the empirical expression:

$$c(z)/c(h) = \exp(-\,\gamma\,(1 - z/h)) \qquad (14)$$

with $\gamma = 4.0$; this compares favourably with the value $\gamma = 4.8$ based on measurements for corresponding conditions (see Bache and Uk, 1975).

TABLE 2

Fraction of airborne droplet concentration at the canopy mid-depth as a function of droplet size and friction velocity

friction velocity	diameter (µm)					
(m s^{-1})	20	30	50	80	150	200
0.1	0.22	0.14	0.08	0.05	0.04	0.04
0.3	0.39	0.26	0.14	0.08	0.05	0.04
0.5	0.48	0.33	0.19	0.10	0.05	0.04

To illustrate the significance of wind-speed, Table 2 shows the dependence of the concentration ratio at the mid-height z = 0.6 m on the droplet size and friction velocity. It is seen that when $d_p \gtrsim 100$ μm the concentration ratio varies little with droplet size or wind-speed - the distribution approaching the limiting form shown by Eq. (14) with $\gamma = f_z \rho = 0.85 \times 6.4 = 5.4$ m-1. For $d_p \lesssim 100$ μm the penetration improves with decreasing droplet size and increasing wind-speed.

Column (6) Table 1 shows the height dependence of the vertical flux ratio $v_g(z)\ c(z)/(v_g(h)\ c(h))$. This is seen to follow, more or less, the same trend as the ratio $c(z)/c(h)$ - due to the relatively small change in the ratio $v_g(z)/v_g(h)$ throughout the canopy depth.

The flux profile is of major importance because it allows one to deduce the deposition pattern i.e. the number of droplets /cm^2 (foliage). For example in the height interval 1.0 to 1.2 m (Table 1), a proportion 1.0 - 0.4 (= 0.6) 'disappears' from the vertical flux due to deposition. To estimate the concentration of the deposit we need to know the foliage area per unit ground area in the selected height interval. For the quoted conditions it is 6.4/5 = 1.28 (per 0.2 m). Thus if there are 100 droplets/cm^2 in this size range, the expected deposit will be 0.6 x 100/1.28 = 46.9 droplets/cm^2. Table 3 shows the fractional losses of vertical flux for a range of droplet sizes at various height intervals. Also shown is the ground flux ratio - consistent with the vertical flux through the lowest boundary i.e. z = 0.2 m. As was evident in Table 2, it is seen that deposition at lower depths increases with decreasing droplet size.

TABLE 3

Distribution of the deposition flux/incident flux ratio as a function of particule size, $u_* = 0.3\ ms^{-1}$ and data quoted within the text

		Deposited flux/Incident flux (= 1.0)				
Droplet diameter (μm)		20	30	50	80	150
Height range (m)	1.0 - 1.2	0.348	0.416	0.511	0.599	0.690
	0.8 - 1.0	0.272	0.283	0.275	0.249	0.207
	0.6 - 0.8	0.188	0.168	0.133	0.099	0.069
	0.4 - 0.6	0.109	0.082	0.053	0.035	0.022
	0.2 - 0.4	0.051	0.033	0.018	0.012	0.008
Ground flux/ Incident flux		0.032	0.018	0.010	0.006	0.004

To make full use of the data shown in Table 3 it is necessary to supplement it with information about the droplet spectrum - such as shown below

d_p (μm)	<25	25-35	35-65	64-125	>125
fraction of droplet numbers	0.24	0.28	0.36	0.11	0.01

From this the deposited fraction of the incident flux of all droplet sizes in the height interval 1.0 to 1.2 m is estimated by the summation (0.24 x 0.348 + 0.28 x 0.416 + 0.36 x 0.511 + 0.11 x 0.599 + 0.01 x 0.690)/1.28 = 0.357. Similar calculations apply at lower levels with the exception of the ground deposit (at which the area index is unity). The resultant trend based on an incident flux of 100 droplets/cm^2 is shown in Fig. 3. Fig. 3 also shows a deposition distribution for a canopy of lower leaf area density (characterised by $\rho = 4.0$ m^2 m^{-3}, $\alpha = 3$, $d/h = 0.7$, $z_0 = 0.4(h - d)$ all other parameters remaining identical to those of the previous example).

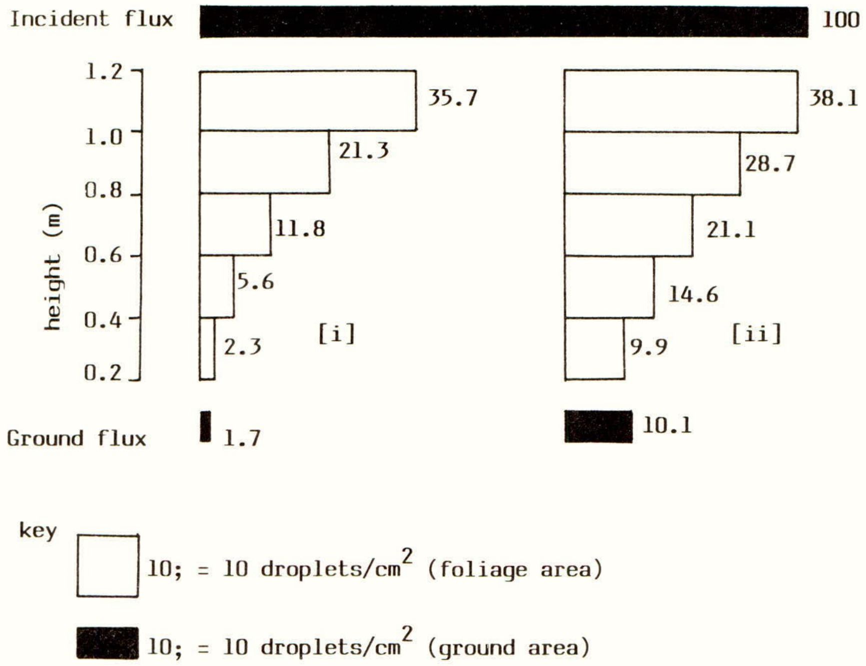

Fig. 3. Vertical distribution of spray deposit based on an assumed application rate of 100 droplets/cm^2 (ground area); [i] depicts the distribution within a dense canopy ($\rho = 6.4$ m^2 m^{-3}), based on data shown in Tables 3 and the sample droplet spectrum in the text; [ii] shows the results of similar calculations for a more open canopy ($\rho = 4.0$ m^2 m^{-3}).

DISCUSSION AND CONCLUSIONS

The analytical scheme described in Fig. 2 is useful for discerning the way in which the vertical distribution pattern is likely to be influenced by droplet size, wind-speed and foliage area. It must be admitted, however, that the scheme demands an intimate knowledge of the crop microclimate - information which may not be at hand. Even when such information is available one is still left with considerable imponderables - particularly for specifying the trapping coefficient β for small droplets.

The theory is most useful if it is used for analysing observed distribution patterns and attempting to gain a better understanding of the trapping ability of foliage elements e.g. Bache (1981).

The theory described is restricted to uniform canopies and must be adapted to other canopy shapes paying particular attention to the distribution of the foliage area density. The theory is also restricted to conditions in which there is near - uniformity in the horizontal spray distribution and to conditions in which the vertical spray distribution is 'well-adjusted' to the crop microclimate. Such conditions do not apply to dispersion pattern emanating from aerial releases at short ranges. Nevertheless the approach gives insight into the expected trends.

For canopies with a uniform area density distribution least penetration is likely for droplets with $d_p \gtrsim 100$ µm, the distribution approaching Eq. (14) with $\gamma = f_x \rho$. For $d_p \lesssim 100$ µm penetration increases with decreasing droplet size and increasing wind-speed.

From the sample calculations it is seen that the deposition distribution more or less reflects the airborne concentration distribution, though care should be taken to distinguish between them. By taking account of the droplet number spectrum (as distinct from the volume distribution) it is seen that the small droplets (say $d_p \lesssim 50$ µm) play a critical role in promoting number concentrations within the canopy. A comparison of Fig. 3(i) and Fig. 3(ii) shows that the foliage density is also an important consideration. For example, if one wishes to achieve a deposit of 50 droplets/cm^2 within the interval 0.6 - 0.8 m, then Fig. 3 shows that it is necessary that the area application rate should be 50/11.8 x 100 = 424 droplets/cm2 for the dense canopy (Fig. 3(i)) and 50/21.1 x 100 = 237 droplets/cm^2 for the more open canopy (Fig. 3(ii)). For the quoted droplet spectrum 100 droplets/cm^2 is almost equivalent to the volume application rate 0.75 ι/ha. Thus the respective rates to attain the target levels within the canopy are ~3.2 ι/ha and ~1.8 ι/ha.

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