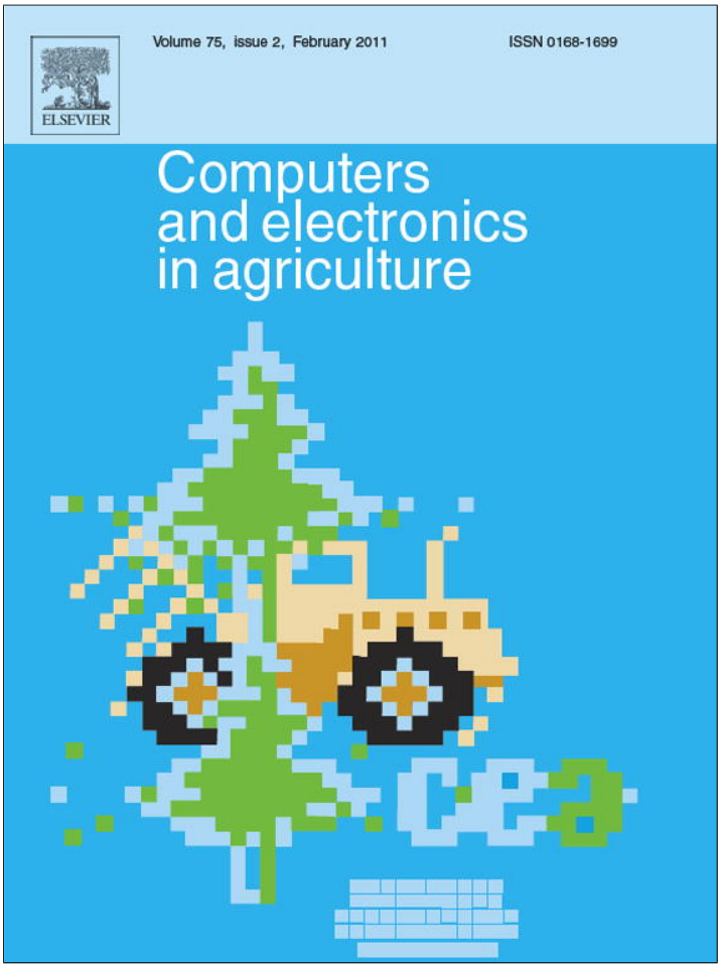
Volume 75, issue 2, February 2011
ISSN 0168-1699
ELSEVIER
Computers
and electronics
in agriculture

Computers and Electronics in Agriculture 75 (2011) 355–362

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original paper

Support system for efficient dosage of orchard and vineyard spraying products

P.J. Walklate[a,*], J.V. Cross[b], G. Pergher[c]

[a] PJWRC, 22 Moore Crescent, Dunstable, Bedfordshire LU55GZ, UK
[b] East Malling Research, Kent, ME196BJ, UK
[c] Dept of Agriculture & Environmental Science, University of Udine, Italy

ARTICLE INFO

Article history:
Received 27 July 2010
Received in revised form
17 December 2010
Accepted 21 December 2010

Keywords:
Pesticide registration
Dose adjustment model
Efficacy
Environmental fate
Target structure

ABSTRACT

This paper establishes a system to support the dose evaluation part of the pesticide registration process so that growers can make more efficient use of different spraying products across a broad range of European orchards and vineyards. The system comprises: a dose adjustment model and a small database of standard target structures (i.e., regional exemplars where efficient and efficacious use of pesticide is obtained at the label dose rate). The model includes a generalised scaling group relationship between the parameters that describe: sprayer output, target row structure and spray volume deposit. The upper limit for dose adjustment is based on the environmental fate of pesticide and this is represented in the model by the ratio of maximum ground area dose rate to minimum efficacious deposit which is normalised for alignment with target structure measurements. The model is used to examine the leaf-wall-area dose rate recently proposed by the European agrochemical manufacturing industry for harmonising pesticide registration. Good agreement is demonstrated between published measurements and model predictions of ground area and leaf-wall-area dose rate variation at constant deposit for a wide range of target structures (i.e., English pome- and stone-fruit orchards and Italian vineyards). The results are used to establish standard target structures for spraying products with different uses. These standards are needed by regulators to: translate between the different methods of expressing dose rate and improve the accuracy of label dose recommendations. The standards are also needed by growers to enable: more accurate calibration of spraying equipment and prediction of the optimum adjustment of label dose rate for different orchards and vineyards.

1. Introduction

The pesticide registration system for commercial orchard and vineyard spraying products in Europe has been developed with the best of intentions to ensure the safe and efficacious use of products across a diversity of growing regions, taking into account the use of different growing practices and spray application equipment. This has resulted in different methods of label dose expression with various claims for improved efficiency of pesticide use (Koch, 1993, 2007; Bjugstad, 1994; Jaeken et al., 1999; Rüegg and Viret, 1999; Rüegg et al., 1999, 2001; Koch and Weisser, 2002; Walklate et al., 2003, 2006; Frießleben and Koch, 2005; Frießleben et al., 2007; Doruchowski et al., 2009). Regulatory harmonization is now needed to enable the mutual recognition of efficacy data (EPPO, 2005) across different climatic zones within Europe (Blenkinsop et al., 2008) and further regulatory support is needed to help growers use pesticides more efficiently (Walklate and Cross, 2010).

Some research papers have suggested that a single method of dose rate expression would best serve the need for regulatory harmonization in Europe. Rüegg et al. (2001) presented the case in support of the tree-row-volume (TRV) dosage model (Byers et al., 1984; Sutton and Unrath, 1984) and Frießleben et al. (2007) presented the case in support of the leaf-wall-area (LWA) dosage model (Morgan, 1981). The latest developments have resulted in a proposal by the European agrochemical manufacturing industry to harmonise, across Europe, the efficacy evaluation part of pesticide registration (Wohlhauser, 2009). However, this proposal ignored the extension of efficient pesticide use beyond the limits imposed by a LWA dosage model. In particular the scaling effect of target density is significant for orchards (Walklate et al., 2006) and vineyards (Pergher and Petris, 2008) and the need for appropriate regulatory support for this appears to have been ignored.

Parallel developments have begun to demonstrate the use of webpage support technologies for unifying the approaches to regulatory harmonization and enabling more efficient use of pesticide based on any method of dose expression. A simple webpage style user interface has been constructed to help UK growers to estimate the adjustment of label dose rate needed for efficient use

* Corresponding author. Tel.: +44 (0) 1582863230.
E-mail address: peter.walklate@pjwrc.co.uk (P.J. Walklate).

0168-1699/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.compag.2010.12.015

Nomenclature

A	target row area per unit length of target row [m]
a	target row area density [m^{-1}]
b	data fitting coefficient
C	tank concentration of the applied product [$l\,l^{-1}$ or $kg\,l^{-1}$]
c_0	empirical coefficient
c_1	empirical coefficient
D	row length dose rate [l or $kg\,m^{-1}$]
d	spray deposit per unit of target area [l or $kg\,ha^{-1}$]
h	sprayed height of target shown in Fig. 1 [m]
L	limit for the normalised ratio of ground area dose rate to efficacious deposit
LAI	leaf area index $\mathrm{LAI} = aw(h/s)$
LLI	leaf layer index or target interception probability $\mathrm{LLI} = aw$
n	extent of target exposure (i.e., the distance between spray release and deposit, expressed as a multiple of the target row spacing)
Q	spray flow rate [$l\,s^{-1}$]
U	forward speed of sprayer [$m\,s^{-1}$]
s	target row spacing shown in Fig. 1 [m]
w	target row width shown in Fig. 1 [m]

Greek symbols

δ	optical density
ε	volume fraction of sprayer output retained as target deposit
σ	target interception probability divided by the cumulative interception probability
τ	optical transmission

Superscript

*	global reference values

Subscript

l	local reference values or standards associated with exemplar target structures where efficient and efficacious use of pesticide is obtained at the label dose rate

of product with different target structures (Walklate and Cross, 2010). The approach was founded on the PACE dose adjustment leaflet for spraying dessert apple orchards (Walklate and Cross, 2005).

The extensions of the UK support system for global use across Europe has been demonstrated using a small database of standards based on target structures where efficient and efficacious use of pesticide is obtained at the label dose rate (http://pjwrc.co.uk/DoseAdjustment.htm). However, a suitably detailed description of this system has not hitherto been published. The objective of this paper is to describe the development of this system for improving the way pesticide registration supports the efficient use of orchard and vineyard spraying products across a wide range of target structures. The system comprises: a model of dose adjustment and a small database of standard target structures (i.e., regional exemplars where efficient and efficacious use of pesticide is obtained at the label dose rate). A brief description is given of surrogate data that is used to evaluate the system. The results and discussion focus on the needs to support different spraying products with specific pre-blossom uses and none growth-stage specific uses.

2. Materials and methods

2.1. Model development

The first problem encountered in the development of a dose adjustment model relates to the variability of dose expression that is allowed by the European pesticide registration system for orchard and vineyard spraying products (EPPO, 2005). Furthermore, the current standards may change in the future as a result of recent commercial proposals for the harmonization of dose expression. Therefore, the model should be flexible enough for use with existing plant protection products and adaptable enough to accommodate future developments of application support technologies leading to more efficient use of pesticide.

2.1.1. Pesticide output from the sprayer

The pesticide output from the sprayer is described in a way that is independent of any target structure parameter. In this way it is possible to isolate the physical process of sprayer adjustment (i.e., using standard operational controls to adjust: tank concentration C, spray flow rate Q and forward speed U) from the calculation of dose rate adjustment for different target structures. To do this the row-length dose rate (i.e., the dose per unit length of target row) is used as the preferred method of expressing the pesticide output from the sprayer (Bjugstad, 1994):

$$D = \frac{CQ}{U} \tag{1}$$

2.1.2. Variation of spray deposit with target structure

To construct a dose adjustment model capable of optimising pesticide use in different orchards and vineyards it is necessary to describe the variation of spray deposit (i.e., the amount of product per unit area of target surface) with target surface area and applied dose. It is also assumed that machine spraying is performed within the normal constraints on spray volume application (i.e., below the spray saturation conditions of the target structure and above the conditions where evaporative losses become significant during spray transport). Within these limits the variation of deposit is represented by the following scaling-group relationship:

$$d \sim \frac{\varepsilon D}{A} \tag{2}$$

where ε is the volume fraction of sprayer output retained by the target and

$$A = awh \tag{3}$$

is the surface area of the target per unit length of target row and is expressed here in terms of the classical target row parameters: a is the area density (i.e., the target area divided by the target row volume), w is the width and h is the height (Fig. 1).

Eq. (2) can be simplified to give the deposit model based on the absolute values of dose and target surface area with $\varepsilon \sim 1$ (Koch and Weisser, 2002). Furthermore, the combination of Eqs. (2) and (3) give the same model as Walklate et al. (2006) and Pergher and Petris (2008), but previously formulated in terms of the ground area rate expressions of dose and crop surface area.

Measurements of the spray volume retained by vines after machine spraying have been shown to vary according to $\varepsilon \propto aw$ (Pergher and Petris, 2008). However, this does not satisfy the expected limit behaviour for high density structures where $\varepsilon \sim 1$ (Walklate et al., 2006). To resolve this conflict the following analysis is made, based on the analogy between the capture of spray droplets with ballistic trajectories and the interception of a light ray of small cross-section (Walklate et al., 2002). This yields the following relationship for the horizontal transmission of spray droplets

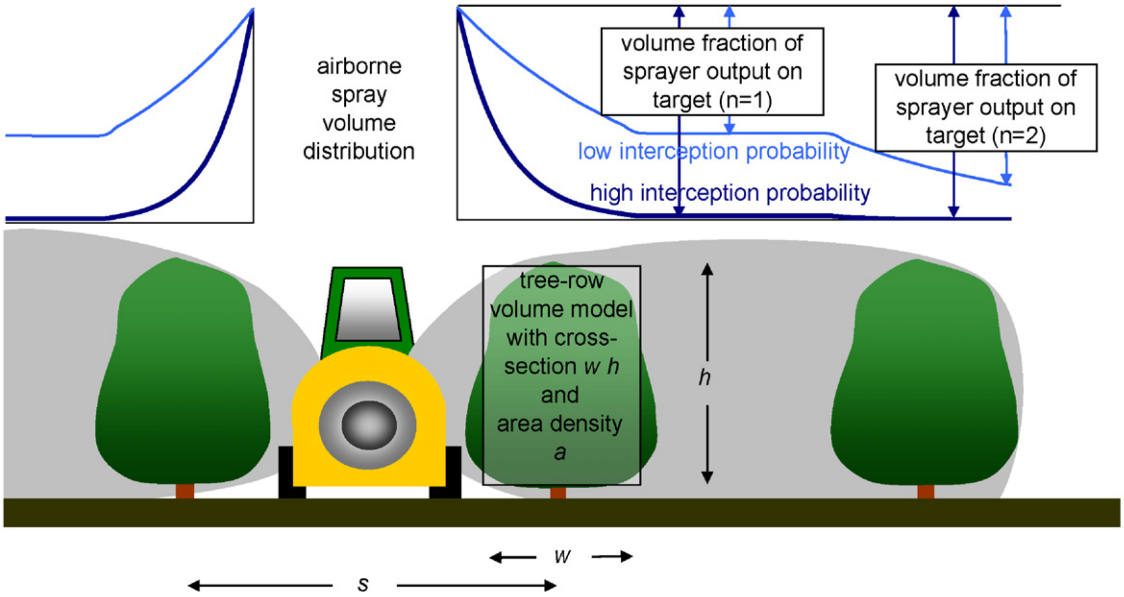

Fig. 1. Schematic diagram showing a cross-section of the target during pesticide application with a broadcast air-assisted sprayer. The model of the target is a rectangular cross-section *wh* with a uniform area density *a*. The inserted graph shows the airborne volume distribution of spray with distance from the sprayer outlet and identifies the volume fraction of sprayer output ε retained by the primary target ($n=1$) and the combined primary and secondary target ($n=2$). (a) English pome-fruit orchard spraying products with specific pre-blossom uses ($n=2$). (b) English pome and stone-fruit orchard spraying products with no growth-stage specific uses ($n=2$). (c) Italian vineyard spraying products with no growth-stage specific uses ($n=1$).

within a typical target row structure (Fig. 1):

$$\varepsilon \sim \delta(n) = \frac{\int_{-nw}^{nw} \tau(x)dx}{\int_{-\infty}^{\infty} \tau(x)dx} = 1 - \exp(-naw) \qquad (4)$$

where $\delta(n)$ is the optical density of n rows of the target and Beer's law of optical transmission is used (i.e., $\tau(x) = \exp(-a\,|x|)$ where x defines the horizontal distance of the spray/light trajectories after removal of the gap $s - w$ between each pair of target rows).

The following relationship for the volume fraction of sprayer output retained by the target is a typical model that is obtained from Eq. (4) using practical calibration:

$$\varepsilon_{est} = c_0(1 - \exp(-c_1 naw)) \qquad (5)$$

where c_0 and c_1 are empirical coefficients derived from exposure measurement for spray application to row structures (where n is the extent of target exposure or the distance between spray release and deposit, expressed as a multiple of s the target row spacing). There are many physical effects that may influence the estimate of these coefficients including: variation in the spray trajectory angle, anisotropic leaf area distribution, streamlining of leaves in an air flow (Raupach et al., 2001) and small-scale aerodynamics of spray droplets near collector surfaces (May and Clifford, 1967). However, the variation of deposit that may be introduced by the variation of these effects is neglected here.

Beyond the region where spray transport is controlled by the air jet flow output of the sprayer some droplets may still be airborne within the highly turbulent, but dissipated mean jet flow. However, these droplets are neglected for the purpose of the analysis here. In reality, some of these droplets may contribute to additional target deposit, but by ignoring this effect the estimate of ε, based on Eq. (4), is good enough for predicting spray deposit and making conservative estimates dose adjustment.

Eqs. (2)–(4) are combined to obtain a simple expression for the variation of spray deposit d with sprayer output D and target structure parameters h and σ:

$$d \sim \frac{D}{\sigma h} \qquad (6)$$

where

$$\sigma = \frac{aw}{(1 - \exp(-naw))} \qquad (7)$$

is identified as the target interception probability divided by the cumulative probabilities of interception and combines the parameters for target row width, area–density and the extent of target exposure in a single parameter.

2.1.3. Asymptotic characteristics of spray deposit

For low density targets (i.e., the limit $naw \to 0$), Eq. (7) simplifies to become $\sigma \sim 1/n$. Therefore, in this limit the variation of deposit, given by Eq. (6), simplifies to the LWA dosage model (i.e., $d \sim nD/h$).

By contrast with this, for high target density (i.e., the limit $naw \to \infty$), Eq. (7) simplifies to become $\sigma \sim aw$. Therefore, in this limit the variation of deposit given by Eq. (6) simplifies to a dosage model based on measured target area (i.e., $d \sim D/awh$).

2.1.4. Data fitting form of dose adjustment model

To help use target deposit measurement for analysing the efficient use of pesticide, it is convenient to reformulate Eq. (6) as the following dose adjustment model:

$$\frac{D}{d} = b\sigma h \qquad (8)$$

where

$$b = \frac{D^*}{d^* h^* \sigma^*} \qquad (9)$$

is a dimensionless coefficient based on suitable reference values: D^*, d^*, h^* and σ^*.

Unity reference values ($h^* = 1$ m, $\sigma^* = 1$) are numerically convenient to use and D^* is very similar, though not strictly identical, to the dose used as the basis for the "unit canopy row method" of sprayer calibration (Furness et al., 1998) which also implies the use of $w^* = 1$.

For the purpose of evaluating product efficacy as part of the pesticide registration process, the model coefficient b can be determined using a standard linear regression method for solving Eq. (8) based on an over-determined set of measurements of D, d, h and σ.

Table 1
Target structure standards needed to support dose adjustment for the different methods of label dose rate expression used in Europe.

Target structure standards			Label dose rate expression is supported (Y)				
Dose adjustment	Environmental fate	Extra	Row length dose rate $\lvert D \rvert_l$	Ground area dose rate $\left\lvert \frac{D}{s} \right\rvert_l$	Leaf wall area dose rate $\left\lvert \frac{D}{h} \right\rvert_l$	Canopy volume dose rate $\left\lvert \frac{D}{sh} \right\rvert_l$	Tree row volume dose rate $\left\lvert \frac{D}{wh} \right\rvert_l$
h_l, σ_l	s_l		Y	Y	Y	Y	-
h_l, σ_l	s_l	w_l	–	–	–	–	Y

2.1.5. Variation of GA dose rate with target structure and the threshold limit for environmental fate

An important part of pesticide registration considers the environmental fate of the product. For this purpose a unique threshold is required to represent the limit of dose adjustment that may be used. Standard regulatory practice represents this limit as a ground-area source (i.e., the dose derived from the label divided by the ground area of application) to establish a worst-case source for environmental transfer processes that move pesticides away from the target site and cause pollution (ex. runoff, leaching, spray drift, volatilization). The ground-area source associated with the dose adjustment model is evaluated here simply by dividing both sides of Eq. (8) by the minimum spatial interval of spray application (i.e., the row spacing s) and after suitable rearrangement, the normalised GA dose rate at constant deposit is expressed as:

$$\frac{D}{dsb} = \frac{\sigma h}{s} \le L \tag{10}$$

where L is the dimensionless threshold limit, and the ratio D/s is the applied GA dose rate for constant target deposit $d = d^*$ on a target structure proportional to $\sigma h/s$.

2.1.6. Variation of LWA dose rate with target structure

The major agrochemical manufacturers of Europe have recently proposed to harmonise data submissions in support of the LWA dose rate for the efficacy evaluation part of pesticide registration. To utilise spray deposit data for examination of this proposal, Eq. (10) is multiplying throughout by s/h to obtain the following expression for the normalised LWA dose rate at constant deposit:

$$\frac{D}{dhb} = \sigma \le \frac{Ls}{h} \tag{11}$$

where the ratio D/h is the applied LWA dose rate that gives a constant target deposit $d = d^*$ on a target structure proportional to σ.

2.2. Target structure standards

So far it appears that a single set of global reference values (i.e., D^*, h^*, σ^*, s^*, etc.) may be all that is needed to enable Eq. (10) or Eq. (11) to be used by the grower. However, the pesticide registration process currently relies on local reference values (standards) to evaluate the label dose so that it represents the worst case scenario for pesticide use in a single country or growing region.

Consider therefore the grower's requirement to make more efficient use of a product by adjusting the output of a sprayer D_l (i.e., the calibrated row length dose rate to deliver the equivalent label dose rate to the standard target) to maintain the minimum efficacious levels of deposit $d = d_l$ on any target structure. Therefore from Eq. (8), the adjustment of the sprayer output, is:

$$\frac{D}{D_l} = \frac{\sigma h}{\sigma_l h_l} \tag{12}$$

where the target parameters that are needed to represent the various standards to support the use of different methods of dose expression are listed in Table 1. Furthermore, Eq. (10) is used to check that the threshold limit for environmental fate is not exceeded for a given structure (i.e., $\sigma h/s \le \left\lvert \sigma h/s \right\rvert_l = L$).

It should be noted that a TRV label also requires a standard for the tree row width w_l or alternatively a standard for the TRV parameter (i.e., $\left\lvert wh/s \right\rvert_l$) as indicated in Table 1. Likewise for other methods of dose expression that may be devised (Walklate et al., 2003), any additional parameters that are introduced by way of explicit use for dose expression will need to be supported by an additional standard.

Finally, Table 2 gives a summary list of the alternative ways to report target structure in support of dose adjustment for the different methods of dose expression used in Europe. This includes alternatives to the parameter σ that have been used to quantify target area (i.e., the leaf area index and leaf layer index). This list represents a development beyond the *ad hoc* list of parameters given in the current standard for efficacy evaluation (EPPO, 2005).

2.3. Surrogate field data and simplification

Two distinctly different sources of deposit trials data are used to represent target structural variability associated with English pome- and stone-fruit orchards and Italian vineyards. These data also represent the results produced by: different measurement methodology and a range of different broadcast air-assisted spraying equipment.

2.3.1. English pome- and stone-fruit orchards

The sources of data for spray trials with pome- and stone-fruit orchards are: Walklate et al., 2008; Richardson et al., 2006. These studies include measurements made at three different fruit farms ('O-ME', 'O-BW', 'O-WH') during the period 2005–2006. The

Table 2
Information needed to describe target structure in support of dose adjustment for use with different methods of dose expression.

Parameters required to describe target structure	Dose adjustment is supported by different methods of label dose rate expression (Y)				
	Row length dose rate D	Ground area dose rate $\frac{D}{s}$	Leaf wall area dose rate $\frac{D}{h}$	Canopy volume dose rate $\frac{D}{sh}$	Tree row volume dose rate $\frac{D}{wh}$
$s, h, \sigma(n)$	Y	Y	Y	Y	–
s, h, LAI, n	Y	Y	Y	Y	–
s, h, LLI, n	Y	Y	Y	Y	–
$s, h, \sigma(n), w$	–	–	–	–	Y
s, h, LAI, w, n		–	–	–	Y
s, h, LLI, w, n	–	–	–	–	Y
s, h, a, w, n	–	–	–	–	Y

Table 3
Summary parameter values from linear regression analysis of orchard and vineyard data. The analysis of different sub-groups of data is based on a standard linear model (i.e., $y = bx$) for fitting Eq. (8) to field data (where $y = D/d$ is the measured ratio of the row-length dose rate to deposit and $x = \sigma h$). The combined analysis (column 6) is based on normalised data (i.e., $y = D/db$) and a normalised data fitting model (i.e., $y = x$).

Parameter name	Sub-group analysis $y = bx$				Combined analysis $y = x$
Data id	English orchards			Italian vineyards	All
	O-ME1O-ME2	O-BW1O-BW2O-BW3	O-WH1O-WH2O-WH3	V-MIX	
Samples	64	72	72	100	308
$n = 1$					
r^2	0.86	0.86	0.87	0.95	0.90
y's Se	2.81	3.80	2.73	1.71	1.69
b	1.73 ± 0.165	1.72 ± 0.153	1.51 ± 0.128	1.51 ± 0.063	1.0 ± 0.036
$n = 2$					
r^2	0.89	0.88	0.88	0.92	0.90
y's Se	2.42	3.55	2.67	2.27	1.47
b	2.06 ± 0.166	1.84 ± 0.151	2.04 ± 0.168	1.65 ± 0.094	1.0 ± 0.036
$n = 20$					
r^2	0.90	0.87	0.86	0.89	0.89
y's Se	2.28	3.7	2.91	2.59	1.52
b	2.17 ± 0.165	1.85 ± 0.159	2.31 ± 0.21	1.66 ± 0.109	1.0 ± 0.039

farms were located in Kent (i.e., the most intensive area of fruit production in England). The combined results represent twenty different orchard sites including different: tree fruit types (apple, pear, plume and cherry), planting systems (1, 2 and 4 row beds) and tree row or bed spacing (s = 3.5–9.85 m). At each orchard, measurements of deposit and target row structure were made at one pre-blossom growth-stage and one or two post-blossom growth-stages around fruit maturity. The target sampling was replicated on four trees in each orchard on each occasion.

The sprayers at farms O-ME and O-WH were axial-fan type air-assisted designs, respectively: a standard radial air duct and a cross-flow air ducted. Both sprayers were equipped with hollow-cone nozzles. The sprayer at farm O-BW was a centrifugal fan design of air-assisted sprayer equipped with flat-fan nozzles. All sprayers were operated at sufficient spray pressure to produce a "very-fine" to "fine" spray quality at volume application rate well below local saturation condition. The sprayers were operated to give a nominal spray flow rate (*c.* 0.167 l s^{-1}) and ground speeds between 1.6 and 2.0 m s^{-1}.

Treatments were applied by spraying the target row from the two avenues between the target tree row and adjacent tree rows on either side. During each traverse of the orchard the sprayer was operated using the nozzles on both sides of the sprayer. So that the total output from the sprayer was the same as that required to treat two rows of the orchard (i.e., the target row plus two half rows on either side). In many of the pre-blossom orchards there was significant secondary deposit on the target row.

2.3.2. Italian vineyards

The sources of data for spray trials in vineyards are: Pergher and Gubiani, 1995; Pergher et al., 1997; Pergher and Petris, 2007, 2008; Pergher, 2007. These studies include 100 deposition measurements performed during the period 1993–2005. The trials include different training systems (i.e., Casarsa, Cortina, Cordone and Guyot), row spacings (s = 2.0–3.6 m) and growth stages (between BBCH 13 for the "third leaf unfolded" and BBCH 81 for the "beginning of ripening"). Different sprayers were used, including: axial-fan type air-assisted sprayers, with either a standard radial ducted design (three different types) or a cross-flow ducted design (two models), and a compressed-air sprayer. Most of the test conditions were originally intended to compare different sprayer settings, so that the applied spray volume rate covered the range 67–1355 l ha^{-1} with variation in forward speed in the range 1.4–2.6 m s^{-1}, and in air flow rate from 3.2 to 9.4 m^3 s^{-1}. The sprayers were fitted with two to six hollow cone nozzles per side in order to adjust the sprayed zone to the height range of the canopy, and were operated at sufficient pressure to produce a "very-fine" to "fine" quality spray well below local saturation condition. This was true even at the highest range of volume application rate (1355 l ha^{-1}, four measurements, Pergher et al., 1997) owing to high air temperature, 31.4–33.5 °C, and low air humidity, 37.5–48.4%.

In three of the trials, treatments were applied by spraying a vineyard area of 21.6–24.0 m width, with six to eight passes in each plot, and assessing foliar deposits in the middle row, so as to include the possibility of secondary deposition from adjacent spray runs. In two of the trials (Pergher and Petris, 2007, 2008), however, the sampled vines were sprayed only from the two avenues between the target row and adjacent rows on either side and did not include secondary deposition.

2.3.3. Simplification of height representation of the sprayed target

An underlying problem with the measurements of target structure is the different approaches to the characterisation of target height. The orchard studies represented here used machine detection methods based on LiDAR measurements of interception probability thresholds to give accurate representation of the maximum target height without the necessity of determining the sprayed height of the target from signal containing interference from non-target structures on the orchard floor. By contrast the vineyard studies made fewer point observations but included both measurements of the maximum height relative to the ground and the sprayed height of the target. The measurements of maximum target height have therefore been used to unify the presentation of data in this study.

3. Results and discussion

3.1. Local evaluation of results for products with different uses

The regression analysis tool (MS Excel 2003) is used to determine the model coefficient in Eq. (8) for different groups of field data (i.e., $y = bx$, where $y = D/d$, $x = \sigma h$). The estimates of the regression coefficients b and additional summary statistics of regression analysis are presented in Table 3 for orchards and vineyards. The variation of estimates of b for the different data groups are attributed to: the different performance characteristics of the spray application equipment and the different methods used to measure the target area and deposit.

Table 3 gives the data fitting statistics of regression analysis based on different levels of target exposure (i.e., the calculation of $\sigma(n)$ using Eq. (7), where $n = 1$ for primary target deposit and $n = 2$, 20 for combined primary and secondary target deposit scenarios of different weight). The results show some of the differences between the various groups of data. For example, during pre-blossom spraying in English orchards with conventional applications equipment it can be difficult to limit exposure to the primary target row; especially when the whole orchard is treated and spray drift effects are significant in winds up to and including wind force 3 (Beaufort scale). Hence for orchards the best fit ($r^2_{OME} = 0.89$, $r^2_{OBW} = 0.88$, $r^2_{OWH} = 0.88$) is given when the model allows for significant secondary exposure of the target in addition to primary exposure ($n = 2$). By contrast, the results for vineyards are fitted best ($r^2_{VMIX} = 0.95$) when the model excluded secondary ($n = 1$) even though observations of secondary deposit were reported. There may be a case for making n real in subsequent use of this model to further resolve model optimisation. However, this is beyond the scope of the present study.

The results for different types of orchard and vineyard spraying products are presented in Fig. 2. The results are plotted with the normalised GA dose rate at constant deposit on the vertical axis ($y = D/dsb$) and the target height to row spacing ratio on the horizontal axis ($x = h/s$). Therefore, the threshold limit for the environmental fate of pesticide can be represented as a horizontal line on this graph and hence the upper limit of variation (shaded area around the data) is also represented as a horizontal line where appropriate (Fig. 2b and c).

Lines of constant LWA dose rate at constant deposit are represented as sloping lines and their equivalent values $\sigma = 0.5$, 1.0, 2.0, 4.0 are shown along the RHS on each figure. The lower limit of LWA dose rate may be represented with an equivalent slope of $\sigma \geq 1/n$ to recognise the practical limit of dose adjustment. It may be readily observed that estimates of σ are possible, below this limit, when measurements of deposit and target height are used. On the other hand the predicted limit (i.e., Eq. (7) with independent measurements of target area density a and width w) will always give estimates of $\sigma \geq 1/n$. For the orchard data (Fig. 2a and b) the lower limit $\sigma \geq 0.5$ is appropriate based on $n = 2$ for optimised data fitting (Table 3). For the vineyard data (Fig. 2c) the appropriate lower limit $\sigma \geq 1.0$ is based on $n = 1$ for optimised data fitting (Table 3).

The characteristic lines for the 90th percentile values of the normalised GA and LWA dose rates at constant deposit (Table 4) are indicated by horizontal and sloping broken lines, respectively. There is also good agreement between the estimate of standards based on left and right hand sides of the model formulations for GA and LWA dose rates at constant deposit (Table 4), with the exception of the case for pre-blossom specific uses on English pome fruit orchards. However, there appears to be very limited opportunity for improving the efficiency of use of this type of product based on a LWA label dose rate (Fig. 2a). Furthermore, if the secondary target exposure effects are ignored (i.e., $n = 1$ and $\sigma = 1$) the lower limit for dose adjustment is similar to the upper limit and in this case LWA dose rate adjustment is inappropriate (e.g., pre-blossom fungicides for pome-fruit orchards).

For spray products with no growth-stage specific uses on English pome- and stone-fruit orchards (Fig. 2b) and Italian vineyards (Fig. 2c), there appears to be great potential for improving the efficiency of use, even if the product label gives a LWA dose rate. However, there is currently no requirement to make any measurement or assessment of σ_l for efficacy evaluation (EPPO, 2005). Furthermore, without some means of communicating this information to the pesticide user, efficient use of this type of product cannot be made on any of the structures with values of σ below the standard. Estimates of the standard values for these products (Table 4) are much greater than the standard values for pre-blossom structures due to the change in target density across the full growing season.

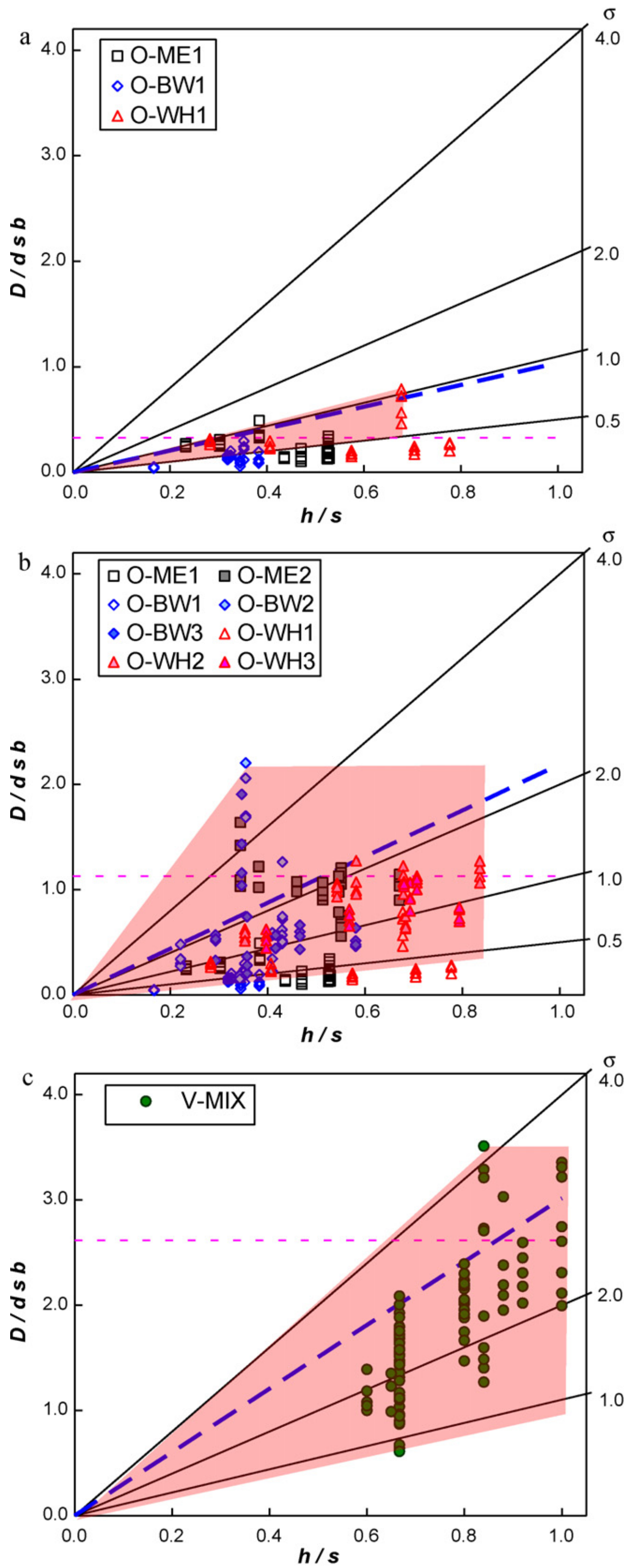

Fig. 2. The variation of normalised ground area dose rate at constant deposit D/dsb plotted against the ratio of target height to row spacing h/s for pesticide with different uses. The equivalent values of σ, inferred from the slope, are given along the right hand side of the graph. The shaded areas represent the possible range of dose adjustments. The horizontal chain line represents the limit of dose adjustment based on the 90th percentile value and might be used to represent the worst-case exposure associated with the environmental fate of different pesticides. The diagonal chain line represents the 90th percentile value of the target density adjustment for LWA dose rate.

Table 4
Estimates of dose adjustment model standards for spraying products with different uses. These are based on 90th percentile values of left and right hand sides of the models defined in column 2.

Label dose rate type	Dose adjustment model		Pre-blossom uses English pome-fruit orchards	No growth-stage specific uses English pome- and stone-fruit orchards	 Italian vineyards
LWA	$\frac{D}{dhb} = \sigma$	LHS	1.04	2.2	3.02
		RHS	0.98	2.08	3.13
GA	$\frac{D}{dsb} = \frac{\sigma h}{s}$	LHS	0.33	1.13	2.62
		RHS	0.64	1.07	2.52

3.2. Global evaluation of results

The regression analysis statistics of combined orchard and vineyard date are shown in Table 3 (RH column). These are based on the same combinations of primary and secondary target exposure that are used for local evaluation of results (i.e., $n = 1, 2, 20$). At this level of data integration the analysis is not very sensitive to the choice of n for target exposure ($r^2_{n=1} = 0.90$, $r^2_{n=2} = 0.90$, $r^2_{n=20} = 0.89$). Some examples of global evaluation results are also presented (Figs. 3 and 4) with estimates of σ based on the assumption that primary and secondary exposure of the target ($n = 2$) is appropriate for vineyards as well as orchards.

Fig. 3 presents the results with $y = D/dhb$ and $x = \sigma$ to evaluate the variation of the LWA dose rate at constant deposit with target structure (Eq. (11)). The results show the linear variation of LWA dose rate with σ in the range $1/n \le \sigma$ (i.e., where dose adjustment is needed to maintain efficiency of use of products that do not have growth-stage specific dose rates). Again this demonstrates the importance of estimating σ when the LWA dose rate is determined so that subsequent dose adjustment can be made by pesticide users with the aid of Eq. (12).

Fig. 4 presents the results with $y = D/dsb$ and $x = \sigma h/s$ (i.e., Eq. (10)) to evaluate the adjustment of the GA dose rate at constant deposit. This representation of combined data shows that the threshold limit for environmental fate of pesticide can be evaluated based on global assumptions about target exposure and is a simplification of the analysis shown in Fig. 2. The distribution of data in Fig. 4 shows that the vineyard data contains examples of spraying where the risk of environmental contaminations is more than double the value for the worst-case orchard structure and this is reinforced by the 90th percentile values of GA dose rate (Table 4).

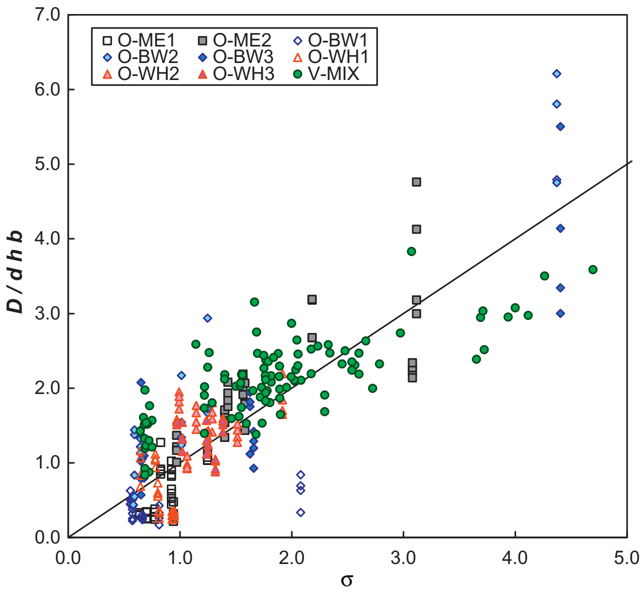

Fig. 3. The variation of normalised leaf-wall-area dose rate at constant deposit D/dhb plotted against the target structure parameter σ. The results show the combined data for English orchards and Italian vineyards with estimates of σ based on Eq. (7) with $n = 2$ for combined primary and secondary target exposure.

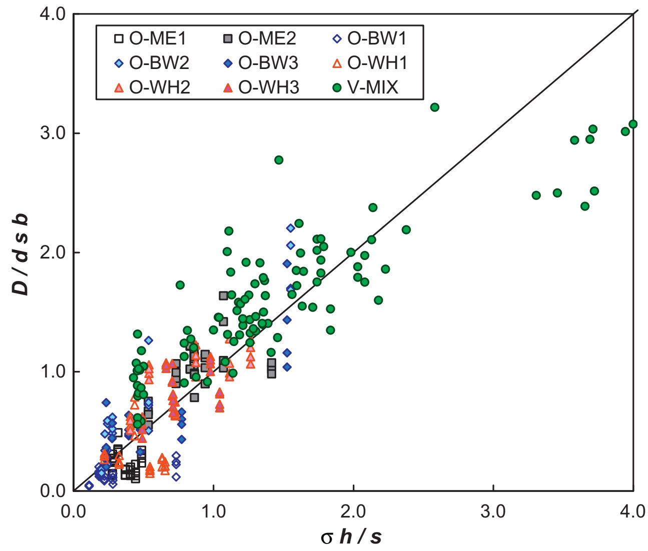

Fig. 4. The variation of normalised ground area dose rate at constant deposit D/dsb plotted against the target structure scaling group $\sigma h/s$. The results show the combined data for English orchards and Italian vineyards with estimates of σ based on Eq. (7) with $n = 2$ for combined primary and secondary target exposure.

4. Conclusions

This paper establishes the components of a support system for efficient dosage of orchard and vineyard spraying products. The system comprises a threshold limited model for computing dose adjustment of product across a wide range of target structures and a small database of standards to enable calibration of the model based on label dose rates.

The model, which gives an account of the scaling effect of target structure on spray deposit for a given sprayer output, is a generalisation of the LWA dosage model recently proposed by the European agrochemical manufacturing industry for harmonizing efficacy evaluation during pesticide registration. The model also implements standard regulatory practices that consider the environmental fate of pesticides based on the equivalent ground area dose rate threshold. The model can easily be adapted for pesticide products with a range of different methods of dose rate expression. Table 2 gives a summary of target structure parameters that should be recorded in the trial report to accommodate specific needs of dose adjustment when it is used with different methods of dose rate expression. Table 4 gives some estimates of target standards that may be suitable to support dose adjustment of pesticides for UK pome- and stone-fruit orchards and Italian vineyards.

The data fitting form of the dose adjustment model Eq. (8) has been shown to give a good account of the variation of deposit measurements for a very wide range of application conditions, including different: application rates, orchard and vineyard structures, environmental condition and applications equipment.

Bearing in mind the proposed harmonization of dose rate expression in Europe for efficacy evaluation based on the LWA dose rate, the generalised model has been used to investigate the consequential need for dose adjustment. For products with specific pre-blossom uses the results demonstrate that the LWA dose rate does not need any further adjustment, in particular, when the application equipment is adjusted for primary target exposure. However, for products with no growth-stage specific uses, the LWA dose rate does require significant adjustment to maintain efficient use across a wide range of target structures.

Acknowledgements

The authors wish to acknowledge funding from the United Kingdom Department for Environment, Food and Rural Affairs and the Italian Ministry of University, Research and Development and Regione autonoma Friuli Venezia Giulia.

References

Bjugstad, N., 1994. Spraying application and deposit of pesticides in orchards. Acta Horticulturae 372, 93–102.

Blenkinsop, S., Fowler, H.J., Dubus, I.G., Nolan, B.T., Hollis, J.M., 2008. Developing climate scenarios for pesticide fate modelling in Europe. Environmental Pollution 154, 219–231.

Byers, R.E., Lyons Jr., C.G., Yoder, K.S., Horsburgh, R.L., Barden, J.A., Donohue, S.J., 1984. Effect of apple tree size and canopy density on spray chemical deposit. Hortscience 19 (1), 93–94.

Doruchowski, G., Balsari, P., Van de Zande, J., 2009. Development of a crop adapted spray application system for sustainable plant protection in fruit growing , ISHS Acta Horticulturae 824: International Symposium on Application of Precision Agriculture for Fruits and Vegetables.

EPPO, 2005. Dose expression for plant protection products, efficacy evaluation of plant protection products. EPPO Bulletin 35, 563–566.

Frießleben, R., Koch, H., 2005. Dose expression in plant protection product field testing in high crops – need for harmonization. In: Book of Abstracts 8th Workshop on Spray Application Techniques in Fruit Growing, Barcelona, Spain, pp. 31–32.

Frießleben, R., Roßlenbroich, H.-J., Elbert, A., 2007. Dose expression in plant protection product field testing in high crops: need for harmonization. Pflanzenschutz-Nachrichten Bayer 60 (1), 85–96.

Furness, G.O., Magarey, P.A., Miller, P.H., Drew, H.J., 1998. Fruit tree and vine sprayer calibration based on canopy size and length of row: unit canopy row method. Crop Protection 17 (8), 639–644.

Jaeken, P., Vanermersch, M., DeMoor, A., Langenakens, J., 1999. Application quality index as an instrument for dose calculation. Aspects of Applied Biology 57, 351–356.

Koch, H., 1993. Application rate and spray deposit on targets in plants. In: ANPP/BCPC 2nd International Symposium on Pesticides Applications, vol. 1 , pp. 175–182.

Koch, H., 2007. How to achieve conformity with the dose expression and sprayer function in high crops. Pflanzenschutz-Nachrichten Bayer 60 (1), 71–84.

Koch, H., Weisser, P., 2002. Expression of dose rate with respect to orchard sprayer function. Advances of Applied Biology 66, 353–358.

May, K.R., Clifford, R., 1967. The impaction of aerosol particles on cylinders, spheres, ribbons and discs. Annals of Occupational Hygiene 10, 83–95.

Morgan, N.G., 1981. Minimizing pesticide waste in orchard spraying. Outlook on Agriculture 10, 342–344.

Pergher, G., Gubiani, R., 1995. The effect of spray application rate and airflow rate on foliar deposition in a hedgerow vineyard. Journal of agricultural Engineering Research 61, 205–216.

Pergher, G., Gubiani, R., Tonetto, G., 1997. Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. Crop Protection 16 (1), 25–33.

Pergher, G., Petris, R., 2007. Canopy structure and deposition efficiency of vineyard sprayers. Rivista di Ingegneria Agraria 2, 53–60.

Pergher, G., 2007. Metodi per adeguare la dose di agrofarmaco alle caratteristiche della chioma nei trattamenti alle colture arboree. In: Proceedings, Incontri Fitoiatrici , Torino 28.2–2.3 2007, pp. 15–19.

Pergher, G., Petris, R., 2008. The effect of air flow rate on spray deposition in a guyot-trained vineyard. Agricultural Engineering International: the CIGR Ejournal X (May), Manuscript ALNARP 08 010.

Raupach, M.R., Woods, N., Dorr, G., Leys, J.F., Cleugh, H.A., 2001. The entrapment of particles by windbreaks. Atmospheric Environment 35 (July), 3373–3383.

Richardson, G.M., Walklate, P.J., Baker, D.E., Cross, J.V., Harris, A.L., 2006. Orchard measurements for optimising label dose rate adjustment. Aspects of Applied Biology 77, 497–504.

Rüegg, J., Viret, O., 1999. Determination of the tree row volume in stone-fruit orchards as a tool for adapting the spray dosage. EPPO Bulletin 29 (1), 95–101.

Rüegg, J., Viret, O., Raisigl, U., 1999. Adaptation of spray dosage in stone-fruit orchards on the basis of tree row volume. EPPO Bulletin 29 (1), 103–110.

Rüegg, J., Siegfried, W., Raisigl, U., Viret, O., Steffek, R., Reisenzein, H., Persen, U., 2001. Registration of plant protection products in EPPO countries: current status and possible approaches to harmonization. EPPO Bulletin 31 (2), 143–152.

Sutton, T.B., Unrath, C.R., 1984. Evaluation of the tree-row-volume concept with density adjustments in relation to spray deposits in apple orchards. Plant Disease 68 (6), 480–484.

Walklate, P.J., Cross, J.V., Richardson, G.M., Murray, R.A., Baker, D.E., 2002. Comparison of different spray volume deposition models using LIDAR measurements of apple orchards. Biosystems Engineering 82 (3), 253–267.

Walklate, P.J., Cross, J.V., Richardson, G.M., Baker, D.E., Murray, R.A., 2003. A generic method of pesticide dose expression: application to broadcast spraying of apple trees. Annals of Applied Biology 143, 11–23.

Walklate, P.J., Cross, J.V., 2005. Orchard spraying: opportunities to reduce rates. In: HDC Factsheet 20/05.

Walklate, P.J., Cross, J.V., Richardson, G.M., Baker, D.E., 2006. Optimising the adjustment of label-recommended dose rate for orchard spraying. Crop Protection 25, 1080–1086.

Walklate, P.J., Cross, J.V., Harris, A.L., Richards, G.M., 2008. Results of the UK PACE project on orchard spraying. Aspects of Applied Biology 84, 403–410.

Walklate, P.J., Cross, J.V., 2010. A webpage calculator for dose rate adjustment of orchard spraying products. Aspects of Applied Biology 99, 359–366.

Wohlhauser, R., 2009. Dose rate expression in tree fruits – the need for harmonization approach from a chemical producer industry perspective. In: Paper Presented at the Tree Fruit Dose Adjustment Discussion Group Meeting , Wageningen, The Netherlands, September 29.