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Review

Bases for pesticide dose expression and adjustment in 3D crops and comparison of decision support systems

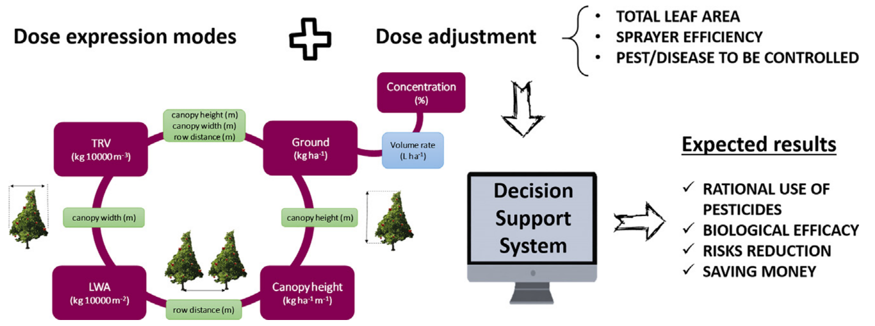
Santiago Planas [a,*], Carla Román [b], Ricardo Sanz [b], Joan Ramon Rosell-Polo [b]

[a] Research Group on Integrated Pest Management, University of Lleida - Agrotecnio CERCA Center, Rovira Roure 191, 25198 Lleida, Spain
[b] Research Group on AgroICT & Precision Agriculture, Department of Agricultural and Forest Engineering, University of Lleida - Agrotecnio CERCA Center, Rovira Roure 191, 25198 Lleida, Spain

HIGHLIGHTS

- Total leaf area is the most relevant parameter for dose adjustment.
- TRV and LWA can be used for initial volume rate and dose adjustment.
- Different decision support systems are described and compared.
- Dose adjustment improves considering leafiness, growth stage and sprayer efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

Authorities around the world have committed to limiting the use of chemical pesticides by reducing doses, among other strategies. Nevertheless, different dose expression models and decision support systems (DSSs) for dose adjustment coexist for high growing crops (3D crops). Among them, leaf wall area (LWA) and tree row volume (TRV) models have recently been proposed by the European and Mediterranean Plant Protection Organization (EPPO) for pre-registration trials. In this paper, the background and technical bases of six dose adjustment DSSs in fruit crops (PACE, AGMET, DOSA3D, OMAX and PULVARBO) and four in grape orchards (AGMET, OPTIDOSE, DOSAVIÑA and DOSA3D) are described and compared. The discussion leads to the conclusion that LWA and TRV represents a substantial improvement compared to the former crop ground area-based dose expression model. However, total leaf area is the most important parameter for dose adjustment, while sprayer efficiency is also a key factor. Additionally, it is suggested that deposition on leaves (mean values and variability) should be reported in pesticide efficacy evaluations in order to establish the required doses independently from the dose expression mode. The DOSA3D system, based on leaf area index estimation, was found to be the most conservative DSS regarding the spraying volume ratio to TRV because low spraying efficiencies are considered. Instead, AGMET was found to be the most effective for dose adjustment. However, despite the differences between the recommendations, all the analysed DSSs are useful tools for rational decision making about spraying volume rate and pesticide doses at national level. Their use should be promoted by the competent authorities.

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* Corresponding author.
E-mail addresses: santiago.planas@udl.cat, santiago.planas@agronoms.cat (S. Planas).

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Contents

1. Introduction

In 2019, nearly 55 Mha of 3D crops, including deciduous fruits, grapes, nuts, almonds, citrus and olives were under cultivation worldwide (FAO, 2021a), with 12 Mha corresponding to Europe (EU-28) and the vast majority (91%) in the European Southern Zone (ESZ) (EC, 2009a, 2009b). This area included 39%, 69% and 86% of the total European area of pome fruits, stone fruits and grapes, respectively and 100% of the total area of almonds, citrus and olives (Eurostat, 2021a). In this scenario, for productive reasons, these 3D crops are usually trained to have a wider and, frequently, higher canopy than is usual in the European Northern and Central Zones (ENZ and ECZ) (EC, 2009a, 2009b).

At the global level, total pesticides traded worldwide amounted to around 5.8 Mt in 2018 (FAO, 2021b). In Europe (EU-27), mean sales of fungicides and bactericides in the last four years for which data are available (2016-2019) were 154.7 Mkg, and 40.3 Mkg, with France, Spain, Italy, Germany, and Poland the main European countries consuming pesticides (Eurostat, 2021b).

Nevertheless, the yearly figures for the consumption of pesticides probably hide the real evolution of the chemical pressure and their associated risks because the dose of active ingredients (a.i.) is progressively decreasing. Indicators other than those related to mass consumption allow a better understanding of the real situation. By way of example, the European Harmonised Risk Indicator 1 (HRI 1) measures the use and risk to human health and the environment from pesticides in the EU-28. The HRI 1 indicator shows a 17% risk reduction in the period 2011-2018 (EC, 2020a).

The use of pesticides is associated worldwide with non-negligible, human and environmental risks. For this reason, both the Sustainable Use of Pesticides Directive 2009/128/EC (SUD) (EC, 2009c) and the consequent national legislation of European states advocate for the reduction of the amount of pesticides consumed in agriculture. As stated in point 6 of Annex 3 of the aforementioned Directive: “The professional user should keep the use of pesticides to levels that are necessary, e.g. by, reduced doses, reduced application frequency or partial applications, considering that the level of risk in vegetation is acceptable and they do not increase the risk for development of resistance in populations of harmful organisms”.

In accordance with the stipulations of Regulation 1107/2009 (EC, 2009a), the requirements for the authorization of new active substances and the periodic renewal of those already authorized are becoming more and more restrictive.

A similar approach exists in other world regions with a common concern for the safe use of pesticides. Nowadays, sustainability, risk mitigation and cost reduction constitute the principles of agriculture worldwide. However, despite the progressive irruption of biopesticides (pesticides containing biological active substances), the current level of agricultural productivity cannot be maintained without the use of conventional synthetic pesticides. This fact is proven every year, especially if environmental conditions increase the pressure due to harmful organisms. The hypothetical economic loss and negative impact on food security if chemical crop protection measures are not implemented has been reported by Damalas (2016), EPRS (2019) and Nishimoto (2019), among others.

More recently, the European Commission has committed to reducing the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50% by 2030. These are plant protection products (PPP) containing active substances that meet the cut-off criteria or are identified as candidates for substitution, as set out in Regulation (EC) 1107/2009. This decision forms part of the Farm to Fork strategy launched by the European Commission as a specific action of the European Green Deal (EC, 2020b). A revision is underway of the SUD with the aim of improving its provisions with respect to Integrated Pest Management (IPM) and promoting the greater use of safe alternative ways of protecting harvests from pests and diseases, including the prioritisation of low risk pesticides and biopesticides.

In this context, the current version of the EPPO standard that recently came into force, PP 1/239(3) (EPPO, 2021), clearly states the difference between dose expression (how the dose of pesticides should be expressed) and dose adjustment (adaption of the dose to the specific circumstances). These issues are addressed in Sections 2 and 3 of this paper, respectively.

The objectives of this paper are to summarize the research carried out on the coexisting dose expression models and dose adjustment systems and, as far as we know, for the first time, to compare them for the adjustment of doses in hedgerow- or trellis-trained intensive fruit and grapevine orchards.

Citrus orchards are not considered in this paper. In the initial period, the canopies of this 3D crop are globular-shaped, but over the years, in high-density orchards, become closer along the row forming a nearly continuous wall without significant gaps between the trees. In this situation, the rows could be sprayed continuously as is usual in fruit hedgerows. However, in low-traditional density orchards, spherical or globular-shaped orchards will remain in particular areas and require a specific approach for dose expression and adjustment (Garcerá et al., 2017; Miranda-Fuentes et al., 2016; Planas et al., 2019). Recently, the dose expression models adopted in globular-shaped crops and wall crops (addressed in this article) have been extensively reviewed by Garcerá et al. (2021).

2. Dose expression models

For field crops, the target is usually considered as roughly two-dimensional (2D) and the dose is expressed in kg or L of formulated product per unit of crop ground area and no changes are expected in the short term.

In 3D crops, concentration or crop ground area dose (kg or L ha^{-1}) expression models continue to appear on the labels of a significant number of formulated products, even though it is largely accepted that these expressions are no longer sufficient because they do not relate to the crop dimensions (Hislop, 1987; Walklate et al., 2003; EPPO, 2012b; EPPO, 2016; EPPO, 2021).

In order to understand the possibility of adapting the applied dose rate, Koch and Weisser (1995) suggested changing the expression models referring to the sprayed area with a view to optimizing pesticide leaf deposition. In the same direction, the EPPO *ad hoc* panel on Expression of Dose pointed out that the ideal method to express the dose rate should take into account the total leaf area (LA) (EPPO, 2001).

Over the last few decades, the majority of pome fruit orchards and vineyards have been transformed to wall crops (trellis or hedgerow shapes) because of their agronomic advantages. Other tree crops, including olives, stone fruits and almonds, are also being adapted to the hedgerow shape. In these regular-shaped orchards, the canopy height (CH: distance from the lowest leaves to the tree top) and mid-width of the crown (distance between outer leaves at the middle of the CH) are consistently used to adapt spraying volume and dose rates to the specific scenario. However, nowadays different models for dose expression coexist: pesticide mass or volume unit (kg or L) associated to a certain reference unit such as crop ground area, spray volume (concentration), CH, leaf wall area (LWA), tree row volume (TRV) or plant row (Codis et al., 2012; Doruchowski, 2017; Rüegg et al., 2001) and are officially accepted for registration and dose recommendation purposes on product labels.

The necessity to harmonize the expression of dose rate in order to allow the free exchange of data between countries has been expressed by EPPO (2001) and supported by Friessleben et al. (2007), Koch (2007) and Planas (2002), among others. At national level, official information on doses is the responsibility of the national authorities, but relevant questions on conversion between dose expression models and information to be labelled remain.

2.1. Tree row volume model

The TRV model assumes that canopy width is as relevant a parameter as CH to determine volume rates and optimal doses. This model was first described by Byers et al. (1971) from the US, and corresponds to the cubic volume of the tree rows per crop ground area. It is calculated according to Eq. (1):

$$TRV = \frac{w \cdot h \cdot 10^4}{r} \tag{1}$$

where TRV is tree row volume expressed as m^3 ha^{-1}, w is mid-width of the canopy (m), h is the CH (m) and r is the row spacing (m).

Byers et al. (1971) established the liquid volume ratio for spraying intensive fruit orchards in 0.093 L m^{-3} of TRV, coinciding with the point of runoff. This ratio was later confirmed by the same author (Byers, 1987). Herrera-Aguirre and Unrath (1980) proposed the ratio 0.116 L m^{-3} in the case of spraying apple trees with ethephon (growth regulator) applications.

In New Zealand, Manktelow and Praat (1997) validated the TRV model in Granny Smith and Red Chief apple orchards and suggested ratios above 0.093 L m^{-3} in large dimension trees (TRV > 23,000 m^3 ha^{-1}). They suggested a more accurate measure of canopy width to calculate the TRV value by considering stratified height intervals of 0.5 m in order to provide more representative estimates of actual canopy row-end profiles than the mid-crown and lower crown widths.

In Europe, Siegfried et al. (1995) advocated the TRV model to adjust dosage and volume and also to harmonize registration protocols for pesticides for both pome and stone fruits. In pome fruit orchards, the authors established the expression [L ha^{-1} = (0.02 * TRV) + 200] for spraying volume rate (SVR) calculation. Meanwhile, Doruchowski et al. (1996) recommended TRV as a reliable method for adjusting SVR to canopy tree dimensions.

In stone fruits, Rüegg et al. (1999) reported that TRV shows good linear correlations ($R^2 = 0.95$ for TRV < 17,000 m^3 ha^{-1} and $R^2 = 0.79$ for TRV > 17,000 m^3 ha^{-1}) with the leaf area index (LAI), defined as the one-sided leaf area per unit crop ground surface (m^2 m^{-2}). They showed that also the LAI correlates well with normalized leaf deposits ($R^2 = 0.84$, logarithmic for TRV < 17,000 m^3 ha^{-1} and $R^2 = 0.92$, logarithmic for TRV > 17,000 m^3 ha^{-1}). The maximum width of the crown is taken into account facilitate the TRV calculation in stone fruits (Rüegg and Viret, 1999).

In apple orchards, Rüegg et al. (2001) also found that LAI correlates well with normalized leaf deposits ($R^2 = 0.88$, logarithmic). They compared the fruit tree CH model, in use at that time in Germany, the surface orchard (SO) model a particular expression of the LWA model, adopted at the time in Belgium, and the TRV model which had already been introduced in Switzerland. Ultimately, they advocated use of the TRV model as it correlated well ($R^2 = 0.81$, linear, in 101 trials) with the LAI, whereas CH alone showed a poor correlation with LAI ($R^2 = 0.60$, linear, in 101 trials).

Also in grapevine orchards, Viret et al. (2005b) determined the correlation between the TRV and the LAI ($R^2 = 0.81$) throughout the season regardless of variety, year or training system. Similarly, Siegfried et al. (2007) found that the TRV correlates well with the LAI in this crop ($R^2 = 0.89$, potential). Finally, in fruits and vineyards, Planas et al. (2016) reported a well correlation ($R^2 = 0.68$, linear). Thus, TRV can be used as a LAI estimator.

In this sense, Siegfried et al. (2007) adjusted doses in vineyards through TRV and realized that leaf deposits depend on vine foliage growth, which are twice as high at initial stages (6 ng cm^{-2} for 1 g of tracer ha^{-1}; LAI = 0.5) than at full-leaf stage (3 ng cm^{-2} for 1 g of tracer ha^{-1}; LAI = 1.5), stating that dosage dependency on the LAI allowed more constant deposition throughout the season. And Viret et al. (2007) reported that adjusted dose to the TRV, as estimator of the LAI, or to the growth stage, gave similar results to the recommended dose when controlling downy mildew (*Plasmopara viticola* (Berk. & Curt.) Berl. & de Toni) and powdery mildew (*Erysiphe necator* (*Schw.*)). The authors stated that the most relevant dose adaptation should be carried out in vine at BBCH stages 55-57 (pre-blossom, according to Meier, 2001).

Following five additional years of trials, no significant differences were found by Viret et al. (2010) in the control of downy and powdery mildews between recommended and adjusted doses. For this 5-year period, 20% of the product was saved on average and these authors concluded that adapting the dosage of fungicides to the actual leaf surface area is a valuable and rigorous way to reduce the amount of product used, while ensuring effective protection.

The TRV model was proposed for dose expression (Rüegg et al., 2001) and the harmonization of registration trials (Siegfried et al., 2007) and is currently accepted by the Swiss authorities for dose expression. A canopy volume of 10,000 m^3 ha^{-1} is assumed as the reference for dose adjustment in pome fruits.

Very recently, the TRV model has been accepted for efficacy trials (EPPO, 2021), being recommended when canopy width is a relevant component of the canopy volume.

2.2. Leaf wall area model

The LWA is a particular case of the TRV model assuming that canopy width is non-varying or non-influencing at a significant level. This model was studied by Koch and Weisser (1995), who suggested that liquid volume and product dose rates should be related to the treated area defined by the virtual plane which the spray passes through and calculated as follows (Eq. (2)):

$$LWA = \frac{2 * h * 10^4}{r} \tag{2}$$

where LWA is the leaf wall area expressed as m^2 ha^{-1}, h is the CH (m) and r is the row spacing (m).

Weisser and Koch (2002) also suggested using the CH to express the dose from early field evaluation to label instructions.

However, Rüegg et al. (2001) demonstrated that the LWA model has a weak correlation with the LAI. And Planas et al. (2016) also found a low correlation in fruit and grapevine orchards ($R^2 = 0.48$, linear).

Regarding on-target (in-canopy) deposition, Koch (2005, 2007) found a linear correlation between the dose delivered per 10,000 m^{-2} treated LWA and the deposits on fruit trees and grapevine leaves. While Pergher and Petris (2008), using the LWA model, verified in vines that LWA-adjusted deposits were nearly independent of the LAI ($R^2 = 0.05$) and much less variable than the fixed-dose per unit ground area deposits ($R^2 = 0.80$). In the absence of biological efficacy confirmation, dose rate reductions of between 8% and 58% (29% on average) could be expected when compared to using a fixed dose. Duga et al. (2015a) observed that canopy width plays a role in efficient deposition in pome fruit trees and that tree volume affects overall on-target deposition.

Cross and Walklate (2008), Walklate et al. (2011) and Walklate and Cross (2012) demonstrated that the LWA dose rate requires significant adjustment to maintain efficient use across a wide range of target structures and that there was a need for additional information when using the LWA method for pesticide registration. For this reason, they argued that the LWA should not be used to calculate the maximum ground area dose rate (for comparison purposes with the regulatory limits on the environmental fate of pesticides).

At a practical level, the LWA seems too simplified to express the complexity of canopy architecture when width is non-negligible and leafiness is a determining factor for on-target deposition. Leafiness is usually understood as the complementary of porosity. In the current situation for intensive fruit and grapevine orchards, mid-crown width can reach values higher than 2.0 m and over 1.5 m, respectively. Porosity ranges from practically 1 (when sprouting) to near 0 (at full leaf stage). This is particularly the case in the ESZ, where end users and advisers are reluctant to use the LWA model because it proposes the same dose for any canopy width or leafiness.

Anyway, the LWA model was subsequently proposed as a common dose expression model by the chemical industry (Toews and Friessleben, 2012; Wohlhauser, 2011) and as the harmonized expression for efficacy evaluation in pome fruit, grapevine and high-growing vegetables by EPPO (2016, 2021) for mutual recognition. Kral et al. (2019) more recently argued that dosage should foliage-dependent and users should decide according to the canopy wall area and proposed rules to facilitate adaptation to the LWA model for end users. This model has been adopted for zonal assessment in pre-registration trials in the ECZ (CZSC, 2017). The German authorities made this agreement mandatory by January 2020 (BVL, 2018). At this moment, Austria, Germany and Belgium, all in the ECZ, have registered pesticides whose dose is expressed in the LWA model.

2.3. Leaf area index model

Pesticide application researchers and specialists generally agree that the dose of pesticides should ideally be linked with the LA (m^2) or leaf density (m^2 m^{-3}) present on the day of application. In this sense, Hislop (1987) stated that the dose expressed in kg or L per crop ground area is inappropriate due to the different forms of the crops and added that the dose should be increased at a constant concentration by increasing the SVR as crop LAI increases. Other authors have backed up this statement, proposing dose dependence on the LAI (Siegfried et al., 2007; EPPO, 2001; Planas et al., 2016). And Garcerá et al. (2021) concluded that leaf density, expressed by the LAI, is the most important factor that must be taken into account in all cases, despite the dose expression model. Based on this evidence, it can be suggested that pesticide doses might be adjusted to the LAI of the orchard to be treated.

In 2002, Walklate et al. demonstrated the relative potential for varying the pesticide application rate according to different crop parameters: LWA, TRV and tree area density (TAD). The TAD was defined by Walklate et al. (2000) and calculated through light detection and ranging (LiDAR) measurements, but can be easily estimated using pictograms reconstructed from LiDAR-measured images (Walklate et al., 2002). The TAD deposition model represents a simplified expression of the LAI model which considers row width as irrelevant. The authors concluded by suggesting use of the TAD method as a deposition model that can be linked to different crop structure scaling parameters because it gives significant improvements over the TRV and LWA methods.

Until recently, the determination of LAI in 3D crops was a high time-consuming task that was very difficult to attempt using direct methods (Jonckheere et al., 2004). However, the emergence LiDAR sensors has meant a remarkable advance in this respect. Before, the LIDAR methodology was only available on an experimental scale (Sanz et al., 2005; Walklate et al., 2002).

In Spain, important LiDAR-based works have been carried out in fruit orchards and vineyards (Escolà et al., 2012; Planas et al., 2013; Rosell-Polo et al., 2009a, 2009b; Sanz et al., 2011, 2013). In particular, Sanz et al. (2018) carried out a series of LiDAR field measurements comprising over 17 pear, 14 apple and 26 vine orchards at different growth stages and provided the basis for developing a simple, quick and accurate non-LIDAR system to estimate *in-situ* the LA. The authors concluded that the height variable does not explain well the LA and, consequently, that CH cannot be used alone to estimate the surface to be covered by spraying treatments. These authors proposed using a combination of height, maximum width and visual estimation of the ratio between the surface of the front visible gaps to the total canopy wall surface (porosity) for LA estimation. For the assessment of this last variable, it was suggested to use a pictogram-based model. The results obtained with this simplified method are consistent with those obtained with LiDAR-based methods. This procedure has made it possible to build a new model for accurate and easy *in-situ* LA estimation from the canopy dimensions, which has been embedded in the DOSA3D system (Section 4.5).

2.4. LAI and growth stage

Siegfried et al. (2007) studied over 7 vineyards located in different regions of Switzerland and Germany where the main growth always occurred during flowering (BBCH scale 62-63) and found that LAI reached maximum values (1.2 to 2.3) depending on canopy management and cultivar.

In deciduous tree crops, the growth stage also correlates well with leaf density according to Holterman et al. (2016), Rinaldi et al. (2013) and Solanelles et al. (2013). In Spain, in 2020, the authors of this paper carried out additional LAI determinations by defoliation in irrigated vineyards throughout the season. In Daramezas (Castilla La Mancha) in a vineyard conducted as a single high-wire sprawling system, at BBCH stages 53-61 (pre-blossom to initiation of flowering), the LAI reached values ranging from 1.2 to 1.7 and, at BBCH stages 75-83 (pea-sized berries to berry colour development), from 1.7 to 3.1. Also in Raïmat (Catalunya), values at BBCH stages 55-57 (during the emergence of inflorescense) were determined ranging from 0.4 to 0.6 and at BBCH 75-83 from 1.0 to 1.8 in vineyards conducted as a trellised system. Regarding pome fruit orchards, the LAI has been determined in Gimenells (Catalunya) at BBCH stages 71-75 (from fruit size up to 10 mm to fruit about half final size) with ranges from 2.3 to 2.9, and at BBCH 76-89 (from fruit about 60% final size to fruit ripe for consumption) with ranges from 2.6 to 4.0. All these works have opened up the opportunity for LAI estimation considering the canopy dimensions and adjusting for growth stage. This useful methodology has been implemented in the DSS DOSA3D, as is reported in Section 4.5.

3. Dose adjustment

Hislop (1987) defined the optimum pesticide deposition in general terms as the application of a biologically effective dose on a target with maximum safety and economy. Hall (1991) spoke about the rising concern about pesticide pollution, the development of resistance to pesticides, the increased cost of pesticides, as well as advances in low volume spraying and IPM, when highlighting the importance of applying the correct amount of pesticide on the foliar target.

Weisser and Koch (2002) found that the delivered dose rate per 10,000 m^2 sprayed area and the retained and resultant dose on the target are quite different and stated that the deposit on a leaf is the effective dose on this leaf, but the biologically appropriate dose needed on the individual leaf is not known, and concluded that the most relevant parameter for any effect of the delivered chemical quantity, including biological efficacy, residue or side effects, is the initial deposit on the target. The authors reported how users must know what chemical dose rate should be applied to a unit crop to comply with the principles of good agricultural practices (GAP).

Additionally, the adjusted doses allow lower pesticide residues in food, not only in compliance with Regulation 396/2005 (EC, 2005), but also to satisfy specific higher requirements of the food distribution and retail companies.

According to that, spraying pesticides at adjusted doses is becoming the norm for economic, health and environmental reasons. In practical terms, dose adjustment can be understood as a result of the adaption of the labelled dose to the specific conditions of the scenario of the treatment (crop dimensions, leafiness, the pests to be controlled and spraying equipment performance).

3.1. Minimum effective dose

A minimum limit has to be considered when adjusting dose. In this sense, Siegfried et al. (2007) and Walklate and Cross (2013) warned that a minimum deposit is required to maintain leaf deposition and not compromise efficacy when dose is reduced. The EPPO defined the minimum effective dose (MED) of a pesticide as that which is necessary to achieve sufficient efficacy (effectiveness) against a target pest across the broad range of situations in which the product will be applied (EPPO, 2012a).

3.2. Dose adjustment to the leaf target

The initial research in this field was carried out by Travis (1981), who studied the relationships between tree volume and deposition on leaves and showed that in pruned apple orchards spray deposition was higher and more uniform than in non-pruned orchards. Dose adjustment was also addressed by Sutton and Unrath (1984) and (Sutton and Unrath, 1988). They considered that the recommended product concentration was sufficiently effective and that the SVR adjustment to the TRV and leafiness (canopy density) provided consistent deposits in terms of uniformity. The study was carried out in different apple orchards with three pruning levels; SVR was adapted to the TRV (0.133 L m^{-3}) and adjusted by applying a correction factor of between 0.7 and 1.0 depending on foliar density. The authors showed that adjusting doses achieved similar deposits among the studied scenarios.

Later, the same authors, in 1988, found that deposits at the tight cluster stage were 1.2-2.0 times greater than leaf deposits achieved on the same canopies at full-leaf stage, and Hall (1991) demonstrated that average spray deposits increased in intensive-shaped (trellis) fruit orchards and argued that tree height, planting distance, tree shape, growth (and seasonal) patterns, and the expertise of the operator to match the application with the target geometry, were all vital factors for determining the efficiency (on-target recovery) of the spray application process.

Koch and Weisser (1995) and Weisser and Koch (2002) found that mean leaf deposits in apple orchards were proportional to the total dose applied and showed a broad variability with a coefficient of variation (CV) from 40 to 80% and a factor of 12 to 15 between the lowest and highest leaf deposits. They stressed the importance of their findings in terms of biological efficacy, the effects on beneficial organisms, the development of resistances, and the level of residues. Solanelles et al. (2004) showed how deposits clearly tended to reduce as TRV increased for any SVR. The study was made in apple and pear orchards at early growth and full-leaf stages using three SVR (400, 800 and 1600 L ha-1).

Dose adjustment in grapevine orchards was initially addressed by Viret et al. (1999) who proposed a system for dose adjustment from the registered standard dose by a factor whose value is equal to 1.00 for a reference orchard (TRV = 10,000 m^3 ha^{-1}, CH = 2.00 m, crown width = 2.00 m and row distance = 4.00 m). Subsequently, Viret et al. (2005a, 2005b) established a curve-type LAI throughout the season and demonstrated that an important reduction in fungicide active ingredients could be obtained with adapted dosage until bloom and, over the whole spraying program, calculated that this reduction could be as high as 20-35% under practical conditions, depending on year and plots.

Walklate et al. (2011) characterized different fruit orchards and vineyards using a LiDAR system in the UK and Italy and argued that dose should have an adjustment range for leaf density. In fact, LWA dose adjustment to target leafiness compared to applied doses based solely on LWA allowed a 17% reduction in pesticide use (Walklate and Cross, 2012). Finally, these authors emphasized the importance of characterizing the vegetation with LiDAR measurements in the efficacy trials of products in order to be able to adjust the dose to different scenarios (Walklate and Cross, 2013).

In accordance with the above information, it can be concluded that LAI is the most rational parameter for dose expression from the point of view of efficacy.

3.3. Sprayer type and setting parameters

It is well known that a perfect distribution and targeting of the pesticide product allows significant reductions in dose rate (Russell, 2004).

The role of the sprayer in achieving this goal has been extensively analysed in numerous research works comparing the performance and efficiency of different sprayer types for pome fruit and grapevine orchards.

In fruit orchards, new air blast sprayers with vertical deflectors and cross-flow sprayers, adapted to the tree-row geometry, have been incorporated for more than two decades. This allowed a considerable reduction of applied volume rates and losses, as well as improved on-target deposit uniformity and, consequently, the possibility of decreasing doses. Doruchowski et al. (1996) showed how cross-flow sprayers enabled an important reduction of pesticide doses. Heijne and Porskamp (1996) explored the possibilities of dose reduction by using cross-flow and recycling tunnels sprayers to control apple scab and powdery mildew in apple orchards.

The development of recycling tunnel sprayer has been one of the most promising advances in spraying technology. This type of sprayer collects the overspray in vertical panels and return the liquid to the main tank. Studies indicate that, they improve the coverage and uniformity and considerably reduce the total applied dose per crop ground area.

Holownicki et al. (1996) reported satisfactory efficacy in the control of apple scab (*Venturia inaequalis* Cooke (Wint.)) by applying treatments at reduced doses with conventional and tunnel sprayers.

Recycling tunnel sprayers have been also reported to be very high performing and environmentally safe equipment and after testing gave very good results in pome fruits (Balsari and Tamagnone, 1996; Doruchowski and Holownicki, 2000; Planas et al., 2002). In peach orchards, Ade et al. (2007) recovered about 20-30% of the sprayed liquid using tunnel sprayers, and Jamar et al. (2010) achieved dose reductions which ranged from 38% to 22% over the course of the growing season.

More recently, Tadić et al. (2014) reported dose reductions using directed spouts (individual outlets) fitted to a radial fan. Duga et al. (2015b) observed that cross-flow and directed spout sprayers resulted in higher in-canopy deposition than conventional sprayers (air-blast), and Wenneker et al. (2014, 2017 and 2018) concluded that the efficiency of multiple row sprayers, including recycling tunnel sprayers, was higher than that of conventional types.

In grapevine orchards, Viret et al. (2003) found that recycling tunnel sprayers achieved higher deposits at early (BBCH 14) and full-leaf stage (BBCH 77), with similar efficacy for the control of powdery mildew and a better prevention of drift in comparison to conventional air-assisted sprayers. These results are in agreement with Tamagnone et al. (2013), who also obtained an increase of 18-30% in leaf deposition with respect to a conventional air-assisted sprayer and to a multi-row sprayer. In this case, the tunnel sprayer allowed a dose reduction of 40-60% with similar disease control. Viret et al. (2005b) obtained a deposition at least 2.5 times greater when spraying with a recycling sprayer in comparison to standard sprayers. Pergher and Zucchiatti (2018) also analysed deposits from treatments with a recycling tunnel sprayer over the course of a whole season for LAI values ranging from 0.15 to 1.60, and found that the on-target recovery rate increased from 14.8% to 53.9%, while liquid recovered to the sprayer tank ranged from 67.2% to 31.0% (from early to full-leaf stages). Finally, in vineyards, in recent years, the authors of the present paper have also demonstrated the high performance of a large-scale recycling tunnel sprayer working in vineyards, with spraying efficiency of around 75% being attained at full-leaf stages (unpublished).

As for sprayer settings, a well-adjusted sprayer will allow improvements in treatment quality. Air flow direction and fan speed should also be taken into account to benefit deposition on both sides of the leaves and thus to improve efficacy (Cross et al., 2001; Pezzi and Rondelli, 2000). Finally, the experimentation with a recycling tunnel sprayer carried out by Carra et al. (2017) showed that increasing forward speed did not cause a decrease in mean foliar spray deposition when spraying vines.

The influence of the SVR and dose adjustment on biological efficacy have also been studied by different authors in fruit orchards (Antonin and Fellay, 1976; Fillat and Planas, 1989; Wicks and Nitschke, 1986). In this regard, Sedlar et al. (2013) found that a reduced application rate of 381 L ha^{-1} gave the same quality of crop protection as a medium application rate of 759 L ha^{-1} on apple orchards controlling scab and powdery mildew (Podosphaera leucotricha (Ell. et Ev.) Salm.).

In grapevine orchards, advanced sprayers improved spray deposition by a factor of two (Viret et al., 2005a) or three compared to conventional types (Siegfried et al., 2007). In this regard, multi-spout sprayers achieved higher deposition and uniformity than conventional air-blast sprayers (Pergher et al., 1997; Planas et al., 1993). Heinzlé et al. (2010) also reported that a 30% dose reduction can be acceptable when using side-by-side pneumatic and air-assisted hydraulic sprayers previously calibrated for the treatment of downy and powdery mildews in grapes. More recently, Codis et al. (2018b), comparing a pneumatic arch sprayer and an air-assisted side-by-side sprayer equipped with hollow cone nozzles, found higher normalized leaf deposits with the air-assisted sprayer throughout the season, particularly at the initial growth stages.

As a conclusion of this section, the sprayer type and setting parameters are important factors when determining the adjusted amount of pesticide to be applied. The use of efficient designs, properly adapted to the scenario architecture, and previously calibrated sprayers can result in valuable product savings, as well as a reduction of residues and the undesirable consequences of the use of pesticides.

3.4. Evaluation of dose adjustment

The effective surface deposit can be initially predicted from laboratory trials (Garcerá et al., 2011, 2012, 2014) and it can be easily and effective measured on leaves during in-field efficacy assessment by determining the a.i. or a tracer deposition per unit leaf surface area (μg cm^{-2}), as is established by the standard ISO 22522:2007 (ISO, 2007). In fact, this standard procedure is currently used for sprayer evaluation or efficacy interpretation at site level by many authors, including Balsari et al. (2005, 2009), Chueca et al. (2011), Codis (2016), Codis et al. (2017, 2018a, 2018b), Duga et al. (2013), Gil et al. (2007), Michielsen et al. (2015), Miranda-Fuentes et al. (2015, 2016), Planas et al. (2013, 2016, 2018), Román and Planas (2018), Román et al. (2019, 2020, 2021), Sinha et al. (2020), Verpont (2017), Wenneker et al. (2014, 2017, 2018), and Zande van de et al. (2018).

Koch and Knewitz (2011) proposed to evaluate spray applications by measuring spray deposits following the aforementioned standard and, instead of considering the mean values, suggested using the portion of targets with deposits lower than 5% of the nominal LWA dose (kg 10^4 m^{-2}), as efficacy occurs on individual targets. For a dose of 1 kg ha^{-1} LWA this threshold is equivalent to 0.5 μg cm^{-2}.

In 2007, Siegfried et al. realized that LAI dosage dependency (estimated through TRV) allows good efficacy against downy mildew and powdery mildew compared to unsprayed and standard dosage in vines and studied the particular case of two fungicides controlling downy mildew in experiments carried out in Switzerland. The amount considered necessary, including a margin of security of 30%, was 0.8 μg cm^{-2} of LA for azoxystrobin (Quadris 0.25% *w*/*v*) and 3.0 μg cm^{-2} for folpet (Folpet WDG 80%) and the doses applied throughout the season should range from 85 to 714 mL a.i. ha^{-1} for azoxystrobin and from 317 to 2600 g a.i. ha^{-1} for folpet (a variation in the LAI from 0.04 to 2.57 is considered along the season) (in Siegfried et al., 2007, Table 2). Consequently, the normalized depositions range between 946 and 115 ng dm^{-2} per g ha^{-1} for azoxystrobin and between 941 and 112 ng dm^{-2} per g ha^{-1} for folpet. These values were similar (in the same range) to the normalized depositions found by Codis et al. (2018b) and in University of Lleida trials (data unpublished), as shown in Fig. 1, for side-by-side hydropneumatic sprayers operating with hollow cone nozzles according to BBCH phenological growth stages.

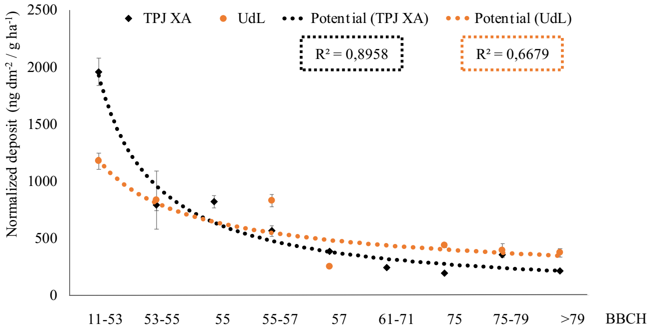

Fig. 1. Normalized leaf deposit (mean ± SE) of tracer achieved by a side-by-side (TPJ XA) hydropneumatic sprayer (data from Codis et al., 2018b) and University of Lleida (UdL) ISO 22522:2007 trials with side-by-side hydropneumatic sprayers (data unpublished) by phenological stage (BBCH scale).

All of these results argue in favour of referencing the target leaf surface area for optimal dose calculations, but show that deposition is not linearly proportional to the existing LAI and that other additional structural factors affect deposition that need to be accounted for when considering dose adjustment.

4. Decision support systems

Due to the risk of non-consistent dose rates, most advisors and end users regularly decide to apply standard (full) label doses. Nevertheless, there is an increasing number of users who try to spray at adjusted doses for an efficient and safe use of pesticides. Several DSSs are available to help them with the decisions that have to be made for each specific scenario. In all cases, it is assumed that a well-calibrated sprayer is operating in accordance with GAP in wall crops (hedgerow-or trellis-trained intensive orchards).

4.1. Pesticide adjustment to the crop environment (PACE)

The fundamentals of the PACE system were described by Walklate et al. (2003, 2006, 2008 and 2011) and updated after new LiDAR field measurements (Walklate and Cross, 2014). The system focusses on pome fruits and is based on the LWA model, considering CH, row distance and leafiness estimated by pictograms. The PACE DSS (www.pace.pjwrc.co.uk/) recommends a percentage of the full pesticide labelled dose in each specific scenario to manage the same pesticide deposits as in a standard crop in different scenarios. A lower dose limit is set in order to not compromise efficacy. An initial evaluation of the system for efficacy was performed by Cross et al. (2004). Nowadays, the system is not commonly used on farms at practical level.

4.2. Dosage adapté - Agrometeo (AGMET)

This system is based on work carried out in Switzerland and Germany by Siegfried et al. (2007) and Viret et al. (2005a, 2005b, 2007, 2010 and 2011). For deciduous fruits and vines, SVR and dose are adjusted according to the estimated LA after accounting for CH, mid-crown width and row distance. The model assumes a good correlation between LAI and TRV ($R^2 = 0.80$ for vineyards) and proposes dosage adaptation assuming that 100% of the registered dose should be applied to a standard fruit orchard with a TRV of 10,000 m^3 ha^{-1} by spraying 1600 L ha^{-1}. For vineyards, the standard TRV considered is 4500 m^3 ha^{-1} with an LAI of 1.66, equivalent to a theoretical median deposition of 2.4 μL cm^{-2} (Appendix A). The system has been validated for efficacy over a long period of trials, with reported savings of at least 20% of sprayed product (Viret et al., 2010; Viret et al., 2011; Dubuis et al., 2015). The system has been officially adopted in Switzerland, and is available at a website run by the Swiss Federal Government (www.agrometeo.ch).

4.3. OPTIDOSE

Optidose was launched in 1996 by the French Institute of Vine and Wine. It is a complete system which considers TRV parameters (height, width and row spacing), the target biomass associated to the growth stage (up to 41 different stages), disease pressure, vineyard cultivar sensitivity to downy and powdery mildews and sprayer efficiency forecasted by the user. This last factor can only be considered in the case of low disease pressure. The system recommends dose reduction in relation to the label dose, and is expressed as maximum kg or L of product per unit of crop ground area. The SVR is not indicated as in France very low volumes provided by pneumatic sprayers are mainly used at the moment. This DSS has been validated for the control of downy and powdery mildews since 2004 (Davy et al., 2010, 2013; Heinzlé et al., 2010). The OPTIDOSE system is available at www.vignevin-epicure.com/index.php/fre/optidose2/optidose and is widely used by French growers.

4.4. DOSAVIÑA

The background to the development of the Spanish DSS called DOSAVIÑA was presented by Gil (2003), Gil and Planas (2003) and Gil et al. (2005). The DSS was subsequently developed to determine the SVR in vineyards on the basis of TRV dimensions or the LAI, estimated from a database considering four growth stages, and the sprayer characteristics and operating conditions (Gil and Escolà, 2009). It was then validated *vs.* standard SVR applications, allowing average pesticide savings of 40% and with positive preliminary results in the control of powdery mildew in cv. Merlot and Cabernet Sauvignon in Lleida (Spain), and of botrytis bunch rot *(Botrytis cinerea)* and grape black rot *(Guinardita bidwellii)* in cv. Riesling in New York State (US) (Gil et al., 2011). The system has recently been updated (Gil et al., 2019), considering LWA, canopy width, leaf density and sprayer efficiency, and established 0.037 L m^{-2} of LWA (equivalent to 0.093 L m^{-3} of TRV, for a standard canopy width of 0.8 m), as the basic SVR. This value matches exactly the previously mentioned ratio established by Byers et al. (1971) for runoff conditions when spraying pome fruits and is close to the ratio suggested by Herrera-Aguirre and Unrath (1980) for apple orchards.

This ratio was evaluated for coverage and impacts by means of water-sensitive papers (Gil et al., 2019; Campos et al., 2020). DOSAVIÑA is available at https://dosavina.upc.edu/ and as an app for smartphones.

4.5. DOSA3D

Initially named DOSAFRUT, this DSS was developed in Spain and introduced by Planas et al. (2006) to determine the SVR in pome fruit orchards, considering the LAI and spraying efficiency. The first expression to calculate the optimal SVR was proposed according to Eq. (3):

$$V = \frac{2 * 10^4 * D * LAI}{E} \tag{3}$$

where *V* is the volume rate (L ha^{-1}), *LAI* is estimated through canopy dimensions and leafiness, *D* is the intended liquid average deposit or dosage index (L m^{-2}) and *E* is the spraying efficiency (%).

Similarly, the LAI was also considered by Pergher and Petris (2008) for dose application rates according to Eq. (4):

$$Q = \frac{2 * 10^2 * d * LAI}{e} \tag{4}$$

where *Q* is the application dose rate (g ha^{-1}), *d* is the intended average foliar deposit (μg cm^{-2}), *LAI* is the leaf area index, and *e* is spraying efficiency (%). Factor 2 is included to account for both leaf sides.

Later, Planas et al. (2011, 2012, 2013) proposed to establish the volume to be sprayed through Eq. (5) for a constant concentration of spray liquid.

$$V = \frac{120 * LAI}{E} \tag{5}$$

where V is the volume rate (L ha^{-1}), LAI is estimated from the CH, mid-crown width and leafiness valued by pictograms, and E is the spraying efficiency (%). Factor 120 corresponds to the theoretical base deposit rate, established as 100 droplets per cm^{-2} with a robust diameter of 225 μm, equivalent to 0.6 μL cm^{-2} or 1.2 μL cm^{-2} if both sides of the leaf are considered.

The system was updated after accurate and extensive canopy characterization using LiDAR and LA measurements (Sanz et al., 2018). It was also validated for efficacy in 20 comparative trials conducted in pome and stone fruit orchards located in Lleida (Spain), with reported pesticide savings of between 14% and 53% (Planas et al., 2013, 2016; Solanelles et al., 2013). Later, the DSS was expanded to grapevine, citrus, intensive almonds and olive orchards providing a common tool for all the main 3D crops grown in the ESZ (Planas et al., 2018, 2019). The pictograms were replaced by 3 growth states to simplify the DSS. It has also been evaluated for efficacy in vineyards to control yellow spider mite *Eotetranychus carpini* (Oud.), leafhoppers *Empoasca vitis* Göethe and *Jacobiasca lybica* Bergenin & Zanon (Román et al., 2021) and powdery mildew, as well as for the main pests and diseases affecting pome fruit orchards in Catalonia (Spain) (Román et al., submitted). DOSA3D is nowadays widely used, recommended by the Plant Health Services of the Catalan Regional Government (http://agricultura.gencat.cat/ca/ambits/agricultura/dar_sanitat_vegetal_nou/mitjans-defensa-fitosanitaria/) and is available at http://dosa3d.cat/en and as a smartphone app.

4.6. Orchardmax (OMAX)

This system was developed in 2013 by the Ontario Ministry of Agriculture and Rural Affairs (Canada) (Deveau, 2017; OMAFRA, 2017) to improve sprayer efficiency for apple orchards. It is based on the crop-adapted spraying model which was tested in semi-dwarf and high-density apple orchards in Ontario and Nova Scotia. To calculate dose reduction, it considers TRV canopy dimensions, growth stage (2 levels: until petal fall and until the end of the season) and leafiness by means of pictograms. Finally, it assumes 0.06 L m^{-3} for a suitable leaves coverage (10-15%), comprising a minimum 85 medium-sized droplets per cm^2. The system does not advise a SVR below 400 L ha^{-1}, considering that the majority of pesticides have their efficacy tested at 1000 L ha^{-1} and doses less than 50% the labelled rate are not recommended. OMAX is available as a smartphone app.

4.7. PULVARBO

This DSS has recently appeared in the framework of the national French Ecophyto II program for reduction of pesticide use. It is the result of work started in 2015 involving several R + D institutes (Verpont, 2017).

PULVARBO establishes a reference value of 17,000 m^2 LWA ha^{-1} to decide the adjusted dose to by applied. When the LWA dimension of the orchard is under this value, the dose to be applied, in relation to the label dose, should be proportional to the ratio between the LWA of the orchard and the reference LWA. Otherwise, if the LWA is over the reference value, the ratio for adjustment depends on the combination of the CH, canopy width and the BBCH growth stage.

PULVARBO is suitable for apple orchards and some restrictions are established in cases of high disease pressure. The DSS has been widely validated following 35 efficacy trials carried out in different fruit regions in France (Verpont, 2021).

4.8. Comparison between decision support systems

A summary of the characteristics and differences between the DSSs described above is shown in Table 1. The PACE system is based on the LWA index for dose recommendation, while the other systems include mid-crown width as a factor to estimate the SVR as used in the TRV system. The DOSA3D calculation is established on the basis of LAI estimation. All the systems require information on height, mid-crown width (excluding PACE), row spacing and canopy density (leafiness) and/or growth stage. Sprayer performance is generally considered too. Regarding to the SVR, all the systems provide an optimum value with exception of the PACE and both French, OPTIDOSE and PULVARBO, systems. Finally, it should be noted that AGMET, DOSA3D and OMAX systems establish a lower SVR threshold to ensure a MED for any orchard scenario.

Very recently, EPPO has advocated for deposit level as a criterion to achieve an expected efficacy under specific circumstances of canopy size and density (leafiness), BBCH growth stage, application method, organism to be controlled and climatic factors (EPPO, 2021). In this context, it should be underlined that, with the exception of climatic factors, only DOSA3D and OPTIDOSE systems consider all of these parameters to establish the optimum SVR and dose, with both systems estimating LA by growth stage. The PACE system does not consider

Table 1
Summary of characteristics and performances for volume or dose adjustment by decision support systems.

DSS	PACE	AGMET	OPTIDOSE	DOSAVIÑA	DOSA3D	OMAX	PULVARBO
Fruit (F)	*	*	–	–	*	*	*
Vine (V)	–	*	*	*	*	–	*
Canopy height (CH)	*	*	*	*	*	*	*
Canopy mid-crown width	–	*	*	*	*	*	*
Canopy leafiness -porosity (levels)	*	–	–	* (4)	–	*(5)	–
Row spacing	*	*	*	*	*	*	*
Growth stage (levels)	* (3)	–	* (41)	–	* (3)	*(2)	*(2)
Leaf area estimation	*	*	*	–	*	–	–
Sprayer efficiency	–	–	*	*	*	*	–
Pest or disease pressure	–	–	*	–	*	–	*
Base for ratio calculation (index)	(a)	(b)	–	(c)	(d)	(e)	(f)
Min dose or volume rate (L ha^{-1})	*	(F) 200	–	–	(F) 100*CH (m) (V) 150	(F) 400	–

a: Height / row spacing as LWA estimator (Walklate et al., 2003).
b: (F) 0.02 + 200/TRV L m^{-3} (Siegfried et al. (1995); (V) 0.07-0.13 L m^{-3} (Siegfried et al., 2007) (Appendix A).
c: (V) 0.037 L m^{-2} LWA, equivalent to 0.079-0.107 L m^{-3} TRV (for different canopy width factors) (Gil et al., 2019).
d: (F, V) 1.2 μL cm^{-2} (Planas et al., 2013).
e: (F) 0.06 L m^{-3} TRV (Deveau, 2017).
f: (F) LWA when LWA <17,000 m^2 LWA ha^{-1}, and TRV when LWA >17,000 m^2 LWA ha^{-1}) (Verpont, 2021).

Table 2
Characteristics of hypothetical scenarios used for DSS comparison. Leaf area index (LAI) estimated by the DOSA3D and AGMET systems (N/A: not available).

	Scenario	Growth stage	BBCH	Canopy dimensions		Row spacing (m)	LWA	TRV	LAI	
				height (m)	width (m)				DOSA3D	AGMET[a]
Pome fruit orchard	1	From petal fall	71-75	2.2	0.5	3.6	12,222	3056	0.61	N/A
	2	Fruit half final size	76-89	2.6	1.5	4.0	13,000	9750	1.85	N/A
	3	Fruit half final size	76-89	3.8	2.2	4.0	19,000	20,900	3.62	N/A
Grapevine orchard	4	Pre-flowering	11-53	0.4	0.2	2.8	2857	286	0.18	0.05
	5	Flowering	55-69	0.8	0.5	2.8	5714	1429	0.73	0.40
	6	From fruit set	71-89	1.2	0.8	2.8	8571	3429	1.48	1.14
	7	From fruit set	71-89	1.7	1.0	2.8	12,143	6071	2.03	2.57

[a] Siegfried et al., 2007 (see appendix A).

canopy width, AGMET ignores leaf density (and no consideration is given to growth stage), PULVARBO considers growth stage but ignores leafiness and LA, and DOSAVIÑA and OMAX estimate porosity but not LA.

The parameters considered for TRV calculation (height, width and row spacing) are very easily measured. Consequently, the AGMET, DOSAVIÑA and OMAX systems provide the volume to be sprayed directly from the TRV value. Nevertheless, the indexes used for the base calculation from these DSS (Table 1) do not coincide. The OMAX systems assumes the constant value of 0.06 L m^{-3}. Instead of that, the DOSAVIÑA system assumes the reference value of 0.093 L m^{-3} and, depending on canopy width, adjusts the value within the range 0.079-0.107 L m^{-3}. Finally, the AGMET system adjusts the value of the ratio to the estimated LA, ranging in vineyards from 0.07 to 0.13 L m^{-3}.

In contrast, the DOSA3D system works on the basis of direct estimation of the LAI and providing the optimal spraying volume assuming a volume average deposition of 1.2 μL cm^{-2}. This value coincides with the median volume deposition value adopted in the AGMET system (1.2 μL cm^{-2}) for a spraying efficiency of 50%, typical for conventional air-assisted sprayers (see Appendix A, data from Siegfried et al., 2007).

The volumes and doses recommended of the considered systems have been analysed for fruit and vine orchards in seven hypothetical scenarios described in Table 2.

The specific conditions that were entered into the different DSSs to calculate the volume and dose rates for each scenario are listed below, and the results are shown in Table 3:

- In all systems, a conventional sprayer (air-assisted) is operating.
- For PACE, standard number of branches and mean growth rate, standard disease.
- For OPTIDOSE, mildew and powdery mildew medium risk, normal sensitivity of the variety, growth stages from inflorescence to berry colour development (scenarios 4 to 7), no dose reduction due to sprayer performance.
- For DOSAVIÑA, canopy density ranges from very low to very dense (scenarios 4 to 7), reference dose equivalent to a volume rate of 1000 L ha^{-1} at the labelled concentration.
- For DOSA3D, pests not requiring additional SVR, reference dose equivalent to a SVR of 1000 L ha^{-1} at the labelled concentration.
- For OMAX, matching trees, spraying every row, cubic canopies, moderate density (scenarios 1, 2), high density (scenario 3).
- For PULVARBO, apple for fresh consumption, low pressure of powdery mildew and tortrix moth group.

5. Discussion

The volume and dose recommended by each system differ because the basis for their calculation varies between the systems and is the result of the application of different correction coefficients related to the specific scenario.

As expected, all the DSSs provided increased SVR (L ha^{-1}) and doses as canopy dimensions and leafiness increased and as the season progressed too. Only the OMAX system gave similar values for fruit at the initial and medium stages (scenarios 1 and 2) due to the minimum threshold of 400 L ha^{-1} which applies at the initial stage (Table 3).

As regards SVR, the DOSA3D was more conservative, both for pome and grapevine orchards. This is a consequence of the reduced spraying efficiency values considered by the DOSA3D, in accordance with the situation at farming level (less than 50% for the sprayer type considered). In contrast, in practically all scenarios, the AGMET system provided the lowest volumes rates (L ha^{-1}) in both crops. However, the lower volume rate (L ha^{-1}) for AGMET tended to be compensated for by a higher percentage of the reference dose (Table 3).

This analysis can be quantified by means of the ratio (R) (Table 4) calculated according to Eq. (6).

$$R = SVR/TRV \tag{6}$$

where SVR is the spraying volume rate shown in Table 3 and TRV the tree volume rate shown in Table 2.

In pome fruit (scenarios 1 to 3), the ratio described on the AGMET website is the exact result of the equation proposed by Siegfried et al. (1995) shown in Table 1. With the exception of the DOSA3D and OMAX systems at initial stage (scenario 1), the R values observed are below the ratios established for fruit by the previously mentioned pioneer authors, 0.093 L m^{-3} (Byers et al., 1971; Byers, 1987), 0.116 L m^{-3} (Herrera-Aguirre and Unrath, 1980), 0.133 L m^{-3} (Sutton and Unrath, 1984) and > 0.093 L m^{-3} for TRV > 23,000 m^3 ha^{-1} (Manktelow and Praat, 1997). This is probably due to two reasons. Firstly, the evolution in the dimensions and geometry of canopies over the last few decades towards a more efficient architecture (smaller dimensions and progressive wall shape), and secondly the continuous improvements

Table 3
Spraying volume rate (L ha^{-1}) and adjusted dose (% of reference dose) established by the analysed decision support systems in the scenarios defined in Table 2 (N/A: not available).

	Scenario	PACE	AGMET	OPTISOSE	DOSAVIÑA	DOSA3D	OMAX	PULVARBO
Pome fruit orchard	1	(61%)	261 (63%)	N/A	N/A	490 (49%)	400 (40%)	(72%)
	2	(76%)	395 (100%)	N/A	N/A	730 (73%)	410 (41%)	(76%)
	3	(100%)	618 (148%)	N/A	N/A	1000 (100%)	878 (125%)	(100%)
Grapevine orchard	4	N/A	50 (9%)	(60%)	108 (11%)	150 (15%)	N/A	N/A
	5	N/A	100 (36%)	(60%)	228 (23%)	240 (24%)	N/A	N/A
	6	N/A	260 (71%)	(80%)	438 (44%)	460 (46%)	N/A	N/A
	7	N/A	550 (178%)	(60%)	503 (50%)	630 (63%)	N/A	N/A

Table 4
Ratio (R) of spraying volume rate to Tree Row Volume (L m^{-3} TRV) for scenarios defined in Table 2.

	Scenario	AGMET	DOSAVIÑA	DOSA3D	OMAX
Pome fruit orchard	1	0.085	N/A	0.160	0.131
	2	0.041	N/A	0.075	0.042
	3	0.030	N/A	0.048	0.042
Grapevine orchard	4	0.175	0.378	0.525	N/A
	5	0.070	0.160	0.168	N/A
	6	0.076	0.128	0.134	N/A
	7	0.091	0.083	0.104	N/A

in spraying techniques for tree crops. Both these factors have resulted in increased spraying efficiency, allowing for a better adjustment of the volume to be sprayed.

In grapevine orchards, for all growing stages (scenarios 4 to 7), the AGMET system showed ratios lower than the other DSSs, with DOSA3D always giving the highest values. Exceptionally, DOSAVIÑA shows the lowest value for the final stage (scenario 7). This is the consequence of the lower volume rates established by the AGMET system (Table 3), and of the reduced spraying efficiency values considered by the DOSAVIÑA and DOSA3D systems. For scenario 7, where the SVR proposed by the AGMET system is close to the others (Table 3), the R value is also in the same order of magnitude.

Comparing DOSAVIÑA and DOSA3D, the R values of the DOSA3D system always remain slightly above those of DOSAVIÑA (Table 4), but the recommended volumes are quite similar for both systems (Table 3), with the exception of scenario 4 where DOSA3D calculates on the safe side establishing a minimum threshold volume of 150 L ha^{-1}.

As regards the coefficient for dose adjustment (% of reference dose) recommended by each system (Table 3), there is a certain similarity in magnitude with the exception of AGMET at the final stage (scenarios 3 and 7) and OPTIDOSE at the initial stage (scenario 4). This different approach to the two ends of the spraying period could conclude in important differences in deposition with regard to the other systems.

5.1. Effective dose comparison

Spray deposition is a key element for successful pests and diseases control. For grapevine orchards (scenarios 4 to 7), the hypothetical depositions were calculated when spraying to control downy mildew according to the recommendations of each DSS, as shown in Table 3. The two previously mentioned products containing folpet or azoxystrobin (Siegfried et al., 2007) were considered. Their content and authorized dose (kg ha^{-1}) for the respective countries are shown in Table 5. Adopted doses are expressed as crop ground area (kg ha^{-1}) with the exception of QUADRIS in Spain where the dose considered is expressed in concentration (0.2%) for a reference volume of 1000 L ha^{-1} (this is equivalent to 2.0 kg ha^{-1} of formulated product). The expected product mass deposition was established according to the ratio between the a.i. dose applied and the LAI indicated in Table 2, taking into account an efficiency of 25% for scenario 4 (initial stage) and an efficiency of 50% for the other scenarios (5 to 7). The LAI estimated by the DOSA3D system was used, except for the AGMET system in grapevine orchards for which the LAI values are those considered by the system itself (Appendix A). The expected results for folpet and azoxystrobin leaf deposition when spraying according to each DSS are shown in Fig. 2.

Table 5
Equivalent formulated products containing folpet (FOLPET) or azoxystrobin (QUADRIS) as a.i. authorized in the countries where the compared DSSs are currently in use.

	Switzerland (AGMET)	France (OPTIDOSE)	Spain (DOSAVIÑA, DOSA3D)
Product	FOLPET 80 WDG	FOLPET 80% WG	FOLPAN 80 WDG
Content a.i.	80%	80%	80%
Dose (kg ha^{-1})	2.50	1.87	1.80
Dose (kg a.i. ha^{-1})	2.00	1.50	1.44
Product	QUADRIS[a]	QUADRIS EXPRESS	QUADRIS
Content a.i.	25%	50%	25%
Dose (kg ha^{-1})	1.50	0.50	1.00
Dose (kg a.i. ha^{-1})	0.37	0.25	0.25
Dose (max. concentration)	N/A	N/A	0.20%

[a] Product currently removed from the Swiss registration list.

For both fungicides, at the initial stage (scenario 4), OPTIDOSE shows a very high expected deposition value compared to the other DSSs. This is a consequence of the higher value of the coefficient used for OPTIDOSE dose adjustment at this stage (Table 3). At this initial stage, this system could overdose and waste a significant amount of pesticide. When comparing systems for expected deposition, at the intermediate and final stages (scenarios 5 to 7), the AGMET system always shows values above the other systems. This is a consequence of the differences between countries in terms of established dose (Table 5) and of the coefficient for dose reduction for the final stage (scenario 7) (Table 3) where AGMET values are considerably higher.

For DOSAVIÑA and DOSA3D systems, deposition of folpet is normally under the efficacy threshold, including a margin of security of 30% (3.0 μg cm^{-2}) indicated by Siegfried et al. (2007). The lowest value (1.77 μg cm^{-2}) corresponds to the expected deposition for DOSAVIÑA at the last growing stage (scenario 7) being also visibly under the base threshold (2.3 μg cm^{-2}). This could lead to a risk situation from the point of view of efficacy. Nevertheless, the rest of the values for DOSAVIÑA are very closed to the base efficacy threshold and, consequently, efficacy level could be acceptable. The same applies to DOSA3D system that achieves results slightly better than DOSAVIÑA in some cases being above or very close to the base threshold.

Deposition of azoxystrobin is normally above or close to the efficacy threshold (0.8 μg cm^{-2}) stated by the same authors and in all cases upper the base threshold (0.6 μg cm^{-2}). In general terms, efficacy seems to be ensured.

It can therefore be concluded that differences in the labelled doses and in the dose adjustment coefficient lead to important differences in the expected deposition, which in some cases is below the efficacy threshold indicated by Siegfried et al. (2007). These differences could be justifiable by the country-specific character of disease pressure and/or varietal sensitivity to downy mildew. This means that normally the number of annual treatments and the recommended doses in Switzerland and France are significantly higher than those required in Spain. These differences highlight the need for dose harmonization and clarification of the efficacy deposition threshold.

High variability among depositions in 3D crops has been reported by several authors, including Koch and Knewitz (2011) and Planas et al. (2016). Because of this variability at specific canopy site (target) level, global efficacy cannot be guaranteed. Undoubtedly, the actual deposition at some specific canopy sites will be below the efficacy thresholds, and the control level may be insufficient. For this reason, some chemical treatments fail in their goal of controlling pests and diseases.

To prevent this possibility of lower dosing, the DOSA3D system includes a methodology to establish the minimum crop ground dose (kg ha^{-1}) to be applied at a spraying volume considerably below the SVRs usually employed for efficacy evaluation in pre-registration trials. The methodology is named Green Way (DOSA3D, 2019).

5.2. Volumetric deposition comparison

All the DSSs which recommend SVRs (AGMED, DOSAVIÑA, DOSA3D and OMAX) provide decreasing volumetric depositions when the SVR refers to the LAI (Fig. 3.A and 3.B for fruit and grapevine orchards, respectively). The same criteria for spraying efficiency were taken into

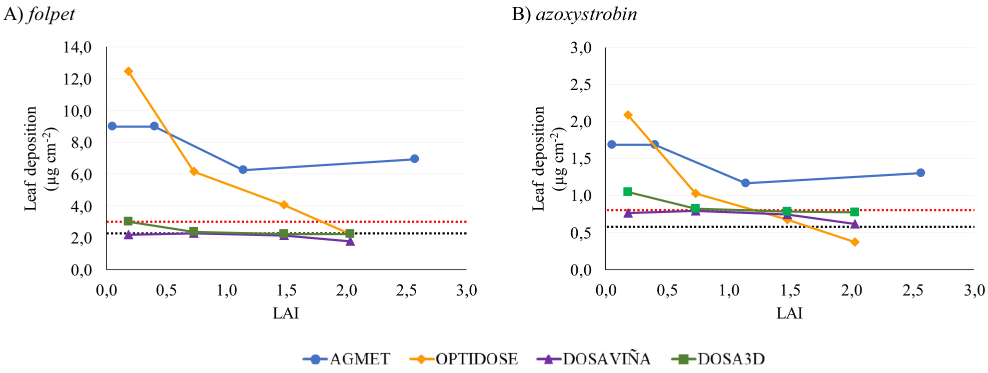

Fig. 2. Expected product mass deposition (µg cm^{-2}) when applying the formulated products of a) folpet and b) azoxystrobin according to Table 5 at the adjusted dose established in Table 3 for the different decision support systems. Expected depositions are calculated accounting for the leaf area index (LAI) of the different scenarios set in Table 2. Red dotted lines indicate the deposition threshold including the safety margin of 30% (3.0 µg cm^{-2} and 0.8 µg cm^{-2} for folpet and azoxystrobin, respectively) and black dotted lines the base threshold (2.3 µg cm^{-2} and 0.6 µg cm^{-2} for folpet and azoxystrobin, respectively).

account (25% for scenarios 1 and 4 and 50% for the other scenarios) and the LAI estimated by the DOSA3D system was used, except for the AGMET system in grape orchards for which the LAI values are those considered by the system itself (Appendix A).

With the exception of AGMET in fruit at the final stage, the calculated deposits are close to or above the threshold (base) for DOSA3D calculation (1.2 µL cm^{-2}) and the median deposition considered for the AGMET system (identical value). Consequently, in general, the SVR established by each DSS can be considered sufficient for pest control objectives.

Similar to what happened with the volumes and ratios, DOSA3D is again found to be the most conservative system. In terms of expected volumetric deposition, this DSS has in all cases a robust security margin with respect to the 1.2 µL cm^{-2} threshold. This is a coherent result from the point of view of efficacy but could be associated to pesticide waste. Conversely, from the mid stages onwards, the AGMET system provides deposition values below the considered threshold, as does OMAX on one occasion. In this case, pesticide waste is probably diminished but efficacy could be compromised. Again, the action of the pesticide at specific site level could be critical.

The challenge is to obtain the deposition threshold at all target sites. This objective is technically not feasible but something that is worth attempting to get as close to as possible. Mean deposition values could hide an important portion of depositions below the effective dose, with the result being compromised efficacy at those specific sites where pests can remain as reservoirs. Consequently, mean values are insufficient for information on pesticide deposition and statistical analyses of deposition variability should be provided by the chemical industry in the dossier for pesticide registration.

6. Conclusions and recommendations

It can be concluded that LAI is the most rational parameter for dose expression. LA can be easily estimated from crop dimensions and growth stage or leafiness, as is done in the DOSA3D system, and has previously been suggested for use in trials in the registration process.

Even though the TRV model correlates better with LAI than the LWA model, both expressing models are supported by EPPO to facilitate the zonal mutual recognition. They represent a substantial improvement compared to the former concentration and crop ground-based dose expression models which remain in force in the ESZ. The LWA model has already been adopted by the Central Zone Steering Committee for evaluation trials in the registration process and several countries in the ECZ have registered pesticides whose dose is expressed in this model.

The sprayer is also a determining factor of the amount of pesticide to be applied. However, high-efficiency sprayers are not yet widely used and the training of users in the calibration of such equipment must be implemented when the intention is to reduce doses. General actions to promote the renewal and maintenance of the equipment and good practices will also undoubtedly have beneficial results.

The different DSSs analysed in this paper consider partially or totally these adjustment factors for the establishment of optimal volume and dose rates in particular scenarios. The DSSs considered do not always provide equivalent results in terms of product per crop ground area and the expected on-target deposition. Nevertheless, the expected volumetric depositions are, in the majority of situations, similar to or above the deposit efficacy threshold (1.2 µL cm^{-2}) considered for the DOSA3D system, which has been shown to be the most conservative system. Consequently, while efficacy seems to be ensured in all situations,

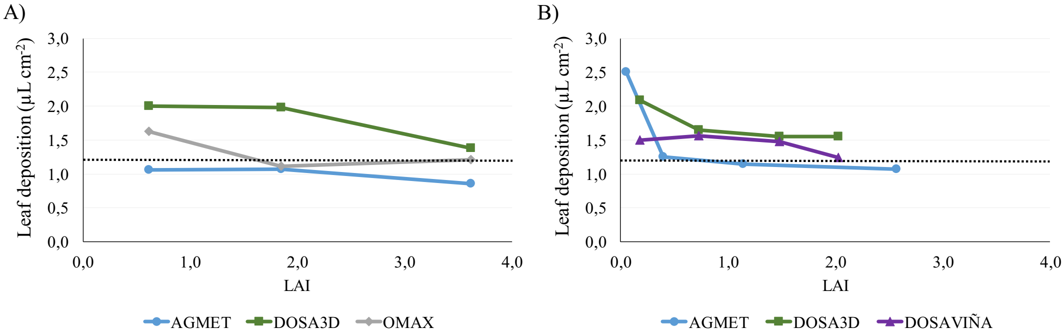

Fig. 3. Expected volumetric depositions (µL cm^{-2}) in A) fruit orchards and B) grapevine orchards, for 50% spraying efficiency, when spraying at the adjusted volume rates established in Table 3 for the different decision support systems in the consecutive scenarios reported in Table 2. Dotted lines indicate the volumetric deposition threshold for the DOSA3D system (1.2 µL cm^{-2}).

dose harmonization and clarification of the efficacy deposition threshold need to be addressed. Nonetheless, all the analysed DSSs are powerful and useful tools for rational decision-making about volume and pesticide doses. Their use should be promoted by the authorities.

For all the considered DSSs, the recommended SVR are below the ratio values that were initially established by different authors in the US when work first began on rationalizing pesticide dosing. This reflects the improvements that have been made in spraying techniques and the systematic reshaping of orchards which have resulted in an important increase in efficiency.

Pesticide deposition on leaves (μg cm^{-2}) is a parameter that is directly related to biological efficacy and enables reliable comparisons between different situations. Therefore, an important pending issue is the minimum effective dose (minimum deposit) required for consistently good efficacy against pests. Minimizing the sites with deposition rates below the effective threshold must be the objective in order to ensure the optimal control of pests and diseases.

Consequently, deposition on leaves should be reported in pesticide efficacy evaluations in order to establish the required doses independently of the dose expression model. For deposition measurements, the international standard ISO 22522:2007 should be taken into account. This standard has been welcomed positively and extensively used by researchers and technicians dealing with spray evaluations.

Contrary to chemical industry considerations reported in Garcerá et al. (2021), it should be reported the deposition that achieves the expected efficacy in the pre-registration trials. The information provided should include not only mean values but also a variability analysis that includes the proportion of samples under the value considered as threshold. The associated cost of deposition assessment is negligible (non-relevant) and totally affordable for the industry in the context of the overall cost of the pesticide registration process. The benefits in terms of human and environmental safety, and economy for growers are more than compensatory.

In the short term, all these actions (adjusting volume and dose rates through the use of DSSs, improvements to spraying equipment and information on minimum deposits in efficacy trials) contribute to reducing overall pesticide use and help to meet the European objectives of the Farm to Fork strategy, as well as the objectives of official programs for the rational use of pesticides worldwide.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

According to Siegfried et al. (2007) from its Table 2 it can be deduced that volume rate (V) is dependent on leaf area index (LAI) [$V = 198 * LAI + 42$]. Hence, the ratio V/TRV is assessed in Table A.1 of this paper.

Theoretical leaf deposition can be calculated from V and LAI. If an efficiency of 100% is considered (all the spray is deposited on the target), depositions vary between 12.5 and 2.1 μL cm^{-2}. However, the reality is that sprayers are not 100% efficient. Therefore, the efficiency is shown at 50% which is a representative value for standard sprayers. In this case, as is highlighted in red in Table A.1, the median deposition is exactly the threshold proposed by DOSA3D (1.2 μL cm^{-2}).

Table A.1

Calculations to determine theoretical leaf deposition through data from Siegfried et al., 2007. TRV: Tree Row Volume. LAI: Leaf area index. V: Volume rate. E: Efficiency.

Data from Siegfried et al., 2007					Deposition	
			V	Ratio V/TRV	(E = 100%)	(E = 50%)
TRV	LAI	V (L ha^{-1})	L ha^{-1}		μL cm^{-2}	μL cm^{-2}
400	0.04	50	50	0.13	12.5	6.25
600	0.08		58	0.10	7.2	3.62
800	0.12		66	0.08	5.5	2.74
1000	0.17	75	76	0.08	4.5	2.23
1200	0.23		88	0.07	3.8	1.90
1400	0.28		97	0.07	3.5	1.74
1600	0.35		111	0.07	3.2	1.59
1800	0.42		125	0.07	3.0	1.49
2000	0.49	150	139	0.07	2.8	1.42
2200	0.56		153	0.07	2.7	1.36
2400	0.64		169	0.07	2.6	1.32
2600	0.73		186	0.07	2.6	1.28
2800	0.81		202	0.07	2.5	1.25
3000	0.90	250	220	0.07	2.4	1.22
3200	0.99		238	0.07	2.4	**1.20**
3400	1.09		258	0.08	2.4	1.18
3600	1.19		277	0.08	2.3	1.17
3800	1.29		297	0.08	2.3	1.15
4000	1.39	350	317	0.08	2.3	1.14
4200	1.50		339	0.08	2.3	1.13
4400	1.61		360	0.08	2.2	1.12
4600	1.72		382	0.08	2.2	1.11
4800	1.83		404	0.08	2.2	1.10
5000	1.95	450	427	0.09	2.2	1.10
5200	2.07		451	0.09	2.2	1.09
5400	2.19		475	0.09	2.2	1.08
5600	2.32		501	0.09	2.2	1.08
5800	2.44		524	0.09	2.1	1.07
6000	2.57	550	550	0.09	2.1	1.07

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