Pesticide dose adjustment in 3D crops

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TESI DOCTORAL

Pesticide dose adjustment in 3D crops

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Ajuste de dosis de pesticidas en cultivos 3D

Tesis doctoral

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EXCELLENCE IN FOOD AND AGRICULTURE RESEARCH

DOSA3D

A mis familias,

las de sangre y la de vida

Sine agricultura, nihil

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Carla Román Rochina

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Índice de contenido

Resumen

En la situación de crecimiento continuado de la población mundial, la producción suficiente de alimentos no puede ser garantizada sin los productos fitosanitarios (PF). No obstante, su empleo no está exento de graves dificultades como el elevado coste de los programas de lucha química contra las plagas y enfermedades que, para el caso de la producción frutal y el viñedo, pueden representar hasta el 30% del total de los costes de producción. Además, el uso de PF conlleva riesgos importantes para la salud humana y el medio ambiente. A todo ello hay que añadir la desconfianza creciente, cuando no el rechazo, de amplias capas de la sociedad en relación a los PF.

Para reducir su impacto, la Comisión Europea mediante el pacto verde y, en concreto, a través de la estrategia de la granja a la mesa, pretende reducir el consumo y el riesgo asociado a los PF en un 50% para el año 2030. En este contexto, se hacen necesarias herramientas científico-técnicas validadas para el ajuste de las dosis a las mínimas imprescindibles sin comprometer la cosecha.

En esta Tesis se presenta y valida el sistema de ayuda a la toma de decisión DOSA3D, el cual permite ajustar el volumen de caldo y la dosis de PF en cultivos arbóreos (o cultivos 3D) a partir de las características del cultivo (área foliar objetivo y geometría), el pulverizador y la plaga o enfermedad a controlar.

La validación del sistema DOSA3D se ha llevado a cabo en tratamientos uniformes y en tratamientos zonales en base a mapas de vigor atendiendo a dos criterios, las deposiciones sobre el objetivo tratado y la eficacia en el control de plagas y enfermedades. A tal fin, las hipótesis contrastadas han sido: i) el *Leaf Area Index* (LAI) o índice de área foliar (parámetro más relevante para el ajuste de la dosis) es estimado correctamente a partir de la geometría de la vegetación y del estado fenológico del viñedo; ii) la eficiencia del pulverizador calculada mediante el sistema DOSA3D se ajusta a la realidad operativa de los tratamientos; iii) la deposición en hojas es un parámetro que se relaciona bien con la eficacia biológica del tratamiento; iv) el volumen de caldo establecido por el sistema DOSA3D permite obtener deposiciones similares al objetivo umbral (1.2 µl cm^{-2}) y, consecuentemente, conseguir la eficacia adecuada; y, v) el tratamiento zonal en viñedo a partir de mapas de vigor, ajustando la dosis mediante el sistema DOSA3D, permite alcanzar deposiciones óptimas y la eficacia biológica esperada en los distintos vigores.

El cuerpo de la Tesis se divide en tres bloques. El primero está dedicado a la revisión del estado del arte en materia de la expresión y ajuste de la dosis y a la comparación entre los diferentes sistemas al uso para el ajuste de la dosis.

El segundo bloque de la tesis incluye dos capítulos dedicados a los fundamentos del sistema DOSA3D y a su validación en viñedo. Para ello se han practicado defoliaciones de tramos de vides en espaldera, dándose por válido el modelo de estimación del LAI del sistema DOSA3D para espalderas de hasta 1.25 m de anchura. Asimismo, mediante la norma ISO 22522:2007, se ha determinado la deposición foliar, lo que ha puesto de manifiesto la tendencia marcada a la homogenización de las deposiciones en la medida que incrementa el LAI. También, el sistema DOSA3D ha sido validado a lo largo de toda la campaña por eficacia en el control de oídio (*Erysiphe necator* Schw.) en cuatro ensayos independientes en los que se ha reducido la dosis entre 0% y 60% respecto a la aplicada por el agricultor.

En el tercer bloque se han validado los tratamientos zonales a dosis ajustadas mediante el sistema DOSA3D en viñedos espacialmente variables. Mediante el índice de vigor *Plant Cell Density* (PCD), establecido a partir de imágenes multiespectales adquiridas desde avión, se han confeccionado mapas de clasificación zonal en dos vigores y el consiguiente mapa de prescripción. La deposición foliar no ha presentado diferencias significativas entre clases de vigor y la eficacia de los tratamientos en el control de ácaro amarillo (*Eotetranychus carpini* Oud.) y mosquito verde (*Empoasca vitis* G. y *Jacobiasca lybica* Berg. & Zanon) han permitido situar la densidad de las plagas por debajo de los umbrales económicos de daño en ambas clases de vigor, comportando ahorros de PF entre el 16.6 y el 24.8% en las zonas de bajo vigor.

Las conclusiones obtenidas en la presente tesis proporcionan las evidencias científico-técnicas necesarias para utilizar el sistema DOSA3D de manera sanitariamente segura (garantizando la eficacia biológica). El sistema se muestra como herramienta a ser considerada por sus efectos beneficios para los agentes interesados (agricultores, asesores en sanidad vegetal, industria química, constructores de equipos de tratamientos y autoridades reguladoras) así como por su contribución a la consecución de los objetivos de la Comisión Europea en materia de reducción del uso de los PF.

Palabras clave: índice de área foliar (LAI), control químico de plagas, dosis, tratamientos de precisión

Resum

En l'actual situació de creixement continuat de la població mundial, la producció suficient d'aliments no pot ser garantida sense l'ús de productes fitosanitaris (PF). No obstant, el seu ús no resta exempt de notables dificultats com l'elevat cost dels programes de lluita química pel control de les plagues i malalties que, en el cas de la fructicultura i la viticultura, representen fins al 30% dels costos totals de producció. A més a més, l'ús de PF comporta riscs importants per la salut humana i el medi ambient. A tot això, s'hi ha de sumar la creixent desconfiança, quan no el rebuig, d'amplis sectors de la societat.

Per tal de reduir el seu impacte, la Comissió Europea mitjançant el pacte verd i, en concret, a través de l'estratègia de la granja a la taula, pretén reduir el consum i el risc associat als PF en un 50% en l'any 2030. En aquest context, són necessàries eines cientificotècniques validades per reduir de les dosis a les mínimes imprescindibles sense comprometre la collita.

En aquesta Tesi es presenta i valida el sistema d'ajuda a la presa de decisió DOSA3D, el qual permet ajustar el volum de caldo i la dosi de PF en cultius arboris (cultius 3D) a partir de les característiques del cultiu (àrea foliar objectiu i geometria), el polvoritzador i la plaga o malaltia a controlar.

La validació del sistema DOSA3D s'ha dut a terme en tractaments uniformes i en tractaments zonals en base a mapes de vigor atenent a dos criteris, les deposicions sobre l'objectiu tractat i l'eficàcia en el control de plagues i malalties. En base a això, les hipòtesis contrastades han estat: i) el "Leaf Area Index" (LAI) o índex d'àrea foliar (paràmetre més rellevant per l'ajust de la dosis) és estimat correctament a partir de la geometria de la vegetació i de l'estat fenològic de la vinya; ii) l'eficiència del tractament calculada mitjançant el sistema DOSA3D s'ajusta a la realitat operativa dels tractaments; iii) la deposició a les fulles és un paràmetre que es relaciona bé amb l'eficàcia biològica del tractament; iv) el volum de caldo establert pel sistema DOSA3D permet obtenir deposicions similars a l'objectiu llindar (1.2 µl cm^{-2}) i, conseqüentment, obtenir l'eficàcia adequada; i, v) el tractament zonal de la vinya a partir de mapes de vigor, ajustant la dosi mitjançant el sistema DOSA3D, permet assolir deposicions optimes i l'eficàcia biològica esperada en els diferents vigors.

El cos de la Tesi Doctoral es divideix en tres blocs. El primer està dedicat a la revisió de l'estat de l'art en matèria d'expressió i l'ajustament de la dosi i a la comparació entre els diferents sistemes existents per a la presa de decisió en l'ajustament de la dosi.

El segon bloc de la Tesi inclou dos capítols dedicats als fonaments del sistema DOSA3D i a la seva validació en el cultiu de la de vinya. això Amb aquesta finalitat, s'han practicat defoliacions de trams de vinyes en espatllera, donant-se per vàlid el model d'estimació del LAI del sistema DOSA3D vinyes de fins a 1.25 m d'amplada. També, mitjançant la metodologia descrita a la norma ISO 22522:2007, s'ha determinat la deposició foliar en tractaments ajustats, posant-se de manifest la marcada tendència a la uniformització de les deposicions en la mesura que incrementa el LAI. També, el sistema DOSA3D ha estat validat al llarg de tota la campanya per l'eficàcia en el control de l'oïdi (*Erysiphe necator* Schw.) en quatre assajos independents en els que les dosis de PF s'han reduït fins al 60% respecte a l'estratègia realitzada per l'agricultor.

En el tercer bloc s'han validat els tractaments zonals a dosis ajustades mitjançant el sistema DOSA3D en vinyes espacialment variables. Mitjançant l'índex de vigor "Plant Cell Density" (PCD), establert a partir d'imatges multiespectrals adquirides des d'un avió, s'han confeccionat mapes de dos vigors i els consegüents mapes de prescripció. En tots els casos, la deposició foliar no ha presentat diferencies significatives entre classes de vigor i l'eficàcia dels tractaments en el control del àcar groc (*Eotetranychus carpini* Oud.) i el mosquit verd (*Empoasca vitis* G. *y Jacobiasca lybica* Berg. & Zanon) ha permès situar la densitat de la plaga per sota dels llindars econòmics de danys en ambdues classes de vigor, comportant estalvis de PF entre el 16,6 i el 24,8% en les zones de baix vigor.

Les conclusions obtingudes en la present Tesi Doctoral proporcionen les evidències cientificotècniques necessàries per utilitzar el sistema DOSA3D de manera sanitàriament segura (garantint l'eficàcia biològica). El sistema es mostra com una eina a ser considerada pels seus efectes beneficiosos per part dels agents interessats (agricultors, assessors en sanitat vegetal, indústria química, constructors d'equips de tractaments i autoritats reguladores) així com per la seva contribució a la consecució dels objectius de la Comissió Europea en matèria de reducció de l'ús dels PF.

Paraules clau: índex d'àrea foliar (LAI), control químic de plagues, dosi, tractaments de precisió

Abstract

In the current situation of a growing world population, it is not possible to ensure the production of sufficient food without phytosanitary products (PPs). However, their use has considerable drawbacks such as high costs of chemical control programs against pests and diseases. For instance, in the integrated pest control strategies implemented in orchards and vineyards they may represent up to 30% of the total production costs. Furthermore, the use of PPs can pose important risks to human health and to the environment. In addition, broad sectors of society increasingly distrust and reject the use of PPs.

In order to reduce the negative impacts of PPs, the European Union developed the green deal and, through the implementation of the "from farm to fork" strategy, aims to reach a 50% reduction of the consumption and risks associated to PPs for the year 2030. In this context, reliable scientific and technical tools are needed to allow adjustment of application doses to the minimum doses required for effective control, that is without reducing the harvest.

Throughout this thesis, the DOSA3D decision support system is presented and validated, this system allows to adjust the volume and dose rates of the PPs for fruit crops (3D crops) according to the characteristics of the crop (leaf area and geometry), the sprayer and the target pest or disease.

The validation of the DOSA3D system has been carried out for both uniform applications and zonal applications based on vigour maps, according to the following two criteria: on-target product deposition and efficacy of pest and disease control. In order to do so, the following hypothesis were tested: i) the LAI or leaf area index (the most relevant parameter for adjusting the dose) is estimated correctly from the geometry of the vegetation and the phenological stages of the vineyard; ii) the efficiency of the sprayer, calculated by means of the DOSA3D system is adjusted to the operational reality of the applications; iii) deposition on leaves is a parameter that correlates well to the biological efficacy of the application; iv) the volume rate established by the DOSA3D system allows to obtain leaf depositions close to the objective threshold (1.2 µl cm^{-2}) and, consequently, achieve the appropriate efficacy; and v) the zonal application in vineyards based on vigour maps, after adjusting the dose by means of the DOSA3D system, allows to achieve optimal depositions and therefore the expected biological efficacy for the different vigour zones.

The body of this thesis is divided into three parts. The first part consists of a revision of the state of the art regarding dose expression and adjustment and different existing dose adjustment decision support systems.

The second part of the thesis includes two chapters dedicated to the technical rationale of the DOSA3D system and its validation in vineyards. Sections along the vine trellis were defoliated in order to validate the LAI estimation model of the DOSA3D system for trellises up to 1.25 m wide. Likewise, the ISO standard 22522:2007 was used to determine the foliar deposition, this evidenced a marked tendency to the homogenisation of the depositions as LAI increases. In addition, the DOSA3D system has been validated throughout the entire season for the control of powdery mildew (*Erysiphe necator* Schw.), in four independent trials in which the dose was reduced up to 60%, compared to the doses used by the farmer.

In the third part of the thesis, the DOSA3D system is validated for zonal applications of adjusted doses in spatially variable vineyards. Zonal classification maps, and the corresponding prescription maps, were built based on the Plant Cell Density (PCD) vigour index, established from aerial multispectral images. Leaf deposition did not present significant differences between vigour classes and the reduced-dose applications for control of yellow spider-mite (*Eotetranychus carpini* Oud.) and leafhoppers (*Empoasca vitis* G. and *Jacobiasca lybica* Berg. & Zanon) allowed to reduce pest density bellow the economic damage thresholds in both vigour classes, resulting in PPs reductions between 16.6 and 24.8% in low vigour zones.

The conclusions reached in this thesis provide the scientific and technical evidences required for the safe use of the DOSA3D system for delivery of reliable control of pests and diseases. The system has proved to be a useful tool due to its benefits for stakeholders (farmers, advisors in plant protection, the chemical industry, constructors of application equipment and regulatory authorities) and its contribution to the achievement of European Commission objectives regarding reduction in the use of PPs.

Key words: LAI, chemical control, dose, precision crop protection

CAPÍTULO 1

Introducción general

Introducción general

1. Antecedentes y justificación de la tesis

En 2019 en el mundo los cultivos 3D (frutales, viñedos, almendros, nogal, avellano, cítricos y olivar) ocupan un total de 54.6 Mha lo que supone apenas el 2% de la superficie cultivada. De esta superficie, corresponden 24.1 Mha a frutales de pepita y de hueso, 10.6 Mha a olivares, 7.7 Mha a viñedos, 6.3 Mha a cítricos, 2.1 Mha a almendros y 3.8 Mha al resto de frutos secos (FAOSTAT, 2020a).

El 51 % de la superficie cultivada de viñedo se distribuye entre España, China, Francia, Italia y Turquía (OIV, 2019). La Figura 1 muestra la distribución de los principales productores de uva con datos de 2016 (Daane et al., 2018).

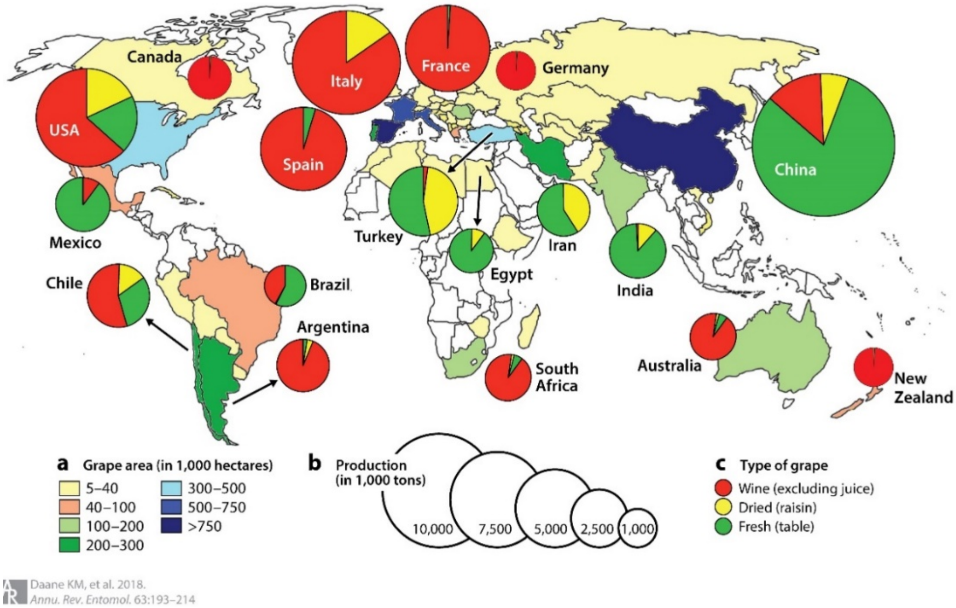

Figura 1. Mapa de los principales países productores de uva dónde se muestra (a) la superficie de tierra plantada con viñedos, (b) la producción de uva de cada uno de los 18 países más productivos, y (c) el porcentaje de la uva (vino, fruta seca y fruta fresca). Fuente: Daane et al 2018 (con datos de 2016).

En Europa (EU-28) la superficie dedicada a cultivos 3D es de 12.0 Mha y supone el 11.3% del total de la superficie cultivada (106.5 Mha en 2017). Los principales países productores, por dimensión de la superficie dedicada, son España, ocupando casi la mitad de la superficie total europea, seguido de Italia, Francia, Grecia y Portugal (Eurostat, 2020a). Solamente estos cinco países ocupan el 90.0% del total de la superficie de cultivos 3D en EU-28. Un análisis por zonas permite afirmar que la práctica totalidad de la superficie de cultivos 3D se sitúa en la Zona Sur a los efectos de autorización y reconocimiento mutuo de productos fitosanitarios (PF) (EU, 2009a). La distribución de superficies por grupos de cultivos y países se muestra en la Tabla 1.

Tabla 1. Superficie cultivada (x1000 ha) de cultivos 3D por países de la Unión Europea (incluido Reino Unido) en el año 2019 (Datos: Eurostat, 2020a).

Localización			***Cultivos***				
	Frutales de pepita	Frutales de hueso	Nueces y avellanas	Almendro	Cítricos	Viñedo	Olivar
EU28	638.3	613.7	1240.1	799.8	512.5	3163.2	5053.1
BE - Belgium	16.15	1.18	0.11	0.00	0.00	0.38	0.00
BG - Bulgaria	4.87	26.30	8.64	1.01	0.00	30.05	0.00
CZ - Czechia	8.12	5.53	0.13	0.00	0.00	16.08	0.00
DK - Denmark	1.68	0.61	0.00	0.00	0.00	0.00	0.00
DE - Germany	36.21	13.11	0.90	0.00	0.00	:	0.00
EE - Estonia	0.57	0.00	0.00	0.00	0.00	0.00	0.00
IE - Ireland	0.71	0.00	0.00	0.00	0.00	0.00	0.00
EL - Greece	14.16	68.90	43.47	15.13	44.23	101.85	903.08
ES - Spain	53.28	140.84	788.41	687.23	296.48	936.89	2601.9
FR - France	55.62	44.18	40.83	1.18	4.61	755.47	17.72
HR - Croatia	5.80	8.46	13.54	0.62	2.20	19.82	18.61
IT - Italy	83.70	119.50	176.17	52.04	140.74	697.91	1139.4
CY - Cyprus	0.45	1.13	2.98	2.71	3.20	6.67	11.06
LV - Latvia	3.97	0.18	0.00	0.00	0.00	0.00	0.00
LT - Lithuania	11.34	1.52	0.14	0.00	0.00	0.00	0.00
LU - Luxembourg	0.29	0.04	0.01	0.00	0.00	1.24	0.00
HU - Hungary	34.24	34.13	6.94	0.31	0.00	64.92	0.00
MT - Malta	0.00	0.00	0.00	0.00	0.00	0.42	0.00
NL - Netherlands	16.51	1.06	0.00	0.00	0.00	0.16	0.00
AT - Austria	7.08	1.50	0.17	0.00	0.00	48.72	0.00
PL - Poland	173.66	54.13	6.02	0.00	0.00	0.74	0.00
PT - Portugal	28.45	12.46	147.88	39.64	21.07	178.78	359.95
RO - Romania	57.10	75.49	2.51	0.00	0.00	176.34	0.00
SI - Slovenia	2.48	0.60	0.62	0.00	0.00	15.57	1.37
SK - Slovakia	2.18	1.43	0.63	0.00	0.00	7.92	0.00
FI - Finland	0.69	0.00	0.00	0.00	0.00	0.00	0.00
SE - Sweden	1.62	0.06	0.00	0.00	0.00	0.05	0.00
UK - United Kingdom	17.40	1.40	0.00	0.00	0.00	2.55	0.00

En Cataluña los cultivos 3D son de gran importancia, la superficie cultivada de frutales de pepita y hueso y de viñedo se muestran en la Figura 2.

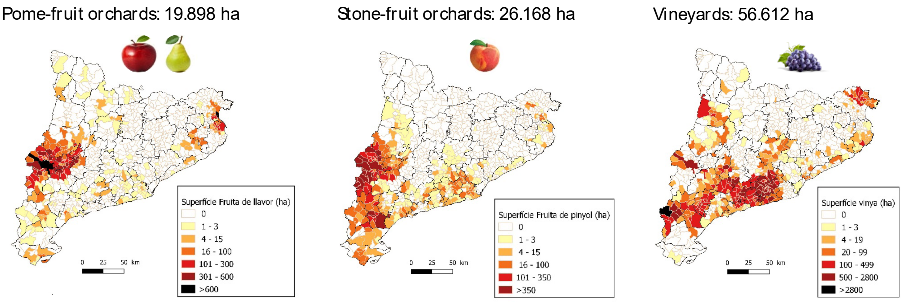

Figura 2. Distribución de la superficie cultivada de frutales de pepita, de hueso y viñedo por municipios en Cataluña en 2019. (Fuente: Departament d'Agricultura, Ramaderia, Pesca i Alimentació http://agricultura.gencat.cat/ca/departament/estadistiques/agricultura/mapes-distribucio-superficie-agricola/)

Los trabajos experimentales realizados durante el periodo de la tesis y que se presentan en los próximos capítulos se han desarrollado, casi en su totalidad, en los viñedos de la Bodega de Raïmat (DO Costers del Segre, Lleida). Se debe mencionar que la finca de Raïmat es un caso único de colonización agraria en la Europa del siglo XX. Gracias a la llegada del agua con el nuevo Canal de Aragón y Catalunya se introdujo la viticultura en 3500 hectáreas baldías (PRODECA, 2018). Actualmente se dedican unas 2200 hectáreas al cultivo de la vid (Figura 3) siendo Chardonnay, Cabernet Sauvignon y Garnacha las variedades más cultivadas. La bodega Raïmat elabora vinos de calidad reconocida. En 2020 les han galardonado en los premios *Bacchus* dos vinos de la cosecha 2019 por sus vinos Raïmat Castell Chardonnay Eco y Raïmat Rosada.

Figura 3. Vistas generales de viñedos en Raïmat (DO Costers del Segre), 19 de abril 2016 (Foto: S. Planas)

Para conseguir una producción de calidad el trabajo empieza en el campo (Jackson y Lombard, 1993). Los factores que influyen en la calidad de la cosecha se pueden agrupar en: permanentes (suelo, variedad, clima…), variables (temperatura, iluminación, edad de plantación…), accidentales (plagas, enfermedades, malas hierbas, accidentes meteorológicos) y modificables (labores de cultivo: podas, abonado, riegos…).

Las labores que se realizan durante una campaña para controlar las enfermedades y plagas de representan entre 10-30% del coste de producción anual en frutales y viña, aunque en frutales de pepita puede incrementarse cuando las condiciones meteorológicas son favorables al desarrollo de los organismos nocivos (comunicación personal, Ramon Torà asesor en gestión integrada de plagas, Xavier Auqué, jefe de la sección de Sanidad Vegetal en Lleida de la Generalitat de Catalunya y Josep Ramon Solans, responsable de gestión de la Bodega Raïmat, 2020).

1.1 La sanidad en frutales y viñedo

Los cultivos de hoja caduca, cómo los frutales y la viña, se caracterizan por dos periodos diferenciados: el estado de reposo, donde la planta no presenta actividad fotosintética, y el estado de actividad, donde existe una absorción de nutrientes a nivel radicular, junto con una actividad fotosintética normal, que asegura el crecimiento de la planta y su reproducción sexual. Las nueve fases por las que pasan las categoriza Meier (2001) en la escala de crecimiento BBCH. En la Figura 4 se muestra el ciclo del manzano y en la Figura 5 el ciclo de la vid.

Figura 4. Ciclo del manzano de acuerdo a la escala BBCH (Fuente: imagen adaptada de van de Zande et al., 2019).

Figura 5. Ciclo de la vid de acuerdo a la escala BBCH.

A lo largo del ciclo, diversas enfermedades y plagas pueden afectar estos cultivos, las cuales requieren aplicar medidas preventivas y curativas para su control (Tabla 2).

Tabla 2. Principales enfermedades y plagas que afectan a diferentes especies de frutales y el viñedo en Cataluña (Fuente: Fruit.Net y Focus Grup DOSA3D viña).

Cultivo	Enfermedad	Agente causal	Plaga	Agente causal	
Manzano	Moteado	*Venturia inaequalis*	Carpocapsa	*Cydia pomonella*	*
	Oídio	*Podosphaera leucotricha*	Polilla oriental	*Grapholita molesta*	↑
Peral	Moteado	*Venturia pyrina*	Psila	*Psylla pyri*	
	Stemphylium	*Stemphylium vesicarium*	Carpocapsa	*Cydia pomonella*	*
Melocotonero	Monilia	*Monilinia spp.*	Anarsia	*Anarsia lineatella*	*
	Rhizopus	*Rhizopus spp.*	Polilla oriental	*Grapholita molesta*	*
	Geotrichum	*Geotrichum candidum*	Mosca de la fruta	*Ceratitis capitata*	
	Abolladura	*Taphrina deformans*	Trips	Fam Thripidae*: Taeniothrips meridionalis, Trips inconsequens, T. angusticeps, T. tabaci.* Fam Aeolothripidae*: Aeolothrips tenuicornis*	↑
	Oídio	*Sphaerotheca pannosa*			
Viña	Oídio	*Erysiphe necator*	Polilla del racimo	*Lobesia botrana*	*
	Mildiu	*Plasmopara viticola*	Ácaros	*Eotetranychus carpini*	↑
	Botritis	*Botrytis cinerea*	Mosquito verde	*Empoasca vitis; Jacobyasca lybica*	↑

* Control eficaz mediante confusión sexual
↑ Importancia en aumento

La gestión integrada de plagas (GIP) consiste en el examen cuidadoso de todos los métodos de protección vegetal disponibles, y posterior integración de medidas adecuadas, para evitar el desarrollo de poblaciones de organismos nocivos y mantener el uso de PF y otras formas de intervención en niveles que estén económica y ecológicamente justificados, y que reduzcan o minimicen los riesgos para la salud humana y el medio ambiente (Figura 6).

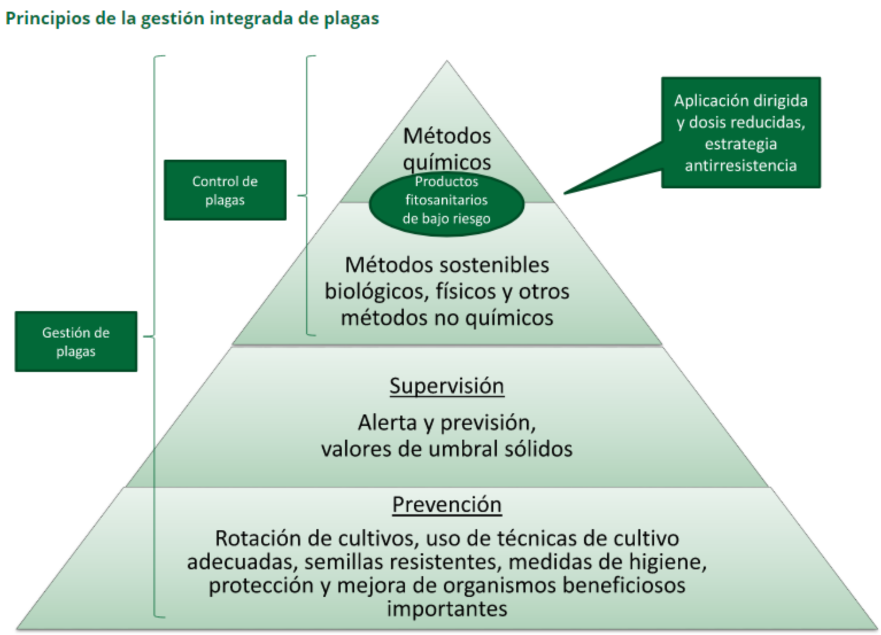

Figura 6. Principios de la gestión integrada de plagas (Fuente: Tribunal de Cuentas Europeo a partir del anexo III de la Directiva 2009/128/CE)

No obstante, en fruticultura y viticultura, la pulverización foliar con PF es la técnica más común de controlar las enfermedades y plagas. Ya sea con productos de origen sintético o no.

En una encuesta realizada por el *Departament d'Agricultura, Ramaderia i Pesca* en 2018 a los técnicos de las Asociaciones de Defensa Vegetal (ADVs) (datos no publicados), estimaron el número de tratamientos fitosanitarios para controlar plagas y enfermedades en fruticultura entre 4 y 30, dependiendo principalmente de si las condiciones meteorológicas son favorables al desarrollo de plagas y enfermedades, de media entre 10 y 16 aplicaciones anuales. Dichas aplicaciones, de acuerdo con la información proveniente del programa FruitNet, corresponden a un mínimo de diez tratamientos insecticidas y de diez tratamientos fungicidas, tanto en frutales de hueso como de pepita, siendo en numerosas ocasiones realizados ambos tipos de tratamiento de forma simultánea. En el caso de la viña, los técnicos indicaron entre 5-10 tratamientos (incluyendo azufre en espolvoreo) por campaña (Figura 7).

En Raïmat, predomina la pulverización foliar de PF contra plagas y enfermedades a excepción de la polilla del racimo que se controla mediante confusión sexual de manera eficaz desde 2004 (Barrios et al., 2006) y aplicaciones de azufre en espolvoreo para controlar oídio. Los patógenos son los organismos que mayor número de intervenciones requieren, entre 5 y 10 aplicaciones anuales dependiendo de las condiciones meteorológicas del año. Mientras que las aplicaciones contra plagas pueden variar entre 1 y 4.

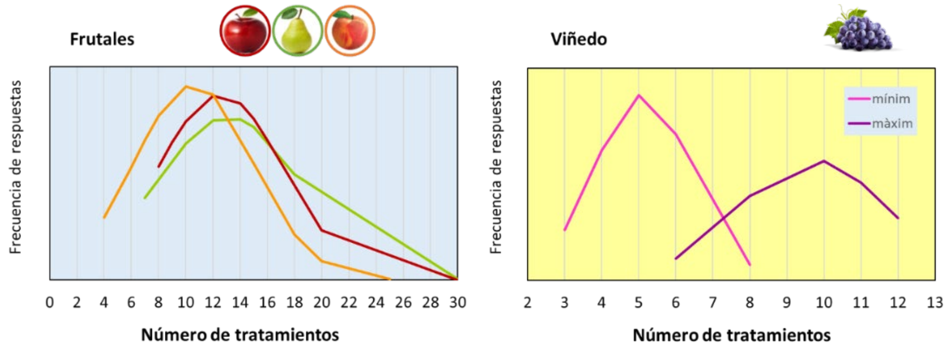

Figura 7. Resultado de la encuesta realizada a técnicos de Asociaciones de Defensa Vegetal sobre el número de tratamientos anuales en frutales (manzano, peral y melocotón) y viñedo (Fuente: DARP, no publicado).

1.2 El uso de productos fitosanitarios

Con una población mundial creciente que se prevé que alcanzará los 8000 millones en 2030, y cuya esperanza de vida va en aumento, la agricultura es el pilar de la alimentación mundial. No obstante, la superficie cultivada en 2015 fue prácticamente la misma que en 1965. Además, se estima que las pérdidas ocasionadas por plagas y enfermedades sin el uso de PF serían 30% superiores (Damalas, 2016). Por lo tanto, para alimentar a la creciente población mundial se debe aumentar la productividad por superficie cultivada, y esto es, a día de hoy, inconcebible sin el uso de PF (FAO, 2017; Gomes et al., 2020; Nishimoto, 2019). La Figura 8 muestra el consumo unitario medio de PF (kg ha^{-1}) a nivel mundial.

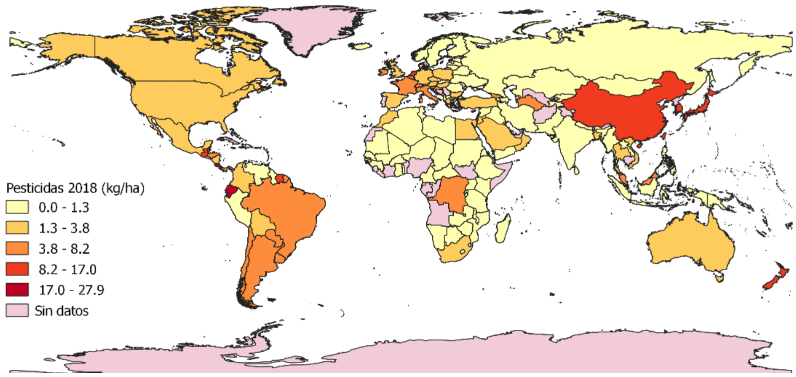

Figura 8. Consumo de productos fitosanitarios por superficie cultivada (kg ha^{-1}) en 2018 (Datos: FAOSTATS, 2020b).

Desde la Revolución verde, el incremento en la cantidad y diversidad de PF ha sido considerable. En 2019 había registradas sobre 500 sustancias activas en Europa, con variaciones entre países (Maggi et al., 2019). Según FAO (2020c), en las últimas tres décadas el consumo total de PF en el mundo prácticamente se ha duplicado. No obstante, la cantidad de fungicidas/bactericidas e insecticidas se ha mantenido estable (Figura 9). La Figura 10 muestra los diez primeros países (o regiones) del mundo consumidoras de PF. Resaltar que Francia y España aparecen en esta lista.

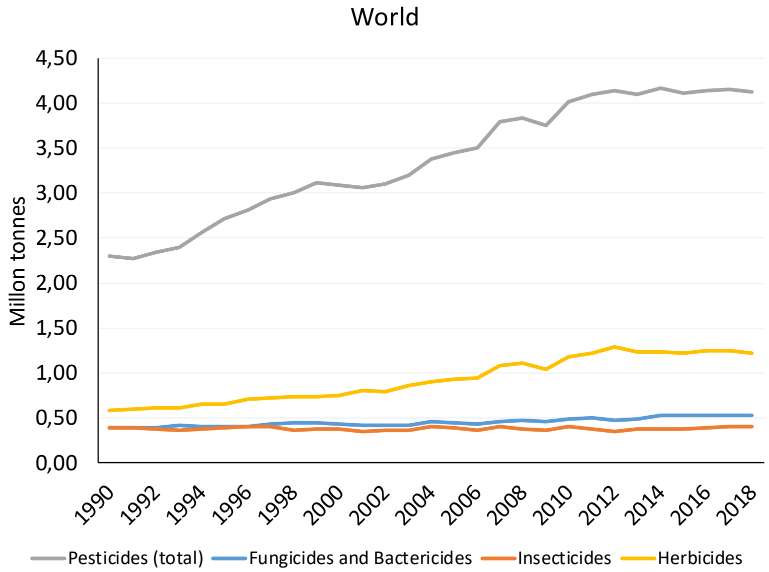

Figura 9. Evolución del consumo total de productos fitosanitaios en Mt en el mundo (Fuente: FAOSTAT, 2020c)

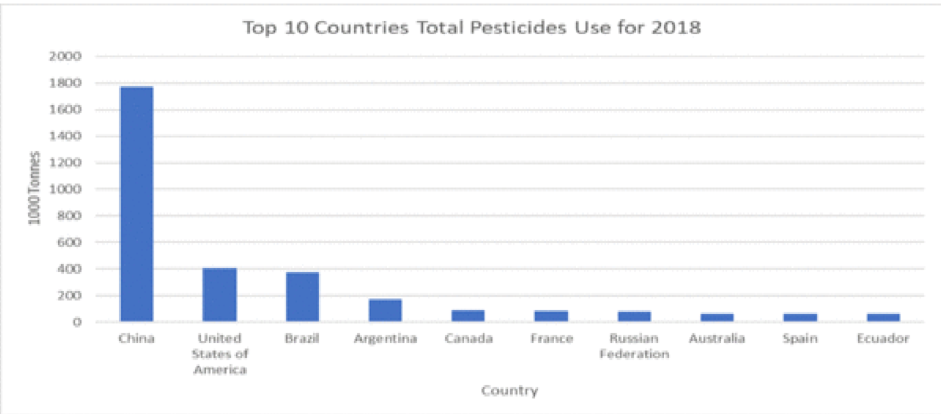

Figura 10. Consumo en los principales países en el último año del que se dispone de estadísticas globales (2018) (Fuente: http://www.fao.org/economic/ess/environment/data/pesticides-use/en/#:~:text=2020%20UPDATE%20HIGHLIGHTS,in%20agriculture%20in%20the%202010s)

En Europa (EU-28) se consumen más de 400.000 toneladas de PF anuales (Eurostat, 2020b). Viendo la evolución de las ventas de PF (Figura 11), más de la mitad corresponden al conjunto fungicidas/bactericidas e insecticidas. En estos grupos de PF la tendencia en la última década ha ido ligeramente al alza. En cuanto al consumo por países en Europa (Figura 12) tres países de la zona sud europea siguen liderando el ranking.

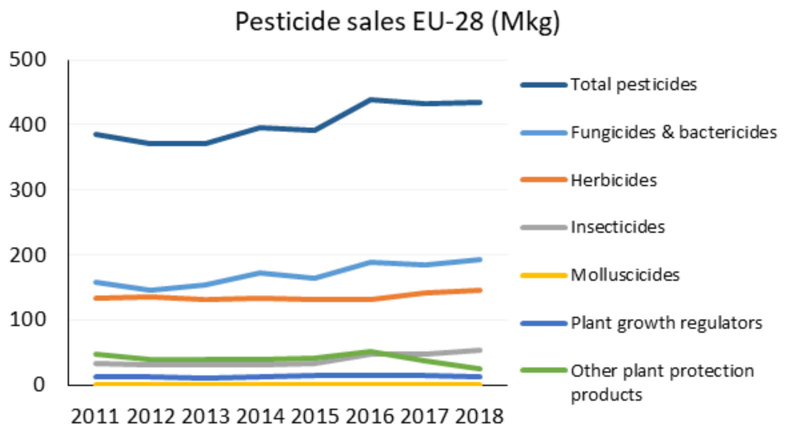

Figura 11. Evolución del consumo de productos fitosanitarios en Europa (EU-28) entre 2011-2018. (Fuente: Eurostat, 2020b)

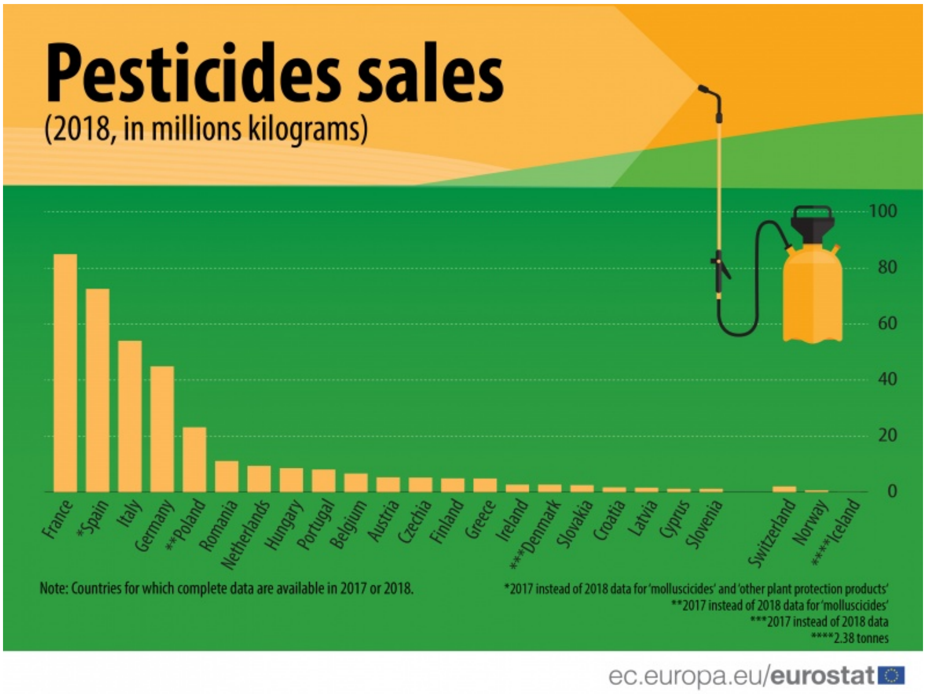

Figura 12. Ventas de productos fitosanitarios (Mkg) en Europa. (Fuente: Eurostat,2020b)

Según Alonso González et al. (2020), en España el 38.4% de la cantidad de fitosanitarios consumida se aplica sobre la viña. Esto puede ser debido a las elevadas dosis de azufre utilizadas para el control del oídio (hasta 12 kg ha^{-1} azufre mojable y hasta 30 kg ha^{-1} en espolvoreo por tratamiento).

Sin embargo, el volumen de ventas no se correlaciona directamente con los riesgos y las repercusiones derivados de su uso. Los riesgos y las repercusiones planteados por los PF varían en función de las sustancias activas que contengan, y también de su composición y de dónde, cuándo y cómo los apliquen los usuarios en la práctica.

El indicador de riesgo armonizado 1 (HRI 1) se calcula multiplicando las cantidades de sustancias activas comercializadas en PF por un factor de ponderación. A efectos prácticos, las sustancias activas se agrupan en 4 categorías en función de su toxicidad, de acuerdo con el Reglamento (EC) nº 1107/2009 (EC, 2009a). Las ponderaciones aplicadas a cada categoría tienen por objeto reflejar la política sobre el uso de PF y respaldar el objetivo de la Directiva sobre el uso sostenible de PF de reducir el riesgo y el impacto del uso de PF y promover enfoques o técnicas alternativos. Se utiliza una línea de base del promedio de tres años 2011-2013 como punto de partida con el que se comparan los valores posteriores. La Figura 13 muestra una disminución del 17% desde el período de referencia en 2011-2013, pero sin cambios en comparación con 2017 (EC, 2020a).

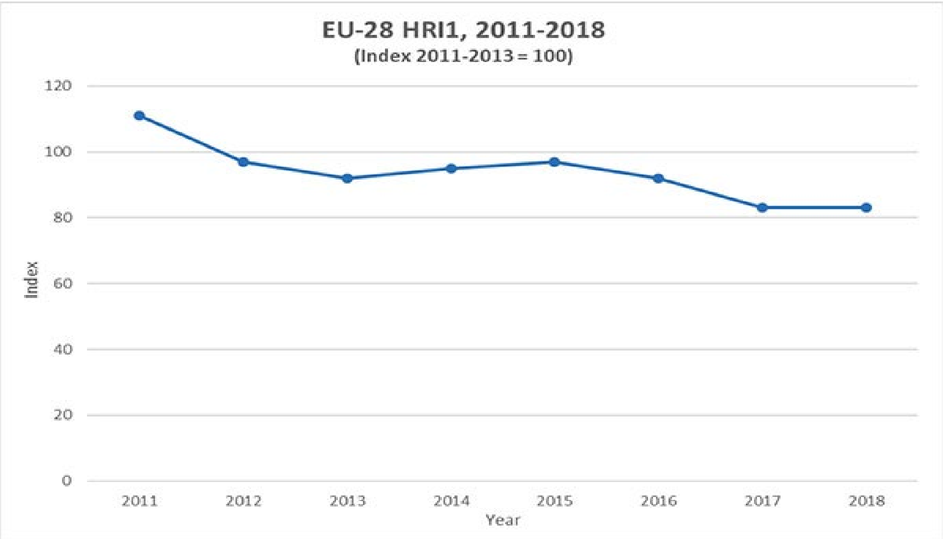

Figura 13. Evolución del indicador de riesgo armonizado (HRI 1) 2011-2018. (Fuente: EC, 2020a)

1.3 Marco normativo y reglamentario

En 2002 en Europa se establece una estrategia temática para el uso sostenible de los PF, la cual pretende reducir su impacto en la salud humana y en el medio ambiente y, en sentido más amplio, conseguir un uso más sostenible de los PF, así como una reducción global significativa de los riesgos, siempre que se garantice la protección necesaria de las cosechas (EC, 2002).

Después entró en vigor el Reglamento (EC) 396/2005 relativo a los límites máximos de residuos (LMR) de PF en alimentos y piensos de origen vegetal y animal, estableciendo criterios de armonización de LMR entre Estados Miembros para proporcionar seguridad jurídica en el comercio intracomunitario de alimentos (EC, 2005).

A finales de 2009 se publicó una nueva legislación comunitaria que modificó profundamente la vigente anteriormente, incorporando los principios de la estrategia para el uso sostenible de PF y atendiendo a lo establecido en el VI Programa Comunitario de Acción Medioambiental. Las nuevas normativas publicadas incluyeron el Reglamento (EC) 1107/2009 en el cual se regula la autorización y comercialización de los PF (EC, 2009a), la Directiva 2009/127/EC en relación a los equipos de aplicación de PF (EC, 2009b) y la Directiva de Uso Sostenible (DUS) de PF 2009/128/EC (EC, 2009c) (Figura 14). El paquete legislativo se completó con el Reglamento (EC) 1185/2009, referido a las estadísticas de PF (EC, 2009d).

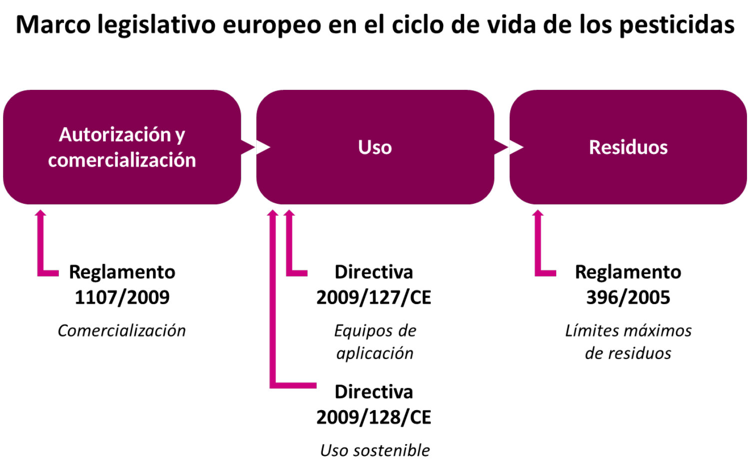

Figura 14. Marco legislativo europeo en el ciclo de vida de los productos fitosanitarios (Adaptado de Herrera-Sebastián, 2019)

En la Unión Europea, todas las sustancias activas se someten a reevaluaciones periódicas, según lo establecido en el Reglamento (EC) 1107/2009. El proceso de reevaluación generalmente sigue la proyección indicada en la Figura 15.

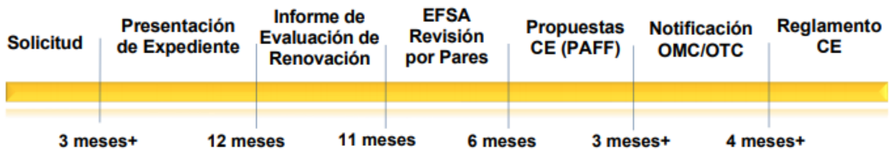

Figura 15. Proceso de reevaluación de sustancias activas (Fuente: https://croplife.org/wp-content/uploads/2020/12/Monitoreo-de-Renovacion-de-Pesticidas-de-la-UE-ES-Noviembre-2020.pdf)

Con carácter cuatrimestral sale publicado el informe de monitoreo de renovación de PF de la UE. En la Figura 16 se muestra la evolución de las sustancias activas que se someterán o se someten actualmente al proceso de renovación. Además, se mencionan las sustancias que caducaron, que no se renovaron o que tuvieron una renovación restringida. Se puede observar una reducción en estas sustancias en el último año.

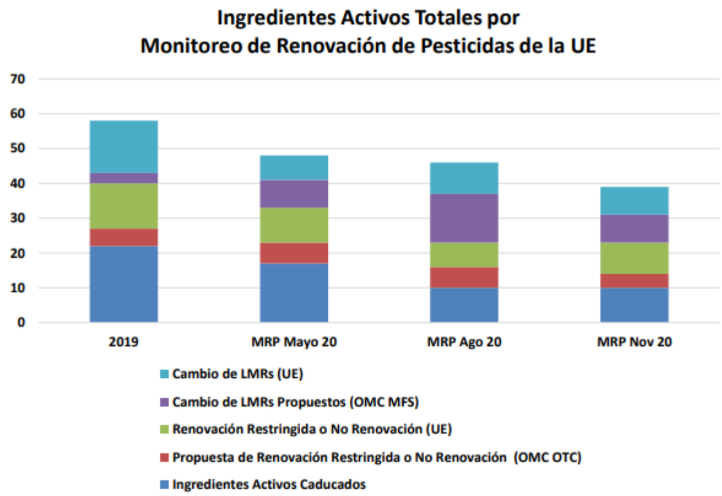

Figura 16. Evolución sustancias activas pendientes de renovación según el Reglamento (EC) 1107/2009. LMR: límite máximo de residios. UE: Unión Europea. OMC: Organización Mundial del Comercio. MFS: notificaciones sanitarias y fotosanitarias OTC: obstáculos técnicos al comercio. (Fuente: https://croplife.org/wp-content/uploads/2020/12/Monitoreo-de-Renovacion-de-Pesticidas-de-la-UE-ES-Noviembre-2020.pdf)

El cobre es el PF que más se utiliza para el control del mildiu en viña. Esta sustancia activa se ha sometido al proceso de revisión y en 2018 la Comisión Europea limitó la cantidad máxima de cobre que se puede utilizar a 28 kg ha^{-1} en un periodo de 7 años (de promedio 4 kg ha^{-1} anuales) mediante la Regulación (EC) 1981/2018 (EC, 2018).

1.3.1 Cuestiones clave de la legislación vigente

De manera más específica los objetivos de la presente tesis se alinean con los diferentes aspectos de la legislación mencionada:

- La importante reducción del número sustancias activas autorizadas, la limitación del uso (reducción de dosis) (Reglamento EC 1107/2009) y la reducción de los límites máximos de residuos (Reglamento EC 369/2009) implícitamente promueven un mejor uso de las sustancias activas autorizadas, por lo que se debe asegurar una buena aplicación de los PF para garantizar su eficacia.
- La aplicación de PF mediante máquinas tiene impacto sobre el medio ambiente y la salud humana, por lo que la Directiva 2009/127/EC introduce los requisitos de protección ambiental en el diseño y fabricación de estos equipos.
- La Directiva 2009/128/EC promueve la GIP, por la cual los tratamientos fitosanitarios deben reducirse a los estrictamente necesarios priorizando el uso de alternativas no químicas. El Anexo 3 especifica que los usuarios profesionales deberán limitar la utilización de PF y otras formas de intervención a los niveles que sean necesarios, por ejemplo, **mediante la reducción de las dosis**, la reducción de la frecuencia de aplicación o mediante aplicaciones fraccionadas, teniendo en cuenta que el nivel de riesgo que representan para la vegetación debe ser aceptable y que no incrementan el riesgo de desarrollo de resistencias en las poblaciones de organismos nocivos

Actualmente, la legislación europea relativa al uso de PF se reconoce como una de las más restrictivas del mundo (Herrera-Sebastián, 2019). Aun así, la Comisión Europea lanzó en 2019 el “Pacto Verde” con el cual propone crear un futuro inclusivo, competitivo y respetuoso con el medio ambiente para Europa (EC, 2019). El plan de acción relativo a la agricultura se presentó en 2020 mediante la estrategia “de la granja a la mesa” (EC, 2020b). Este plan de acción contempla reducir el uso general y el riesgo de PF químicos en un 50% y el uso de PF más peligrosos en un 50% para 2030. Para conseguirlo, propone revisar la DUS en 2022, reducir significativamente el uso, el riesgo y la dependencia de los PF y mejorar la GIP.

1.4 El Ajuste de la Dosis de Productos Fitosanitarios

La dosis de un PF se establece cómo la masa o volumen (kg o L) de PF vinculado a una unidad de referencia, que caracteriza el objetivo del tratamiento, y la expresión de la dosis es la unidad en la que se indica dicha dosis.

Esta unidad de referencia puede ser superficie (ha), concentración (%) más volumen de aplicación (L), superficie de pared vegetal (LWA, de sus siglas en inglés *Leaf Wall Area*, m^2) o el volumen de cultivo (TRV, de *Tree Row Volume,* m^3), entre otros. Estos sistemas de expresión de la dosis se relacionan entre sí de acuerdo con la Figura 17.

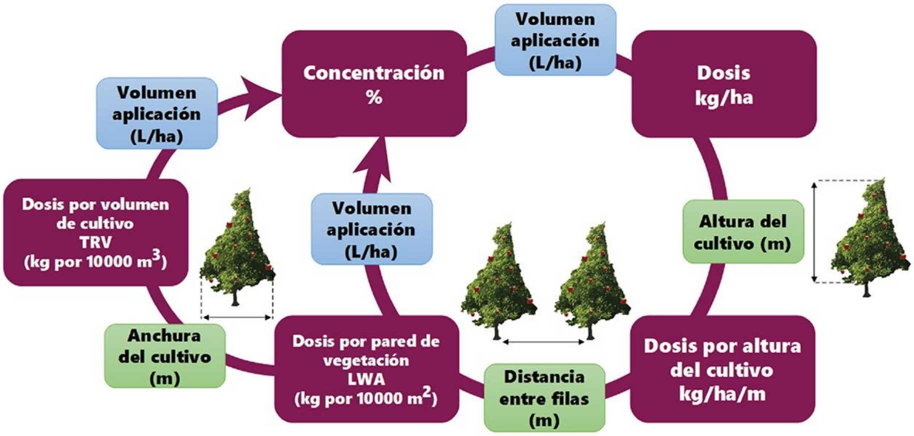

Figura 17. Conversión entre sistemas de expresión de dosis. (Fuente: EPPO, 2012 después de Friessleben et al., 2007). Los cuadros morados hacen referencia a los sistemas de expresión de dosis, en verde los parámetros de la vegetación y en azul el volumen de caldo.

Actualmente en Europa coexisten diferentes modelos de expresión de dosis en las etiquetas que acompañan a los PF de cultivos 3D (Figura 18). En la Zona Sud Europea, predominan las indicaciones por concentración. Cuando no se indica lo contrario, el volumen de referencia son 1000 L ha^{-1}. No obstante, es cada vez más frecuente encontrar intervalos de volumen de aplicación. En el caso de los frutales este rango puede variar entre 500-1500 L ha^{-1}, mientras que en viñedo entre 300 y 1500 L ha^{-1}. Las etiquetas de PF también indican una dosis máxima (kg o L ha^{-1}) establecida por razones sanitarias que no deberá sobrepasarse en ningún caso (EC, 2009a).

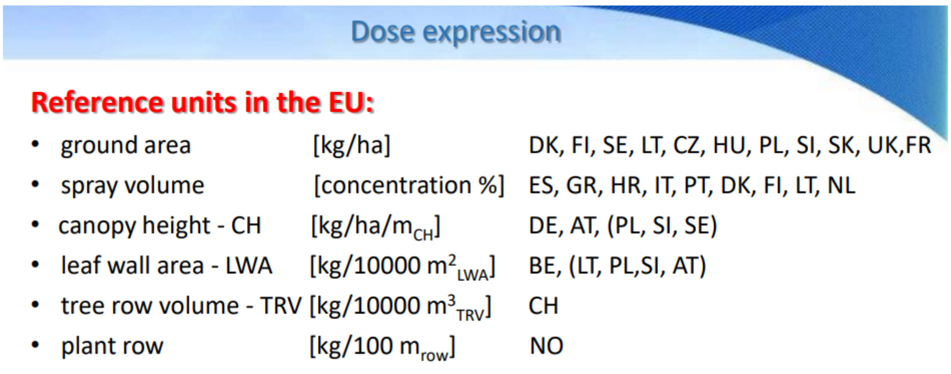

Figura 18. Diferentes expresiones de dosis coexistentes en Europa (Fuente: Doruchowski, 2018)

Esta situación lleva a una serie de objeciones:

- **Sobredosificación**. En muchas ocasiones la falta de directrices para ajustar la dosis hace que el aplicador decida aplicar la dosis máxima por hectárea. Esta dosis máxima, en principio son las requeridas para las situaciones más desfavorables: plantaciones de gran dimensión tratadas con equipos de baja eficiencia. Con esta premisa la mayoría de situaciones se estaría sobredosificando. La Figura 19 muestra dos hipotéticos escenarios de viña con diferentes marcos de plantación a lo largo de una campaña. Convendríamos pues que no se necesitará la misma dosis de PF en cada caso.

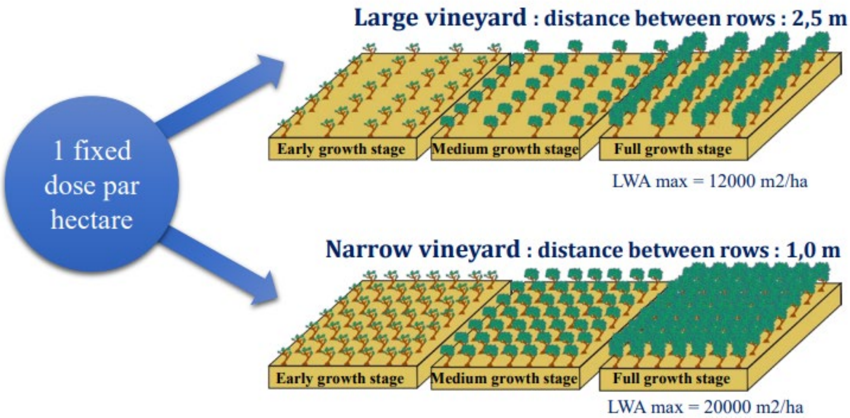

Figura 19. Variación de la vegetación en dos plantaciones de viña donde varía la distancia entre filas a lo largo del ciclo de cultivo. (Fuente: Codis, 2016).

- **Volúmenes de caldo obsoletos**. Los volúmenes de caldo reflejados en las etiquetas de PF no reflejan la realidad de la fruticultura y, especialmente, de la viticultura actual. Corresponden a los empleados antaño cuando la pulverización se realizaba con equipos de mochila o con pistola (Figura 20.A) conectada a mangueras (también utilizados en los ensayos oficiales de evaluación de eficacia de PF). Actualmente se pulveriza con equipos hidroneumáticos con asistencia de aire (Figura 20.B). En el caso de los PF autorizados para frutales, la mayoría indica un volumen fijo de 1000 L ha^{-1}. La práctica habitual de los fruticultores es aplicar un volumen sobre 500 L ha^{-1} a inicio de vegetación y hasta 1000 L ha^{-1} en plena vegetación. En el caso de la viña, el volumen de aplicación a inicio de vegetación suele ser próximo 100 L ha^{-1} y en plena vegetación no llega a sobrepasar los 500 L ha^{-1} en la mayoría de los casos, muy lejos de los 1000 L ha^{-1} recomendados cómo valor de referencia. Es decir, si se mantiene la concentración de la etiqueta, en viñedo se aplicaría una décima parte de la dosis máxima a inicio de vegetación, y la mitad en plena vegetación.

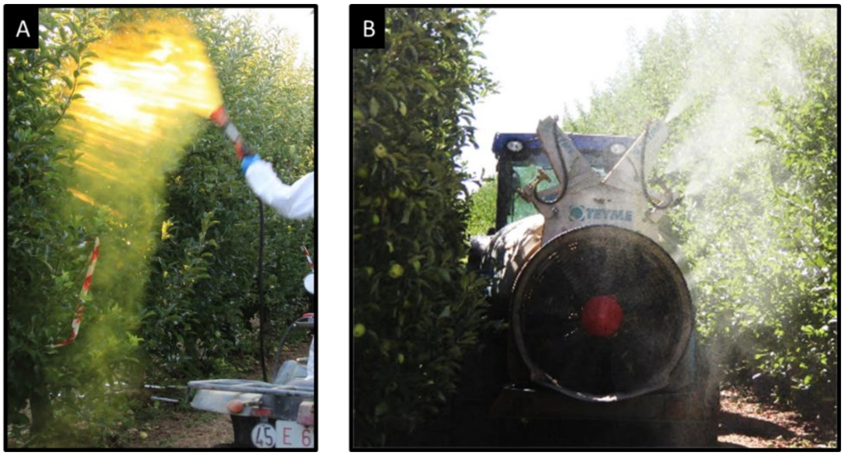

Figura 20. Pulverización en manzano mediante A) equipo con pistola y B) equipo hidroneumático con deflectores.

- **Se ignora el factor eficiencia de la aplicación**. Las recomendaciones de PF no dan ninguna directriz respecto al tipo de pulverizador con el que se aplica. Un tratamiento eficiente supone un incremento sustancial de las deposiciones sobre el objetivo a tratar en relación a las alcanzadas por un tratamiento de baja eficiencia, por lo que para obtener una deposición similar las dosis a aplicar con un pulverizador más eficiente serán menores. La Figura 21 muestra las curvas teóricas que relacionan la dosis aplicada y la eficacia alcanzada para dos tipos de pulverizadores.

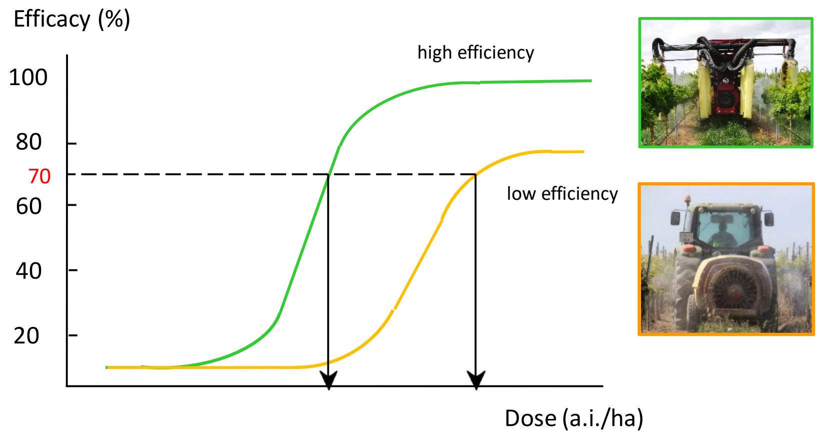

Figura 21. Para alcanzar una eficacia del 70% el pulverizador más eficiente (en verde) necesitará aplicar una dosis inferior que el pulverizador convencional (en amarillo).

Vistas las objeciones anteriores, el agricultor se mueve en la incertidumbre a la hora de determinar la dosis de PF a aplicar. Frente al dilema el agricultor tiende a sobredosificar para evitar la posibilidad de merma en la eficacia del tratamiento que pueda conllevar pérdidas de cosecha.

La *European and Mediterranean Plan Protection Organization* (EPPO) en su norma PP1/225 define la **dosis mínima efectiva** de un PF cómo la dosis mínima necesaria para lograr una eficacia suficiente contra una plaga objetivo en una amplia gama de situaciones en las que se aplicará el producto (EPPO, 2012a).

Por lo tanto, para ajustar la dosis se deberá caracterizar el escenario concreto del momento de la aplicación del PF y, en consecuencia, aplicar la dosis mínima efectiva. En el capítulo 3 se realiza una profunda revisión bibliográfica sobre los trabajos realizados para asentar las bases del ajuste de dosis de PF. En términos generales, los factores más importantes para caracterizar la situación concreta de un tratamiento son:

- **Arquitectura del cultivo**, la cual viene definida por las **dimensiones de la copa** (altura y anchura) y el **índice de área foliar** (LAI, de sus siglas en inglés *Leaf Area Index*). El LAI se define como el área foliar de una cara por unidad de área de superficie. Muchos autores están de acuerdo en que este parámetro es el que mejor describe el objetivo a tratar, ya que para un control eficaz de plagas y enfermedades se debe depositar una cantidad suficiente de PF por unidad de superficie foliar. No obstante, su cuantificación es compleja (Planas et al., 2013; Rüegg et al., 2001; Siegfried et al., 2007). El LAI se puede determinar por métodos directos (defoliación de un tramo y superficiado de hojas) o métodos indirectos (cómo el método del cuadrante del punto inclinado, utilización de sensores, etc.). Estos métodos los revisan Jonckheere et al. (2004). Los métodos directos son los más precisos, pero tienen la desventaja de consumir mucho tiempo y, como consecuencia, hacer que la implementación a gran escala sea solo marginalmente factible. Mientras que todos los métodos indirectos revisados tienen problemas y limitaciones específicos, la decisión sobre qué método utilizar depende de muchos factores, tales como: la precisión requerida, el período de tiempo de medición, la escala de investigación, el presupuesto disponible, etc.

- **Pulverizador utilizado**. El tipo de pulverizador más utilizado en fruticultura y viticultura es el atomizador con asistencia de aire (Figura 22.A). Sin embargo, cada vez son más comunes los equipos que adaptan la pulverización a la geometría del cultivo (Figura 22.B). Estos equipos avanzados son más eficientes ya que permiten reducir fracción pulverizada fuera del objetivo a tratar (por deriva o pérdidas al suelo) y por lo tanto reducir la dosis. No obstante, el tipo de pulverizador no se tiene en cuenta en la dosificación propuesta en las etiquetas de PF.

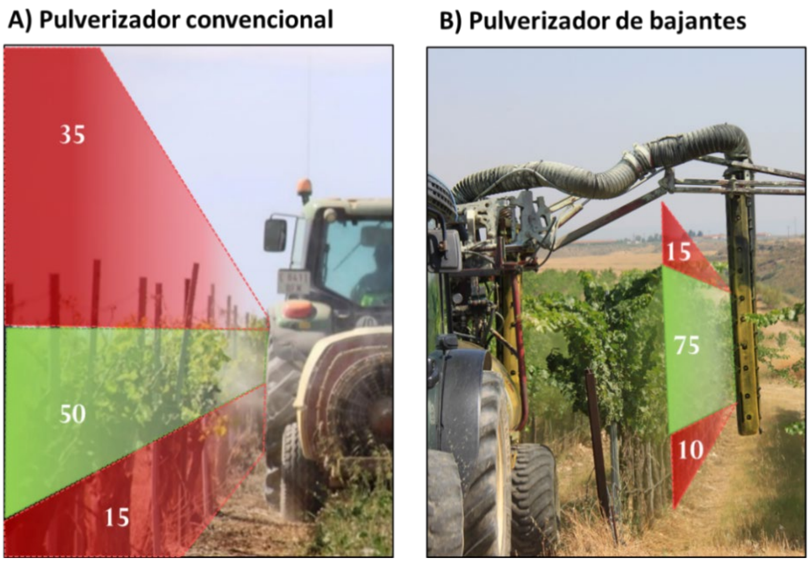

Figura 22. Fracción de la pulverización (%) depositada sobre el objetivo (en verde), perdida por deriva (sombra roja superior) o depositada en el suelo (sombra roja inferior) producidas por A) pulverizador convencional y B) pulverizador de bajantes adaptado a la geometría del cultivo.

- **Plaga o enfermedad a controlar.** Algunas plagas y enfermedades, cómo los ácaros tetraníquidos, por el modo de acción de los productos que se aplican para controlarlas, necesitan aumentar el volumen de aplicación. Es el caso de los productos que actúan por asfixia (Marcic, 2012).

Para facilitar el cálculo de la dosis ajustada se han desarrollado diferentes sistemas de ayuda a toma de decisión en frutales y viñedo, los cuales se detallan y comparan en el capítulo 3. La presente tesis se centra en el desarrollo y validación del sistema DOSA3D en viñedo el cual se introduce a continuación.

1.4.1 El sistema DOSA3D

El sistema DOSA3D (www.dosa3d.cat) es la evolución del sistema DOSAFRUT (Figura 23), específico para frutales (Planas et al., 2006).

Figura 23. Cabecera del sistema de ayuda a la toma de decisión DOSAFRUT

El sistema inicial calculaba el volumen de aplicación ajustado a partir de la estimación del LAI considerando la altura de la vegetación, la anchura de la vegetación, la distancia entre filas y la porosidad del dosel foliar a partir de una serie de pictogramas (Figura 24).

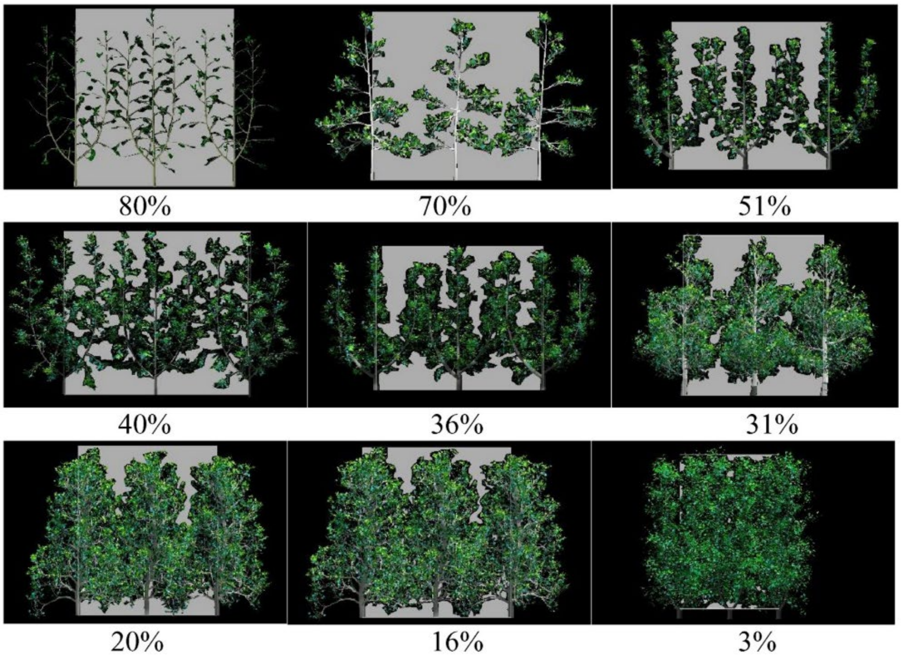

Figura 24. Serie de pictogramas para estimar la porosidad propuestos en DOSAFRUT y publicados por Sanz et al. 2018

La base teórica de cálculo de DOSAFRUT se estableció considerando 100 impactos por cm^2 de hoja con gotas de un diámetro representativo de 225 µm. Esta base resulta en una deposición foliar equivalente a 0.60 µL cm^{-2} si se trata una cara de la hoja y a 1.20 µL cm^{-2} cuando se tratan ambas caras. Lo que corresponde a 120 L por ha de hojas (LAI = 1). DOSAFRUT también consideraba la eficiencia global de la aplicación teniendo en cuenta: las dimensiones del dosel foliar (anchura y altura), tipo de pulverizador, tipo de boquilla, parámetros operativos de la aplicación, condiciones meteorológicas previstas, plaga o enfermedad a controlar y adición de coadyuvantes.

Este sistema se aplicó en parcelas comerciales de perales, manzanos y melocotoneros consiguiendo ahorros de PF entre el 10 y el 53% y validándose en campo contra psila (*Psylla pyri* L.), araña roja (*Tetranychus urticae* K.) y trips (*Frankliniella occidentalis* P.), respectivamente (Planas et al. 2013; Solanelles et al. 2013).

Posteriormente se modelizó la estimación del LAI para diferentes cultivos 3D, lo cual promulgó la primera versión de la plataforma en línea DOSA3D (www.dosa3d.cat) (Planas et al, 2016). El objetivo de DOSA3D era simplificar la usabilidad de la aplicación. En este sentido, las principales novedades fueron:

- El sistema se amplió a otros cultivos 3D: viñedo, cítricos, olivar y árboles aislados.
- En vez de utilizar las medidas exactas de altura y anchura, se propusieron rangos de distancias.
- Los pictogramas de porosidad del dosel foliar se sustituyeron por tres rangos de la fenología del cultivo o la densidad foliar.
- La eficiencia global se redujo a la influencia de los factores altura y anchura, al tipo de pulverizador utilizado y a la adición o no de coadyuvantes.
- Las plagas o enfermedades de difícil control no contaban en la eficiencia global, pero al seleccionarlas incrementa 40% más de volumen al cálculo.
- La plataforma se ligó al registro de PF del Ministerio de Agricultura, Pesca y Alimentación (https://www.mapa.gob.es/es/agricultura/temas/sanidad-vegetal/productos-fitosanitarios/registro/productos/conregnom.asp) pudiendo descargar las fichas para comprobar la dosis.
- Además de estimar el LAI, se añadió el cálculo del LWA y el TRV, así como la equivalencia entre sistemas de expresión de dosis.
- Los parámetros de la operativa (condiciones meteorológicas y velocidad de avance) dejaron de intervenir en el cálculo. No obstante, era obligatorio seleccionarlos. Cuando los parámetros estaban fuera de las

recomendaciones de las buenas prácticas de aplicación de PF no permitía el cálculo.

- Incorporación de un apartado específico para la calibración del pulverizador, en el que se facilitaba una hoja de cálculo para la selección de boquillas operáticas y determinación de la presión de trabajo.
- Igualmente, de un apartado general en el que se recogían documentos técnicos y científicos relativos al sistema.

Las limitaciones observadas en la primera versión de la plataforma DOSA3D fueron:

- En viñedo, los rangos de distancias (en altura y anchura) eran demasiado amplios, sobreestimando los cálculos de LAI, LWA y TRV, y por lo tanto sobredosificando.
- Los formulados de PF ya incorporan coadyuvantes, por lo que se ponía en duda su intervención en el cálculo.
- Todos los componentes que no intervienen en el cálculo se debían introducir obligatoriamente, disminuyendo la usabilidad del sistema.
- La dosis se podía introducir en concentración (%) o en relación a la superficie de terreno (L o kg ha^{-1}). La EPPO, en la recientemente aprobada norma PP 1/239(3) (pendiente de publicación, versión anterior: EPPO, 2012b) recomienda expresar la dosis de cultivos de porte alto en relación al LWA o al TRV en los ensayos de evaluación de eficacia por lo que en la nueva versión de DOSA3D se debería permitir introducir la dosis en relación a este sistema de expresión de dosis.

Todos los antecedentes del sistema, así como la justificación técnica del motor de cálculo de la versión 2 de DOSA3D en frutales y viñedo se exponen con detalle en el capítulo 4.

Paralelamente a los trabajos en viñedo que se presentarán en los siguientes capítulos, DOSA3D está siendo validado mediante ensayos de eficacia de toda la campaña en frutales, cítricos y olivar. Los seguimientos de estos ensayos los realiza un *Focus Grups* (FG) específico de cada cultivo. Cada FG está integrado por asesores en GIP, funcionarios del Servicio de Sanidad Vegetal e investigadores. Actualmente DOSA3D se recomienda en la página web Rural.cat gestionada por la Generalitat de Catalunya (https://ruralcat.gencat.cat/sanitat-vegetal).

1.5 Tratamientos de precisión en cultivos 3D

La agricultura de precisión (AP) se define como "una estrategia de gestión que recoge, procesa y analiza datos temporales, espaciales e individuales y los combina con otras informaciones para respaldar las decisiones de manejo de acuerdo con la variabilidad estimada, y así mejorar la eficiencia en el uso de recursos, la productividad, la calidad, la rentabilidad y la sostenibilidad de la producción agrícola" (ISPA, 2019).

Aplicado a la protección de cultivos sería un manejo que, utilizando los avances tecnológicos, optimice el uso de los insumos (por ejemplo, los PF) maximizando el rendimiento, la calidad de la producción y minimizando el impacto y el riesgo medioambiental.

Si bien las parcelas de cultivos 3D no son siempre homogéneas en vigor, la optimización del uso de PF en AP vendrá definida por la aplicación de la dosis mínima efectiva (kg ha^{-1}) adaptada a las diferentes características del objetivo a tratar (vegetación) dentro de cada parcela. Los avances en hardware, software, sistemas globales de navegación por satélite (*Global Navigation Satellite Systems*, GNSS), sensores de caracterización de la vegetación (próximos y remotos) y tecnologías de aplicación variable, ofrecen la posibilidad de llevar la adaptación de la aplicación a la práctica.

1.5.1 Caracterización de la vegetación (sensores próximos y remotos)

El primer paso para ajustar la dosis es caracterizar el objetivo a tratar, en concreto, la superficie foliar. La estimación directa del LAI es destructiva y consume mucho tiempo, por lo que diversos sensores permiten medir de manera precisa las características geométricas y estructurales de la vegetación (altura, anchura, volumen, densidad foliar, área foliar). Estos sensores pueden ser próximos, cercanos al objeto (en AP se refiere a mediciones desde el suelo) o remotos (en AP generalmente se refiere a aquellos sensores montados sobre satélites, avionetas o vehículos aéreos no tripulados).

Los sensores próximos que se utilizan para caracterizar la vegetación y sus aplicaciones en AP los revisan Rosell y Sanz, (2012). Entre los sensores terrestres más utilizados en este ámbito están los sensores de ultrasonidos, los sensores multiespectrales (radiación electromagnética), los sensores de visión estereoscópica y los sensores laser con tecnología LiDAR (*Light Detection and Ranging*) (Gil et al., 2014). El Grupo de Investigación en AgróTICa y Agricultura de Precisión de la Universitat de Lleida (GRAP), se ha especializado en la caracterización de la vegetación mediante el sensor LiDAR. Los primeros trabajos se publicaron en 2009 utilizando el LiDAR bidimensional SICK LMS200 (SICK AG, Düsseldorf, Germany), el cual no incorporaba ningún sistema de posicionamiento, pero permitió obtener parámetros geométricos cómo la altura y la anchura de la vegetación (Rosell-Polo et al., 2009). Actualmente se utilizan sensores LIDAR más avanzados que permiten obtener nubes de puntos georeferenciados de la vegetación más densas y disminuir el tiempo en la obtención de los datos. Estos dispositivos proporcionan perspectivas favorables en cuanto a su uso a gran escala. No obstante, la limitación principal es el procesado de la gran cantidad de datos, por lo que la clave es el desarrollo de softwares que procesen los datos de manera automática y sean capaces de generar mapas de parámetros cómo la altura, anchura, la porosidad, el LAI o la cantidad y posicionamiento de frutos. Cabe destacar los resultados obtenidos por Sanz et al. (2018) con mediciones en frutales y viñedo que han permitido desarrollar sendos modelos de estimación de la superficie de pared foliar los cuales se incorporan en el sistema DOSA3D.

En cuanto a sensores remotos, los más utilizados (y también empleados en esta tesis) son los sensores multiespectrales. Las cámaras en color tradicionales suelen proporcionan tres bandas de información por cada imagen (rojo, verde y azul), tratando de imitar el proceso de visión del sistema humano. Sin embargo, en una imagen multiespectral, el número de bandas empleadas para representar una escena contempla una mayor cantidad de bandas (Figura 24). Con la combinación de las bandas del rojo e infrarrojo se obtienen los denominados Índices de vegetación, los cuales se definen como un parámetro obtenido a partir de la combinación de dos o más valores de reflectancia a distintas longitudes de onda, para resaltar alguna propiedad de la vegetación cómo el desarrollo del cultivo (Bellvert, 2014). Para caracterizar el vigor de la vegetación los índices más utilizados son el NDVI (índice de vegetación de diferencia normalizada) (Di Gennaro et al., 2019; Hall et al., 2003; Martinez-Casasnovas et al., 2012) y el PCD (*Plant Cell Density*) (Bramley et al., 2003, 2011; Bramley y Hamilton, 2004). Algunos autores han relacionado diferentes índices de vigor con el LAI (Hall et al., 2008; Johnson et al., 2003; Towers et al., 2019). No obstante, los índices de vigor se suelen relacionar mejor con la densidad foliar que con la superficie foliar, por lo que no proporcionan una cuantificación del objetivo a tratar, habiendo de relacionar los valores de los índices con medidas realizadas en el campo (Du et al., 2008). Lo que sí permiten es diferenciar el vigor y clasificarlo en zonas de manejo (Arnó et al., 2009). En cultivos con mayor densidad de vegetación el vigor se contrasta mejor a través del índice PCD que del NDVI, probablemente debido a la mayor capacidad del PCD de detectar diferencias en la biomasa fotosintética activa (Proffitt et al., 2006) o cambios en el LAI por lo que su uso se ha generalizado en la viticultura australiana (Towers et al., 2019), y es el índice utilizado en la presente tesis.

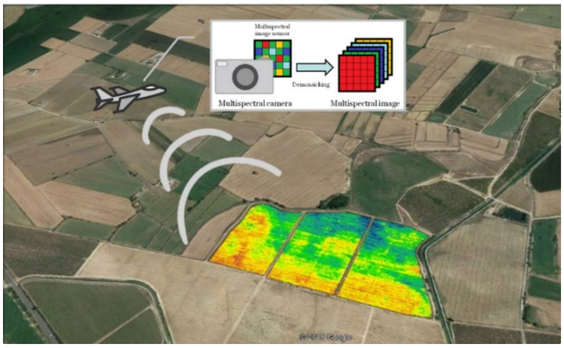

Figura 25. Caracterización de la vegetación mediante sensor multiespectral. El índice representado en la parcela es el Plant Cell Density (PCD).

1.5.2 Tecnologías disponibles para la aplicación variable

Los pulverizadores ajustan el volumen de aplicación impulsando el líquido que sale por las boquillas a una presión predeterminada. El volumen de aplicación final (L ha^{-1}) es función del caudal que proporcione el conjunto de boquillas (en L min^{-1}) y la velocidad de avance (km h^{-1}). En un tratamiento convencional se consigue aplicar un volumen de aplicación homogéneo al mantener la velocidad de avance constante. Para conseguir una pulverización variable se necesita instalar algún tipo de tecnología que permita regular las dosis a las características de la vegetación. Entre los sistemas tecnológicos disponibles para la aplicación variable están los que actúan sobre al caudal emitido por las boquillas. En la Tabla 3 se muestran los más utilizados en cultivos 3D.

Tabla 3. Tecnologías que actúan sobre el caudal de las boquillas.

Tecnología	Descripción	Referencias
Sistema on/off	Control mediante electroválvulas permitiendo la apertura o cierre del circuito de alimentación de las boquillas	(Wellington et al., 2012)
Electroválvulas proporcionales	Modificación del caudal de las boquillas en función de la presión de trabajo	(Campos et al., 2020; Escolà et al., 2013; Llorens et al., 2010)
Electroválvulas pulsantes de modulación de ancho de pulso	Regulación de la frecuencia de maniobra (apertura / cierre) de las válvulas que controlan la alimentación de las boquillas *(pulse with modulation, PWM)*	(Chen et al., 2020; Salcedo et al., 2020)

1.5.3 Aplicación variable

Hay dos enfoques en la aplicación variable: a tiempo real y basada en mapas de prescripción.

En la aplicación variable a tiempo real, los sensores de caracterización de la vegetación que van montados sobre el tractor o pulverizador "leen" la vegetación a medida que el tractor avanza entre las filas del cultivo permitiendo ajustar las dosis de manera continua.

Se han desarrollado diversos prototipos de pulverizadores de aplicación variable a tiempo real (Abbas et al., 2020). Entre los más destacados están, por una parte, los prototipos que caracterizan la vegetación en tramos de altura con un número variable de sensores de ultrasonidos, permitiendo aplicar diferentes dosis en cada estrato en altura (Escolà et al., 2013; Gil et al., 2007; Llorens et al., 2010). Por otra parte, los prototipos que integran el escaneo de la vegetación con sistema LiDAR y la aplicación variable con válvulas PWM (Chen et al., 2020; Salcedo et al., 2020).

Actualmente la empresa Pulverizadore Fede (Valencia, España) está desarrollando el sistema "see & spray" (en fase de investigación). El pulverizador llevará embarcadas cámaras que caracterizan la vegetación y actuarán sobre el caudal y número de boquillas accionadas (Interempresas, 2020).

Visto desde otro enfoque, a nivel de laboratorio, se ha desarrollado un prototipo capaz de detectar las zonas de la hoja infectadas por *P. viticola* con imágenes multiespectrales y pulverizar sobre éstas (Oberti et al., 2016).

En la práctica el sistema más utilizado es el sistema on/off en cultivos de árboles aislados que mediante sensores de ultrasonidos permiten detectar la vegetación. La complejidad del resto de sistemas (sensorización, computación y actuación) hace que no se haya generalizado su uso (Abbas et al., 2020).

En cuanto a la aplicación variable en base a mapas o zonal, la caracterización de la vegetación se realiza con el objetivo de diferenciar zonas de manejo. Para este fin se pueden utilizar sensores LiDAR (del-Moral-Martínez et al., 2020) o imágenes multiespectrales (Campos et al., 2019). Una vez diferenciadas las zonas de manejo, el mapa de prescripción se genera asignando una dosis a cada zona y cada dosis irá en función del volumen de caldo a aplicar. El mapa de prescripción se carga en un monitor de a bordo que variará la presión de trabajo de forma automática o manual. La Figura 26 muestra las fases que se siguen para la aplicación zonal de PF.

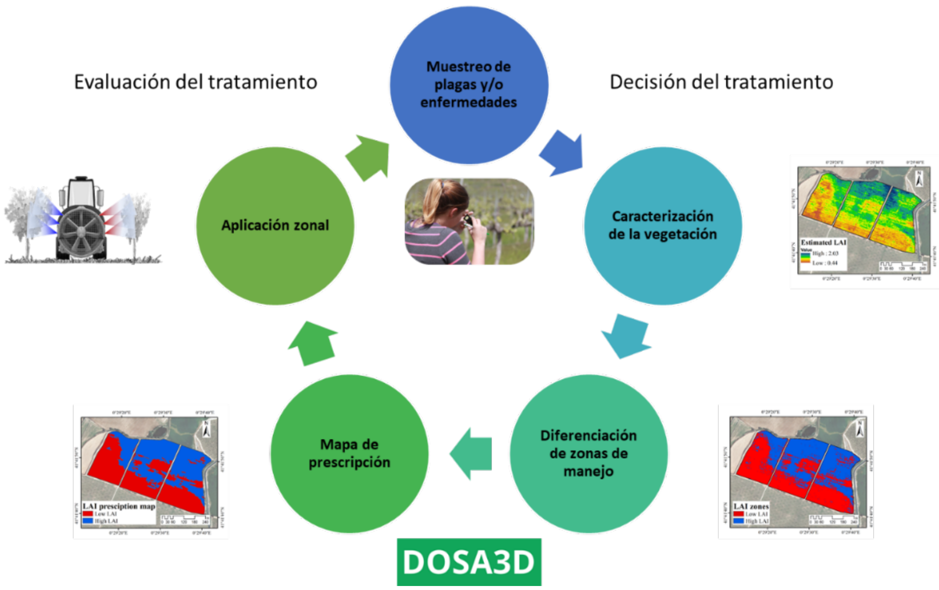

Figura 26. Fases de la aplicación zonal de productos fitosanitarios.

La aplicación en tiempo real permite una actuación más precisa, ya que la caracterización de la vegetación y el ajuste de dosis se realiza de manera continua, consiguiendo ahorros de producto entre el 30% y el 80% (Wandkar et al., 2018). En cambio, la dosificación en base a mapas de vigor suele diferenciar un número inferior de zonas de manejo (2 o 3) por lo que el potencial de ahorro se prevé inferior. No obstante, la electrónica embarcada en este segundo tipo es menor, disminuyendo costes y problemas operativos.

1.6 Proyectos de investigación que enmarcan la tesis

Esta tesis ha sido financiada mediante dos grandes proyectos cuyos objetivos se muestran a continuación.

1.6.1 EUCLID

El proyecto europeo del Horizonte 2020 EUCLID (de sus siglas en inglés *Europe-China Lever for Integrated Pest Management Demonstration*) se desarrolló entre 2015 y 2018 (www.euclidipm.org).

El objetivo general fue asegurar la producción de alimentos para la creciente población mundial y desarrollar metodologías de producción sostenibles para combatir las plagas desde un enfoque más sostenible desde la GIP con el fin de reducir los efectos negativos de los PF en la salud humana y el medio ambiente, reducir las pérdidas económicas en la agricultura y proporcionar apoyo científico a las políticas de la UE y China.

Dentro de este proyecto se adaptó el sistema Dosafrut (ahora DOSA3D) para el cultivo de la viña, validándose contra diferentes plagas y enfermedades.

1.6.2 GOPHYTOVID

El proyecto de grupos operativos suprautonómicos GOPHYTOVID (www.gophytovid.es) tuvo como objetivo principal minimizar, de forma demostrativa y real, el uso de fitosanitarios de origen químico en viticultura y evaluar la aplicación práctica de alternativas bioprotectoras en los viñedos españoles, mediante la aplicación de tecnologías existentes para el análisis de mapas de vegetación y/o vigor y de equipos de tratamiento de alta eficiencia para optimizar los tratamientos químicos y minimizar el impacto medioambiental y el riesgo para las personas, reduciendo los costes económicos.

El proyecto se desarrolló entre 2018 y 2020. Durante este tiempo se validó la aplicación de la viticultura de precisión basada en mapas de vigor como sistema de gestión sostenible.

2. Propósito, hipótesis y objetivos

Como se ha mencionado anteriormente, la protección de los cultivos 3D contra plagas y enfermedades representa un coste importante para las explotaciones frutícolas y vitícolas, además de un impacto negativo en el medio ambiente y la salud de las personas. Además, debido a la variabilidad intraparcelar en el viñedo, se pueden diferenciar zonas de manejo en las cuales se pueden aplicar dosis diferentes de PF.

A nivel práctico, el ajuste de las dosis de PF es una cuestión compleja para el agricultor, el cual se muestra a priori reacio a reducir las dosis, debido a la falta de evidencias científico-técnicas sobre la eficacia de estas dosis y a los posibles riesgos sanitarios y, especialmente, económicos en los que se puede incurrir.

Una vez identificado el problema, el propósito principal de esta tesis es validar dos vías para la reducción de las cantidades de PF aplicadas: el ajuste de la dosis mediante el sistema DOSA3D en tratamientos uniformes a toda la parcela y en tratamientos zonales en base a mapas de vigor.

Se contrastaron las siguientes hipótesis:

- **Hipótesis 1**. El LAI (parámetro más relevante para el ajuste de la dosis) es estimado correctamente a partir de la geometría de la vegetación y del estado fenológico del viñedo.
- **Hipótesis 2**. La eficiencia del pulverizador calculada mediante el sistema DOSA3D se ajusta a la realidad operativa de los tratamientos.
- **Hipótesis 3**. La deposición en hojas es un parámetro que se relaciona bien con la eficacia biológica del tratamiento.
- **Hipótesis 4**. El volumen de caldo establecido por el sistema DOSA3D permite obtener deposiciones similares al objetivo umbral (1.2 $\mu l\ cm^{-2}$) y, consecuentemente, conseguir la eficacia adecuada.
- **Hipótesis 5**. El tratamiento zonal en viñedo a partir de mapas de vigor, ajustando la dosis mediante el sistema DOSA3D, permite alcanzar deposiciones óptimas y la eficacia biológica esperada en los distintos vigores.

Para contrastar las hipótesis mencionadas, se establecieron los siguientes objetivos específicos:

- **Objetivo 1**. Profundizar en las evidencias científicas que fundamentan la expresión y el ajuste de la dosis, expresamente la geometría de la vegetación, la densidad foliar y la eficiencia del pulverizador.
- **Objetivo 2**. Comparar los diferentes sistemas de ayuda a la decisión disponibles para el ajuste de dosis en frutales y viñedo.
- **Objetivo 3**. Mejorar la precisión de cálculo y la usabilidad de la interface del sistema DOSA3D.

- **Objetivo 4**. Validar el modelo de estimación del LAI utilizado en DOSA3D en viñedo.
- **Objetivo 5**. Validar el sistema DOSA3D en tratamientos uniformes en viñedo mediante el análisis de deposiciones y la evaluación de la eficacia.
- **Objetivo 6**. Validar técnica y económicamente los tratamientos zonales, basados en mapas de vigor en parcelas de viñedo a gran escala.

3. Estructura de la tesis

El presente capítulo (1) es una introducción general a la temática de esta tesis: el ajuste de la dosis de PF en cultivos 3D. El capítulo 2 detalla la metodología utilizada en los ensayos realizados y se pone en paralelo con los objetivos planteados. El capítulo 3 está escrito como un artículo en formato “revisión bibliográfica”. En este capítulo se hace una profunda revisión del estado del arte en materia de la expresión y el ajuste de las dosis de PF. Además, por primera vez se comparan las deposiciones teóricas de los diferentes sistemas de ajuste de dosis disponibles para frutales y viñedo. En el capítulo 4, se explican los antecedentes y fundamentos científico-técnicos en los que se basa el nuevo sistema DOSA3D.

Los capítulos experimentales (5, 6 y 7) siguen el formato clásico de artículo científico: introducción, material y métodos, resultados, discusión y conclusiones, forman el cuerpo de la tesis y son independientes entre sí. En el capítulo 5, se relatan los ensayos llevados a cabo para validar el sistema DOSA3D en viñedo desde tres perspectivas: el modelo de estimación del LAI, la deposición en tratamientos uniformes y la eficacia contra oídio. Los capítulos 6 y 7 abordan el ajuste de las dosis con el sistema DOSA3D en viñedos de vigor heterogéneo. En el capítulo 6 se estudian las deposiciones al realizar tratamientos ajustados con DOSA3D uniformes a toda la parcela y en tratamientos a dosis zonal. Este capítulo se ha publicado en la revista *Biosystems Engineering* del cuartil 1 en la categoría *Agronomy and Crop Science* (SJR 2019: 0.86). En el capítulo 7 se valida el ajuste de dosis zonal en viñedo mediante ensayos de deposiciones y eficacia contra ácaro amarillo y mosquito verde. Este capítulo se ha publicado en la revista *Crop Protection* del cuartil 1 en la categoría *Agronomy and Crop Science* (SJR 2019: 0.88).

El capítulo 8 provee la discusión general de los resultados obtenidos en la presente tesis de acuerdo a las hipótesis planteadas que derivan en las conclusiones generales en el capítulo 9. Este último capítulo incluye recomendaciones y cuestiones pendientes.

La intención final es publicar cuatro artículos en revistas de impacto a partir de los resultados obtenidos. La Figura 27 muestra la relación de capítulos.

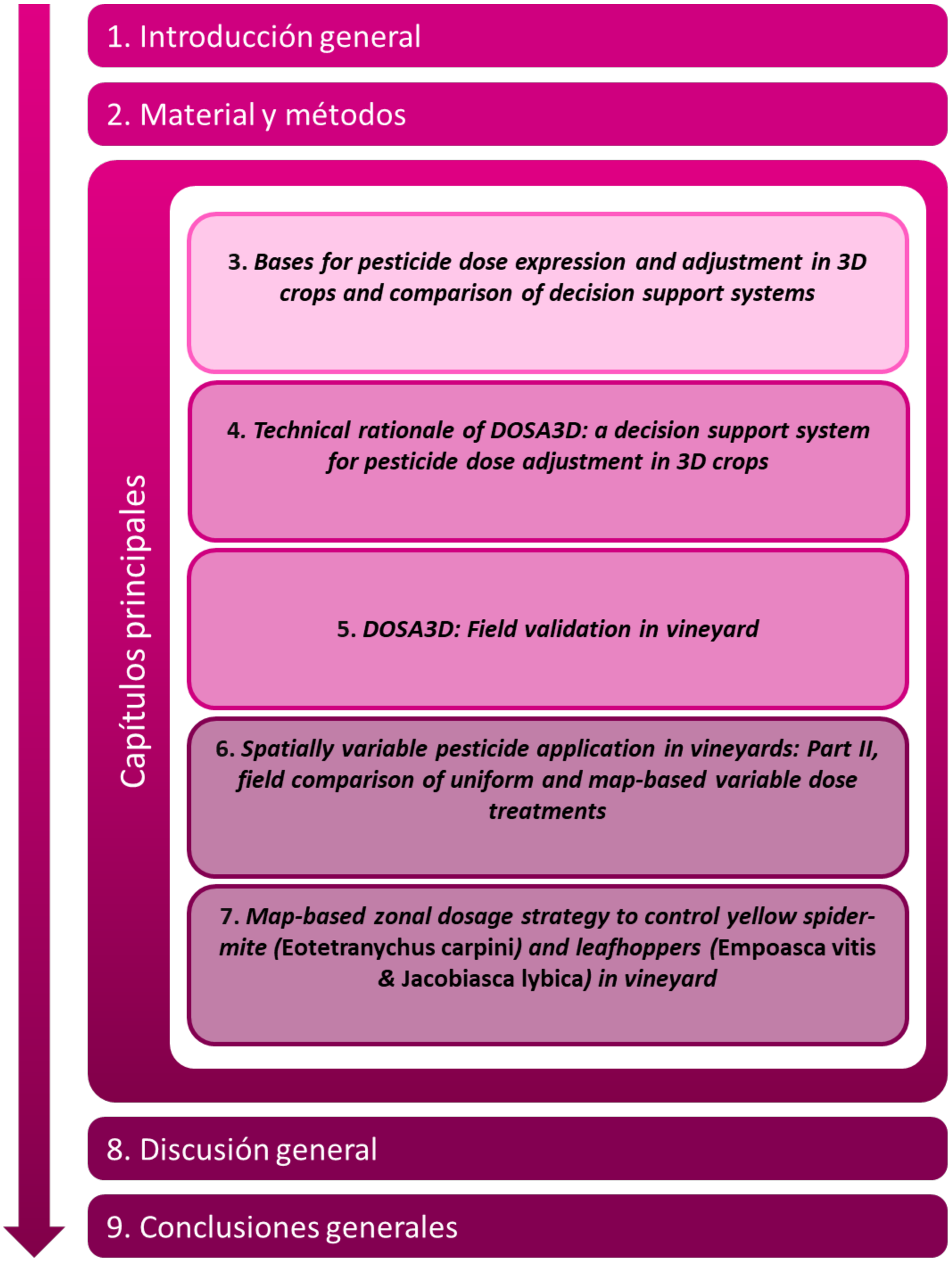

Figura 27. Estructura de la tesis con sus diferentes capítulos.

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CAPÍTULO 2

Material y métodos

Material y métodos

En este capítulo se detallan las metodologías seguidas durante el transcurso de la tesis para alcanzar los objetivos planteados. En la Tabla 1 se ponen en paralelo los objetivos, la metodología (Figura 1) y la ubicación de su desarrollo dentro de la tesis.

Tabla 1. Relación de objetivos, metodología y capítulos en la tesis.

	Objetivos de la tesis	Metodología	Número de ensayos	Capítulo
1	Profundizar en las evidencias científicas disponibles relacionadas con la expresión y el ajuste de la dosis: caracterización de la vegetación a tratar y eficiencia de la pulverización.	Revisión bibliográfica.	-	3
2	Comparar los diferentes sistemas de ajustes de dosis disponibles para tratamientos en frutales y viñedo.	Cálculos comparativos entre sistemas de ajuste de dosis.	-	3
3	Mejorar el sistema DOSA3D, simplificando la interfaz del usuario.	Rediseño y mejoras en la plataforma DOSA3D.	-	4
4	Validar el modelo de estimación del índice de área foliar utilizado en DOSA3D.	Defoliación de tramos de viña.	21	5
5	Validar técnicamente el sistema DOSA3D en tratamientos uniformes a dosis ajustadas y el control de plagas y enfermedades en viñedo.	Ensayos de deposición foliar a volumen ajustado.	37	5
		Ensayos de eficacia contra oídio.	4	
		Ensayo de deposición de volumen ajustado en parcelas con vigor variable.	1	6
6	Validar técnica y económicamente los tratamientos zonales ajustados con DOSA3D, basados en mapas de vigor, y el control de plagas en parcelas de viñedo a gran escala.	Ensayo de deposición de dos volúmenes ajustados al vigor (alto y bajo) en parcelas con vigor variable.	1	6
		Ensayos de deposición foliar.	3	
		Ensayos de eficacia contra plagas.	3	7

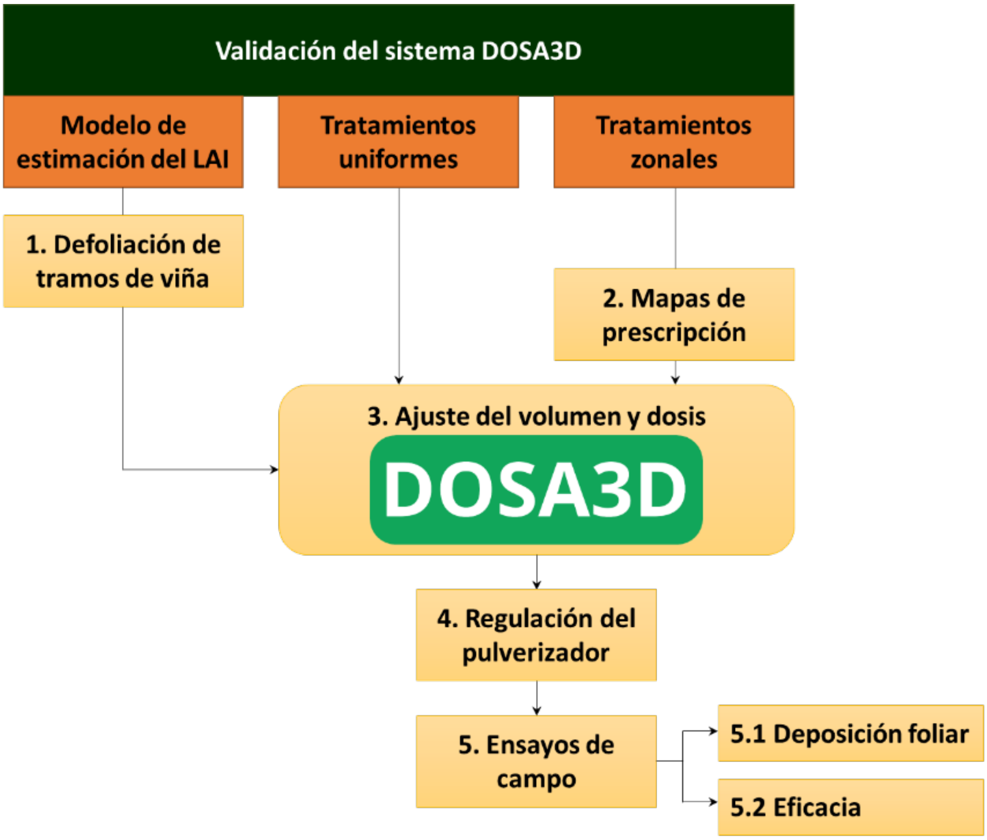

Figura 1. Esquema de la metodología seguida para validar el sistema DOSA3D. LAI: Índice de área foliar.

1. Defoliación de tramos de viña

Para validar el modelo de estimación del índice de área foliar (LAI) del viñedo implementado en DOSA3D se defoliaron 21 tramos de viña (var. Chardonnay, Albariño, Tempranillo, Cabernet Sauvignon, Merlot, Godello, Xarel·lo y Airén) equivalentes a la distancia entre cepas (Figura 2), con el objetivo de relacionar el LAI estimado con el modelo y el LAI real.

Figura 2. Defoliación de un tramo de viña (var. Tempranillo) en junio de 2016.

La superficie foliar se midió por dos procedimientos. El primero, utilizado hasta 2018, todas las hojas defoliadas se midieron utilizando un superficiador foliar (Delta-T Devices Ltd., Cambridge, UK). El segundo, utilizado en 2019 y 2020, el área total se estimaba correlacionando la masa y la superficie de al menos 100 hojas. La superficie de cada hoja se midió con el software ImageJ (Schneider et al., 2012). A partir de la relación lineal entre masa y superficie (Figura 3) y la masa total de las hojas defoliadas se calculó la superficie total.

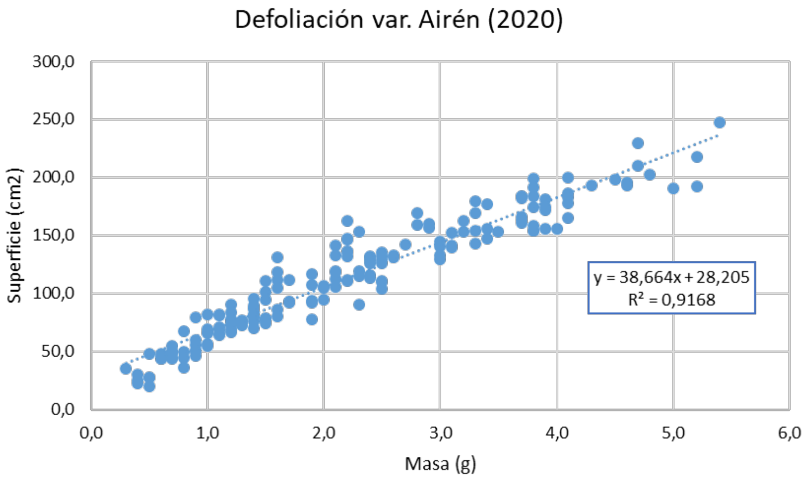

Figura 3. Ejemplo de correlación lineal entre masa (g) y superficie (cm^2) de hojas defoliadas para medir el LAI (n=177).

Finalmente, con la superficie total de la muestra, el LAI se calculó mediante la ecuación 1:

$$LAI = \frac{S_f}{d * r} \qquad \text{Ec. 1}$$

donde *LAI* es el índice de área foliar (adimensional), S_f es la superficie total de la muestra defoliada (m^2), *d* es la distancia del tramo defoliado (m) y *r* es la distancia entre filas (m).

2. Mapas de prescripción

En viñedos donde el vigor es heterogéneo se pueden definir zonas diferentes que probablemente recibirán diferentes prácticas de manejo o dosis. Generalmente se definen dos, tres o cuatro clases. Una forma de caracterizar el vigor es mediante la obtención de imágenes multiespectrales (reflectancias espectrales a diferentes longitudes de onda). Con la combinación de las bandas del rojo e infrarrojo se obtienen los denominados *Índices de vegetación*, los cuales se definen como un parámetro obtenido a partir de la combinación de dos o más valores de reflectancia a distintas longitudes de onda, para resaltar alguna propiedad de la vegetación (Arnó et al., 2009).

En los trabajos de dosificación zonal presentados en esta tesis se ha utilizado el índice *Plant Cell Density* PDC (Bramley et al., 2003) el cual se calcula a partir de la ecuación 2:

$$PCD = \frac{NIR}{R} \qquad \text{Ec. 2}$$

donde *NIR* es la reflectancia espectral del infrarrojo cercano (760-900 nm) y *R* es la reflectancia espectral el rojo (630-690 nm). Después los valores se normalizan en una escala de 8 bits con valores entre 0 y 255 (ambos incluidos). Es decir, para cada parcela e imagen, al valor mínimo obtenido con la ecuación 1 se le asigna el valor 0, y al máximo el 255. Los valores intermedios se interpolan de manera lineal. Por lo tanto, este índice es relativo y los mapas obtenidos en diferentes momentos y parcelas no se pueden comparar.

Las imágenes multiespectrales se obtuvieron desde una avioneta con una resolución de 0.5 m. El viñedo, al ser un cultivo en filas, tiene zonas de terreno sin vegetación, por lo que en las imágenes (*raster*) transformadas en PCD, la empresa proveedora de las imágenes (Agropixel SL), eliminó los pixeles correspondientes a las bandas sin vegetación situadas entre las filas mediante algoritmos. Los pixeles restantes se vectorizaron para interpolar los datos (Figura 4).

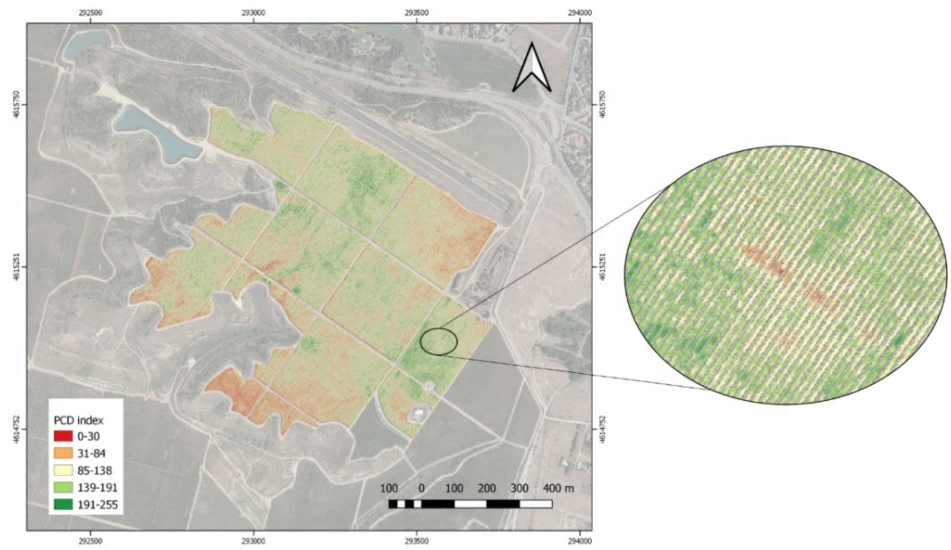

Figura 4. Índice Plant Cell Density (PCD) en una parcela de viñedo (imagen tomada el 5 de julio de 2019). Detalle de eliminación de pixeles entre filas.

2.1 Interpolación de datos

Al eliminar los píxeles entre filas del cultivo, el mapa deja de ser continuo y no podría clasificarse. Para conseguir el mapa continuo, los datos experimentales (en este caso valores de PCD restantes) se interpolaron. En primer lugar, los datos se ajustaron a un modelo empírico: el variograma o “semivariograma” utilizado en geoestadística para predecir la dependencia espacial (Oliver, 2010). El variograma experimental se calcula mediante la ecuación 3:

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m\,(h)} [z\,(x_i) - z(x_i + h]^2 \qquad \text{Ec. 3}$$

Donde *h* es distancia entre los pares, *m* es número de pares y $Z(x_i)$ es la localización y valor de la muestra. La cantidad γ(h) se conoce como la semivarianza en la distancia *h* y corresponde a la diferencia cuadrática esperada de una variable entre dos localizaciones.

Los tres parámetros más importantes que proporciona el variograma son el *range, el sill* y el *nugget* (Figura 5). El *range* (o meseta) es la distancia a la que el modelo se estabiliza. El *sill* (umbral) es valor que alcanza el modelo de semivariograma en el *range* (el valor en el eje y). Las localizaciones a mayor distancia del *range* se consideran espacialmente independientes. Por último, el *nugget* (o pepita) generalmente refleja errores de medida o variación que ocurre en distancias inferiores a los puntos muestreados. Además, en el caso de la viña (cultivo en filas) el patrón de distribución espacial de la variabilidad puede ir ligado a la dirección de las filas indicando anisotropía en la región de estudio (Webster y Oliver, 2007).

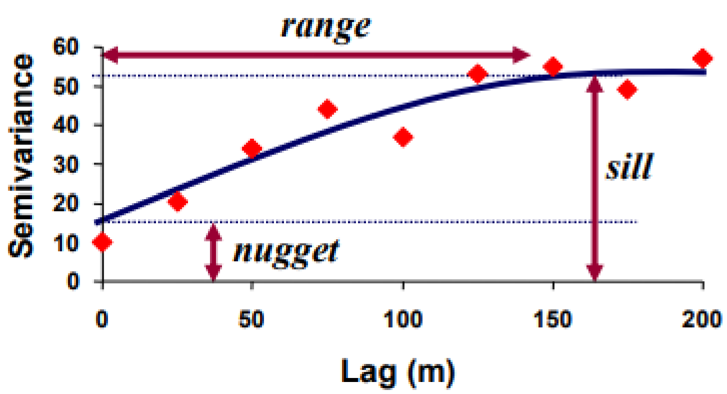

Figura 5. Ejemplo de semivariograma (Fuente: Apuntes de geoestadística Master PIC).

Se utilizó el software de análisis geoestadístico ArcGIS® 10.5 (ESRI, Redlands, CA) para ajustar en cada caso los datos experimentales (en la Figura 5 serían los rombos rojos) al modelo (esférico, exponencial, gausiano, etc) que mejor los describió (en la Figura 5 sería la línea azul).

El paso siguiente fue la interpolación de los datos en sí o predicción de los valores de la variable regionalizada en zonas no muestreadas. La técnica del kriging (o krigeado) es la más utilizada, y la que se utilizó en la presente tesis. Esta técnica utiliza el modelo de variograma para la obtención de los ponderadores que se dan a cada punto de referencia usado en la estimación. La técnica, no sólo proporciona las predicciones, sino también pronósticos, errores y variancias de kriging, que son una guía para la confiabilidad de las estimaciones (Oliver, 2010). El método del kriging ordinario es el utilizado para las interpolaciones de PCD realizadas en esta tesis.

2.2 Clasificación de los valores

Para la clasificación de los valores de PCD a partir del mapa interpolado se utilizó el algoritmo no supervisado ISODATA (*iterative self-organising data analysis technique* o técnica iterativa de análisis de datos auto-organizado) integrado en el software ArcGIS® 10.5. Es un procedimiento de clasificación optimizado de iteración para calcular la distancia euclidiana mínima cuando se asigna cada celda candidata a una clase. El proceso comienza con la asignación de valores medios arbitrarios por parte del software, uno para cada clase (en este caso se asignaron 2 clases, alto y bajo vigor, Figura 6). Cada celda se asigna lo más cercana posible a estos valores medios (todas en el espacio de atributos multidimensional). Los nuevos valores medios se vuelven a calcular para cada clase en base a las distancias de los atributos de las celdas que pertenecen a la clase después de la primera iteración. El proceso se repite: cada celda se asigna al valor medio más cercano en el espacio de atributos multidimensional, y los nuevos valores medios se vuelven a calcular para cada clúster basándose en la pertenencia de las celdas de la iteración. Se debe especificar la cantidad de iteraciones del proceso (se utilizó el valor asignado por defecto). Este valor debe ser lo suficientemente grande como para garantizar que, después de ejecutar el número de iteraciones especificado, la migración de celdas de una clase a otra sea mínima; entonces, todas las clases se volverán estables (ESRI, 2020).

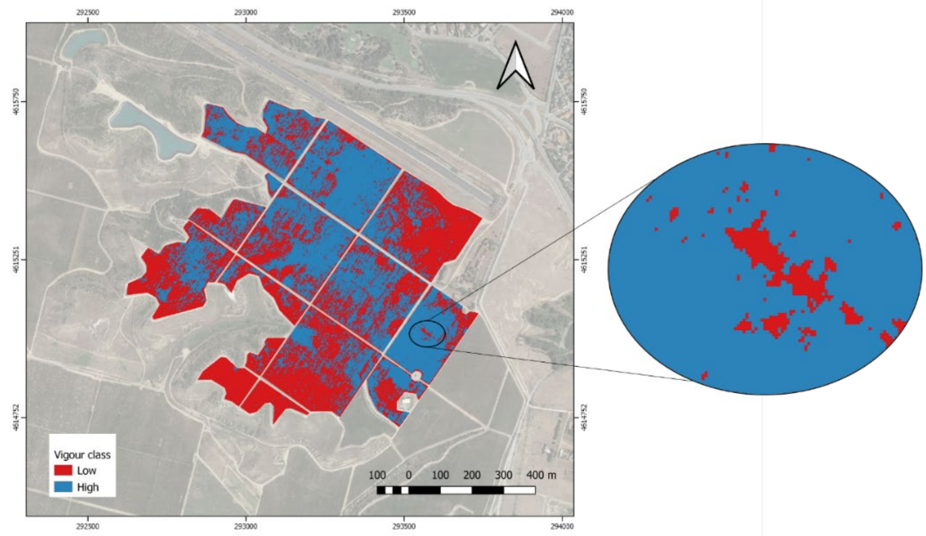

Figura 6. Mapa de vigor clasificado en bajo (low) y alto (high) con el algoritmo ISODATA (imagen tomada el 5 de julio de 2019). Detalle del resultado.

2.3 Refinar el mapa clasificado y mapa de prescripción

El mapa clasificado contiene áreas que son impracticables para la operativa del pulverizador, por lo que este mapa se refinó poligonizando las clases originales y eliminando los polígonos con una superficie inferior a 100 m^2, ya que la operativa del pulverizador es impracticable en estas subzonas.

Finalmente, para obtener el mapa de prescripción se asignó a cada clase un volumen de aplicación con el sistema de ayuda a la toma de decisión DOSA3D. Al mantener constante la concentración de producto en el depósito del pulverizador, indirectamente a cada clase se le asignó una dosis de producto fitosanitario (Figura 7).

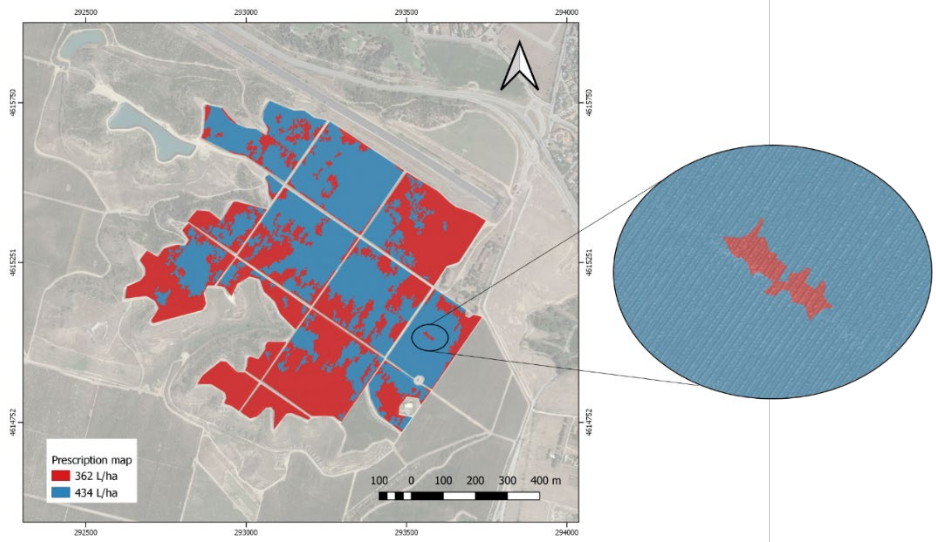

Figura 7. Mapa clasificado refinado transformado a mapa de prescripción de volumen de aplicación (L/ha) utilizando el sistema DOSA3D (imagen tomada el 5 de julio de 2019). Detalle de eliminación de polígonos el polígono rojo tiene una superficie superior a 100 m^2.

3. Ajuste de volumen y dosis: Sistema DOSA3D

Los ajustes de volumen de caldo y dosis de productos fitosanitarios de los ensayos se realizaron utilizando el sistema de ayuda a la decisión DOSA3D. El sistema DOSA3D se utilizó desde la plataforma web (www.dosa3d.cat) o desde la App para móviles sistema Android.

Para el cálculo en cada ensayo se tomaron medidas de la altura y anchura de la vegetación, y la distancia entre filas. Además, se tuvo en cuenta el tipo de pulverizador utilizado y la plaga a controlar.

4. Regulación del pulverizador

Una vez establecido el volumen de la aplicación con el sistema DOSA3D se llevó a cabo la calibración y el ajuste del pulverizador a la estructura del viñedo dentro de la parcela.

4.1 Elección de las boquillas y presión de trabajo

El caudal total (Q) en L min^{-1} que deben proporcionar el conjunto de boquillas operativas se calcula mediante la Ecuación 4:

$$Q = \frac{V * a * v}{600} \qquad \text{Ec. 4}$$

Donde *V* es el volumen unitario de la aplicación (L ha^{-1}), *a* es la anchura de trabajo (m) y *v* es la velocidad operativa (km h^{-1}). Los dos últimos parámetros se muestran en la Figura 8.

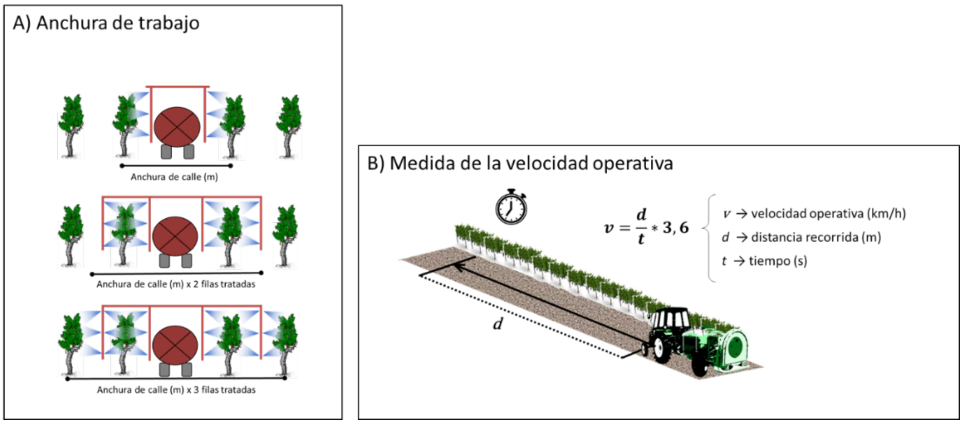

Figura 8. A) Anchura de trabajo equivalente a la distancia entre filas x1, x2 o x3 dependiendo del pulverizador. B) Medida de la velocidad operativa.

El caudal total, a su vez, equivale a la suma del caudal de cada una de las boquillas operaritvas (ecuación 5):

$$Q = (n_1 \cdot q_1) + (n_2 \cdot q_2) + \ldots + (n_n \cdot q_n) \qquad \text{Ec. 5}$$

Donde n_i representa el número de boquillas de un tipo determinado (modelo, calibre) que operan a un determinado caudal unitario (q_i). En tratamientos de cultivos 3D, normalmente, se instalan como máximo 3 modelos diferentes ($_n$≤3). Todos los ensayos se han realizado con boquillas de cono hueco[1] Albuz ATR (Solcera, Francia).

El caudal de caldo pulverizado por una boquilla (q_i, en L min^{-1}), de forma general, se puede expresar con la función potencial de descarga de un orificio de un líquido sometido a presión (ecuación 6):

$$q_i = k * P^x \qquad \text{Ec. 6}$$

donde *k* representa el coeficiente de descarga, característico para cada modelo de boquilla, y *p* la presión de trabajo. En todos los casos, el valor del exponente *x* es muy cercano a 0,5.

Para un determinado modelo de boquilla, el valor del coeficiente *k* y el exponente *x* se pueden estimar a partir de los valores de descarga (caudal / presión) proporcionados por el fabricante.

[1] En la pestaña BOQUILLAS de DOSA3D se pueden descargar las características de trabajo de los modelos de boquillas de cono hueco más utilizados. Se recomienda trabajar dentro de un rango de presiones de 5.0 a 15.0 bar.

Durante el transcurso de esta tesis, se desarrolló una hoja de cálculo donde se estimaron los coeficientes *k* y los exponentes *x* de los principales modelos de boquillas de cono hueco disponibles en el mercado (Román et al., 2018). Este documento calcula la presión de trabajo y el caudal unitario de los diferentes modelos de boquillas seleccionados a partir del volumen de aplicación, anchura de trabajo y velocidad de avance. Actualmente, se ha adaptado para los tratamientos zonales en los que se aplican dos volúmenes de caldo en su versión html y ha sido incorporado a la plataforma web del sistema DOSA3D.

4.2 Comprobación del caudal de las boquillas operativas y la presión de trabajo

De acuerdo con la norma ISO 16122-3:2015, el caudal nominal de las boquillas (indicado en las especificaciones técnicas del fabricante) no debe desviarse en más de un 15% respecto al caudal medido (ISO, 2015). Por ello, antes de cada ensayo, se comprobó que cada boquilla se ajustaba a este requisito. Para ello se recogió individualmente el volumen pulverizado durante un minuto en jarras calibradas (Figura 9).

Figura 9. Material utilizado para la calibración del pulverizador (jarras y mangueras).

Asimismo, se contrastó la presión indicada por el manómetro del pulverizador con la existente en ambos extremos de los conductos de distribución (posición de la última boquilla). Generalmente se comprobó que existía una reducción aproximada de 1.0 bar entre la lectura del manómetro del pulverizador y la del manómetro conectado al portaboquillas situado al final de cada línea (Figura 10A). En la ejecución de los tratamientos se consideró la presión indicada por ambos manómetros terminales.

Todos los ensayos se han realizado en parcelas comerciales con pulverizadores trabajando en condiciones reales. En determinadas ocasiones, se constató que alguna de las boquillas operativas proporcionaba un caudal considerablemente inferior al resto debido a obstrucciones por residuos de productos fitosanitarios o impurezas (Figura 10B).

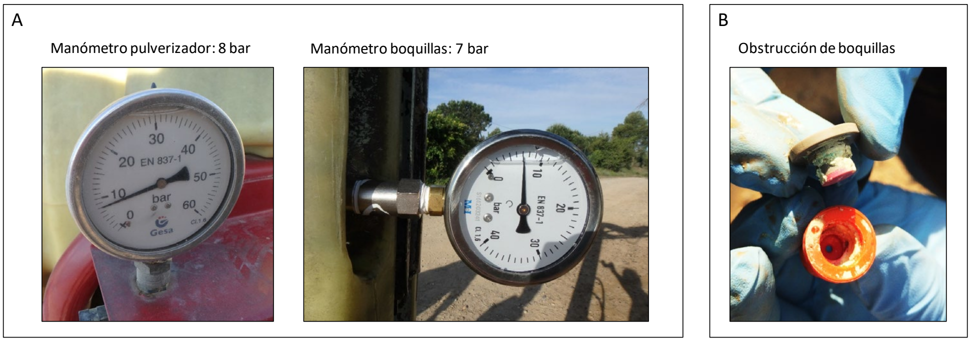

Figura 10. A) Diferencia de presión entre el manómetro del pulverizador y el manómetro situado en la zona de boquillas. B) Boquilla obstruida por azufre.

4.3 Valoración visual de la pulverización

Antes de cada ensayo se realizó una aplicación sin producto fitosanitario (sólo agua) en condiciones operativas reales. El control se realizó en primer momento visualizando a contraluz el abanico de pulverización, y, en segundo lugar, mediante papeles hidrosensibles grapados sobre hojas (haz y envés) situadas en diferentes zonas de la copa (Figura 11). Por norma general los códigos de Buenas Prácticas Agrícolas recomiendan una densidad de impactos mínima de 60-80 impactos/cm^2 (Planas, 2013; Román et al., 2015).

Figura 11. Control visual de la pulverización previa a los ensayos.

5. Ensayos de campo

La parte experimental de esta tesis para validar el ajuste de dosis mediante el sistema DOSA3D ha comportado una doble evaluación consistente en la determinación analítica de las deposiciones de producto en hojas y la evaluación de la eficacia biológica.

5.1 Medida de deposición en hojas

La evaluación de las deposiciones en hojas se realizó adaptando la norma de medición de campo de la distribución de la pulverización en cultivos de árboles y arbustos ISO 22522:2007 (ISO, 2007).

Se utilizaron para ello los trazadores siguientes: en los ensayos realizados en 2016 y 2017 fueron quelatos metálicos (Cu^{++} o Mn^{++}), mientras que a partir de 2018 se utilizó tartrazina (colorante alimentario E-102). Ambas sustancias son admitidas por la norma citada. La concentración en el depósito varió entre 1-5 g L^{-1}. Se tomaron muestras del caldo del depósito, antes y después de la pulverización para analizar la concentración real y conocer la dosis de la aplicación (kg ha^{-1}).

Se tomaron muestras de entre 3 y 12 cepas (dependiendo del ensayo) consideradas cómo repeticiones. El sistema de muestreo fue por zonas dentro de la vegetación. El número de muestras por cepa varió en función de las dimensiones de la vegetación (altura y anchura) tal como se muestra en la Figura 12. Antes de iniciar la aplicación se tomaron 3-4 hojas de cada cepa que sería posteriormente muestreada para detectar posibles residuos, bien de aplicaciones anteriores o procedentes de contaminación cruzada. Cada muestra se compuso de entre 2 y 4 hojas asegurando una superficie foliar mínima de 100 cm^2 (en la mayoría de casos fue superior a 200 cm^2) que fueron introducidas en una bolsa con cierre hermético.

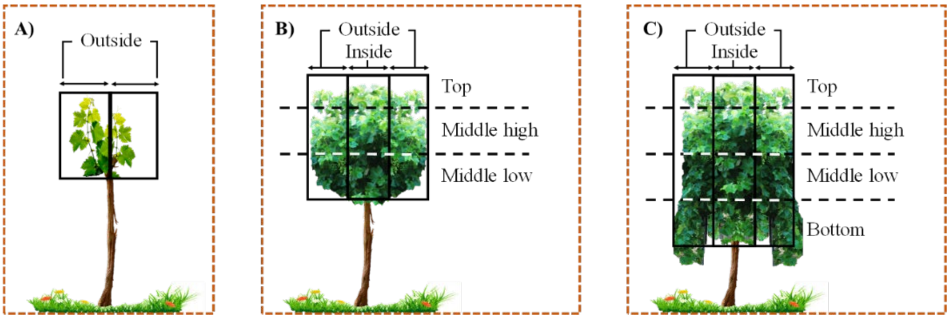

Figura 12. Ejemplo de distribución de las zonas de muestreo de cada cepa en A) inicio de vegetación, B) plena vegetación viñedo estándar, y C) plena vegetación de viñedo vigoroso.

Las muestras se mantuvieron en cajas oscuras para su traslado al laboratorio. El proceso general se muestra en la Figura 13. La extracción del trazador se realizó el día del ensayo introduciendo agua desionizada en las bolsas. El volumen de agua varió en función de la concentración de trazador (50 - 1000 mL). Una vez introducido el volumen de agua en las bolsas, el contenido se removió durante 30 segundos y se dejó reposar 20 minutos. Parte del contenido se introdujo en viales (50 mL), agitando previamente, para la posterior cuantificación del trazador. Cuando no se pudo analizar en el mismo día, los viales se mantuvieron en cámara refrigerada hasta su análisis.

La concentración de metal en cada muestra (Cu^{++} o Mn^{++}) se determinó por espectrometría de absorción atómica (AAnalyst 400, Perkin Elmer, Waltham, USA), mientras que la concentración de tartrazina se determinó por espectrofotometría a una longitud de onda de 427 nm (Spectronic 301, Milton Roy, New York, USA).

Las hojas de cada muestra se secaron en papel absorbente durante una noche. La superficie de las hojas de cada muestra se midió en los primeros años (2016-2018) mediante un superficiador de análisis de imagen (Delta-T Devices Ltd., Cambridge, UK). A partir de 2019, cada muestra se fotografió para determinar el área foliar con el software de análisis de imagen libre ImageJ (Schneider et al., 2012).

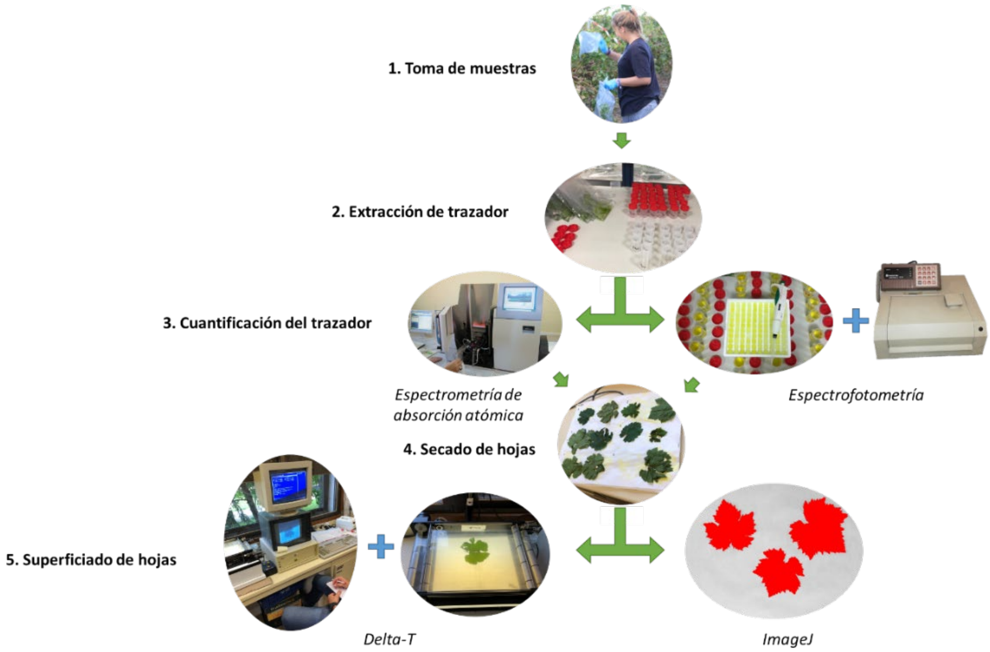

Figura 13. Proceso de toma de muestras, extracción y cuantificación del trazador y superficiado de hojas.

La deposición foliar de cada muestra (en µg cm^{-2}) se calculó mediante la ecuación 7.

$$d = \frac{v_w * C}{s * 1000} \quad \text{Ec. 7}$$

donde v_w es el volumen del agua desionizada de extracción (L), C es la concentración del trazador en la muestra (mg L^{-1}), s es la superficie de la muestra (cm^2) y 1000 es el factor de conversión de unidades.

Para obtener los valores de deposición volumétrica (µL cm^{-2}), se dividieron los resultados por la concentración del caldo pulverizado.

5.2 Ensayos de eficacia

La validación final del sistema DOSA3D en viñedo se realizó evaluando la eficacia de los tratamientos en el control de oídio (*Erysiphe necátor* (Schw.)), ácaro amarillo (*Eotetranychus carpini* Oud.) y mosquito verde (*Empoasca vitis* G. y *Jacobiasca lybica* Berg. & Zanon), aplicando dosis de productos fitosanitarios ajustadas.

Por una parte, el control de oídio se evaluó en cuatro viñedos situados en la zona del Penedès (España). Cada parcela se dividió en dos mitades y en una el agricultor aplicó cada tratamiento a las dosis y volúmenes de caldo que consideró y en la otra mitad en cada tratamiento se aplicó el sistema DOSA3D durante toda la campaña.

Por otra parte, se realizaron tres ensayos de tratamientos zonales en Raïmat (España) en los que se determinó la eficacia de diferentes tratamientos contra ácaro amarillo (2) y mosquito verde (1) a dosis ajustadas a dos vigores (alto y bajo) establecidas mediante el sistema DOSA3D.

Todos los ensayos se realizaron en parcelas comerciales por lo que en la mayoría de casos no se pudo mantener una zona sin tratar (o testigo). En estos casos se compararon las estrategias (agricultor vs. DOSA3D) seguidas mediante pruebas *t-student*.

En las ocasiones en las que se pudo mantener una zona sin tratar, además de comparar entre estrategias se calculó la eficacia mediante la fórmula de Abbott (Abbott, 1925).

Cabe destacar que durante el periodo de la tesis también se ha desarrollado y validado un protocolo de evaluación y toma de decisión para el control de ácaro amarillo (Planas y Román, 2020). Este protocolo se basa en un muestreo secuencial adaptado en el que se tiene en cuenta el número de hojas ocupadas por *E. carpini* en mínimo 4 puntos de la parcela. El número total de muestras en cada punto es 10 o 20, en función de si hay presencia o no (Figura 14). Por lo tanto, como mínimo se muestrearán 40 hojas por parcela. La razón de aumentar el número de muestras cuando hay presencia de *E. carpini* es para asegurar que se sobre pasa el umbral de tratamiento.

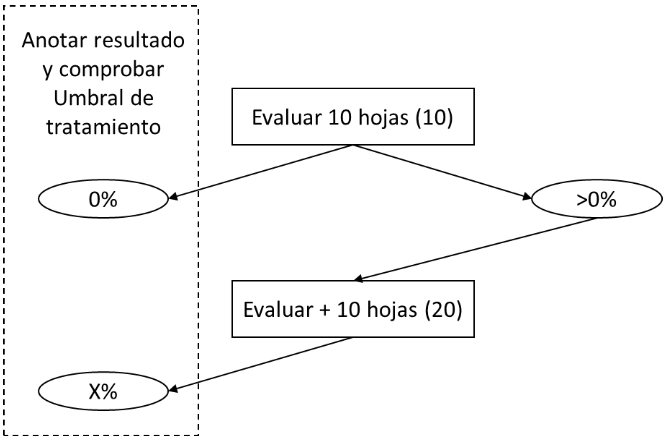

Figura 14. Muestreo secuencial adaptado en cada punto de control.

Finalmente, en cada parcela se calcula el promedio de hojas ocupadas en los diferentes puntos de control para la toma de decisión sobre un posible tratamiento. El umbral de tratamiento es distinto dependiendo de la fenología del cultivo debido a las diferencias existentes en el potencial de daños a lo largo del período vegetativo. A mayor riesgo potencial, menor valor del umbral de tratamiento (Figura 15).

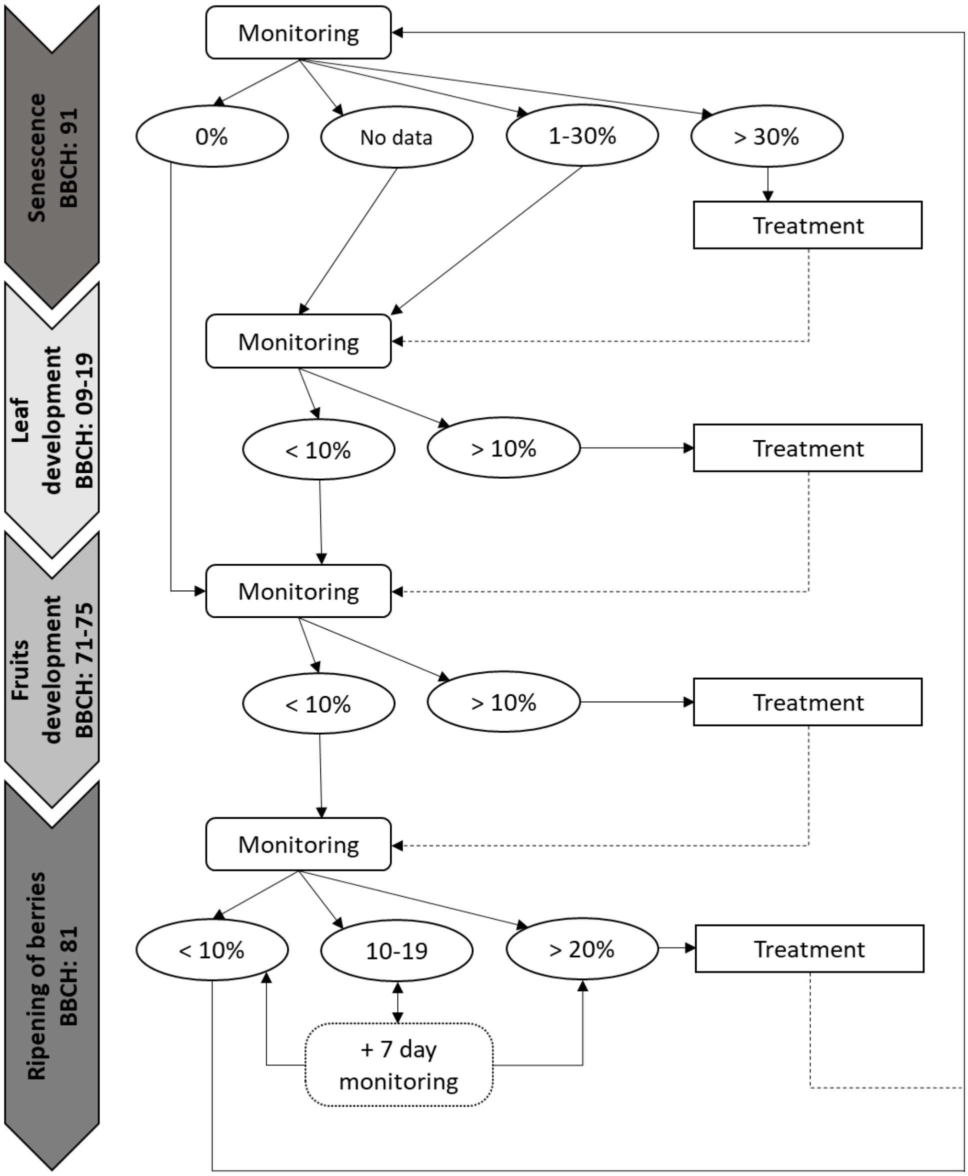

Figura 15. Esquema de decisión y umbrales de tratamiento para Eotetranychus carpini.

6. Método estadístico

En los capítulos 6 y 7 se comparan las deposiciones en hojas entre tratamientos en diferentes ensayos. El estudio estadístico se realizó mediante el modelo de análisis de varianzas lineal mixto (LMM, de sus siglas en inglés *linear mixed model*). Este modelo lo empezaron a utilizar Pascuzzi y Cerruto en 2015 para el análisis de deposiciones en hojas.

Antes de llevar a cabo el análisis se comprobó que se cumplían las asunciones de normalidad (test de Shapiro Wilk) y heterocedasticidad (test de Barlett), en caso contrario, los datos se transformaron mediante su raíz cuadrada antes de analizarlos.

El LMM es un modelo que contiene efectos fijos y aleatorios. En este caso se consideraron los efectos tratamiento y vigor como fijos. Y las cepas (o repeticiones) como factores aleatorios. Además, la altura y profundidad de las muestras dentro de la cepa (zonas de muestreo) se consideran factores anidados a la cepa. En los capítulos mencionados se detalla cada modelo seguido.

Para el análisis se utilizó el paquete "mixlm" dentro del software libre Rstat (R versión 3.3.3). A modo de ejemplo el código utilizado en uno de los ensayos fue:

```
modelo <- lm(Deposition ~ Treatment+Vigour+Treatment:Vigou
r+r(Vine)%in%(Treatment:Vigour)+Height%in%(r(Vine)%in%(Tre
atment:Vigour))+Depth%in%(r(Vine)%in%(Treatment:Vigour))+H
eight%in%(r(Vine)%in%(Treatment:Vigour)):Depth%in%(r(Vine)
%in%(Treatment:Vigour)), data = Deposition)
tAnova <- Anova(modelo, type="III")
tAnova
```

Finalmente, si el resultado del LMM rechazaba la hipótesis nula de igualdad de medias, se realizaba la separación de medias mediante el Test HSD (*Honest Signigicant Differences*) de Tuckey.

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CAPÍTULO 3

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

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

1. Introduction

At the global level, total pesticides use worldwide in agriculture remained stable since 2012 around 4.1 Mt (FAO, 2021a). In Europe the sales of pesticides in the last three accounted years (2016-2018) was also constant around 0.43 Mt, being France, Spain, Italy, Germany, and Poland the main European countries consuming pesticides (Eurostat, 2021a).

Nevertheless, the yearly figures on the consumption of pesticides probably hide the real evolution of the chemical pressure and their associated risks because the dose of new active ingredients (a.i.) is lowering progressively. Beyond the mass consumption, other indicators allow a better understanding of reality. This is the case of the European Harmonised Risk Indicator (HRI 1) measuring the use and risk to human health and the environment from pesticides since 2011 in the EU-28. The HRI 1 indicator shows a 17% reduction in the risk in the period 2011-2018 (EC, 2020).

While the use of pesticides continues to be unavoidable for productive and quality reasons, it is nevertheless associated worldwide with non-negligible, human and environmental risks. For this reason, both the Sustainable Use of Pesticides Directive 2009/128/EC (SUPD) (EC, 2009a) 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 this context, and in accordance with the stipulations of Regulation 1107/2009 (EC, 2009b), 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 regions around the world with a common concern for the safe use of pesticides. Sustainability, risk mitigation and cost reduction constitute the mandatory principles of agriculture throughout the world, but the current level of agricultural productivity cannot be sustained without the use of pesticides (Nishimoto, 2019).

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 (PPPs) containing active substances that meet the cut-off criteria or are identified as candidates for substitution, as set out in various points 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, 2020). Additionally, 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 pesticides containing biological active substances (biopesticides).

1.1 Objectives of dose adjustment

In these circumstances, the use of adjusted pesticide doses to levels that are strictly necessary, along with the minimization of pesticide wastage and its environmental impact, becomes an obligatory rule to be usually adopted.

Other important reasons for dose adjustment include reducing the cost of chemical pest control and pesticide residue levels in food, not only in compliance with Regulation 396/2005 (EC, 2005), but also to satisfy specific conditions established by food distribution and retail companies. The ultimate goal is to achieve a level of zero residues.

In fact, dose adjustment has for a long time been an objective that is fully in line with the aforementioned requirements. This is particularly important in three-dimensional (3D) crops, where very different scenarios are possible depending on crop dimensions, vigour, leafiness, the pests to be controlled and spraying equipment performance.

In 2019, near 55 Mha of 3D crops, including deciduous fruits, grapes, nuts, almonds, citrus and olives were located worldwide (FAO 2021b), which 12 Mha correspond to Europe (EU-28), where mainly (91%) in the European Southern Zone (ESZ) (EC, 2009b, 2009c). This area included 39%, 69% and 86% of the total area of pome fruits, stone fruits and grapes, respectively and 100% of the total area of almonds, citrus and olives (Eurostat, 2021b). 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).

Some time ago, 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, while 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) also 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).

According to the European and Mediterranean Plant Protection Organization (EPPO), the minimum effective dose of a pesticide is defined as the dose that is the minimum necessary to achieve sufficient efficacy (effectiveness) against a target pest across the board range of situations in which the product will be applied (EPPO, 2012a).

2. Dose expression systems

For field crops, including arable crops and many vegetables, 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 ground area. However, when substantially increasing crop dimensions occur over the course of the season, the dose may be adapted (adjusted) to the leaf area or growth stage. For the case of 2D crops, this dose expression system is considered the most rational and no changes are expected in the short term.

However, in 3D crops there are several issues that arise. Firstly, evaluation or efficacy trials are generally carried out using portable hand-held sprayers whose performance and efficiency are not necessarily equivalent to those of the sprayers used at farm level. Secondly, the volume rates also tend not to coincide. For purposes of evaluation, reference volumes of 1000 L ha^{-1} or greater are frequently adopted for 3D crops, but these values differ significantly from the volumes sprayed in real conditions which are gradually being lowered thanks to technical improvements. Finally, the results of evaluation trials can be expressed in a different mode to that expressed on the label. This triple gap introduces uncertainty which has been repetitively exposed by the scientific community and is well known by the authorities. In the end, advisors and final users have to make specific decisions to understand and adapt the dose to the real conditions. All of this implies a weakness on the part of the regulatory system of pesticide registration and use.

Consequently, while dose adjustment may be the rule, the question remains as to how to establish the dose to be applied to achieve the hoped-for efficacy in 3D crops. At farm level, significant efforts are being carried out to reduce the amounts of pesticide that are applied through the use of better performing sprayers specifically adapted to the crop. But how should the dose be expressed and how should it be adjusted?

The current version of the EPPO standard recently in force PP 1/239(3) “Dose expression for plant protection products” addresses this issue (EPPO, 2021). This standard clearly states the difference between dose expression (how the dose of pesticides should be expressed in high growing crops) and dose adjustment (adaption of the dose to the specific circumstances as canopy density, grow stage, application method, pest to be controlled, etc..).

Consequently, an accurate (refined) adjusted dose should also take into account the conditions of the specific scenario. Hislop (1987) previously pointed out the difficulties of obtaining an optimal deposition of pesticides due to the different variables involved (characteristics of the crop, pests to control, spraying technique, etc.).

For high-growing crops the target should be considered as a 3D crop. 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 and productive advantages. These training systems now predominate. And other tree crops, including olives, stone fruits and almonds, are also being adapted to the hedgerow shape.

The dimensional parameters of wall crops, regular-shaped canopies, are relatively easy to determine. The canopy height (from the lowest leaves to the tree top) and mid-width of the crown (distance between outer leaves at the middle of the canopy height) are used to calculate spraying volume and dose rates. In this case, dose can be expressed as pesticide mass or volume unit (kg or L) associated to a certain reference unit such as ground area, spray volume (concentration), canopy height, leaf wall area (LWA), tree row volume (TRV) or plant row (Doruchowski, 2017). Nevertheless, the experts assume that ground area and concentration expression modes are no longer sufficient and should not be used except as additional information to the dose expressions considering crop structure (EPPO, 2016; EPPO, 2021).

One particular case is citrus because, in the initial period, the canopies are globular-shaped but over the years become closer along the row forming a nearly continuous wall shape without significant gaps between each tree. In this situation, the rows could be sprayed continuously as is usual in hedgerows. However, 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). These particular tree shapes are not studied in this paper. Nevertheless, globular-shaped crops jointly the wall crops addressed in this article have been recently widely reviewed by Garcerá et al. (2021).

2.1 Changing dose expression modes

Concentration and crop ground area dose expression modes, at the present time, continue to appear on the labels of a significant number of formulated products for 3D crops in a large number of countries. It is largely accepted that these expressions are no longer sufficient because they do not relate to the dimensions of the target unit. In order to understand the possibility of reducing the applied dose rate, Koch and Weißer (1995) suggested changing the expression modes to quantities related to the sprayed area with a view to optimizing pesticide leaf deposition. Walklate et al. (2003) argued that concentration or hectare-based dose recommendations have an intrinsic risk of dose errors that can lead to negative impacts on efficacy or resistance management. In the same line, the EPPO has repeatedly commented on the issue of evaluating the efficacy of PPPs (EPPO, 2012b; EPPO 2016).

In 2001, the EPPO *ad hoc* panel on Expression of Dose recognized the need to harmonize the expression of dose rate in order to allow the free exchange of data between countries and concluded that the ideal method to express the dose rate should take into account the total leaf area in relation to the field area but should be sufficiently simple to be understandable on the product label and practical for farmers. Additionally, the expression mode should take into account the efficiency of spraying techniques (EPPO, 2001). For high-growing crops (3D), this proposal received broad support (Friessleben et al., 2007; Koch, 2007; Planas, 2002). The chemical industry also submitted requests for harmonization and proposed the LWA as a common dose expression (Toews and Friessleben, 2012; Wolhauser, 2011). Finally, this system was proposed as the harmonized dose expression for efficacy evaluation in pome fruit, grapevine and high-growing vegetables (EPPO, 2016) for mutual recognition in accordance with the provisions in Annex I of Regulation (EC) 1107/2009.

The LWA has now been adopted for zonal assessment in the ECZ (CZSC, 2017) and the German authorities made this agreement mandatory by January 2020 (BVL, 2018). For the moment, the Steering Committee of the ESZ has not adopted any definitive decision on this matter.

Official information on doses addressed to users is the responsability of the national authorities of each EU member state. Austria, Germany and Belgium, all in the ECZ, have registered pesticides whose dose is expressed in the LWA system. However, in European countries which correspond to the majority area of 3D crop cultivation, the old expression modes (concentration, kg or L ha^{-1}) continue to remain in force. Kral et al. (2019) assume that in the meantime different dose expression modes will have to coexist and offer suggestions to facilitate adaptation to the LWA mode for end users.

During the same period, new dose expression modes, as well as several decision support systems (DSSs) for dose adjustment, have been successively proposed in Europe and the US to establish the optimal dose based on dimensional parameters of the orchard to be sprayed. However, any advanced decision on pesticide dose must be based on experimental works that allow consistent and clear criteria.

This paper summarizes the research carried out on the coexisting dose expression modes and dose adjustment systems and, for the first time, brings together and compares them for the adjustment of doses in fruit orchards and vineyards.

2.2 Tree row volume system

The TRV system was first described by Byers et al. (1971) from the US, and corresponds to the cubic volume of the tree rows per ground area. It is calculated according to Eq. 1:

$$TRV = \frac{w \cdot h \cdot 10^4}{r} \qquad \text{Eq. 1}$$

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

Byers established the point of runoff of 1 L of water per 10.67 m^{-3} of TRV (0.093 L m^{-3}) as the liquid volume ratio for spraying intensive fruit orchards. This ratio was later confirmed by the same author (Byers, 1987). Herrera-Aguirre and Unrath (1980) proposed the ratio 1 L 8.62 m^{-3} (0.116 L m^{-3}) in the case of spraying apple trees with ethephon (growth regulator) applications. Subsequently, Travis (1981) studied the relationships between tree volume and pesticide deposition on leaves when spraying and showed that in pruned apple orchards spray deposition was higher and more uniform. Sutton and Unrath (1984) analysed the influence of foliar density and established that differences in tree structure and growth stage may also account for some of the variation in deposition. Later, the same authors, Sutton and Unrath (1988), found that deposits at the tight cluster stage were 1.2-2.0 times greater than deposits achieved on the same canopies at full-leaf stage.

Moreover, Hall (1991) demonstrated that average spray deposits increased in intensive-shaped (trellis) 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 of the spray application process. Doruchowski et al. (1996) recommended TRV as a reliable method for adjusting spray volume to canopy tree dimensions.

In New Zealand, Manktelow and Praat (1997) validated the TRV model in Granny Smith and Red Chief apple orchards and suggested ratios above 1 L 10.67 m^{-3} in large dimension trees (TRV > 23000 m^3 ha^{-1}). Additionally, they suggested a more accurate measure of canopy width to calculate the TRV value, considering the height stratified in 0.5 m intervals as this provides 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 volume rate calculation. For their part, Rüegg et al. (2001) recommended using the maximum width of the crown to calculate the TRV value for goblet-pruned stone fruits and a minimum volume rate of 200 L ha^{-1}.

Rüegg et al. (2001) also compared the fruit tree crown height (CH) system, in use at that time in Germany, the surface orchard (SO) system, a particular expression of the LWA mode, adopted at the time in Belgium, and the TRV mode which had already been introduced in Switzerland (Viret et al., 1999). Ultimately, they advocated use of the TRV mode as it correlated well with the leaf area index (LAI) (R^2=0.81, linear, in 101 trials), whereas tree crown height alone showed a poor correlation with LAI (R^2 = 0.60, linear, in 101 trials). Additionally, the authors 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=10000 m^3 ha^{-1}, crown height = 2.00 m, crown width = 2.00 m and row distance = 4.00 m).

Solanelles et al. (2004) showed how deposits clearly tended to reduce as TRV increased for any spraying volume rate. The study was made in apple and pear orchards at early growth and full-leaf stages using three spray volume rates (400, 800 and 1600 L ha^{-1}).

In addition, 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.

The TRV model assumes that canopy width is as relevant a parameter as canopy height to determine volume rates and optimal doses. It was proposed for dose expression and the harmonization of registration trials (Rüegg et al., 2001). The TRV model is currently accepted by the Swiss authorities for dose expression. A canopy volume of 10000 m^3 ha^{-1} is adopted as the reference for dose adjustment in pome fruits (OFAG, 2020).

2.3 Leaf wall area system

The LWA is a particular case of the TRV assuming that canopy width is non-varying or non-influencing at a significant level. This model was studied by Koch and Weiβer (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 expressed as follows (Eq. 2):

$$LWA = \frac{2*h*10^4}{r} \qquad \text{Eq. 2}$$

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

Weisser and Koch (2002) subsequently suggested that it would be logical to use this dose expression for all tasks, from early field testing to label instructions. In this respect, Koch (2005) demonstrated that a linear correlation exists between the dose delivered per 10000 m^{-2} treated area (LWA) and the deposits on fruit tree leaves. The same correlation was found for grapevine leaves, and Koch (2007) suggested changing to the LWA mode in field biological efficacy trials for registration purposes. As mentioned before, the LWA system has been adopted in the ECZ for these trials.

More recently, Kral et al. (2019) argued that dosage should not be dependent on growth stage since vegetative development may depend on age or variety. They therefore considered that dose expression should only be related to the LWA.

Previously, Pergher and Petris (2008) had verified that normalized foliar deposits and LAI did not correlate well for LWA-adjusted doses (R^2=0.050) in vineyards (similar to the relationship found between LWA and LAI by Rüegg et al. 2001, mentioned above). However, they preferred to use the LWA than the LAI system method for dose adjustment in vineyards arguing that LAI values are very difficult to determine under field conditions. These authors, using the LWA model, verified that dose rate reductions of between 8% and 58% (29% on average) could be expected when compared to using a fixed dose per unit ground area.

In the meantime, in the UK a large and substantial work on dose adjustment was being undertaken. In successive papers, it was 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) without information about worst case target structures (i.e. maximum target height to row spacing ratio) (Cross and Walklate, 2008; Walklate et al., 2011a; Walklate and Cross, 2012).

At a practical level, the LWA does not take into account canopy width or leafiness. In the current situation for intensive fruit and grapevine orchards, canopy width can reach values higher than 2.0 m and over 1.5 m, respectively. This is particularly the case in the ESZ, where end users and advisers are reluctant to use a system that proposes the same dose for any canopy width or leaf density.

As mentioned previously, the LWA is the dose expression system advised by the EPPO (2016). Nonetheless, at national level, questions remain. How should the LWA dose be translated to the national labelling expression mode? Which dose expression modes will be accepted by the regulatory authorities? How should the dose be adjusted to the specific target characteristics (dose adjustment)? What instructions should be provided on the product label?

In the meantime, as highlighted by Codis et al. (2012) and Doruchowsky (2017) among others, different expression modes coexist at present in Europe and are officially accepted for registration and dose recommendation purposes on product labels.

2.4 Area density, porosity and leaf area index

The LAI is defined as the one-sided leaf area per unit ground surface ($m^2\ m^{-2}$). As mentioned previously, several authors and dealers have considered leaf surface area and sprayer efficiency for dose application rates. This idea was initially expressed by Pergher and Petris (2008) through Eq. 3:

$$Q = \frac{2*10^2*d*LAI}{e} \qquad \text{Eq. 3}$$

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

Pesticide application researchers and specialists generally agree that the dose of pesticides should ideally be linked with the leaf area present on the day of application. Hislop (1987) stated that the dose expressed in kg or L per 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 spraying volume rate as crop LAI increases. Other authors have stated 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 expressed as ng cm^{-2} plant surface area (Weisser and Koch, 2002).

Several initial works indicated the relevance of the total leaf area for dose adjustment. Rüegg et al. (1999a) reported that in pome and stone fruit orchards the LAI shows a good linear correlation with the TRV. For the case of stone fruits (TRV < 17000 m^3 ha^{-1}) they calculated the regression (R^2=0.95, linear).

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 is 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 same 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.

Subsequently, Viret et al. (2005b) determined the correlation (R2 = 0.81) between the TRV and the LAI in vineyards throughout the season regardless of variety, year or training system. For the same conditions, Planas et al. (2016) reported a similar correlation (R2=0.78, linear), but found a poor correlation with the LWA in vine and fruit orchards (R2=0.21, linear and R2=0.05, linear, respectively). For their part, Siegfried et al. (2007) noted that in vineyards the TRV gives a good approximation of the LAI (R^2=0.89, potential) and found that dosage dependency on the LAI allowed more constant deposition throughout the season. Additionally, Viret et al. (2005b) demonstrated that an important reduction in active ingredients could be obtained with adapted dosage until bloom in vineyards. Calculated over the whole spraying program, this reduction could be as high as 20-35% under practical conditions, depending on year and plots.

Viret et al. (2007) reported that dose adjusted to the TRV, as LAI estimator, or to the growth stage, gave similar results when controlling downy mildew (caused by *Plasmopara viticola* (Berk. & Curt.) Berl. & de Toni) and powdery mildew (caused by *Erysiphe necator* (Schw.)) in grapevines. Following five additional years of trials, no significant differences were found in the control of downy and powdery mildews between standard and adjusted doses. For this 5-year period, 20% of the product was saved on average (Viret et al., 2010). The authors concluded that adapting the dosage of fungicides to the actual leaf surface area to be protected is a valuable and rigorous way to reduce the amount of product used, while ensuring effective protection.

2.5 LAI and leaf deposition

Rüegg et al. (1999b) confirmed in small stone fruit orchards (TRV < 17000 m^3 ha^{-1}) that LAI correlates well with normalized deposits (R^2=0.84, logarithmic), as well as in large stone fruit trees (TRV > 17000 m^3 ha^{-1}) (R^2 = 0.91, logarithmic).

According to Weisser and Koch (2002), the delivered dose rate per 10000 m² sprayed area and the retained and effective dose on the target are quite different. In fact, 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.

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

Pergher and Petris (2008) summarized the work carried out by different authors from nearly 400 deposit measurements performed in vineyards and apple orchards and evidenced that the application of a constant dose per unit ground area consistently resulted in average foliar deposits that decreased as crop LAI increased. Based on this evidence, it can be suggested that pesticide doses might be adjusted to the LAI of the orchard to be treated.

Koch and Knewitz (2011) proposed a methodology to evaluate spray applications by measuring spray deposits following ISO 22522:2007 and, instead of considering the mean values, suggested using the proportion 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}.

Some results have been reported on efficacy when dosage has been related to LAI. Weisser and Koch (2002) argued in favour of considering deposits on the plant surface as the most relevant parameter to determine the biological efficacy of the delivered chemical quantity. Siegfried et al. (2007) confirmed that LAI dosage dependency allows good efficacy against downy and powdery mildews compared to unsprayed and standard dosage. In 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 leaf area for azoxystrobin (Quadris 0.25% w/v) and 3.0 µg cm^{-2} for folpet (Folpet WDG 80%). To meet this objective, the authors explained that 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, 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 Figure 1, for side-by-side hydropneumatic sprayers operating with hollow cone nozzles according to BBCH phenological growth stages (Meier, 2001). In the same work, Codis et al. (2018b) found that deposition decreased as phenology progressed in a non-linear way, with this observation concurring with the data registered by the authors of the present paper and with the conclusion of a previously mentioned study in which nearly 400 deposit measurements were taken in vineyards and apple orchards (Pergher and Petris, 2008).

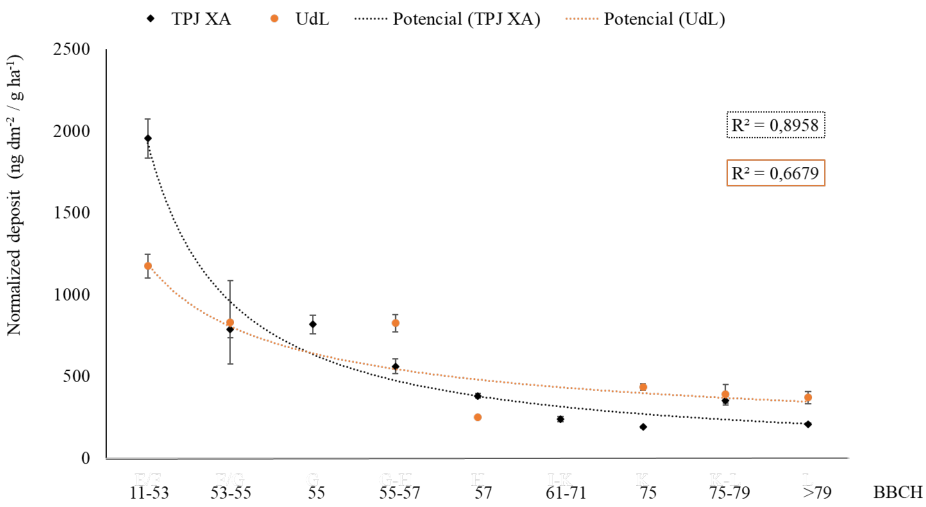

Figure 1. Normalized leaf deposit (mean±SE) of tracer achieved by a side-by-side (TPJ XA) hydropneumatic sprayer (data from Codis et al. 2018b) and University of Lleida (UdL) ISO 22522:2007 trials with side-by-side hydropneumatic sprayers by phenological stage (BBCH scale).

Additionally, Siegfried et al. (2007) confirmed that LAI dosage dependency allowed good efficacy against downy and powdery mildews compared to unsprayed and standard dosage. The authors also considered that a minimum deposit is required for consistently good efficacy against diseases. The authors concluded that adapting dosage to leaf area provides a practical system for the standardization of field experiments for the registration process and enables vine growers to calculate precisely the amount of product to use per hectare. The same authors also verified that 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).

Finally, Duga et al. (2015a) analysed the spray-deposition profiles in different pome fruit trees and concluded that tree characteristics such as total leaf cover, leaf wall porosity and tree volume strongly affected total on-target deposition.

All of these results 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. Such arguments favour referencing the target leaf surface area for optimal dose calculations. Despite this, it should not be forgotten that many experts have pointed out the difficulty of measuring the LAI (Pergher and Petris, 2008).

3 Dose adjustment

Dose adjustment is the determination of the quantity of product necessary to achieve the requested efficacy under specific circumstances (Weisser and Koch, 2002). How should dose be varied according to the dimensional parameters (height, width, row-spacing), leafiness and sprayer performance? As mentioned before, the total amount of the product must be the amount that is strictly necessary to achieve the threshold deposit on a sufficient proportion of zones within the canopy.

3.1 Leaf area, leafiness and growth stage

Sutton and Unrath (1984) considered that the recommended product concentration was sufficiently effective and that the applied dose varied when the application volume rate was adapted to the TRV (1 L 7.48 m^{-3}) (0.133 L m^{-3}). The study was carried out in different apple orchards with three pruning levels and dose was adjusted by applying a correction factor to the volume rate of between 0.7 and 1.0 depending on foliar density. The authors showed that adjusting doses to leafiness achieved similar deposits among the studied scenarios.

In this respect, Walklate, Cross and Pergher (2011) characterized different fruit orchards and vineyards using a LiDAR system in the UK and Italy. They argued that dose should have an adjustment range for PPP without any growth-stage specific uses. In fact, LWA dose adjustment to target density compared to applied doses based solely on LWA allowed a 17% reduction in pesticide use (Walklate and Cross, 2012). In a later work, the same 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). However, they set a lower dose adjustment limit to maintain leaf deposition and not compromise efficacy when dose is reduced.

In Spain, important LiDAR-based works have been carried out in fruit orchards and vineyards (Escolà et al., 2012; Rosell-Polo et al., 2009a, 2009b; Sanz et al., 2005, 2011, 2013). Sanz et al. (2018) also 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 leaf area (LA). They concluded that the height variable does not explain well the LA and, consequently, that canopy height 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 proportion of gaps (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 can lead to good *in-situ* LA estimation.

In deciduous crops, the growth stage also correlates well with leaf density (Holterman et al., 2016; Rinaldi et al., 2013; Solanelles et al. 2013).

In vinegrapes, Viret et al. (2005) established a curve-type LAI throughout the season and found that fungicide doses could be reduced by up to 20-30% when adapted to the growth stage. In this regard, in a subsequent paper Viret et al. (2007) stated that the most relevant dose adaptation should be carried out in vine at BBCH stages 55-57 (pre-blossom). Likewise, 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 62-63) and found that LAI reached maximum values (1.2 to 2.3) depending on canopy management and cultivar.

In Spain, the LAI has been determined in trellis-trained irrigated vineyards throughout the season, with LAI values determined in, for instance, Castilla La Mancha (Daramezas) at BBCH stages 53-61 (pre-blossom to starting flowering) 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. In Catalonia (Raïmat), 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.

Regarding pome-fruits orchards, the LAI has been determined in Lleida (Gimenells) at BBCH stages 71-75 (from fruit size up to 10 mm to fruit about half final size) when LAIs ranged from 2.3 to 2.9 and at BBCH 76-89 (from fruit about 60% final size to fruit ripe for consumption) when LAIs ranged from 2.6 to 4.0.

3.2 Sprayer

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 type of sprayer in achieving this goal has been extensively studied and numerous important papers have been published comparing the performance and efficiency of spray deposits 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, were incorporated about three decades ago in several fruit producing regions. This allowed a considerable reduction of applied volume rates and losses, as well as improved spray distribution and the possibility of lowering pesticide doses. Doruchowski et al. (1996) showed how cross-flow sprayers enabled an important reduction of pesticide doses. More recently, Tadić et al. (2014) reported improvements using directed spouts (individual outlets) fitted to a radial fan. Subsequently, Duga et al. (2015b) observed that crossflow 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 tunnel sprayers, was higher than that of conventional types, that spray deposition was improved and that doses could therefore be reduced accordingly without reducing biological efficacy.

Likewise, recycling sprayers have been reported to be very high performing and environmentally safe equipment after testing gave very good results in pome fruits (Balsari et al., 1996 Heijne and Porskamp, 1996; Holownicki, 1996; Planas et al., 2002). In grapevines, Viret et al. (2005b) obtained a deposition at least 2.5 times greater when spraying with a recycling sprayer in comparison to standard sprayers. Doruchowski and Holownicki (2000) evaluated this technique in fruit trees, achieving a 30% reduction in the use of chemicals. In peach orchards, Ade et al. (2007) recovered about 20-30% of the sprayed liquid, and Jamar et al. (2010) achieved dose reductions which ranged from 38% to 22% over the course of the growing season.

As for sprayer settings, a well-adjusted sprayer will allow improvements in treatment quality (Pergher and Petris, 2008; Siegfried et al., 2007; Viret et al., 2007). 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).

The influence of the water volume rate and dose adjustment on biological efficacy have also been studied by different authors in fruit orchards (Antonin and Fellay, 1976; Wicks and Nitschke, 1986). For their part, Fillat and Planas (1989) achieved an acceptable efficacy for the control of psyllids (*Psylla pyri* L.) and mites (*Panonychus ulmi* K.) in pear and apple trees, respectively, when spraying indistinctly 400 or 1000 L ha^{-1}. Later, Koch and Weiβer (1995) 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 40-80% 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. In this regard, Heijne et al., (1996) explored the possibilities of dose reduction by using cross-flow and recycling tunnels to control apple scab (*Venturia inaequalis* Cooke (Wint.)) and powdery mildew (*Podosphaera leucotricha* (Ell. et Ev.) Salm.).

In the same year, Holownicki et al. (1996) reported satisfactory efficacy in the control of apple scab by applying treatments at reduced doses with conventional and tunnel sprayers. Later, Frieβleben et al. (2003) studied the efficacy of coarse droplets (because of its drift reduction potential) and found no significant differences between coarse droplet (from drift reduction nozzles) and fine droplet (from standard) applications after 130 biological trials in apple orchards.

In vineyards, Viret et al. (2003) found that 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.

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}. A two-year efficacy trial on apple orchards controlling scab and powdery mildew also showed that there was no significant difference in crop protection results for different types of orchard application techniques and application rates. In vineyards, 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). The same benefits were obtained by multi-row sprayers. Heinzlé et al. (2010) 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. These results are in agreement with Tamagnone et al. (2013), who also obtained an increase of 18-30% in leaf deposition. 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.

One of the most promising advances has been the development of the recycling tunnel sprayer. These sprayers collect the overspray in vertical panels and return the liquid to the tank. Studies of these sprayers indicate that, in addition to improving coverage and uniformity, they considerably reduce the total applied dose per hectare. Tamagnone et al. (2013) showed a dose reduction of 40-60 % (recovered by the tunnel sprayer) with similar disease control. Carra et al. (2017) showed that increasing forward speed did not cause a decrease in mean foliar spray deposition when spraying vines. Pergher and Zucchiatti (2018) also analysed deposits from treatments with a recycling tunnel over the course of a whole season for LAI values ranging from 0.15 to 1.60, and found that on-target deposition increased from 14.8% to 53.9% of volume applied while spray recovery rates (efficiency) ranged from 67.2% to 31.0% (from early to full-leaf stages). Furthermore, 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 a conclusion of this section, the sprayer is a relevant and important factor when determining the adjusted amount of pesticide to be applied. The use of efficient designs, properly adapted to the scenario, and previously calibrated reports can result in valuable product savings, as well as a reduction of residues and the undesirable consequences of the use of pesticides.

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 proportion 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 hedgerow-or trellis-trained intensive orchards.

4.1 Pesticide Adjustment to the Crop Environment (PACE)

The fundamentals of the PACE system were described in 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 mode, considering canopy height, row distance and leafiness. 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 farm 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, volume rate and dose are adjusted according to the estimated leaf area after accounting for canopy height, 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 10000 m^3 ha^{-1} by spraying 1600 L $ha^{-1}$and to a standard vineyard of 4500 m^3 ha^{-1} with an LAI of 1.66, equivalent to a theoretical median deposition of 2.24 μL cm^{-2}. 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 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. The system recommends the proportion of dose reduction in relation to the label dose, and is expressed as maximum kg or L of product per unit of ground area. The application volume rate is not indicated as in France very low volumes provided by pneumatic sprayers are mainly used. 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 employed by French growers.

Recently several R+D French institutes have launched and validate PULVARBO[†] DSS for apple orchards (CTIFL, 2021) in the framework of the National French Ecophyto II program for reduction of perticides.

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 volume rate in vineyards on the basis of TRV dimensions, growth stage, estimated LA, sprayer characteristics and operating conditions (Gil and Escolà, 2009). It was then validated for deposits, efficiency and biological efficacy vs. standard volume rate 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, 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 (1 L 10.67 m^{-3}), for a standard canopy width of 0.8 m, as the basic spraying volume rate. 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 also previously mentioned ratio of Herrera-Aguirre and Untrath (1980).

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.

[†] PULVARBO is not considered in this thesis since the chapter was written before knowing its validation work.

4.5 DOSA3D

Initially named Dosafrut, this DSS was also developed in Spain and introduced by Planas et al. (2006) to determine the volume rate in pome fruit orchards, considering LA estimated through canopy dimensions, leafiness and spraying efficiency. The theoretical base deposit rate was 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. Following this, the DSS calculates the volume to be sprayed through Eq. 4 (Planas et al., 2011, 2012, 2013).

$$V = \frac{120 * LAI}{E} \qquad \text{Eq. 4}$$

where *V* is the volume rate (L ha-1), *LAI* is the estimated leaf area index of the orchard, and *E* is the application efficiency (%).

The system was updated after accurate and extensive canopy characterization using LiDAR and LA measurements (Sanz et al., 2018) and was 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 renamed DOSA3D and expanded to grapevine, citrus and olive orchards in order to have the same tool for all the main 3D crops grown in the ESZ (Planas et al. 2018, 2019). It has also been evaluated for efficacy in vineyards to control yellow spider mite *Eotetranychus carpini* (Oud.) (Roman and Planas., 2018) and downy and powdery mildews, as well as for the main pests and diseases affecting pome fruit orchards in Catalonia (Spain) (unpublished). DOSA3D is recommended by 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 J, 2017; OMAFRA, 2017) to improve sprayer efficiency for apple orchards. It is based on the crop-adapted spraying (CAS) 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. Finally, it assumes 0.06 L m^{-3} (1.0 L 16.7 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 volume rate below 400 L ha^{-1}, considering that the majority of pesticides have their efficacy tested at 1000 L ha^{-1}, nor a dose less than 50% the label rate. OMAX is available as a smartphone app.

4.7 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 volume rate 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. Finally, it should be noted that some systems (AGMET, DOSA3D and OMAX) establish a minimum volume rate threshold to ensure efficacy for any orchard scenario.

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

	Decision support system					
	PACE	AGMET	OPTIDOSE	DOSAVIÑA	DOSA3D	OMAX
Fruit (F)	*	*	-	-	*	*
Vine (V)	-	*	*	*	*	
Canopy height	*	*	*	*	*	*
Canopy mid-crown width	-	*	*	*	*	*
Canopy density-porosity (levels)	*	-	-	* (4)	-	*(5)
Row spacing	*	*	*	*	*	*
Growth stage (levels)	* (3)	-	* (41)	-	* (3)	*(2)
Leaf area estimation	*	*	*	-	*	-
Sprayer (efficiency)	-	-	*	*	*	*
Base for ratio calculation (index)	Height / row distance as LWA estimator (Walklate et al. 2003)	(F) 0.02 +200/TRV (Siegfried et al. (1995) (V) 0.07-0.13 l m^{-3} (Siegfried et al. 2007) (Annex 1)		(V) 0.037 l m^{-2} LWA 0.093 l m^{-3} TRV (for w=0.8 m) (Gil et al. 2019)	(F, V) 1.2 µl cm^{-2} (Planas et al., 2013)	(F) 0.06 l m^{-3} TRV (Deveau, 2017)
Min dose or volume (L ha^{-1})	*	(F) 200	-	-	(F) 100*height (m) (V) 150	(F) 400
Disease pressure	-	-	*	-	*	-

Duga et al. (2015a) analysed the spray-deposition profiles in different pome fruit trees and concluded that tree characteristics such as total leaf cover, leaf wall porosity and tree volume strongly affected total on-target deposition. DOSA3D and OPTIDOSE consider all of these parameters to establish the optimum volume rate and dose, with both systems estimating leaf cover by growth stage. The PACE system does not consider canopy width, AGMET ignores leaf density (and no consideration is given to growth stage), and DOSAVIÑA and OMAX estimate porosity but not LA.

As previously mentioned, several authors have reported that LAI is the most rational parameter for dose adjustment from the point of view of efficacy at a specific site on the canopy to control pests and diseases (Hislop, 1987; Rüegg et al. 1999b, 2001; EPPO, 2001; Pergher and Petris, 2008; Planas et al. 2016). Nonetheless, the LAI is difficult to determine under field conditions and pesticide dose need to be easily adjusted. With the aim of simplifying and facilitating comparisons between trials, the LWA was proposed by EPPO in 2016 and adopted in 2018 in the ECZ as a harmonized system for dose expression in pre-registration trials.

However, as explained earlier, this mode of dose expression has a poor correlation with LAI (Rüegg et al. 2001; Pergher and Petris 2008; Planas et al. 2016). Additionally, 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.

Contrastingly, the TRV correlates well with the LAI and can be used as its estimator (Rüegg et al., 2001; Viret et al. 2005b; Siegfried et al., 2007; Planas et al.; 2016). The parameters considered for TRV calculation (height, width and row distance) are very easily measured and estimation of total leaf cover can be refined if leaf density (porosity) and/or growth stage are considered. This is the background to the AGMET DSS which has been officially adopted in Switzerland. The other systems (OPTIDOSE, DOSA3D, DOSAVIÑA and OMAX) for dose adjustment are currently used in countries with a representative 3D crop (fruit and/or vine) growing area. Of these systems, AGMET, DOSAVIÑA and OMAX provide the value of the volume to be sprayed from the ratio of the spraying volume to the TRV.

In contrast, the DOSA3D DSS works on the basis of direct estimation of the LAI given the proven correlation between dimensional parameters and leafiness with the LAI (Planas et al., 2013, 2016). From the estimated LAI, DOSA3D provides the optimal spraying volume assuming a volume deposition of 1.2 µL cm^{-2}. This value is adopted as a threshold for spray evaluation and is totally comparable to the volume deposition values adopted in the AGMET system (median value = 1.2 µL cm^{-2}) for a spraying efficiency of 50%, typical for conventional air-assisted sprayers (see Annex 1, data from Siegfried et al., 2007).

To compare systems, the ratio between spraying volume rate and TRV shown in Table 1 can be used. For DOSA3D, this ratio depends on spraying efficiency and growth stage and can be calculated from the base deposition (1.2 µL cm^{-2}). In fruit trees, the ratio for AGMET is established as a function of the TRV (ranging from 0.020 to 0.080 L m^{-3} for the usual tree dimensions), while for DOSA3D the ratio ranges from 0.025 to 0.062 L m^{-3}. The ratio adopted by the OMAX system (0.06 L m^{-3}) is within these intervals.

In grapevine, the ratios are very similar for the AGMET (0.07-0.09 L m^{-3}) and DOSAVIÑA (0.093 L m^{-3} equivalent to 0.037 L m^{-2} LWA for a canopy with of 0.8 m) systems. These values are again within the interval values of DOSA3D (0.043-0.187 L m^{-3}).

Since the basis for calculation differs among the considered DSSs, the recommended volume rates and doses should also differ. In addition, the volumes and doses recommended in each DSS are also the result of the application of correction coefficients related to the specific scenario where the spraying will take place. This has been analysed for fruit and vine orchards in seven hypothetical scenarios described in Table 2.

Table 2. Characteristics of hypothetical scenarios used for DSS comparison (N/A: no available).

	Scenario	Growth stage	BBCH	*Canopy dimensions* height (m)	width (m)	Row spacing (m)	LWA	TRV	LAI[1]	LAI[2]
Pome fruit	1	From petal fall	71-75	2.2	0.5	3.6	12222	3056	0.6	N/A
	2	Fruit half final size	76-89	2.6	1.5	4.0	13000	9750	1.8	N/A
	3	Fruit half final size	76-89	3.8	2.2	4.0	19000	20900	3.6	N/A
Vineyard	4	Pre-flowering	11-53	0.4	0.2	2.8	2857	286	0.2	0.05
	5	Flowering	55-69	0.8	0.5	2.8	5714	1429	0.7	0.40
	6	From fruit set	71-89	1.2	0.8	2.8	8571	3429	1.5	1.14
	7	From fruit set	71-89	1.7	1.0	2.8	12143	6071	2.03	2.57

[1]DOSA3D value estimated
[2]AGMET value considered (Siegfred et al. 2007) (Annex 1)

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 volume rate, reference dose equivalent to a volume rate 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).

Table 3. Spraying volume rate (L ha-1) and adjusted dose (% of reference dose) established by the analysed DSSs in the scenarios defined in Table 2 (N/A: no available).

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

5. Discussion

As expected, all the DSSs provided increased volume rates (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} (Table 3).

The DOSA3D was more conservative, particularly in pome fruit orchards, because the assessed volumes were visibly higher than the other DSSs. This is a consequence of the small spraying efficiency factor values considered by the DOSA3D, in accordance with the situation at farming level. In contrast, the AGMET system provided the lowest volumes rates (L ha^{-1}) in both crops. Nevertheless, in terms of product per ground area in each growth stage the differences could be less relevant. The lower volume rates (L ha^{-1}) for AGMET tended to be compensated for by a higher proportion of the reference dose (Table 3).

This analysis can be quantified by means of the resulting ratio of the spraying volume to the TRV (L m^{-3}) (Table 4). In pome fruit, the ratio described on the AGMET website is the exact result of the equation proposed by Siegfried et al. (1995). With the exception of the initial stage (scenario 1), where the DOSA3D and OMAX systems have a minimum volume superior to that of the AGMET system, the other values observed are below the ratios established for fruit by the previously mentioned pioneer authors, namely Byers (1971, 1987): 0.093 L m^{-3}; Herrera-Aguirre and Unrath (1980): 0.116 L m^{-3}; Sutton and Unrath (1984): 0.133 L m^{-3} and Manktelow and Praat (1997): > 0.093 L m^{-3} for TRV > 23000 m^{3} ha^{-1}. This is probably due to two reasons. Firstly, the evolution in the dimensions and geometry of canopies over the last few decades (smaller dimensions and progressive wall shape), and secondly the continuous improvements 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. This is probably a consequence of the underestimation of the LAI used by the AGMET system (Table 2).

Table 4. Ratio of spraying volume to TRV (L m^{-3} TRV)

	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
Grape 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

Continuing with the comparison between systems and only considering the scenarios for grapevine orchards (4 to 7), the estimated depositions were calculated when spraying following the recommendations established by each DSS, as shown in Table 3. The content and dose (kg ha^{-1}) of the previously mentioned authorised products containing folpet or azoxystrobin (studied by Siegfried et al., 2007) are shown for the respective countries in Table 5. The expected weight deposition was established according to the ratio between the active ingredient dose applied and the LAI indicated in Table 2, taking into account an overall treatment efficiency of 50%. The LAI estimated by the DOSA3D system was used, except for the AGMET system for which the LAI values are those considered by the system itself. The expected results for folpet and azoxystrobin leaf deposition when spraying according to each DSS are shown in Figure 2.

Table 5. Equivalent formulated products containing folpet (FOLPET) or azoxystrobin (QUADRIS) as active ingredient (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	1.8
Product	QUADRIS[1]	QUADRIS EXPRESS	QUADRIS
Content a.i.	25%	50%	25%
Dose (kg ha^{-1})	1.5	0.5	1.0
Dose (max. concentration)	N/A	N/A	0.20%

[1] Product currently deleted from the registration list

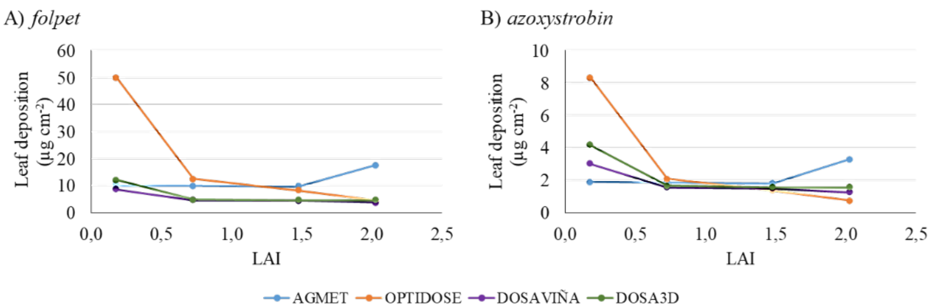

Figure 2. Expected weight deposition (µg cm^{-2}) when applying the formulated products of a) folpet and b) azoxystrobin indicated in Table 5 at the adjusted dose established in Table 3 for the different DSSs according to the leaf area index (LAI) of the different scenarios proposed.

For both fungicides, at the initial stage (scenario 4), OPTIDOSE shows a very high deposition value compared to the other DSSs. This is a consequence of the difference in 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. In all the other growth stages (5 to 7), when comparing systems, the expected deposition moves within the same range, and for each DSS deposition remains nearly constant until the final stage in accordance with the principle of adjustment to leaf cover (area). It can be concluded that, with the exception of the initial stage, there is sufficient coherence (similarity) between DSSs.

Deposition of folpet is, in all cases, above the efficacy threshold (3.0 μg cm^{-2}) indicated by Sigfried et al. (2007). The lowest value (3.58) corresponds to the expected deposition for DOSAVIÑA at the last growing stage (scenario 7). Deposition of azoxystrobin is also always above the efficacy threshold (0.8 μg cm^{-2}). Generally speaking, efficacy seems to be ensured in all situations. Nevertheless, 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, DOSA3D system includes a methodology to stablish the minimum ground dose (kg ha^{-1}) to be applied at a spraying volume very under the volume rates usually sprayed for efficacy evaluation in the pre-registration trials. The methodology is named Green Way (http://www.dosa3d.cat/en/documentation).

In addition, all the DSSs which recommend spraying volume rates provide decreasing volumetric depositions when the volume rate refers to the LAI (Figure 3.A and B for fruit and grapevine orchards, respectively). At earlier stages, values were over 2.0 μL cm^{-2} (with the exception of AGMET in grapevine), while at medium to late stages deposits ranged from 1.0 to 2.0 μL cm^{-2}, remaining nearly constant till the final stage. These values are in agreement with the threshold (base) deposit for DOSA3D calculation (1.2 μL cm^{-2}) and the median deposition considered for the AGMET system.

The results show that deposition is not linearly proportional to the existing LAI and that other additional structural factors that affect deposition need to be accounted for when calculating dose adjustment. At the initial stages, deposition is mostly higher than in the later growth stages because all the DSSs consider a minimum volume to be necessary to ensure consistency in spray distribution and the deposition process for small target dimensions and very low spraying efficiency. 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 referred 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.

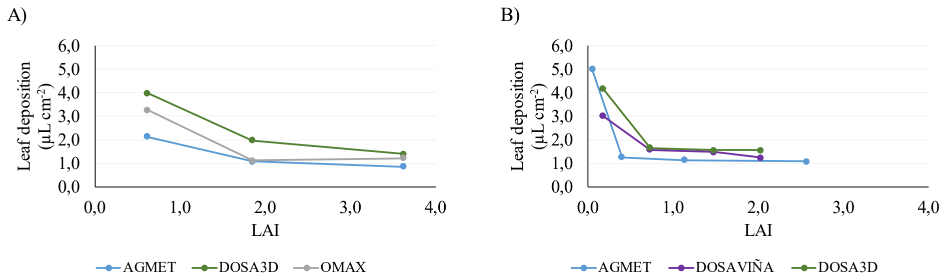

Figure 3. Expected volumetric depositions (µL cm^{-2}) in A) fruit orchards and B) grapevine orchards, for 50% spraying efficiency, when spraying at the adjusted volume rates established in Table 3 for the different DSSs in the consecutive scenarios. The estimated DOSA3D LAI is considered, with the exception of AGMET for grapevine where the LAI corresponds to the values estimated by the AGMET system itself. (see Annex 1 for values).

As mentioned before, Koch and Knewitz (2011) established a minimum deposition threshold (0.5% of LWA dose) to ensure the desired efficacy level. This threshold is equivalent to the DOSA3D threshold (1.2 µl cm^{-2}) when spraying at a concentration rate of 0.042%. Additionally, the 0.05% of the DOSA3D mean expected volumetric dose is achieved at 0.06 µl cm^{-2}. This ratio is exceeded in practice in all spraying events at site level according to the experience of the authors of the present paper (ISO 22522:2007 trials). Consequently, from the point of view of efficacy, the DOSA3D threshold seems to be robust.

The challenge is to obtain the deposition threshold at all target sites, something that is technically not feasible but something that is worth attempting to get as close to as possible. Mean deposition values could hide an important proportion of depositions below the effective dose, with the result being compromised efficacy at those specific sites. 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

Expressing the dose as a function of LWA represents a substantial improvement compared to the former ground-based dose expression mode. As EPPO has announced, the LWA method facilitates the possibility of zonal mutual recognition and has already been adopted by the Central Zone Steering Committee for evaluation trials in the registration process. However, the total leaf area is the most relevant parameter for dose adjustment. Leaf area can easily be estimated from crop dimensions and growth stage or leafiness, and has previously been suggested for use in trials in the registration process (Siegfried et al., 2007). Sprayer efficiency is also a key factor when determining the dose for a specific scenario.

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 provide equivalent results in terms of product per ground area and the expected on-target deposition, with the exception of the French system OPTIDOSE which provides higher doses at the earliest grapevine stages. The expected depositions are, in the majority of situations, similar to or above the deposit efficacy threshold (1.2 $\mu L\ cm^{-2}$) considered for the DOSA3D system, which has been shown to be the most conservative system. Generally speaking, efficacy seems to be ensured in all situations.

For all the considered DSSs, the recommended spraying volume rates are below the ratio values that were initially established in the US, several decades ago, 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.

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.

Pesticide deposition on leaves ($\mu g\ cm^{-2}$) 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 deposit (therapeutic dose) required for consistently good efficacy against pests, as well as information about the degree of its success in specific target sites within the canopy. Minimizing the sites with deposition rates below the efficacy 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 mode. 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. In these activities, the cost of deposit evaluation is not excessive.

Contrary to chemical industry considerations reported in Garcerà et al. (2021), it should report 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 a threshold (therapeutic dose).

While this may mean an additional cost, it is negligible (non-relevant) and totally affordable in the context of the overall cost of the pesticide registration process. The benefits in terms of safety, prevention of side effects and economy for growers are more than compensatory.

The sprayer that is used is also a determining factor of the amount of pesticide to be applied. 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. Additional general actions to promote the renewal and upkeep of the equipment and good practices will also undoubtedly have beneficial results.

In the short term, all these actions (adjusting volume and dose rates through the use of DSSs, improvements to spraying equipment and new regulations that expand the information that is available for the evaluation of pesticides) 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.

Annex I

According to Table 2 showed in Siegrfried et al. (2007) it can be deducing that volume rate (V) is dependent of leaf area index (LAI) [V= 198 * LAI + 42]. So the ratio V/TRV is assessed (Table 1).

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 1, the median deposition is exactly the threshold proposed by DOSA3D (1.2 µL cm^{-2}).

Table 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	(E=100%)	(E = 50%)
TRV	**LAI**	**V (L ha^{-1})**	**L ha^{-1}**	**V/TRV**	**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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CAPÍTULO 4

Technical rationale of DOSA3D: a decision support system for pesticide dose adjustment in 3D crops

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Technical rationale of DOSA3D: a decision support system for pesticide dose adjustment in 3D crops

DOSA3D DSS estimates the leaf area index (LAI) to calculate the optimum volume rate to be applied and adjust it taking into account the overall spraying efficiency. The optimal advised volume is usually below the volume rate practiced by farmers. Moreover, this adjusted volume is usually considerably less than the volume rates used in the preregistration trials of pesticide evaluation for efficacy and those advised sometimes on the labels. This happens specifically when working with high efficiency sprayers (new generation sprayers), such as tangential flux sprayers in fruit orchards and vertical booms or recycling sprayers in vineyards.

1. Background

The DSS was initially named DOSAFRUT and developed in Spain to determine the volume rate in pome fruit orchards (Planas et al., 2006). It was uploaded to the net and made freely available in 2010 (Planas et al., 2011a, 2011b). At that time, the system estimated the targeted leaf area considering canopy dimensions (height and width) and porosity through a series of pictograms.

For volume rate calculation, a theoretical base deposit rate was established of 100 droplets per cm^{-2} with a robust diameter. This droplet dimension was decided upon after laser Doppler analysis of the droplets produced by ALBUZ ATR nozzles, which are commonly fitted in air-assisted sprayers working in fruit orchards. Because of their drift ability, it was further assumed that small droplets were less effective for the control of pests and diseases than large droplets. Consequently, the system adopted a 225 µm diameter droplet as the representative droplet size. This is a sufficiently safe and robust assumption for orchard treatments and is larger than the median diameter volume (DV_{50}) of droplets for turbulent hollow cone nozzles according to the data provided by the nozzle manufacturers and more extensive laboratory measurements made by Doppler LiDAR (Torrent et al., 2019). The aforementioned value gives a theoretical volume deposition of 0.60 µl cm^{-2} or 1.20 µl cm^{-2} if both leaf sides (upper and under) are considered, which corresponds to 120 l per leaf hectare. Following this, the system calculates the total volume to be sprayed through Equation 1 (Planas et al., 2011a, 2011b, 2012, 2013).

$$V = \frac{120 * LAI}{E} \qquad \text{Eq. 1}$$

where *LAI* is the estimated leaf area index of the orchard (dimensionless) and *E* the overall application efficiency.

The first field validations for efficacy trials were conducted on fruit orchards during the period 2009-2012 in Spain in the municipalities of Alcarràs, Bellvís and Lleida (Planas et al., 2013). These works comprised spray treatments to control psylla (*Psylla pyri* L.), red spider mite (*Tetranychus urticae* K.) and thrips (*Frankliniella occidentalis* P.) in commercial pear, apple and peach orchards, respectively. Twenty comparative field trials were carried out in total. In each trial, the orchard was divided into three representative blocks sprayed respectively as follows: untreated (control), standard volume rate (farmer decision) and adjusted volume rate (DOSAFRUT result). Volume rate reductions in relation to standard volumes ranged from 14% to 53%. The tank-mix concentration was identical for the standard and adjusted volume rates. In seven trials pesticide on-leaf deposits were measured for standard and adjusted volume rates. The resulting depositions were similar between the standard and the adjusted volume rate. For all cases, there were no significant differences between dosing methods in terms of efficacy in the control of the aforementioned pests (Tukey's test, $\alpha = 0.01$).

Additionally, a number of seasonal trials were conducted by splitting the orchards into two plots. The first trial was carried out in 2012 in Alcarràs (Lleida, Spain) and was summarized by Solanelles et al. (2013). It included seven successive spraying treatments to control three consecutive generations of psylla in a pear orchard (cv. Williams). Reductions of 10-40% in the volume rate and, consequently, dosing were achieved. Over the considered period, the LAI increased from 1.37 to 2.60 between the first treatment (19/04/12) and the last treatment (11/06/12), and volume rates ranged from 700 to 800 l ha^{-1} for standard treatments, and from 420 to 720 l ha^{-1} for adjusted treatments. A Star 2091 air-blast sprayer (Teyme S.L., Torreserona, Spain) was used in all the treatments. The total ground dimension of the orchard was 0.98 ha (0.49 ha per plot). To evaluate the volume and dose effect, psylla nymphs on five shoots and damage on fruits (expressed as a proportion) were monitored in six blocks per treatment from May to August (13 monitoring dates). For both indicators, a similar evolution was recorded in each volume rate and no significant differences were found at harvest time (P=0.35 and P=0.53, respectively). Additionally, no pesticide residues were found on fruits in either the adjusted dose or standard treatment.

Subsequently, more accurate leaf area measurements and canopy characterizations were carried out using LiDAR by Sanz et al. (2018). This enabled the development of a model for leaf area estimation which took into account crop dimensions for different growth stages in fruits and grapevines. As a result, the system was updated and renamed DOSA3D.

The system was expanded to grapevine, citrus and olive orchards in order to offer an appropriate tool for all the main tree crops grown in the Southern Europe Zone (Planas et al., 2016, 2018, 2019). Since 2017, DOSA3D has been available online (www.dosa3d.cat) and can be downloaded as a smartphone app. In addition, its use has been recommended by the Plant Protection Service of the Catalan Regional Government (DARP, 2018).

2. Leaf area index estimation

A LAI estimation model was developed on the basis of the characterization of canopy structures using the LiDAR system in fruit and grape orchards mentioned above. The model calculates the leaf area using the concept of canopy solid housing (CSH), which is determined from the canopy dimensions (height and width) and the estimated porosity (proportion of gaps within the canopy) (Equation 2):

$$CSH = 2 * h * (1 - p) + w \quad \text{Eq. 2}$$

where *h* is canopy height (m), *p* is wall porosity (dimensionless), and *w* the canopy mid-crown width (m). The DOSA3D system proposes canopy height and width ranges to avoid errors in exact in-field measurement and adopts the higher value of the range (Table 1). With respect to porosity assessment over the season, porosity ranges from 1 (no leaves at initial stage) to 0 (non-significant appreciable gaps, usually in full season) for trellis- or hedgerow-trained deciduous tree crops.

To transform CSH to LAI, row spacing (*r*) is taken into account. Figure 1 shows the correlation between CSH r^{-1} and LAI measured after full defoliation of a representative row stretch. Measured LAIs were up to 3.8 and 1.8 for fruit tree and grapevine orchards, respectively. Linear regressions were forced through origin because deciduous crops do not present leaves at initial stages.

Following the respective regression functions, LAI (dimensionless) is estimated according to Equation 3:

$$LAI = \frac{f * CSH}{r} \quad \text{Eq. 3}$$

where *f* is the slope factor (Figure 1), *CSH* is the canopy solid housing value (m), and *r* is the row spacing (m).

Table 1. Canopy height and width dimension ranges for fruit trees and grapevines and the dimension values adopted by DOSA3D (N/A, not available).

	Fruit trees		Grapevines	
	Range	value (m)	Range	value (m)
Canopy height	< 1.0 m	1.00	< 0.25 m	0.25
	1.0 - 2.0 m	2.00	0.25 - 0.50 m	0.50
	2.0 - 3.0 m	3.00	0.50 - 0.75 m	0.75
	3.0 - 4.0 m	4.00	0.75 - 1.00 m	1.00
	N/A	N/A	1.00 - 1.50 m	1.50
	N/A	N/A	1.50 - 2.00 m	2.00
	N/A	N/A	> 2.00 m	2.50
Canopy width	< 1.0 m	1.00	< 0.25 m	0.25
	1.0 - 2.0 m	2.00	0.25 - 0.75 m	0.75
	2.0 - 3.0 m	3.00	0.75 - 1.00 m	1.00
	> 3.0 m	4.00	1.00 - 1.50 m	1.50
	N/A	N/A	> 1.50 m	2.00

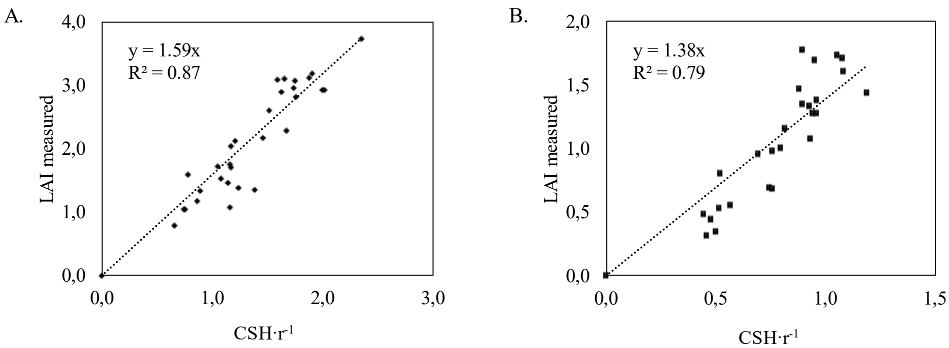

Figure 1. Correlation between measured leaf area index (LAI) and LAI estimated through canopy solid housing (CSH) and row spacing (r) in A) pome fruit orchards (n=28) and B) vineyards (n=25).

Along the season, sprayers are usually calibrated and set up on at least three occasions, at the start of the early, medium and full leaf stages, respectively. At least, on each occasion, a decision on the spraying volume rate is required. Canopy dimensions can be measured or estimated easily in-field. However, direct quantification of porosity may be difficult for end-users. In the former version, the pictogram-based decision system proposed by Sanz et al. (2018) was used for porosity estimation, but uncertainly was not eliminated when users had to opt for one specific pictogram. After a long period accumulating practical experience in multiple scenarios, porosity was generally found to be in the ranges 1.0-0.7, 0.6 -0.3 and 0.2-0.0 for the early, medium and full leaf stages, respectively. Therefore, with the aim of facilitating this assessment, porosity is currently quantified by a reference value for the three mentioned stages according to the BBCH growth scale (Meier, 2001) as indicated in Table 2.

Table 2. DOSA3D porosity assessment for different growth stages in pome fruit and grapevine orchards.

period	Pome fruit growth stage	BBCH	Grapevine growth stage	BBCH	reference value
early	Until petals fallen	10-69	Until flowering	11-53	0.8
medium	From petals fallen to half final fruit size	71-75	Flowering	55-69	0.4
full leaf	From half final fruit size to harvesting	76-89	From fruit set to harvesting	71-89	0.1

3. Efficiency

The application efficiency is the proportion of pesticide product deposited on target with respect to the total amount sprayed. The overall spraying efficiency (E) that DOSA3D uses is determined according to crop structure (E_c) and sprayer performance (E_s) and is calculated through Equation 4.

$$E = E_C * E_S \qquad \text{Eq. 4}$$

The influence related to canopy structure (E_c) takes into account the height and width of the green vegetation and is calculated through Equation 5:

$$E_c = \frac{EC_h + EC_w}{2} \qquad \text{Eq. 5}$$

where E_h is the vertical shape component and E_w is the width component.

With respect to the vertical shape component, E_h, air-blast sprayers are not geometrically adapted to the verticality of hedgerow vegetation and operate differently in fruit tree orchards and vineyards. In fruit trees, efficiency decreases as the distance between the sprayer nozzles and the tree top increases (higher vegetation). In contrast, efficiency in vineyards is lower at the beginning of the vegetation (low height) due to the relevance of losses which are mainly due to non-target deposition on the soil surface. Figure 2 shows how efficiency varies in a vineyard when applying with three different side-to-side vine sprayers during a season (height from 0.30 to 1.20 m). Consequently, when the sprayers are adapted to the vertical component in vineyards (as with tangential flow sprayers, multi-spouts, vertical booms or recovery tunnels) the height component increases efficiency. The general E_h factors adopted by DOSA3D DSS range from 0.70 to 0.80 and are shown in Table 3.

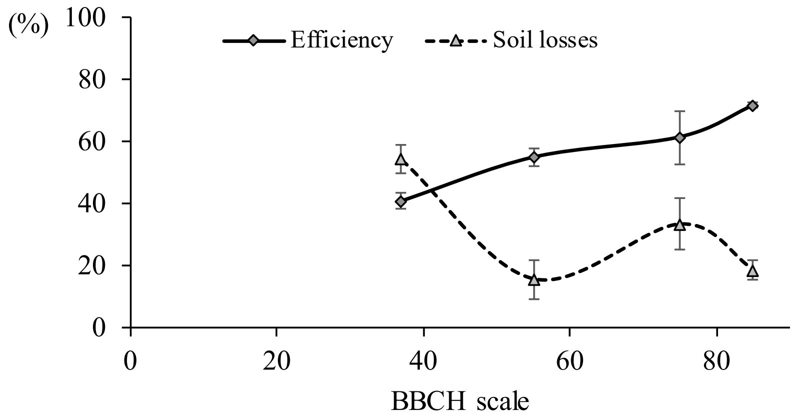

Figure 2. Efficiency and soil losses (mean ± SE) from three side-to-side sprayers in different growth stages of the vineyard along the season. The data summarize the results of four field trials carried out in vineyards in the Raïmat (Spain) winegrowing zone in 2018.

The efficiency factor that depends on canopy width (E_w) takes into account spray penetrability within the canopy. Penetrability can be defined as the capacity of the crop to allow balanced deposits at any depth of the canopy. Figure 3A shows different depth distribution patterns from series of trials for apple, pear and grapevine orchards when applying on one side of the row. When comparing these crops, differences in the aerodynamic behaviour of the canopies can be observed. In general, fruit trees are better able to allow the stream of air droplets to pass through the canopy than grapevines which have a greater active barrier role. This is especially important at full leaf stage when grapes are hidden behind the leaves and no trimming or only light summer pruning is practiced, since pesticide spraying may not reach the clusters and efficacy could be compromised. The penetrability index (*P*) is calculated as the ratio between internal and external deposits and can be used to compare different crops and scenarios. Figure 3B shows normalized deposits from the same series of trials when both sides of the rows are treated. The *P* values were 86.5%, 76.4% and 70.5% for apple, pear and grapevine, respectively. In view of these results, the efficiency of the system will decrease as canopy width increases. The *Ew* factors are shown in Table 3.

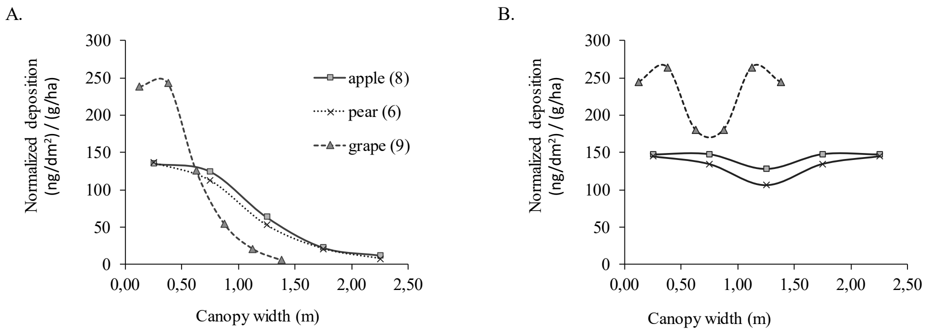

Figure 3. Normalized deposition for grape and fruits throughout the canopy (ng dm^{-2} per g ha^{-1} applied) Values correspond to the mean of 8 trials (apple), 6 trials (pear), 9 trials (grape) at full leaf stage by measuring leaf deposition every 0.50 m for fruit trees and every 0.25 m for grapevines. A) Application on one side of the row, and B) Simulation of the application on both sides of the row from the results of one side application (A). The same air-assisted sprayer model was used for all three crops (unpublished data from the 1997 Air-Assisted Sprayers project).

Table 3. Efficiency factor adopted for canopy height (Eh) and width (Ew). N/A: Not available.

	Fruit trees		Grapevines	
	Dimension	factor	Dimension	factor
Canopy height (E_h)	< 1.0 m	0.80	< 0.25 m	0.70
	1.0 - 2.0 m	0.75	0.25 - 0.50 m	0.71
	2.0 - 3.0 m	0.73	0.50 - 0.75 m	0.73
	3.0 - 4.0 m	0.70	0.75 - 1.00 m	0.75
	N/A	N/A	1.00 - 1.50 m	0.78
	N/A	N/A	1.50 - 2.00 m	0.79
	N/A	N/A	> 2.00 m	0.80
Canopy width (E_w)	< 1.0 m	0.80	< 0.25 m	0.80
	1.0 - 2.0 m	0.75	0.25 - 0.75 m	0.80
	2.0 - 3.0 m	0.73	0.75 - 1.00 m	0.75
	> 3.0 m	0.70	1.00 - 1.50 m	0.73
	N/A	N/A	> 1.50 m	0.70

The efficiency related to sprayer performance (E_s) corresponds to the efficiency ratio when the sprayer is working in ideal conditions and is dependent solely on sprayer performance. DOSA3D allows to choose between different types of air-assisted sprayers that operate in fruit orchards or vineyards. The efficiency it gives to each sprayer is shown in Figure 4.

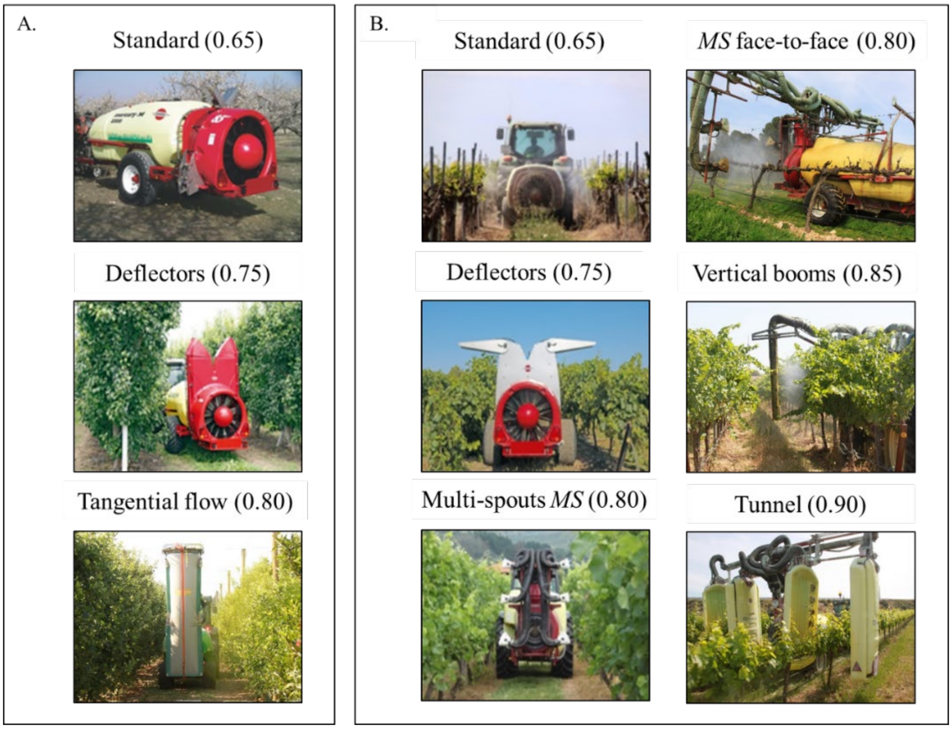

Figure 4. Types of hydropneumatic sprayers considered by DOSA3D and the spray factor (Es) that it adopts (%) for A) fruit trees and B) vineyards.

Finally, taking into account the components E_c and E_s explained above, the overall efficiency (*E*) ranges obtained with Equation 4 that DOSA3D attributes depending on the specific scenario are shown in Table 4. These values can be assumed under good management practice conditions when the sprayer operates with prior calibration, an appropriate set-up and at a suitable forward speed under acceptable weather conditions (Balsari et al., 2015). The resulted efficiencies are similar to those compiled by Jensen and Olesen (2014) and reported by different authors in pome fruit and grapevine orchards.

Table 4. Global efficiency ranges calculated by DOSA3D.

	Fruit trees		Grapevines	
Sprayer type	min	max	min	max
Standard	0.46	0.52	0.46	0.52
Deflectors	0.53	0.60	0.53	0.60
Tangential flow	0.56	0.64	0.56	0.64
Multi-spout	N/A	N/A	0.56	0.64
Vertical booms	N/A	N/A	0.60	0.68
Recycling tunnel	N/A	N/A	0.63	0.72

4. Volume rate and therapeutic dose threshold

Optimum pesticide deposition on leaves can be defined as the application of a biologically effective dose on a target with maximum safety and economy (Hislop, 1987). In this regard, Koch and Knewitz (2011) proposed a methodology to evaluate spray applications by measuring spray deposits following the methodology of standard ISO 22522:2007 (ISO, 2007) and underlined that efficacy occurs within the canopy at individual target level. With this in mind, individual deposits of each sample should be considered instead of mean values as the latter could hide a significant proportion of samples below the effective dose, thereby compromising the efficacy of the treatment. This consideration has been verified in a large number of field trials when evaluating commercial sprayers or pesticides for efficacy.

DOSA3D adopts the criteria related to on-target coverage explained in the background section (1.1). The system initially assumes that the pesticide concentration in the sprayer tank corresponds to the labeled concentration, and the total volume rate (l ha^{-1}) for optimal coverage is calculated through Equation 1. The theoretical expected mean deposition is 1.20 µl cm^{-2}. This is the acceptance threshold for the assessment of the distribution of deposits at individual sites within the canopy.

As the authors have shown, on some occasions leaf deposition tends to present a normal distribution. Figure 5 shows leaf deposition (µl cm^{-2}) on each sample following the aforementioned methodology of standard ISO 22522:2007, corresponding to an efficacy trial at commercial scale carried out in Raïmat (Spain) with grapevine (cv. Tempranillo) spraying using vertical boom equipment. The results showed that, although mean average deposition (1.74 µl cm^{-2}) was above the volumetric DOSA3D threshold (1.20 µl cm^{-2}), a significant proportion of values (20%) were below this threshold. Moreover, some samples were found to have a deposition one third lower than this threshold. It is expressly in such sites where efficacy could be seriously compromised.

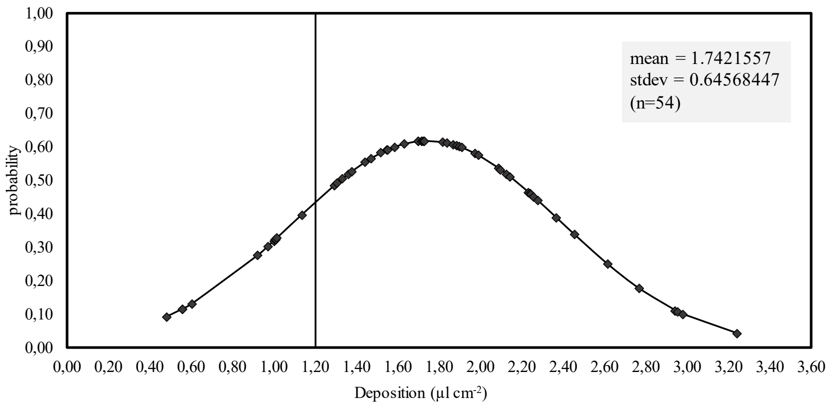

Figure 5. Normal distribution of grapevine (cv. Tempranillo) on-leaf volumetric deposits. Shapiro-Wilk normality test: $p < 0.6597$. Samples acquired following the ISO 22522:2007 methodology. Date of trial: 26-Aug-2016. Growth stage: BBCH 83-85.

At initial stages, deciduous crops have low LAI values (zero at dormant stage and near zero at very early stages) and overall spraying efficiency is usually very low due to ground losses and drift. In consequence, the volume rate calculated according to the general expression could be too low to provide a consistent spraying flux that ensures a correct good coverage of leaves and branches. In this situation, to avoid underdosing sites, and in accordance with practical spraying experience and a large number of on-target deposition assessments, a minimum volume was established for fruit trees (100 l ha^{-1} for 1 m height) and vines (150 l ha^{-1}). In this regard, the general volume rate expression is now as follows:

- For fruit orchards: V = max [100 *h*; (120 LAI) E^{-1}]
- For vineyards: V = max [150; (120 LAI) E^{-1}]

where *V* (l ha^{-1}) is the volume rate to be applied, *h* (m) is the canopy height (Table 1), LAI is the estimated leaf area index and *E* is the application efficiency (Table 4).

Another important factor to be considered is that the efficacy of pesticides could be compromised at adjusted volume rates depending on the pest or disease that it is hoped to eliminate. This concerns in general (fruit trees and grapevines) mites, but also aphids and psylla on pome fruit trees, and aphids, powdery mildew (*Podosphaera pannosa* (Wallr.: Fr.)) and monilinia (*Monilinia* spp.) on stone fruit trees. For the control of these pests and diseases, according to the experience of experts in the field, contact with the pesticide or suffocation of the causal agents must be ensured. This condition is achieved by applying an extra volume rate equivalent to 40% of the adjusted volume rate initially established by the system.

As for the pesticide dose, the rates are established according to the product label indications. Usually in Spain, if the dose is expressed as a concentration (%) the ground area dose will be directly proportional to the spraying volume rate. If the dose is directly expressed as kg or l per ground area, the dose can be transformed to the concentration system using the reference volume rate. However, as this volume is indicated only very occasionally on the label, 1000 l ha^{-1} can be adopted as the reference volume rate. In preregistration trials, a volume close to this amount is regularly sprayed for efficacy assessment in 3D crops, usually by means of portable sprayers whose efficiency is not the same as that of commercial sprayers at farm level.

Generally, the adjusted volume rates recommended by DOSA3D are lower than the reference volume rate mentioned above, especially when using advanced-type sprayers. Consequently, as the volume rate decreases a lower dose will be applied if the labelled or calculated concentration is employed.

To prevent underdosing in this scenario, a methodology called the Green Way is being developed. This method assumes the possibility that the pesticide concentration in the tank could be greater than the labelled concentration. If, according to the label, the dose is a fixed value per ground area, the dose can also be adjusted. In all cases, a minimum threshold dose is considered. In any case, the dose applied will be under the maximum admissible dose according to Regulation 1107/2009, art. 31.3, as stated at national level when pesticide uses are approved (EC, 2009).

5. User interface

DOSA3D sets the optimal dosage based on the spray volume required to meet specific application conditions and taking into account the following factors: crop, pests or diseases to be controlled, product to be applied, and spraying equipment.

The DOSA3D system can be used with all kinds of air-assisted sprayers equipped with hydraulic nozzles operating in vineyards and almond, olive and citrus orchards, in continuous row form or as isolated trees (in goblet form). The DOSA3D system assumes the use of spraying equipment that is in good working order and which has been correctly calibrated.

DOSA3D DSS is available online for free (www.dosa3d.cat/en) (Figure 6) and as a smartphone app for Android and iOS systems. The tool is operational in Spanish, Catalan, English, French, Italian and Chinese. To obtain recommended adjusted volume rates and doses, users have to introduce various data concerning crop, pest, sprayer and product characterization (Table 5). Once the crop parameters have been introduced, DOSA3D provides LAI, leaf wall area (LWA) and tree row volume (TRV) estimations. The list of results provided is shown in Table 6. Users can create an account to save each calculation within the system.

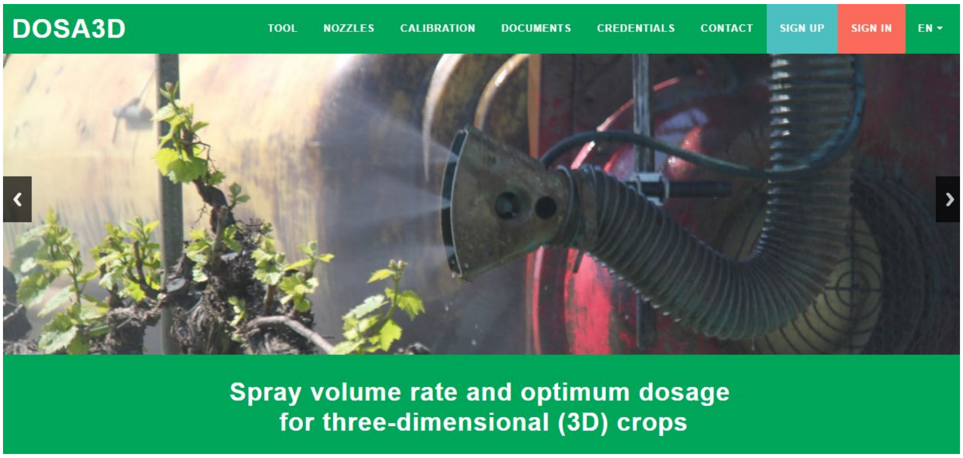

Figure 6. DOSA3D home page.

Table 5. DOSA3D inputs for volume rate and dose decision.

		Input	
Crop	*	Crop	Select the crop: Apple, Pear, Peach & Nectarine, Grape, Hedgerow almond, Hedgerow olive, Citrus or Isolated trees
		Variety	Identification purpose
		Orchard identification (name)	Identification purpose
	*	Crop area to be sprayed (ha)	Determine the amount of product to be used
	*	Tree spacing (m)	Add exact value
	*	Row spacing (m)	Add exact value
	*	Canopy height (m)	Choose between range (Table 1)
	*	Crosswise mid-width of canopy (m)	Choose between range (Table 1)
	*	Growth stages	Choose between range (Table 2)
Pest or disease	*	Pest or disease to be controlled	Increase volume rate by a factor 1.4
Sprayer	*	Sprayer type	Choose between the proposed sprayers (Figure 4)
	*	Main tank capacity (l)	Add exact value. Calculate number of tanks of a treatment
	*	Rows treated simultaneously	Choose 1 to 3 in grapevines
Operational parameters and weather forecast		Forward speed (km h^{-1})	Gives information about good pesticide application practices and link to information on weather forecasts in several countries.
		Temperature	
		Relative humidity	
		Wind speed	
Product to be used		Product	Link to Spanish register database to ensure allowed doses
	*	Dose	Introduce numeric value
	*	Dose expression	Choose between % or kg ha^{-1} or LWA

** Mandatory inputs*

Table 6. DOSA3D outputs

DOSA3D result	Application efficiency (%)
	Minimum recommended volume rate (l ha^{-1})
	Minimum recommended volume rate per tree (l ha^{-1})
Product amount and number of tanks to be sprayed	Product concentration in the tank (%)
	Product per tank (kg or l)
	Total amount of product to be applied (kg or l)
	Number of tanks to be sprayed
Equivalence between dose expression systems	Ground dose (kg ha^{-1})
	LWA dose (kg or l $10000m^{-2}$)
	TRV dose (kg or l $10000m^{-3}$)

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CAPÍTULO 5

DOSA3D: Field validation in vineyards

Supervised and reviewed: Dr. Santiago Planas

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DOSA3D: Field validation in vineyards

1. Introduction

Pome and stone fruit trees and vineyards are crops of high economic value. In 2019, they represented a worldwide area of 31.8 Mha (FAO, 2020). Productivity is linked to the health status of the crop. Good plant protection practice (GPPP) means a practice whereby the treatments with plant protection products applied to given plants or plant products, in conformity with the conditions of their authorized uses, are selected, dosed and timed to ensure acceptable efficacy with the minimum quantity necessary, taking due account of local conditions and of the possibilities for cultural and biological control (EC, 2009a in art. 3.18) To achieve GPPP, nowadays integrated pest management (IPM) programs are usual in farms. Nevertheless, the main mode of defense for farmers against harmful plant organisms continues to be the use of chemical pesticides. It is estimated that losses due to pests and diseases could be 30% higher without the use of pesticides (Damalas, 2016), and so current agricultural productivity could not be sustained without them (Nishimoto, 2019).

In recent decades, the number of active ingredients available to control pests and diseases has been reduced due to the side effects they have for both humans and the environment, but a significant number of pesticides are still authorized for the control of pests and diseases in fruit and grape orchards (Pertot et al., 2017; Simon et al., 2011). The number of spraying events in a year varies principally due to climatic circumstances, though other factors come into play. In the Mediterranean region, for a normal season, around 10-12 treatments in fruit orchards and around 4-6 in vineyards are common. However, in years with climatic conditions that favor the development of in-field diseases and/or pests, as was 2020 in Spain, the number of treatments can easily reach 18-20 in fruit orchards and 10-12 in vineyards. This intensive use of pesticides entails significant risks for persons and the environment, as well as high economic costs for farmers.

Consequently, it is vital that, if chemical intervention is finally deemed necessary after due deliberation, the dose to be applied is adjusted to the particular scenario and that all measures to prevent side effects are adopted. These considerations are fully in line with the Sustainable Use Directive (SUD) currently in force (EC, 2009b) and the recently published A Farm to Fork (F2F) strategy (EC, 2020).

Several papers have widely reported the background precedents with respect to dose expression modes and dose adjustment concepts, including the recent studies of Gil et al. (2019) and Garcerá et al. (2021). In addition, a comparison of systems that allow volume and dose adjustment in fruits and grapevine orchards is presented in Chapter 2 of this thesis and will be submitted for publication.

Specific tools are needed to meet these objectives in specific scenarios. In this respect, several decision support systems (DSS) have been developed to decide the optimum volume and dose rates when spraying 3D crops. For pome and stone fruit orchards, the

DSS that are available are: Pesticide Adjustment to the Crop Environment (www.pace.pjwrc.co.uk/), Dosage adapté (www.agrometeo.ch), DOSA3D (www.dosa3d.cat/en) and Orchard Max (app for smartphone). The DSS for vineyards are: Dosage adapté, Dosaviña (https://dosavina.upc.edu/) and DOSA3D. Finally, for citrus the DSS available are: DOSA3D, CitrusVol (http://gipcitricos.ivia.es/recomendacion-de-volumen) and Dosacitric (http://dosacitric.webs.upv.es/).

The scientific and technical arguments, as well as the empirical results achieved when a DSS is used at a farm level, need to be made widely available so that the authorities, chemical industries, advisers and final users can have confidence in their suitability and applicability. That is, the conceptualization, feasibility and, in particular, the efficacy of treatments at adjusted doses are the principal issues for validation of the system by the aforementioned stakeholders (agents).

DOSA3D is a free DSS for the adjustment of pesticide doses in fruit trees, grapevines and other three dimensional (3D) crops (Planas et al. 2016). It is based on the principles laid out in the SUD and F2F strategy for reducing the use of pesticides. The objectives of the DOSA3D system are (i) to prevent overdosing and contamination by pesticides in order to minimize human exposure and environmental risks and (ii) to reduce production costs.

DOSA3D has been validated in pome and stone fruit orchards (Planas et al. 2013, Solanelles et al. 2013) and more recently in pome and stone fruit farms where adjusted volume rates are usually sprayed throughout the season (Planas and Román, 2020). This chapter sets forth and explains the work that has been carried out for its field validation in vineyards, giving and discussing the results achieved on-farm when spraying according to the volume and dose rates advised by this system. The objectives are i) to validate the leaf area index (LAI) estimation model implemented in DOSA3D; ii) to validate the adjusted volumes rates using DOSA3D by studying on leaf deposition; and iii), to validate the system through the biological efficacy of the adjusted treatments against powdery mildew (*Erysiphe necator* (Schw.)) in seasonal trials.

2. Material and Methods

2.1 Leaf area index model

The LAI estimation model implemented in DOSA3D system (Equation 1) is based on the results presented by Sanz et al. (2018). To validate the model, in 21 different vineyards a row section with a length equivalent to the distance between plants in the row was fully defoliated during the period 2016-2020 (cv. Chardonnay, Albariño, Tempranillo, Cabernet Sauvignon, Merlot, Godello, Xarel·lo and Airén). The area of the leaves from the canopy was laboratory measured to estimate real LAI. Until 2018, total leaf measurements were done using a leaf-meter (Delta-T Devices Ltd., Cambridge, UK). Subsequently, the total area was estimated in each case by correlating the weight and area of 100 individual leaves with the area of each leaf measured using ImageJ image analysis software (Schneider et al., 2012). Before defoliating, height and width measurements and porosity assessments were performed to calculate the canopy solid housing (Equation 2). Finally, a linear regression between real LAI and estimated LAI was forced through the origin and its confidence intervals (95%) were calculated and represented.

$$LAI = \frac{1.38 * CSH}{r} \qquad \text{Eq. 1}$$

where *1.38* is a slope factor, *CSH* is the canopy solid housing value (m), and *r* is the row spacing (m).

$$CSH = 2 * h * (1 - p) + w \qquad \text{Eq. 2}$$

where *h* is canopy height (m), *p* is wall porosity (dimensionless), and *w* the canopy mid-crown width (m).

2.2 On-target deposition

At farm level, DOSA3D adjusted volume rates were assessed in vineyards by 37 leaf deposition tests in different growth stages in the years 2016 to 2020 in Spain at Raïmat (Lleida) and Daramezas (Toledo). The main objective was to reach the coverage threshold of 1.2 µl cm^{-2}, which corresponds to the calculation base of the system.

Table 1 shows the specific conditions of each trial and volume rates decision. Excessive deviations in the actual volume rate were essentially due to the on-farm experimentation approach and corresponded to farmers' decisions to increase the volume rate when spraying to control tetranychid mites or when vine canopies were wide. The sprayers used in all trials (Table 2) were side-by-side two rows type (except in trial 2.19) equipped with hollow cone nozzles (Albuz ATR).

All trials were performed in accordance with standard ISO:22522 to assess spray deposition by canopy zones (ISO, 2007). The sample unit was 3-4 leaves per zone within the vine canopy. Sampling zones within the canopy varied in height and depth, as well as the number of repetitions, depending on the trial (Table 2). Tracers used were metal chelates (Cu^{++}, Mn^{++}) in 2016 and 2017 and tartrazine (food dye E-102) the following years. The tank tracer mix concentration ranged from 1.0 to 5.0 g l^{-1}. The amount of metal chelate tracer recovered from leaves was determined by means of atomic absorption spectrometry (AAnalyst 400, Perkin Elmer, Waltham, USA), while the tartrazine was measured with a spectrophotometer (Spectronic 301, Milton Roy, New York, USA). Then, the amount of tracer on samples was related to the sample surface area and divided by the sprayer tank concentration to volumetrically normalize data (expressed as µl cm^{-2}). The coefficient of variation (CV), normalized deposition (expressed as µg dm^{-2} per 1 g ha^{-1}), efficiency (percentage of the tracer recovered on leaves), percentage of samples under the DOSA3D threshold (<1.2 µl cm^{-2}) and penetrability were also calculated.

Table 1. Date of trials (year-month-day), canopy characterization (BBCH: phenology; h: height; w: width; r: row spacing; LAI: leaf area index estimated by DOSA3D), sprayer type (VB: Vertical Booms; MS: Multi-spouts; T: Tunnel; MAF: Multi-axial fan) and volume rate (DOSA3D recommendation and applied).

				Canopy characterization				*Volume rate (l ha^{-1})*		
Trial	Date	Cultivar	BBCH	h (m)	w (m)	r (m)	LAI DOSA3D	DOSA3D		Applied
1.1	20160426	Chardonnay	53	0.35	0.30	3.00	0.44	150	*	257
1.2	20160502	Chardonnay	53	0.35	0.30	3.00	0.44	150	*	279
1.3	20160503	Chardonnay	53	0.35	0.30	3.00	0.44	150	*	257
1.4	20160615	Albariño	75	1.20	0.90	3.00	1.73	330		375
1.5	20160615	Albariño	75	1.20	0.90	3.00	1.73	340		375
1.6	20160615	Albariño	75	1.20	0.90	3.00	1.73	340		375
1.7	20160824	Tempranillo	83-85	0.80	0.60	3.20	1.12	300	*	318
1.8	20160824	Tempranillo	83-85	1.20	0.90	3.20	1.60	430	*	418
1.9	20170614	Cabernet Sauvignon	71-73	0.57	0.55	2.50	1.18	308	*	298
1.10	20170614	Cabernet Sauvignon	71-73	1.02	0.90	2.50	1.57	420	*	387
1.11	20170621	Chardonnay	78	1.10	0.60	3.00	1.61	310		341
1.12	20170803	Chardonnay	83	1.20	0.90	3.00	1.73	340		366
1.13	20170807	Cabernet Sauvignon	83	0.80	0.50	2.50	1.43	270		306
1.14	20170807	Cabernet Sauvignon	83	1.20	0.90	2.50	2.07	400		407
1.15	20170809	Cabernet Sauvignon	83-85	0.90	0.55	2.50	1.43	380	*	384
1.16	20180518	Merlot	55	0.71	0.62	3.00	0.77	210	*	269
1.17	20180524	Godello	51	0.50	0.30	2.50	0.53	150		261
1.18	20180605	Godello	53	0.70	0.30	2.50	0.53	150		245
1.19	20180720	Xarel.lo	80	1.20	0.50	2.60	1.86	360		343
1.20	20180829	Merlot	81	1.87	0.83	3.00	2.15	380		305
1.21	20190509	Chardonnay	55-57	0.60	0.28	3.00	0.77	150		158
1.22	20190704	Airén	75-77	1.76	1.50	3.30	2.16	530	**	600
1.23	20190704	Airén	75-77	1.76	1.50	3.30	2.16	410	**	600
1.24	20190712	Cabernet Sauvignon	75-77	1.10	0.80	2.50	2.07	400		362
1.25	20190712	Cabernet Sauvignon	75-77	1.50	1.20	2.50	2.35	460		432
1.26	20200506	Chardonnay	55-57	0.70	0.50	3.00	0.91	160		183
1.27	20200508	Chardonnay	55-57	0.70	0.50	3.00	0.91	170		227
1.28	20200519	Airén	55	0.75	1.00	3.30	0.81	220	*	250
1.29	20200519	Airén	55	0.75	1.00	3.30	0.81	280	*	250
1.30	20200617	Airén	75-77	1.20	1.00	3.30	1.57	300	**	400
1.31	20200617	Airén	75-77	2.25	1.50	3.30	2.55	490	**	550
1.32	20200701	Malbec	77	0.75	0.60	2.50	1.18	290	*	313
1.33	20200723	Airén	79-81	1.17	0.97	3.30	1.57	300		350
1.34	20200723	Airén	79-81	1.76	1.25	3.30	2.16	410		420
1.35	20200723	Airén	79-81	2.04	1.45	3.30	2.55	490	**	550
1.36	20200723	Airén	79-81	2.04	1.45	3.30	2.55	490	**	550
1.37	20200806	Airén	81-83	1.85	1.45	3.30	2.16	530	**	660

* 40% extra volume to control tetranychids; ** Extra volume for wide vines.

Table 2. Sprayer (brand and model) and type (VB: Vertical Booms; MS: Multi-spouts; T: Tunnel; MAF: Multi-axial fan) and volume rate (DOSA3D recommendation and applied). Number of samples within the canopy vine per h: height, w: width and R: repetitions (sampled vines).

	Sprayer		Samples			
Trial	BRAND model	type	h	w	R	total
1.1	HARDI Mercury-Iris	VB	1	2	12	24
1.2	MAKATO MB 3000	MS	1	2	12	24
1.3	HARDI Mercury	MS	1	2	12	24
1.4	HARDI Mercury-Iris	VB	3	3	12	108
1.5	MAKATO MB 3000	MS	3	3	12	108
1.6	HARDI Mercury-	MS	3	3	12	108
1.7	HARDI Mercury-Iris	VB	3	3	6	54
1.8	HARDI Mercury-Iris	VB	3	3	6	54
1.9	HARDI Mercury-Iris	VB	3	3	6	54
1.10	HARDI Mercury-Iris	VB	3	3	6	54
1.11	MAKATO MB 3000	MS	3	3	12	108
1.12	HARDI Mercury	MS	3	3	12	108
1.13	HARDI Mercury-Iris	VB	3	3	6	54
1.14	HARDI Mercury-Iris	VB	3	3	6	54
1.15	HARDI Mercury-Iris	VB	3	3	6	54
1.16	HARDI Mercury-Iris	VB	3	2	6	36
1.17	HARDI Mercury-Iris	VB	3	2	6	36
1.18	HARDI Optimus 55	T	3	2	6	36
1.19	MAKATO MB 3000	MS	3	3	12	108
1.20	HARDI Optimus 55	T	4	3	3	36
1.21	HARDI Optimus 55	T	2	2	3	12
1.22	FEDE-Quantum prototype	MAF	5	4	3	60
1.23	FEDE Tecnovid	VB	5	4	3	60
1.24	HARDI Mercury-Iris	VB	3	3	3	27
1.25	HARDI Mercury-Iris	VB	3	3	3	27
1.26	HARDI Optimus 55	T	3	2	3	18
1.27	HARDI Mercury-Iris	VB	3	2	3	18
1.28	FEDE Tecnovid	VB	2	3	6	36
1.29	FEDE-Quantum prototype	MAF	2	3	6	36
1.30	FEDE Tecnovid	VB	3	3	6	54
1.31	FEDE Tecnovid	VB	3	3	6	54
1.32	HARDI Optimus 55	T	3	3	3	27
1.33	FEDE Tecnovid	VB	2	-	15	30
1.34	FEDE Tecnovid	VB	2	-	21	42
1.35	FEDE Tecnovid	VB	2	-	28	56
1.36	FEDE Tecnovid	VB	4	3	3	36
1.37	FEDE-Quantum prototype	MAF	4	3	3	36

2.3 Efficacy assessment

DOSA3D recommendations were also followed in four commercial vineyards located in the wine areas of Penedès and Tarragona (Spain) (Table 3). Efficacy against powdery mildew was assessed throughout the season. These vineyards were divided into two subplots in which the farmer's usual pesticide treatments were carried out in one part (standard volume rate and dose) and in the other each treatment was adjusted to the specific canopy development by DOSA3D (Table 4). As usual in the growing area, the pesticide program against powdery mildew included 1-2 powdered sulphur applications, so these treatments were applied to the whole vineyard at the beginning of the summer.

To assess differences between treatment strategies (standard and DOSA3D) against powdery mildew prior to harvest, disease severity was evaluated in trials 2.1 and 2.2 on 6-7 grape bunches from 15 vines randomly selected in each treatment plot using a six-level scale (0: 0%; 1: 0-5%; 2: 5-10%; 3: 10-25%; 4: 25-50%; 5 :50-100%). Data were transformed to severity percentage according to the Townsend-Heuberger equation (Püntener, 1981). In these trials it was not possible to maintain an untreated area (reference control).

However, in trials 2.3 and 2.4 an untreated area (control) was maintained within the field. In these trials, between 60-90 random grape bunches were monitored in each treatment and control zone. The severity of powdery mildew in each bunch was expressed as the percentage of damage on the fruit. A t-test was performed for the four trials to analyze differences between standard and DOSA3D strategies. The overall efficacies of each strategy in trials 3 and 4 were additionally calculated using Abbott's formula (Abbott, 1925).

Table 3. Description of vineyards and sprayers.

Trial	Year	Location	Coordinates ETRS89	Area (ha)	Cultivar	Row distance (m)	Sprayer	Sprayer type	Nozzles
2.1	2018	Pla de Manlleu	41.3794444 1.5091374	0.87	Muscat	2.8	MAKATO Ecopowder MB	Multispouts	Albuz ATR
2.2	2019	Pla de Manlleu	41.379444 1.5091374	1.00	Parellada	2.7	BALVEN	Multispouts	Albuz ATR
2.3	2020	Perafort	41.199645 1.256406	3.01	Chardonnay	2.7	ILEMO 1500	Multispouts	Albuz ATR
2.4	2020	Torrelavit	41.437869 1.728959	0.40	Chardonnay	2.8	SAHER 150	Standard	Albuz ATR

Table 4. List of pesticide treatments conducted in four trials (T). For each date, active ingredients, tank concentration (C), volume rate (V) and dose (D) applied on standard (STD) and adjusted (DOSA3D) subplots.

		Product	Tank concentration (%)		Water volume rate (l ha^{-1})		Dose (l or kg ha^{-1})		Adjustment (%)	
T	Application date	Active ingredient	C_{STD}	C_{DOSA3D}	V_{STD}	V_{DOSA3D}	D_{STD}	D_{DOSA3D}	V	D
2.1	04 May 2018	sulphur 72%	0.6		280	150	1.68	0.90	46%	
	17 May 2018	sulphur 72%	0.6		220	200	1.32	1.20	9%	
	11 June 2018	sulphur 72%	0.6		270	250	1.62	1.50	7%	
	26 June 2018	sulphur 72%	0.6		310	250	1.86	1.50	19%	
	03 July 2018	sulphur 99%	(powdered sulphur 30 kg ha^{-1})							
	15 July 2018	sulphur 99%	(powdered sulphur 30 kg ha^{-1})							
2.2	21 May 2019	sulphur 82.5%	0.8		180	150	1.44	1.20	17%	
	05 June 2019	sulphur 82.5%	0.6		270	200	1.62	1.20	26%	
	22 June 2019	sulphur 80%	0.8		310	250	2.48	2.00	19%	
	03 July 2019	sulphur 99%	(powdered sulphur 30 kg ha^{-1})							
	19 July 2019	sulphur 99%	(powdered sulphur 30 kg ha^{-1})							
	02 Aug. 2019	sulphur 80%	0.8		400	350	3.20	2.80	13%	
2.3	08 Apr. 2020	penconazole 10%	0.065	0.060	441	243	0.29	0.15	45%	49%
	29 Apr. 2020	tetraconazole 12.5%	0.066	0.047	441	243	0.29*	0.12	45%	60%
	19 May 2020	boscalid 20% + kresoxim-methyl 10%	0.075	0.079	661	364	0.50*	0.29	45%	42%
	29 May 2020	boscalida 20% + kresoxim-methyl 10%	0.062	0.090	759	440	0.47*	0.40	42%	16%
		sulphur 80%	0.750	0.800			5.69	3.52		38%
	05 June 2020	kresoxim-methyl		0.045	--	441	--	0.20	--	
	15 June 2020	kresoxim-methyl	0.039	0.045	759	441	0.30*	0.20	42%	33%
		sulphur 80%	1.000	0.807			7.59	3.56		53%
	03 July 2020	sulphur 99%	(powdered sulphur 30 kg ha^{-1})							
2.4	17 Apr. 2020	sulphur 72%	1.170	1.140	168	150	1.97	1.71	11%	13%
	27 Apr. 2020	proquinazid 20%	0.078	0.050	248	160	0.19	0.08	35%	59%
	08 May 2020	sulphur 80%	0.530	0.500	337	225	1.79	1.13	33%	37%
	01 June 2020	proquinazid 20%	0.077	0.050	460	460	0.35	0.23	0%	35%
	08 June 2020	sulphur 98.5%	(powdered sulphur 40 kg ha^{-1})							

* Higher dose than the maximum officially allowed

3. Results and discussion

3.1 Leaf area index model

Each LAI measured value is represented in Figure 1 associated to the corresponding LAI calculated through Equation 1. The low confidence interval is very close to the x=y function. However, the model underestimates the LAI when it is higher than 2.5. These LAIs correspond to canopy widths greater than 1.25 m. As the canopy width approaches 1.5 m, several layers of leaves overlap and the actual LAI can reach values over 3.0. In fact, the points in Figure 1 showing measured LAI higher than 2.5 correspond to a specific cv. Airén vineyard conducted as a single high-wire sprawling system (Kurtural et al., 2019). In practice, commonly the LAI of trellised vineyards does not exceed 2.5 (Pergher and Petris, 2008). Up to that value, the estimation of LAI in vineyards provided by DOSA3D is validated. In scenarios with canopy width greater than 1.25 m, sprayer calibration must be made very accurately in order to achieve the correct on-target coverage, particularly in the inner parts of the canopies. In these exceptional situations, the volume rates proposed by DOSA3D may be increased by 20-30%.

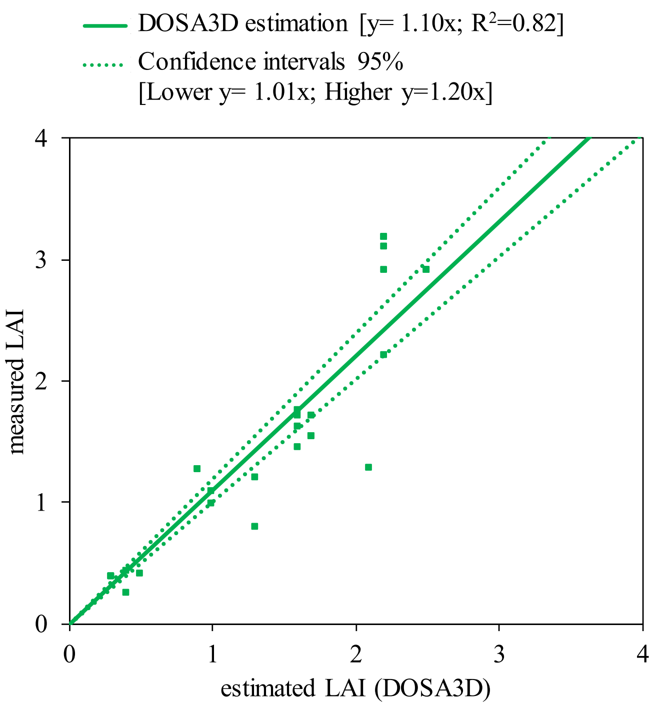

Figure 1. Measured leaf area index (LAI) correlation with estimated LAI by DOSA3D system.

3.2 On-target deposition

The objective of DOSA3D is to adapt doses to the different specific scenarios by adjusting volume rates. Figure 2 shows how the application volume rate, based on the DSS recommendations, increases with LAI. This is the basis of any DSS that characterizes vegetation to recommend doses (Gil et al., 2019; Planas et al., 2013; Siegfried et al., 2007).

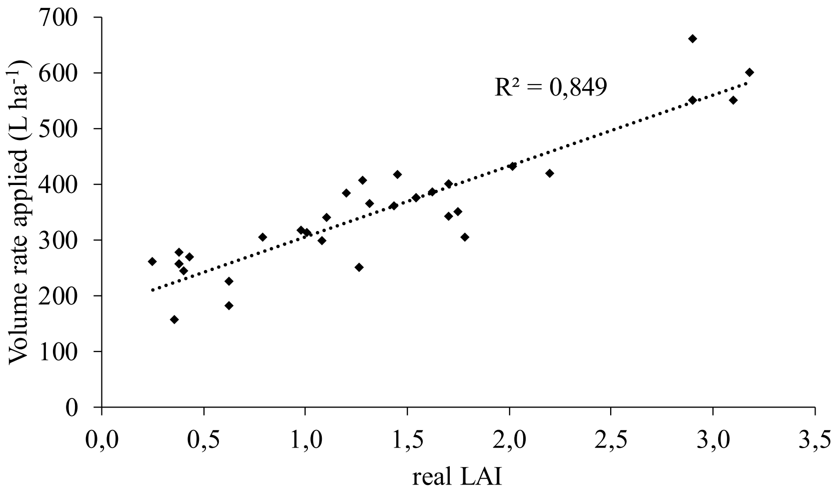

Figure 2. Linear correlation between volume rate applied following DOSA3D recommendations in different trials and measured leaf area index (real LAI)

Mean leaf deposition are shown in Table 5. The parameter used to validate the volume rate decision was a minimum mean deposit of 1.2 µl cm^{-2}, which is the threshold proposed by DOSA3D as optimum coverage. In this regard, Figure 3.A shows the relation between LAI and leaf deposition expressed as µl cm^{-2}. The highest deposits were achieved at early stages when LAI was < 0.5 (points inside the oval light grey shadow). In these initial trials the applied volume rate was higher than the recommended minimum. The reason was that the treatment against tetranychid mites with mineral oil as a pesticide was being evaluated and this treatment only occurs at the beginning of the season. The mode of action of mineral oil is by suffocation when mites are over-sprayed (Marcic, 2012). From LAI > 0.5, leaf disposition tended to remain parallel to the proposed threshold (dark grey shadow). Assuming an optimal deposition range of 1.2-1.75 µl cm^{-2}, 80% of the tests performed with LAI > 0.5 met this condition. In contrast, 13% were over-dosed and 7% under-dosed. Pergher G. and Petris R. (2008) also reported that dose-adjusted depositions (in this case according to the LWA) were almost independent of the LAI. However, Rüegg et al. (2001), in a study on leaf deposition in 102 trials carried out in apple orchards in several countries, showed that when foliar deposits are normalized by the tracer applied (g ha^{-1}) the result is LAI-dependent, following a logarithmic curve ($R^2 = 0.87$). The normalized deposits obtained in the trials performed to validate DOSA3D showed a similar curve with an acceptable correlation

(R^2 = 0.80) (Figure 3.B). This is also in agreement with the results obtained by Gil et al. (2011) and Pergher and Petris (2008).

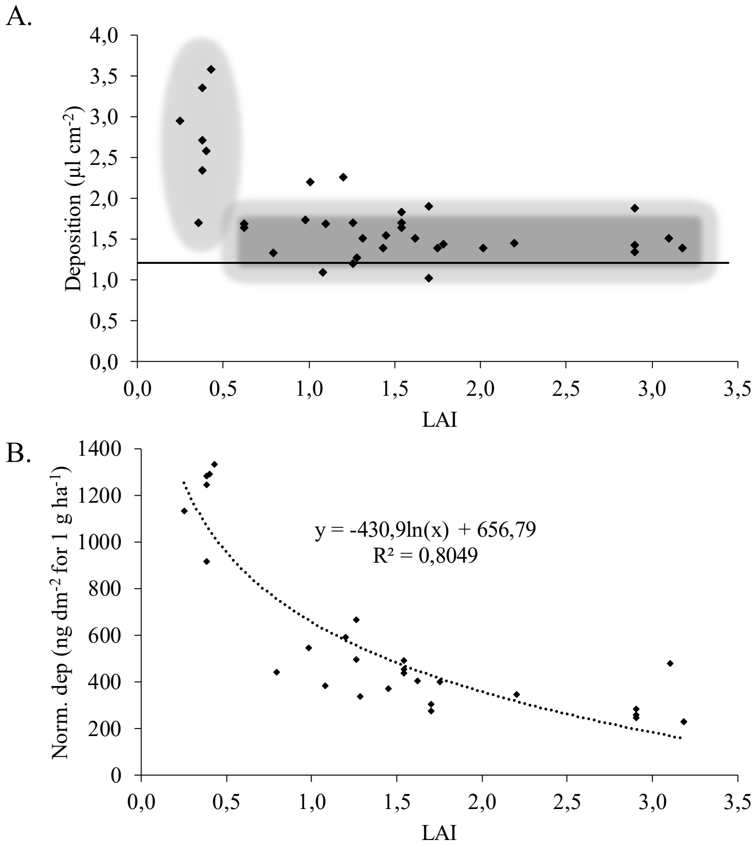

Figure 3. A) Leaf deposition (µl cm^{-2}) related to LAI, grey shadows show different patterns; and B) Logarithmic correlation between normalized tracer deposits expressed as (ng/dm^2)/(g/ha) and LAI.

The efficiency proposed by the DOSA3D system for the tested sprayers was similar in all trials (61-69%). However, total leaf recovery ranged between 28.0% and 85.8%. This variability on efficiencies was also shown by Jensen and Olesen (2014). Efficiencies of below 50% correspond to early stage trials, since losses to the ground and drift are higher when there is little vegetation (Viret et al., 2003). Accordingly, DOSA3D set a minimum volume rate of 150 l ha^{-1} for low LAI, implicitly taking into account the decrease in efficiency in these cases. In general terms, efficiency increased as the season progressed. The highest efficiency rates (>80%) were achieved only for very specific situations, as for example with the recycling tunnel at full-leaf stage (trial 2.20) and with cv. Airén conducted as a single high-wire sprawling system (trials 2.30, 2.31 and 2.37), again at full-leaf stages.

Penetrability percentages of 59-100%, 42-101% and 25-68% were found for the DOSA3D-proposed width ranges of 0.25-0.75 m, 0.75-1.00 and 1.00-1.50 m, respectively (Table 5). Penetrability therefore tended to decrease as vine width increased, and so under-dosed sites were found in the inner zone of the vines. The recycling tunnel was the only sprayer assessed that reached 100% penetrability (trials 1.20 and 1.32).

Table 5. Leaf deposition (mean ± standard deviation), coefficient of variation (CV), normalized deposition, efficiency (E), percentage of samples under the DOSA3D threshold (<1.2 µl cm^{-2}) and penetrability (P) for each trial.

Trial	Deposition (µl cm^{-2}) mean	SD	CV (%)	Norm. deposition (ng/dm^2)/(g/ha)	E (%)	Samples < 1.2 µl cm^{-2} (%)	P (%)
1.1	2.35	0.77	32.8	914	35.11	5.6	-
1.2	2.71	0.91	33.6	1284	37.9	0.0	-
1.3	3.08	1.37	44.5	1245	50.1	7.5	-
1.4	1.69	0.83	49.1	452	74.4	32.1	65.0
1.5	1.64	1.07	65.2	438	67.6	38.4	54.0
1.6	1.84	0.74	40.2	490	49.0	20.5	58.4
1.7	1.74	0.64	36.8	547	53.4	19.6	68.9
1.8	1.55	0.67	43.2	370	53.6	30.6	61.5
1.9	1.14	0.59	51.8	384	41.4	51.4	67.2
1.10	1.56	0.92	59.0	402	65.2	34.2	42.5
1.11	1.69	1.33	78.7	495	53.5	45.9	59.3
1.12	1.52	1.48	97.4	416	54.8	55.9	57.7
1.13	1.35	0.64	47.4	440	34.76	43.3	66.2
1.14	1.38	0.68	49.3	339	43.3	46.8	64.2
1.15	2.27	0.53	23.4	590	67.1	0.1	78.4
1.16	3.69	3.84	104.1	1331	62.6	11.5	-
1.17	2.95	2.71	91.9	1132	28.0	28.3	-
1.18	3.17	2.22	70.0	1291	51.7	10.2	-
1.19	1.03	0.50	50.5	304	42.39	62.5	72.5
1.20	1.44	0.79	54.9	471	84.1	38.1	101.2
1.21	1.62	0.52	32.1	850	38.0	31.0	-
1.22	1.39	0.76	54.7	231	69.9	47.2	47.2
1.23	1.37	0.905	66.1	229	71.6	61.5	68.1
1.24	1.44	0.56	38.9	400	59.8	37.1	69.4
1.25	1.39	0.66	47.5	321	64.7	41.8	54.1
1.26	1.69	0.49	29.0	902	55.6	11.3	-
1.27	1.64	0.66	40.2	723	44.6	30.0	-
1.28	1.68	1.16	69.0	665	79.8	36.9	40.4
1.29	1.23	0.8	65.0	497	59.6	50.0	41.6
1.30	1.91	1.07	56.0	276	81.2	43.0	49.1
1.31	1.52	1.31	86.2	478	85.8	50.3	24.6
1.32	2.20	0.66	30.0	703	77.4	4.0	100.0
1.33	1.39	0.46	33.1	398	69.7	-	-
1.34	1.46	0.43	29.5	347	76.2	-	-
1.35	1.35	0.46	34.1	246	71.1	-	-
1.36	1.43	0.94	65.7	260	75.3	43.0	47.4
1.37	1.88	1.32	70.2	285	82.6	38.9	26.2

3.3 Efficacy assessment

Trials 2.1 and 2.2 followed a similar pesticide program against powdery mildew, based on sulphur applications. In these cases, tank concentrations were identical for both strategies, and so sulphur doses (kg ha^{-1}) varied according to the volume rate adjustments. Pesticide reductions of between 7 and 43 % were achieved (mean 20%). Nonetheless, there were no significant differences between standard and DOSA3D strategies. In trial 2.1, disease incidences on grape bunches were 15.2% and 16.6% for standard and DOSA3D strategies, respectively (Figure 4), while in trial 2.2 there were no symptoms for either strategy. According to the Plant Health Services of Catalonia, the incidence of untreated plots in the growing area was 100% and 30% for trials 2.1 (2018) and 2.2 (2019), respectively. Powdery mildew is a key disease in this wine-growing area, with temperatures and humidity favouring its development from May to July-August. However, in 2019 there were three periods (June 27 to July 4; July 20 to July 25; and August 8 to August 12) when mean daily temperatures were above 30ºC and relative humidity under 40%. Some daytime temperatures were above 36ºC for more than 6 hours, a temperature threshold that is considered lethal for this pathogen (Peduto et al., 2013). This could be the reason why there was no damage on grapes in trial 2.2 and even in untreated areas the incidence was low (30%).

Weather conditions in 2020 were more severe than in 2019 (similar to 2018), so a high incidence of powdery mildew was expected. In trial 2.3, volume rate reductions were 45% in the first treatments and 42% in the later treatments. In this case, tank concentrations were different for the standard and DOSA3D strategies. In four treatments of the standard strategy, the farmer's decision was to apply higher doses than the maximum allowed, whereas the DOSA3D recommendation remained below this maximum value. Due to this, dose reductions ranged from 16 to 60%. On May 28, the vineyard was monitored and 1%, 12% and 80% of damage on grapes were found in the standard, DOSA3D and control subplots, respectively (Figure 4). As a consequence, the advisor decided to undertake a curative treatment on DOSA3D and control subplots. Before the harvest, significant differences were found in pest incidence on grape bunches ($p = 0.0005$) which ranged from 0.6% in standard to 12.4% in DOSA3D subplots. That is to say, efficacy was higher following the standard strategy (99.1%) than the adjusted one. Nonetheless, the efficacy of the DOSA3D strategy was still high at 81%.

Finally, in trial 2.4, volume rate adjustments resulted in reductions ranging between 0% and 35%. and dose rate reductions of between 13% and 59%. As in trial 2.3, tank concentration varied between strategies, but doses were always lower than the maximum allowed. In this trial, no significant differences were found in disease severity, although in both strategies it was higher than 40%. This translates into efficacies of 50.2% and 51.9% for the standard and DOSA3D strategies, respectively. This is possibly attributable to the lower number of powdery mildew treatments performed and, unquestionably, to the high pressure of powdery mildew in the winegrowing region.

These results confirm that the application volume and doses can be reduced while maintaining the same efficacies, and that the DOSA3D tool allows this adjustment to be made in a rational way, thus fulfilling the general objective of reducing the use of pesticides.

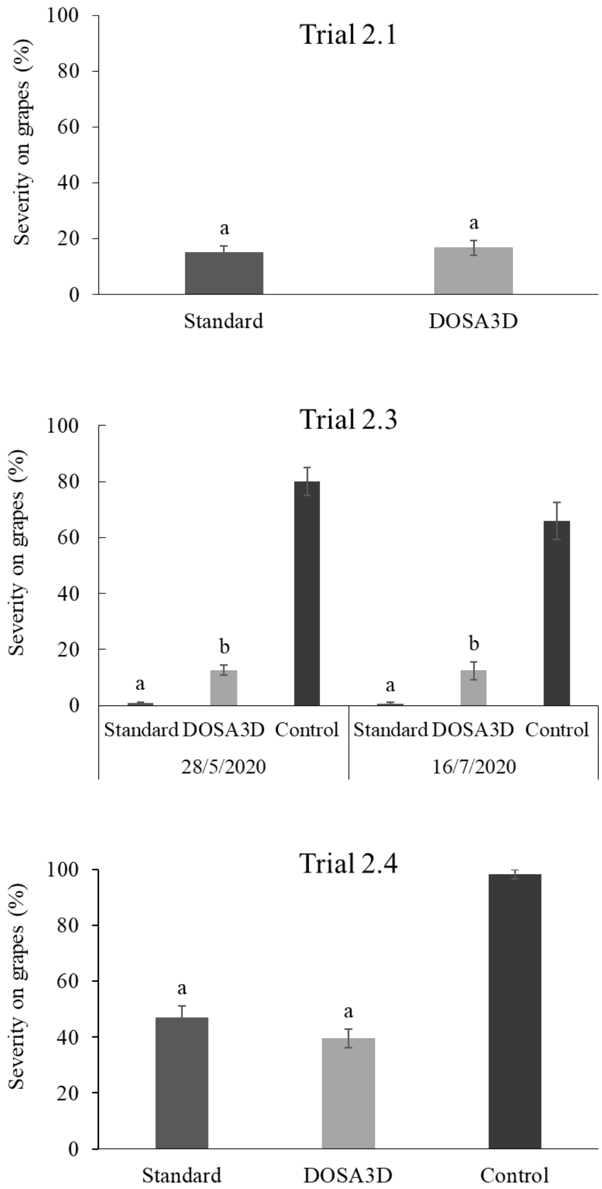

Figure 4. Powdery mildew (Erysiphe necator) severity on grape bunches for standard and DOSA3D treatments and the control (untreated) area. Different letters above the bars in each trial indicate significant differences (t-test, $p < 0.05$).

4. Conclusions

The DOSA3D system can easily estimate the LAI in vineyards up to a canopy width of 1.25 m along the season for three different growth stages (early, medium, full leaf) on the basis of canopy width and height dimensions and distance between rows. The results achieved in the validation tests prove the consistency of this methodology.

Volume and dose rate adjustment following DOSA3D recommendations ensures that leaf deposition remains at or above an optimal threshold and, therefore, achieves an efficacy similar to that of standard treatments. This means a reduction of human exposure to pesticides, lower environmental risks and reduced costs for farmers, meeting the general objective of the European Commission to reduce pesticide use and mitigate environmental and human risks.

The DOSA3D system calculates the optimal volume rate on the basis of a minimum unitary leaf deposition equivalent to 1.2 µl cm^{-2}. The experimental results obtained from a large number of trials endorse this value as a threshold to be attained in maximum zones within the canopy. Deposition rates which are below this threshold may reduce efficacy, increase the possibility of pest reservoirs and result in the need for a subsequent treatment.

To minimize the sites that are underdosed, DOSA3D includes extra volume rates which are inversely proportional to the overall spraying efficiency. This ratio is estimated according to canopy structure (width and height) and sprayer efficiency. Spraying is assessed in terms of deposition variability, penetrability (canopy penetration ability) and, at global level, in terms of efficiency (percentage of on-target tracer leaf recovery related to the total applied). All the results obtained in the experimental trials verify the suitability of the efficiency ratios adopted by the DOSA3D system.

Moreover, the following rules for the interpretation of leaf deposition have been confirmed and can be taken into account in future developments: i) Any decision on volume rates should be rationalized following a positive dependence on the LAI; ii) Spraying efficiency, which depends on canopy structure and sprayer performance, should be taken into consideration when deciding on final spray volumes; iii) In general terms, efficiency increases as the season progress iv) On-target deposition uniformity and, especially, penetrability into the canopy decrease as canopy width increases, and; v) Sprayer performance strongly determines the quality of the treatment. In vineyards, the recycling tunnel seems to have the highest potential capacity to provide better treatments, although work should continue on improving side-to-side designs.

DOSA3D system has shown its efficacy for adjusted treatments in vineyards to control powdery mildew. However, if climatic conditions continue to favour a high pressure of diseases and/or pests, the adjusted treatments may result insufficiently effective. In such situations, on-target depositions must be maintained or increased.

DOSA3D aims to be a dynamic tool that can evolve with new evaluations of volume and dose rates adjustment for the different crops it contemplates.

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CAPÍTULO 6

Spatially variable pesticide application in vineyards: field comparison of uniform and map-based variable dose treatments

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Research Paper

Spatially variable pesticide application in vineyards: Part II, field comparison of uniform and map-based variable dose treatments

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Reducing pesticide use is an important concern for many including the European Commission. One way to achieve this goal is to adjust the amount of pesticides in relation to canopy geometry and foliage. This objective currently poses an important challenge in vineyards with uniform vegetation but it is an added difficulty when the canopy shows spatial variability within the field. Is it possible to set a constant volume rate adjusted to this variability? Or is it more convenient to adjusting different volume rates based on a prescription map? Assuming a plant cell density (PCD) vegetation index from multispectral images to be optimal for detecting variations in vigour, two methods to adjust volume rates in spatially variable vineyards were proposed and tested: i) adjustment of a constant volume rate uniformly applied using a conventional sprayer, and ii) adjustment of two volume rates adapted to two vigour classes according to a prescription map. In both methods, PCD was previously correlated to the leaf area index (LAI), then taking the 70th percentile of LAI to determine adjusted volume rates through DOSA3D decision support system (www.dosa3d.cat/en). Leaf deposition with tracer was analysed to compare the proposed methods with the standard volume rate commonly used in the area. Statistical analysis showed no significant differences between treatments. Since pesticide savings can be achieved using the two methods, specifically 25.6% in adjusted uniform and 25.3% in adjusted map-based treatments, adjusted volume rate strategies can be recommended in vineyards with spatial variability.

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Spatially variable pesticide application in vineyards: Part II, field comparison of uniform and map-based variable dose treatments

1. Introduction

Since the enactment of European Directive 2009/128/EC on the sustainable use of pesticides, various integrated pest management programs have been developed to reduce the amount of plant protection products (PPPs) used in the field. However, pest and disease management in vineyards usually still requires a large number of PPP applications. This is especially relevant for fungicides, with an average of 12-15 annual treatments (Pertot et al., 2017). Downy mildew (*Plasmopara viticola* Berl. & de Toni) is one of the diseases that requires the largest number of treatments, and PPPs that contain copper are commonly used for its control (Cabús et al., 2017). However, the European Commission has recently reduced the maximum amount of copper that can be used to 28 kg ha^{-1} for a 7-year period (average 4 kg ha^{-1} year^{-1}) (Commission Implementing Regulation 2018/1981).

Due to these official restrictions, PPP dose adjusting techniques are becoming more relevant in viticulture. To achieve dose reductions without affecting protection efficacy, many authors propose adapting the dose to the canopy characteristics (or target surface to be treated). In the case of three-dimensional (3D) crops, this is done by estimating the target surface to be sprayed and calculating the optimum volume rate to be applied that provides the minimum coverage of the target area that ensures product efficacy. This is especially relevant in the case of trellised vineyards since the vegetative cycle begins with non-green vegetation until the full development stages. To facilitate the calculation, several decision support systems (DSS) have been developed for vineyards: Optidose® (Davy et al., 2010), DOSA3D (Planas, Román, Sanz & Rosell-Polo, 2016), Dosaviña (Gil et al., 2019) and Dosage adapté (Agroscope). DOSA3D is the updated version of Dosafrut (Planas et al., 2013), and has been adapted for different 3D crops using the same base calculation principles. DOSA3D (www.dosa3d.cat/en) has been used in this work. To decide the optimum volume rate (and doses) adapted to canopy dimensions and leafiness, vineyard LAI estimation is based on the method established by Sanz et al. (2018).

Vineyards are often spatially variable in vigour. Possibly due to factors linked to soil variability, grapevines usually present different canopy volume and leaf development depending on the location within the plot. This spatial variability has been referred to by many authors working on soil characterisation (Martinez-Casasnovas, Agelet-Fernandez, Arno & Ramos, 2012) or grape yield and phenology mapping (Arnó, Rosell, Blanco, Ramos & Martínez-Casasnovas, 2012; Bramley & Hamilton, 2004; Verdugo-Vásquez et al., 2019). It is this use of remote sensing that has allowed within-field variability in vigour to be described and, as appropriate, easily delimited according to potential management zones (Borgogno-Mondino, Lessio, Tarricone, Novello & de Palma, 2018). Although the normalised difference vegetation index (NDVI) has been widely used in agriculture, the plant cell density (PCD) or ratio vegetation index has generally been used in applications within the scope of precision viticulture. The PCD is similar to the NDVI in that the difference between the high reflectance in the near-infrared waveband versus the low reflectance in the red waveband is highlighted. However, areas of higher vegetation density are better contrasted through PCD images than NDVI images. This difference is probably attributable to the greater ability of PCD to detect differences in the photosynthetically active biomass (Proffitt, Bramley, Lamb & Winter, 2006).

In short, knowing in advance the foliar variability within a plot is a tool that can be used repeatedly if its impact on improving treatment efficiency is clearly demonstrated. Volume rate adjustment according to delimited areas of different vigour is a real possibility (Campos et al., 2019, 2020; Román & Planas, 2018). Moreover, some diseases also seem to be correlated to vine vigour. Ferrer et al., (2019) showed a relationship between high vigour areas within a vineyard and fungus attack due to the lack of water restriction in these areas. Bramley, Evans, Dunne & Gobbett (2011) revealed that high vigour areas tended to be more affected by botrytis (*Botrytis cinerea* Pers.) compared to areas of lower vigour development, and Román & Planas (2018) also showed the influence of high vigour areas on the abundance of yellow spider mite (*Eotetranychus carpini* Oud.). However, none of the DSS mentioned above take into account the assumption of within-field variability in crop vigour when volume rates are recommended.

Consequently, it might be necessary to adapt PPP dose to vine vigour. This adaptation could be done using real-time technologies to sense crop vigour status. Different real-time variable rate technologies have been shown to be able to adapt dosage to canopy characteristics and qualitatively and quantitatively improve the sprayed deposition (Wandkar, Bhatt, Jain, Nalawade & Pawar, 2018). Variable rate application usually requires the use of sensors and electronic devices mounted on the sprayer that may require specific technical training for the operators, and they are still economically beyond the reach of small- and medium-sized wine growers (Tona, Calcante & Oberti, 2018). Major growers are reluctant to implement these devices because of their reliability and maintenance needs, as well as for reasons of cost. Nevertheless, vigour maps that growers use for other vineyard management practices can be adapted for site-specific PPP applications (Campos et al., 2019, 2020), and low cost pressure controllers could be mounted in sprayers to allow variable rate spraying to be adopted by many farmers with savings of around 10 - 27% in PPP costs (Petrović, Mladen, Tadić, Plaščak & Barač, 2018).

A two-stage research programme was designed to address the problem of PPP dosing when vineyard plots are spatially variable in vigour. In Part I (del-Moral-Martinez, Rosell, Uribeetxebarria & Arnó, 2020), a geostatistical approach was developed that included demonstrating how geostatistics could allow optimal volume rates in spatially variable plots to be adopted. Specifically, it was proposed to use LAI values in volume rate expressions between the 65th and 80th percentile as ancillary information to minimise the risk (probability) of vulnerable areas being underdosed. Field validation allowing the proposed method to be assessed under real application conditions constitutes the main objective of this paper (Part II), completing the second phase of the research. In short, the aims of this paper are (i) to validate by on-target spray deposition measurement the methodology proposed in Part I to adjust volume rates for uniform and map-based treatments in vineyards with spatial variability in vigour, and (ii) to establish a protocol that integrates the use of the DOSA3D decision support system to recommend volume rates and doses in spatially variable vineyards.

2. Material and Methods

2.1 Vineyard

The experiments were carried out in 2017 and located at Raïmat, Spain (41°41'52.92"N, 0°29'18.56"E). They were conducted in a commercial 17.5 ha vineyard var. Cabernet Sauvignon during the fruit development growth stage (BBCH scale: 71 - 73) (Meier, 2001). Grapevines were planted in 2011 in a trellis system with 2.50 m spacing between rows and 1.65 m spacing within the rows (Figure 1).

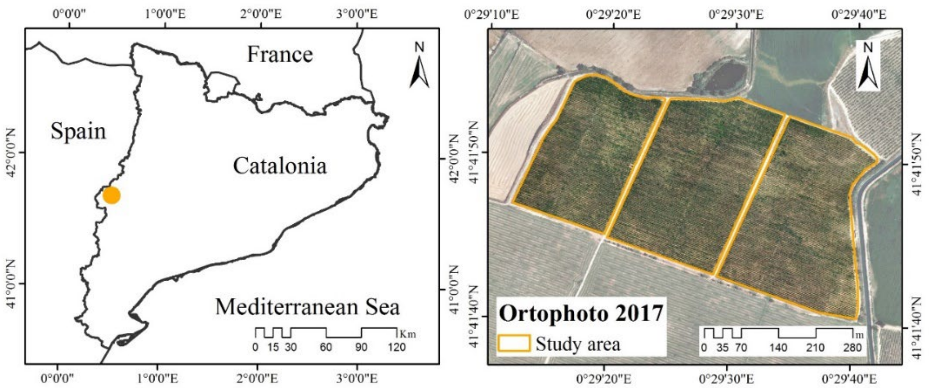

Figure 1. Field location and study area.

2.2 Maps

A multispectral airborne image was taken on 25 May 2017 using a 4-band multispectral camera. The 50 cm spatial resolution image was supplied by Agropixel SL (Lleida, Spain). The spectral regions captured were: (i) blue (445 - 520 nm), (ii) green (510 - 600 nm), (iii) red (510 - 600 nm), and (iv) near-infrared (757 - 853 nm). The high resolution of the image allowed pixels on grapevines to be precisely delimited. The pixels outside the canopy corresponding to the inter-row spaces were then deleted, avoiding distortions in vigour interpretation. The PCD index (Bramley, Pearse & Chamberlain, 2003) was then calculated for each canopy pixel using:

$$PCD = \frac{NIR}{R} \quad (1)$$

where NIR refers to near-infrared and R to the visible spectral region of red. The resulting image was classified into 5 quantiles according to the distribution of PCD values (Figure 2.A). In this way, 3 vines from each PCD quantile were selected and manually defoliated to measure leaves using a leaf-meter (Delta-T Devices Ltd., Cambridge, UK). Once transformed to LAI measures, each LAI value was related to the PCD mean value of the six nearest pixels to the defoliation point by a simple linear regression (y =0.0087x; R^2 = 0.89). The resulting equation allowed PCD values to be converted into LAI values for the vineyard pixels. For that, pixels were converted to vector points using ArcMap 10.5 (Environmental Systems Research Institute, Redlands, CA, USA). Then, a continuous LAI surface map was obtained by ordinary kriging using an exponential model for semi-variogram adjustment. The interpolation grid was set at 1 m (spatial resolution), on which the LAI point values were referred (Figure 2.B). Subsequently, the interpolated LAI map was classified into two LAI classes (high and low) using cluster analysis and an unsupervised algorithm (ISODATA, iterative self-organising data analysis technique) implemented in ArcGIS 10.5 (Figure 2.C). Finally, from this classified map, a prescription map to apply two different volume rates was generated by polygonising the original classes and eliminating those smaller than 0.01 ha (Figure 2.D).

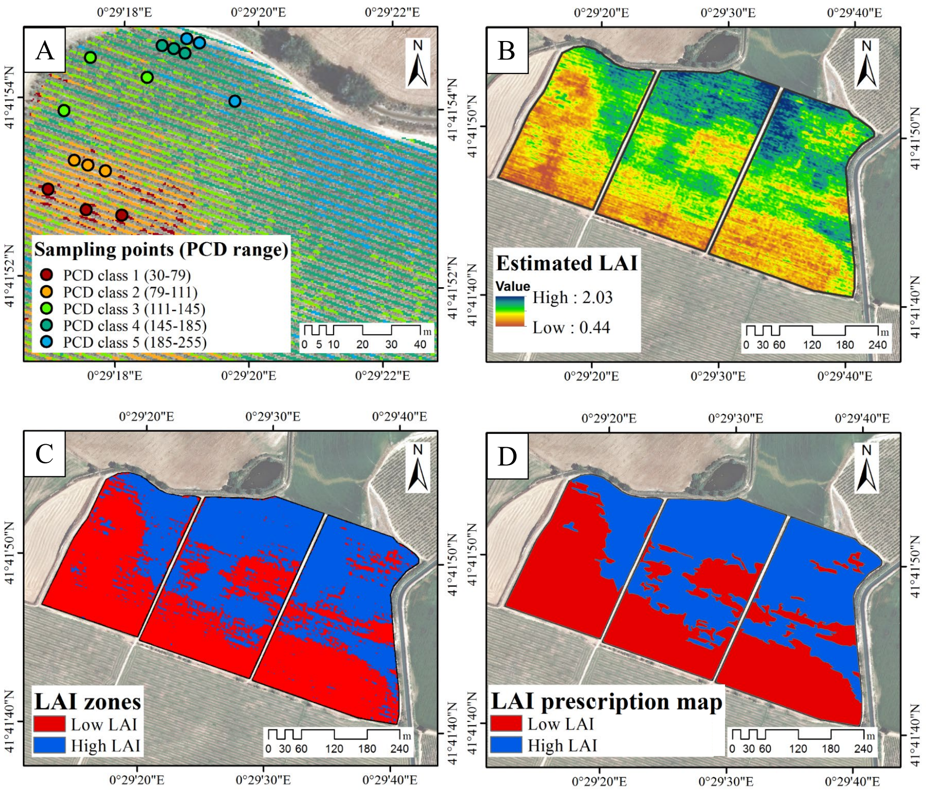

Figure. 2. A) Sampling points to measure LAI. B) LAI continuous map. C) LAI classification into two vigour classes. D) final prescription map.

2.3 Spray technology

A two-row face-to-face IRIS sprayer fitted with an HF-540 tangential-flow fan (540 mm diameter) (Ilemo Hardi, S.A.U., Lleida, Spain) was used for all treatments (Figure 3). For application using the prescription map, the sprayer was modified to change the working pressure as necessary. A three-way ball solenoid valve (M853L14A55, Arag S.R.L, Rubeira, Italy) was added to divert the flow to one of the two installed manual pressure regulators (model number 4755612, Arag S.R.L, Rubeira, Italy) (Figure 4). The working pressure was changed via a bypass switched by the action of the operator each time the zone border was crossed over in accordance with the map and the Global Navigation Satellite System indications shown on the on-board monitor. The on-board monitor consisted of a tablet with PixelMaps 1.0.3 (Agropixel SL, Lleida, Spain) software installed.

Figure 3. Two-row IRIS sprayer used in all treatments.

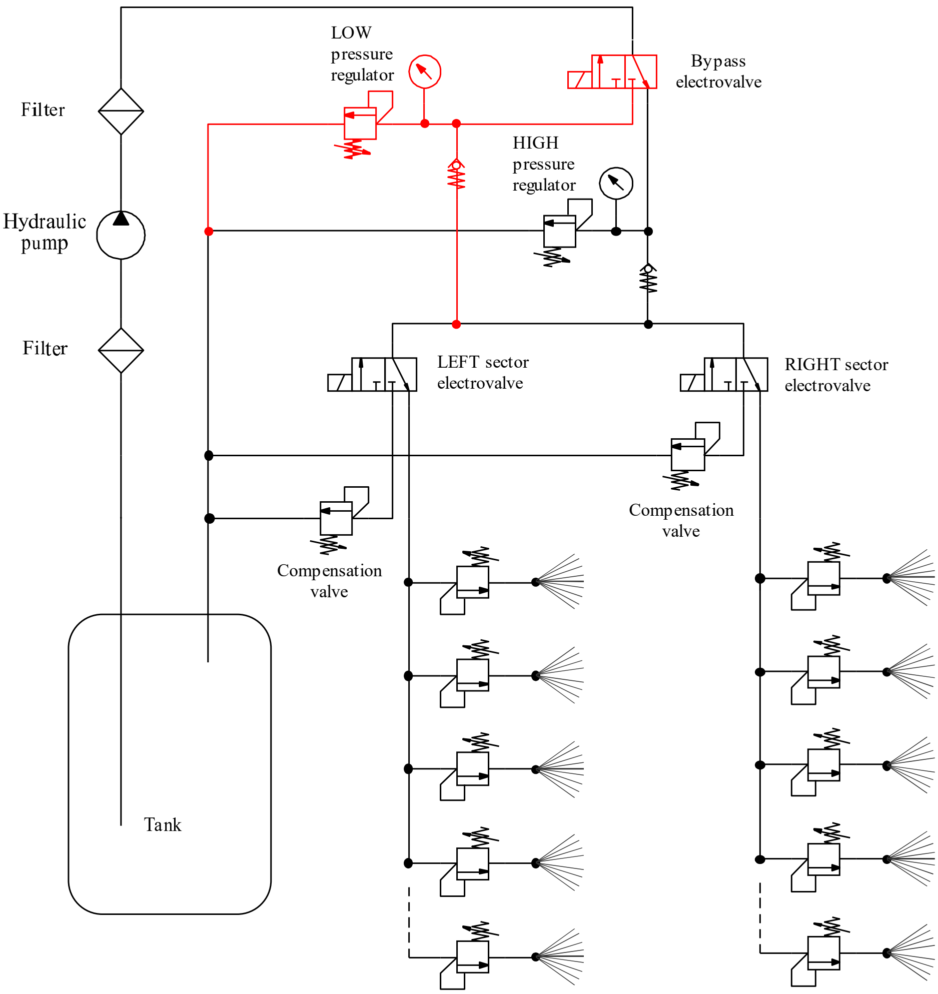

Figure 4. Hydraulic circuit of the sprayer. In red: circuit modification for two volume rates application by means of pressure regulators.

2.4 Experimental design

Three treatment strategies using different volume rates were performed: (i) conventional uniform volume rate set by the farmer (T1, standard volume rate), (ii) adjusted uniform volume rate (T2, adjusted volume rate) and (iii) adjusted map-based volume rates according to two vigour classes (T3, adjusted high and low volume rates). DOSA3D was used to calculate T2 and T3 adjusted volume rates through Eq. (2) below (proposed by Planas et al., 2013).

$$V = \frac{120 * LAI_e}{E} \quad (2)$$

where V is the volume rate in l ha^{-1}, LAI_e is the estimated leaf area index, and E is the treatment efficiency.

Considering the recommendation of Part I, LAI 70th percentiles (Figure 5) and a regular efficiency of 50% were used to calculate the adjusted volume rates (Table 1). The tractor power take-off was set at 430 rev min-1. Air speed was measured upon target arrival (canopy) with an anemometer (Meteo Digit type 916, Lambrecht meteo GmbH, Göttingen, Germany) and resulted 5.6 ± 1.1 m s^{-1} (mean ± standard deviation). Forward speed was established by the farmer at 6.5 km h^{-1} and was kept constant for all treatments. The working pressure values were previously established to ensure the volume rate to be sprayed (Table 1). However, to prevent treatments with much lower working pressures than the range recommended by the manufacturer of the nozzles used (1 – 1.5 MPa), it was decided to increase the application volume rate in the T3 treatment by 14% for low vigour areas.

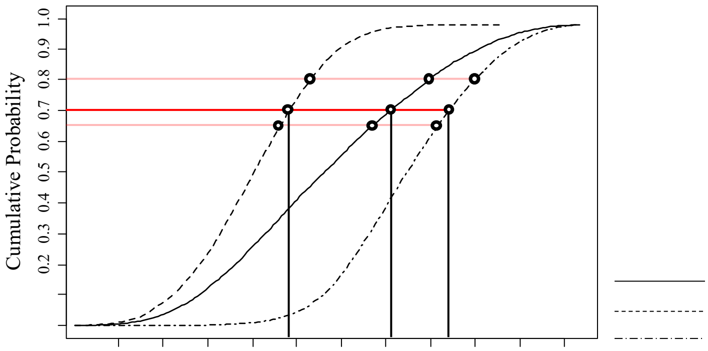

Figure 5. Distribution of LAI values and LAI 70th percentile. Continuous curve includes all plot LAI values and correspond to treatment strategy T2 (adjusted uniform treatment) while the dashed and dot-dashed curves represent separately LAI distributions for low and high vigour classes, respectively, and the management of both curves corresponds to treatment strategy T3 (adjusted high and low volume rates).

Table 1. Volume rates, sprayer settings and dose rates of manganese by treatments. T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based.

Treatment		LAI_{70} percentile	Volume rate (l ha^{-1}) *Calculated*	*Measured*	Nozzle model (number)	Working pressure (MPa)	Mn^{++} (g l^{-1})
T1		-	450	456	Albuz ATR yellow (24)	1	1.90
T2		1,42	341	340	Albuz ATR yellow (20)	0.8	1.95
T3	Low vigour	1,08	259	295	Albuz ATR yellow (16) &	0.7	1.95
	High vigour	1,62	389	387	Albuz ATR brown (4)	1.2	

The experiments were carried out in a small part of the vineyard so that each row contained the two vigour classes (Figure 6.A). Treatments were applied on six continuous rows (0.255 ha), and samples were picked from the two central rows to prevent cross contamination. To analyse depositions, manganese (Sarcan Mn 13%, Exclusivas Sarabia, Lleida, Spain) was used as tracer (Table 1). In accordance with the requirements of ISO 22522:2007, leaf spray depositions were measured in three randomly selected vines per vigour class and treatment. In each vine, nine different positions of the canopy were sampled according to different heights and depths (three heights and three depths within the canopy, Figure 6.B). For each sampling position, 3 - 5 leaves were collected, introduced in a zip-lock bag and stored in dark conditions until laboratory analysis. Manganese (Mn^{++}) was determined by means of atomic absorption spectrometry (AAnalyst 400, Perkin Elmer, Waltham, USA). Spray Mn^{++} depositions were then related to sample surface area and expressed as µg cm^{-2}. Tracer concentration in the tank and blank samples taken before treatments were also quantified.

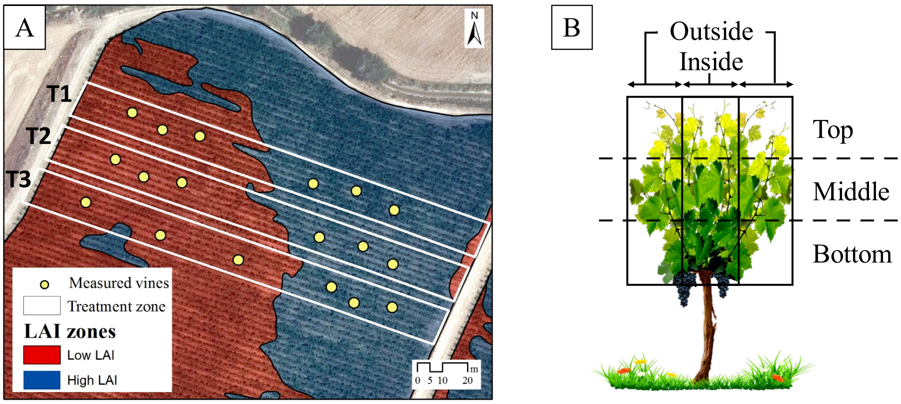

Figure 6. Experimental design. A) Treatments location inside the vineyard. Dots indicate sampled vines location. B) Sampled zones within the vines.

2.5 Data analysis

Leaf deposition was statistically analysed using a linear five-factor model with mixed effects (LMM), considering treatment strategy and vine vigour as fixed factors and the sampled vines and deposition zones within the vines (height and depth) as random factors. A total of 9 mean deposition values from each vine were obtained depending on the location (deposition zone) sampled within the canopy, and this for each of the crossed levels of the fixed factors. The final model was (3):

$$y_{ijklmn} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + C_{k(ij)} + D_{l(k(ij))} + E_{m(k(ij))} + DE_{lm(k(ij))} + e_{ijklmn} \quad (3)$$

where i = 1,…,3, j = 1,2, k = 1,…,3, l = 1,2, m = 1,…,3, n = 1 for l = 1 and n = 2 for l = 2, with y_{ijklmn} the deposition value n obtained within the canopy at height m (top, middle or bottom) and depth l (inside or outside of the canopy) for the vine k within the combination of vigour class j (low or high) and volume rate strategy i (treatment T1, T2 or T3), μ the general average, α_i the effect of level i of the fixed factor A (volume rate strategy), β_j the effect of level j of the fixed factor B (vine vigour), $\alpha\beta_{ij}$ the effect of the interaction between fixed factors A and B, $C_{k(ij)}$ the random effect of vine factor nested in each combination of fixed factors, $D_{l(k(ij))}$ and $E_{m(k(ij))}$ the effects of positional factors 'depth' and 'height' nested within the random factor C (vine), $DE_{lm(k(ij))}$ the interaction between the two previous positional factors, and e_{ijklmn} the error term.

Because of the random character of nested factor C (vine) and, consequently, also for the nested canopy factors 'depth' and 'height', significant variation within these factors was assessed by applying different contrasts arranged, for example, for factor C as follows:

$$H_0: \sigma_C^2 = 0$$

$$H_1: \sigma_C^2 > 0$$

As it was possible to obtain the variance components, the relative contribution of each significant random factor on the variation of deposition values was then quantified. In addition to leaf deposits, leaf recovery was estimated as the proportion of the sprayed tracer recovered on target, for which LAI 70th percentile values for each vigour class (Fig. 4) were used as a reference for each treatment strategy under study (standard, uniform and map-based volume rates).

Data were normalised by the standard Mn^{++} treatment concentration, and then square root transformation was applied to meet the assumptions of homogeneity of variances (Bartlett test) and normality (Shapiro-Wilk test). Tukey's honest significant difference was used in each case for pairwise multiple comparisons to search for specific differences. Open source R software (RStudio 1.2.1335 using R 3.3.2) was used for data analysis.

3. Results and discussion

3.1 Spray on target

Mean normalised leaf deposition per treatment and vigour class are reported in Table 2. Comparing adjusted treatments (T2 and T3) to standard (T1), T2 achieved the lowest deposition both in high and low vigour classes, while T3 increased normalised deposition in high vigour areas and decreased it in areas of low vigour within the plot. However, according to the LMM (Table 3), there were no significant differences between treatments or between vigour classes or interaction. On the other hand, the coefficient of variation (CV) is used as a spatial uniformity indicator of leaf deposition within the whole canopy. Analysing this parameter (Table 2), both uniform treatments (T1 and T2) behaved similarly, while the map-based treatment (T3) allowed deposition uniformity to be improved.

Table 2. Normalised manganese deposit average values, coefficient of variation (CV) and leaf recovery (LR) for each treatment (T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based) and vigour class (HV: high vigour; LV: low vigour).

		Leaf deposition (µg cm^{-2})				
Treatment	Vigour	mean ± SE			CV (%)	LR (%)
T1	HV	2.32	±	0.32	72.4	43.3
	LV	2.69	±	0.34	66.3	33.5
T2	HV	1.61	±	0.20	65.7	40.5
	LV	2.13	±	0.29	70.4	35.8
T3	HV	2.93	±	0.33	59.1	65.2
	LV	2.14	±	0.21	51.6	41.4

Table 3. Results of the linear mixed model (LMM) analysis of variance for leaf deposition.

			LMM ANOVA	
Source of variation	DF	Sum Sq	F-value	p-value
Treatment (T)	2	1.22	2.49	0.1249^{ns}
Vigour (V)	1	0.08	0.34	0.5690^{ns}
T x V	2	0.90	1.82	0.2035^{ns}
Vine [T x V] *random*	12	2.95	0.30	0.9811^{ns}
Vine [T x V] [Height] *random*	36	9.54	1.54	0.0985*
Vine [T x V] [Depth] *random*	18	12.85	4.16	0.0001***
Vine [T x V] [H x D] *random*	36	6.18	1.17	0.2989^{ns}
Residuals	52	7.79	-	-

DF: degrees of freedom; Sum Sq: sum of squares; ns: not significant; * : significant at p = 0.1; ** : significant at p = 0.05; *** : significant at p ≤0.001.

Concerning the random effects of the model, height and depth were found to be significant, indicating different patterns of spray distribution within the canopy (Figure 7). According to the LMM analysis, "height" component variability represents 9.8% of the model. This is probably attributable to the setting of the nozzles, since treatments T2 and T3 were performed with the lowest nozzle of each vertical boom shut-off. Furthermore, the "depth" component proved to be the most significant, with 38.4% of model variability attributed to it. Penetrability, expressed as the ratio between the inside and outside deposits were 45%, 46% and 52% for T1, T2 and T3, respectively. In vineyards, many authors have reported difficulties with a lack of spray penetration during applications. However, they agree that spray penetration is maintained or even improved in optimised treatments with adjustment of volume rates compared to conventional treatments (Gil, Escolà, Rosell, Planas & Val, 2007; Llorens, Gil, Llop & Escolà, 2010; Pergher, Gubiani, Cividino, Dell'Antonia & Lagazio, 2013; Román & Planas, 2018). Sprayer operation also plays a key role as optimal calibration can improve leaf deposition by up to 50% (Siegfried, Viret, Huber & Wohlhauser, 2007).

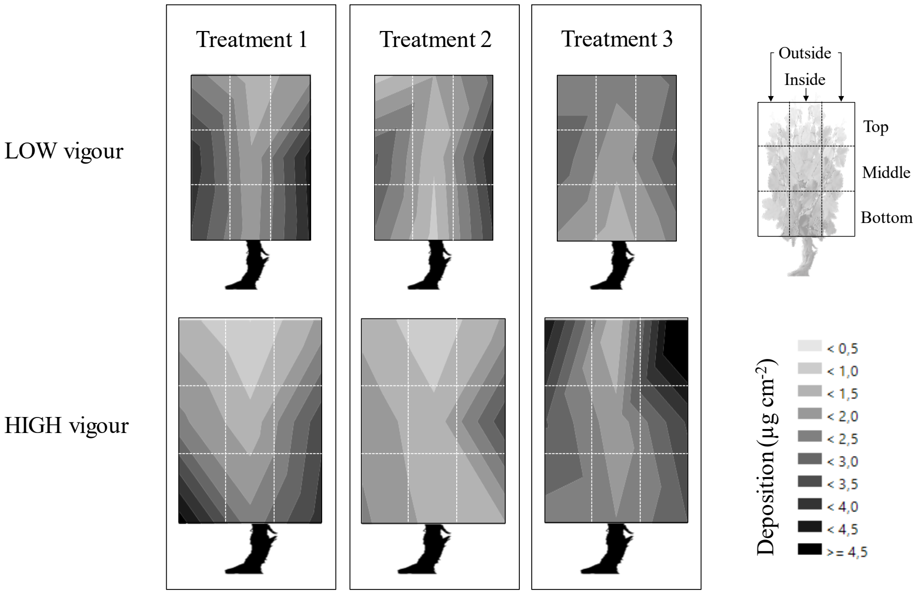

Figure 7. Contour plots of mean depositions inside the vines (µg cm-2) by vigour class (low and high) for each treatment (T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based).

When comparing leaf recovery as a percentage of the total spray (Table 2), the results coincide with those reported by other authors in that optimized uniform treatments allow similar efficiencies to conventional ones to be obtained, while in variable rate treatments (in this case, based on vigour maps) PPP application efficiency is improved (Gil et al., 2007; Llorens et al., 2010). Moreover, increased recovery in map-based treatment (T3) may indicate a reduction in drift losses (Balsari & Scienza, 2003).

According to Planas et al (2013), a deposition of 1.2 µl cm^{-2} leaf surface is needed to obtain an optimal leaf coverage and ensure the efficacy of PPP treatments. Leaf Mn^{++} depositions were transformed to µl cm^{-2} and the percentages of samples over this threshold are shown in Figure 8. Treatment T2 (adjusted uniform) obtained more than 50% of samples with leaf deposits below the threshold proposed by these authors. This may have negative implications in pest and disease control, especially in high vigour areas where only 21% of samples met the proposed premise, with these areas more vulnerable to and at greater risk of phytosanitary problems (Bramley et al., 2011; Ferrer et al., 2019; Román & Planas, 2018). On the other hand, it is assumed that the map-based variable rate treatment (T3) will have a similar biological efficacy to that obtained by conventional treatments (T1).

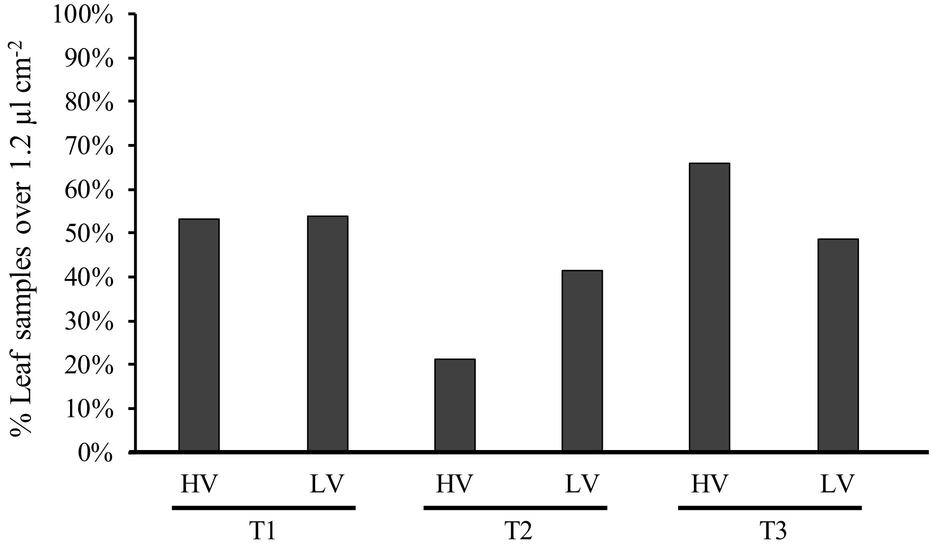

Figure 8. Percentage of leaf samples with depositions over 1.2 µl cm-2 by treatments (T1: Standard uniform; T2: adjusted uniform; T3: adjusted map-based) and vigour classes (HV: high vigour; LV: low vigour).

In the Part I paper, a LAI between the 65th and 80th percentile to calculate optimized volume rates was proposed. According to the results of the present study, in which the LAI 70th percentile was used, it would probably have been more appropriate to use the LAI 80th percentile (1.53) in the case of the adjusted uniform treatment (T2). In this way, the volume rate in treatment T2 would have increased up to 372 l ha^{-1}, similar to that applied in treatment T3 for high vigour areas. Therefore, one would expect similar behaviour in treatment T2 compared to treatments T1 and T3, at least in high vigour areas where grapevines are more vulnerable to disease pressure (Ferrer et al., 2019).

3.2 Savings in pesticide used

In terms of total pesticide savings (Table 4), and assuming the concentration in the tank remains constant, both adjusted treatment strategies achieved similar dose reduction, 25.6% for the adjusted uniform treatment (T2) and 25.3% for the adjusted map-based treatment (T3). The reduction of applied volume keeping the leaf depositions similar in the adjusted treatments (T2 and T3) implies a decrease in the losses compared to the standard treatment (T1) bringing not only economic but also environmental savings. Similar theoretical results were obtained in Part I. Moreover, in the case of adjusted uniform treatments, this result is similar to those obtained by Zhou, He & Landers (2012) who compared three different volume rate DSSs, obtaining average volume rate reductions of 31% throughout the season. Other studies have reported savings of up to 40% in adjusted uniform treatments (Gil, Llorens, Landers, Llop, & Giralt, 2011). In the case of adopting a site-specific precision crop protection strategy based on real-time sensors, for example using ultrasonic sensors mounted on the sprayer, savings can reach

40 - 76% (Gil et al., 2007; Llorens et al., 2010). However, the method proposed in this work also achieves satisfactory results taking into account that the objective is to improve the volume rate adjustment for conventional sprayers (predominant among the winegrowers in the area), or to promote the use of slightly modified sprayers that manage to modify the volume rate in only two different values according to a prescription map adapted to areas of low and high grapevine vigour. Another recent study proposes the use of three-class vigour maps using a sprayer prototype allowing treatments based on a prescription map combined with on-the-go on-off volume rate adjustment within each class to be performed. Dose reduction of between 44.3-47.3% has been achieved (Campos et al., 2019), basically due to the fusion of map-based and sensor-based technologies and a more accurate performance of the on-board technology. However, according to Tona et al. (2018), the use of these new technologies makes sprayers more expensive and is not economically viable in 10-100 ha farms. Faced with this problem, the proposed method is an option to consider because it is adaptable to the use of conventional sprayers and only requires low-cost technology to be implemented.

Table 4. Savings comparison between treatment strategies.

		Total area (ha)	Volume rate (l ha^{-1})	Total volume applied (l)
(T1) Standard volume rate		17,5	456	7986
(T2) Optimised volume rate		17,5	340	5945
(T3) Optimised class-based volume rates	Low vigour	9,2	295	2718
	High vigour	8,4	387	3250
Savings				
▪ T2 versus T1				25.6%
▪ T3 Versus T1				25.3%

4. Practical approaches to decide application volume rates in spatially variable vineyards using vigour maps as ancillary information

While winegrowers with sprayers capable of performing site-specific treatments in vineyards are still very few, the use of multispectral images allowing different vegetation indices (PCD, NDVI) to be obtained is a widespread and accepted practice. So, to add value to DOSA3D as an improved DSS with greater benefits, two practical approaches to decide volume rates in spatially variable vineyards are proposed (Figure 9). On the one hand, farmers can adjust a uniform volume rate adapted to vineyards variable in vigour (useful for many farms with conventional sprayers) and, on the other, farmers can adjust two volume rates adapted to two different vigour classes previously delimited within the plot (here the use of a specific sprayer is required).

Steps to follow in the adjusted uniform treatment:

- Take a multispectral image of the vineyard to calculate the PCD index (Figure 9.A).
- Obtain the PCD histogram to calculate the 80th percentile of the vegetation index distribution. Next, highlight the pixels with this value (or near) on the PCD map to locate the areas that the grower can inspect (Figure 9.C).
- Select a representative vine within this area (80th percentile) and make a field estimation of the vine canopy dimensions (width and height) (Figure 9.D).
- Use the DOSA3D DSS to obtain a recommended volume rate to apply an adjusted uniform treatment for the entire plot (Figure 9.E).

Steps to follow in the map-based adjusted treatment:

- Take a multispectral image of the vineyard to calculate the PCD index (Figure 9.A).
- Classify the PCD image into two vigour classes (high and low) using cluster analysis and an unsupervised algorithm (ISODATA or similar) (Figure 9.B).
- Obtain the PCD histogram for both vigour classes (high and low) to calculate the 70th percentile of the PCD for each class. Next, highlight the pixels with these values (or near) on the PCD map to locate areas (high and low vigour) that the grower can inspect (Figure 9.C).
- Select a representative vine within each area (70th percentile of high and low vigour) and make a field estimation of the vine canopy dimensions (width and height) (Figure 9.D).
- Use the DOSA3D DSS to obtain two recommended volume rates (for high and low vigour areas) (Figure 9.E) to apply an adjusted map-based treatment according to the prescription map.

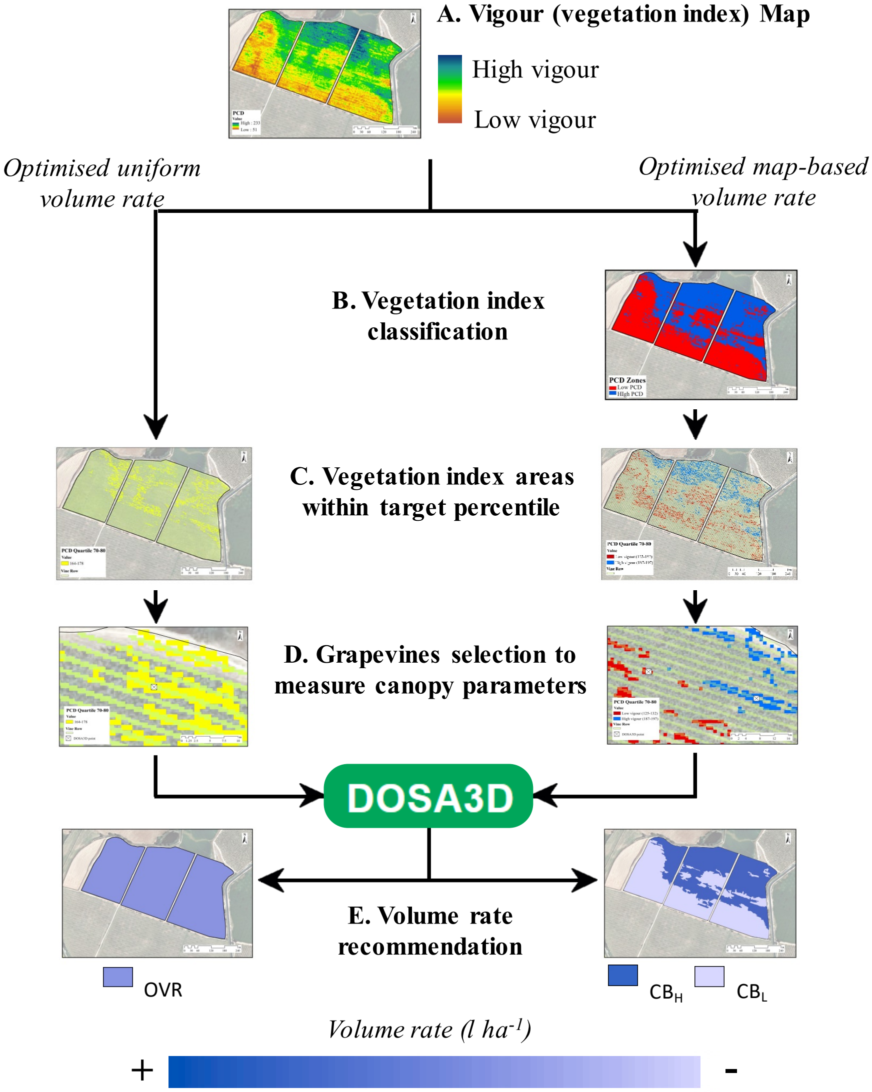

Figure 9. Flowchart for obtaining adjusted volume rates from a vigour (vegetation index) map as ancillary information using the DOSA3D decision support system. OVR: Optimised volume rate. CBH: Optimised class-based high volume rate. CBL: Optimised class-based low volume rate.

5. Conclusions

Vineyards are usually variable in their vigour, and this within-field spatial variability in the vine canopy makes it difficult for farmers to decide an optimal application volume rate adapted to this variation when pesticide applications are needed. On the basis of the standard volume rate normally used by many growers, two simplified volume rate adjustment strategies are proposed in this work and validated in terms of efficiency. In both cases, uniform adjusted or map-based, volume rates can be established using a specific percentile of the PCD vegetation index for the field and its corresponding LAI as a reference value to be considered in the DOSA3D decision support system. Our recommendation is to set the 70th percentile of the distribution of the LAI as a threshold value, although the 80th percentile may be more appropriate for uniform treatments at a constant volume rate for the entire plot. Concerning efficiency, pesticide savings of around 25% are expected without observing significant reductions in leaf deposition. This is important for control purposes, although biological efficacy validation remains the pending task. For conventional sprayers, the use of uniform adjusted volumes is an option to consider but better results can be expected in map-based strategies using slightly modified sprayers. In fact, improved uniformity of leaf deposition within the canopy is expected in the latter case since volume rates are better adapted to variable vigour within the plot. Finally, as the proposed protocol is based on the use of the DSS system DOSA3D, this has allowed its scope to be expanded to spatially variable vineyards.

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CAPÍTULO 7

Map-based zonal dosage strategy to control yellow spider-mite (*Eotetranychus carpini*) and leafhoppers (*Empoasca vitis & Jacobiasca lybica*) in vineyard

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Map-based zonal dosage strategy to control yellow spider mite (*Eotetranychus carpini*) and leafhoppers (*Empoasca vitis* & *Jacobiasca lybica*) in vineyards

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Viticulture

ABSTRACT

The particularly high incidence of yellow spider mite and leafhoppers in southern European viticulture means that between 1 and 4 interventions are required each year for their effective control. In vineyards with spatial variability in vigour, decision support systems such as DOSA3D (www.dosa3d.cat/en) have proven useful to adjust dose rates according to vigour classes delimited in on-board monitor prescription maps. However, there remain some doubts as to whether this variable dosage allows pests to be controlled when reducing conventional doses in vines with low vegetative development. To check the efficacy of using variable dose rates according to two vigour classes (low and high), field trials were carried out against the aforementioned pests in vineyards located in Raïmat (Catalonia, Spain). After classifying vigour through multispectral images, doses were reduced by 16.6%–24.8% in low vigour areas without losing control efficacy. Biological efficacy was always higher in low vigour areas, reducing the initial pest population below the corresponding economic damage threshold. In areas of high vigour, subsequent applications will probably be necessary to avoid exceeding the economic threshold, as there is normally a higher pest population density in vines with more vegetative development.

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Map-based zonal dosage strategy to control yellow spider-mite (*Eotetranychus carpini*) and leafhoppers (*Empoasca vitis* & *Jacobiasca lybica*) in vineyard

1. Introduction

In the last decades, pest management in vineyards tends to be carried out with more sustainable practices. Integrated Pest Management (IPM) is defined as “a decision-based process involving coordinated use of multiple practices for optimizing pests control (arthropods, pathogens, weeds, vertebrates) in an ecologically and economically sound manner” (Prokopy, 2003). The European Directive on Sustainable Use of Pesticides, in force since 2014, collects these principles and stats “when pesticides are used, appropriate risk management measures should be established and low-risk pesticides as well as biological control measures should be considered in the first place” (EU, 2009). As the recent Farm to Fork (F2F) strategy estates, IPM will encourage the use of alternative control techniques, and will be one of the main tools in reducing the use of, and dependency on, chemical pesticides in general, and the use of more hazardous pesticides in particular (European Commission, 2020).

However, in practice, the use of pesticides (synthetics or non-synthetics) continues to be a mainstay in vineyard protection. Between 5 and 10 annual pesticide treatments are still carried out, comprising this activity 38.5% of the total pesticide consumption (kg ha^{-1}) in Spain (Alonso González et al., 2020). Therefore, the vineyard is a productive sector of special relevance in those matters related to human health and environmental risk, this fact having been reflected in consumer opinion in recent years. The afore mentioned F2F strategy urges farmers to make the best use of nature-based, technological, digital, and space-based solutions to deliver better climate and environmental results, increase climate resilience and reduce and optimize the use of inputs, including pesticides. Accordingly, more and more winegrowers are transitioning to ecologically-based pest management (EBPM) to reduce negative impacts and achieve more sustainable productions. In fact, there is a trend towards greater use of certain pesticides (i.e. certified organic) which, even though they are somewhat more expensive than conventional ones, can end up being an advantage by adding value to the final product (Wilson and Daane, 2017).

Eotetranychus carpini Oudemans (Acari: tetranychidae), named Yellow Spider-Mite (YSM), is a phytophagous mite whose cycle is completed on the vines. Fertilized females spend the winter under the bark. At the beginning of budding, the females move to the new buds. In spring, populations are kept on the basal leaves and then spread by new shoots after flowering (Barrios and Reyes, 2010). YSM colonizes the back side of the leaves, particularly the parts located along the main nerves, and most eggs are located at the junction between the primary and secondary nerves or occupying the length of the latter ones. During the growing season, YSM is more concentrated on leaves located at an average height of vegetation (Baillod et al., 1979). Depending on the environmental conditions, YSM can complete annually between 4 and 8 generations. In southern France, the population peak usually occurs between mid-July and early August, with a second peak in September (Laurent and Agulhon, 1987). In north eastern Spain, in the wine area where the experiments were carried out (DO Costers del Segre, Lleida) the first fertilized females to emerge from hibernation are detected in earlier varieties (i.e. Chardonnay) the second half of April and several generations occurs before harvest. At the end of the summer (beginning of autum), the females migrate from the leaves to the places where they will stop their activity during the cold months. The symptomatology of YSM is diverse. At the beginning of budding, leaf deformation and shortened internodes will produce small-size grape bunches. In summer, yellow spots appear on the leaves in white varieties, or red in the case of red varieties (Figure 1, left) which, in severe attacks, can invade the entire limb keeping the nerves green. When the pest population is high, vine can defoliate prematurely causing a decrease in the quantity and quality of yield (Barrios and Reyes, 2010). YSM had become an important pest in South Europe due to pesticides disuse (in particular, ethylene-bis-dithiocarbamates and organophosphates) or over-use (sulphur-based) (Kumari et al., 2019; Lorenzon et al., 2018). Nevertheless, organophosphates are no longer used in the study area as the European grapevine moth (*Lobesia botrana* Denis & Schiffermüller (Lepidoptera: Tortricidae)) is controlled by mating disruption (Barrios et al., 2006). Despite this, YSM is still considered a pest. Regarding the applications with sulfur, the authors have confirmed that more than three applications of powdered sulfur (30 kg ha^{-1}) very contiuous in time (every 10 days) significantly reduces the natural predators, increasing the density of YSM.

Leafhoppers (LH) *Empoasca vitis* Goethe and *Jacobiasca lybica* Bergenin & Zanon (Hemiptera: Cicadellidae) are poly-phytophagous insects that affect the vineyards (Figure 1, right). LH adults overwinter on several host plants and move to grapevines in spring. Adults are green and elongated, 2 -3 mm long. They perform a characteristic "jumping" movement when the vine leaves are touched. Nymphs are similar to adults, smaller in size, without fully formed wings and generally moving diagonally on the underside of the leaves. Both stages of the insect feed on the phloem of the plant. Symptomatology is a redness or yellowing of the edges of the leaves depending on whether the cultivars affected are white or red grapes, respectively. In severe attacks, necrosis of edge and twitching with coiling on the underside are observed. Important damages can cause premature defoliation, making it difficult for the grapes to ripen (Fornasiero et al., 2016; Martín Gil et al., 2014). In southern Europe, four to five generations are reported. Spraying treatments are recommended from the second generation (latter June to August) when the attack is severe (Kreiter, 2000). As happens with YSM, the importance of this pest is increasing since the control of the European grapevine moth became widespread by mating disruption, reducing, even eliminating completely, insecticide treatments in the vineyard (Pertot et al., 2017). In Spain, both species of LHs (*E. vitis* and *J. lybica*) are present, which only can be differentiated by genitalia under laboratory conditions (La Spina et al., 2005). Both species are jointly monitored in this study.

Figure 1. Yellow spider-mite symptoms on red-grape vines (left). Leafhoppers nymph and adult, early symptoms (circle) and advanced damage.

Determining the spatial distribution of pests within a field may reduce significantly the amount of pesticide to use. Indeed, this information could be used to apply a different dose according to zones of different affectation, or even not apply pesticides in those areas where it is not necessary. This concept is commonly referred as site-specific or precision pest management (Roubos et al., 2014). There is no literature regarding the spatial distribution of YSM, but LHs usually follow an aggregation pattern within a field (Decante and Van Helden, 2008; González Andújar et al., 2005).

Many factors such as soil characteristics, topography and microclimate play an important role on vigour heterogeneity within a vineyard (Arnó et al., 2009). In recent studies (mentioned below), experiences on the use of prescription maps for the variable application of pesticides have been reported in spatially variable vineyards in vigour. The vigour spatial variability classified into 2 classes and the geostatistical approach to generate prescription maps to adapt doses to each vigour class was studied by del-Moral-Martínez et al., (2020). The advantages are obvious as map-based applications improve product on-target deposition (Román et al., 2020), and allow to maintain the efficacy controlling powdery mildew reducing the amount of pesticides in the vineyard (Campos et al., 2020).

To meet the objectives of the F2F strategy mentioned above, the aim of this paper is to validate both, technically and biologically, the application of plant protection products (PPP) based on vigour maps. Two tests were carried out against YSM, the first applying an abamectin-based product (Apache®) and the second a plant fortifier with acaricidal action (Boundary®). Regarding LHs, a test was carried out to control this pest using a product based on natural pyrethrins (Pirecris®). In all the trials, variability within the vineyards was classified in low and high vigour, then adjusting the dose for each vigour class using the decision support system DOSA3D www.dosa3d.es/en (Planas et al., 2016). Leaf deposition was evaluated as well as biological efficacy for each field test and vigour class.

2. Material and Methods

2.1 Experimental vineyards

Two trials were carried out to control yellow spider-mite in 2016 (trial 1) and 2017 (trial 2), and another in 2019 to control leafhoppers (trial 3). Trials were located in different commercial trellised vineyards in Raïmat (Lleida, Spain). The characteristics of the experimental vineyards are shown in Table 1. Vineyard for trial 1 was conducted under IPM general principles, while the vineyard for trials 2 and 3 was additionally managed under the principles of EBPM for organic certified farming. All trials were conducted at full-leaf stages according to BBCH scale (Meier, 2001), so contrasting differences in vigour within the field were shown.

Table 1. Characteristics of experimental vineyards

Trial	Treatment date	Geographic coordinates	Cultivar	BBCH	Row distance x Tree spacing (m)
1	August 24, 2016	41°39'51.94"N 0°29'44.11"E	Tempranillo	83-85	3.2 x 2.0
2	August 7, 2017	41°39'52.00"N 0°31'2.29"E	Cabernet Sauvignon	83	2.4 x 1.7
3	July 12, 2019	41°39'30.43"N 0°31'9.42"E	Cabernet Sauvignon	75-77	2.4 x 1.7

2.2 Prescription maps

To assess spatial variability in each vineyard, three airborne multispectral images were taken on July 27, 2016, August 2, 2017 and July 5, 2019 for trials 1, 2 and 3, respectively. Images were taken using a 4-band multispectral camera with a spatial resolution of 50 cm, and were conveniently processed to delete inter-row pixels. Then, Plant Cell Density (PCD) index was calculated for each canopy pixel (Bramley et al., 2003) and the resulting layers were vectorised in order to interpolate data by ordinary kriging (Figure 2). PCD is a relative index, so the different maps are not comparable with each other. The interpolated maps were classified into two classes (low and high PCD, Figure 2) by cluster analysis using an unsupervised algorithm (ISODATA, iterative self-organising data analysis technique) implemented in ArcGIS 10.4 (Environmental Systems Research Institute, Redlands, CA, USA).

Maps with different well delimited freehand zones seeking to eliminate small areas for better operability were obtained for trials 1 and 2, once the vigour was rated high and low by Agropixel SL (Lleida, Spain). In a similar way, the classified map for trial 3 was obtained following the methodology explained in Román et al. (2020). In short, having classified the map applying the cluster algorithm ISODATA, boundaries of the different classes were polygonised and smoothed, in addition to eliminating those polygons whose area was less than 0.01 ha.

Assigning a volume rate (dose) to each class was the last step in converting maps classified in areas of low and high vigour into prescription maps (Figure 2). As the LAI must be known to establish the volume rate to be applied, two different LAI estimation strategies were adopted according to each specific trial (Table 2). In trials 1 and 2, one representative vine from each vigour class was manually defoliated and leaves area was measured using a leaf-meter (Delta-T Devices Ltd., Cambridge, UK). Alternatively, the method followed in trial 3 was the one proposed by Román et al. (2020). Thus, vines whose PCD reached the 70th percentile value within each class were first located, selecting one of them for each vigour class. Then, in field inspection, geometric characteristics of the canopy (height and width) were measured to later estimate the LAI through the DOSA3D system. Although trials 2 and 3 were carried out in the same vineyard, a green pruning was done at the time of trial 2, and this would explain the lower LAI values in this trial compared to the trial 3.

Specifically, adjusted volume rates for trials 1 and 2 were calculated making use of the base formula of DOSA3D system (Planas et al., 2013):

$$V = \frac{120 * LAI}{E} \qquad \text{Eq. 1}$$

where *V* is the volume rate (l ha^{-1}), *LAI* is the estimated or measured leaf area index, and *E* is the overall efficiency of the spraying operation. In this work, volume rates were established considering a regular sprayer efficiency of 50%, but, accordingly to the DOSA3D fundamentals, adding 40% more volume to ensure YSM control. Finally, volume rates in trial 3 were also fixed by using DOSA3D system, but in this case no additional volume was considered to control LHs. In all trials, the volume rates finally applied varied slightly from those recommended by the DOSA3D system depending on the final sprayer settings.

Table 2. Vigour characterization and volume rates for trials 1, 2 and 3.

Trial	Vigour	Area (ha)	Canopy height (m)	Canopy width (m)	LAI	Volume rate (l ha^{-1})
1	Low	2.6	0.8	0.6	0.98	318
	High	10.4	1.2	0.9	1.45	418
2	Low	43.8	0.8	0.5	0.79	306
	High	21.2	1.2	0.9	1.28	407
3	Low	25.3	1.1	0.8	1,41	362
	High	30.5	1.5	1.2	1,99	434

LAI: leaf area index (1=10,000 m^2 leaf area per ha)

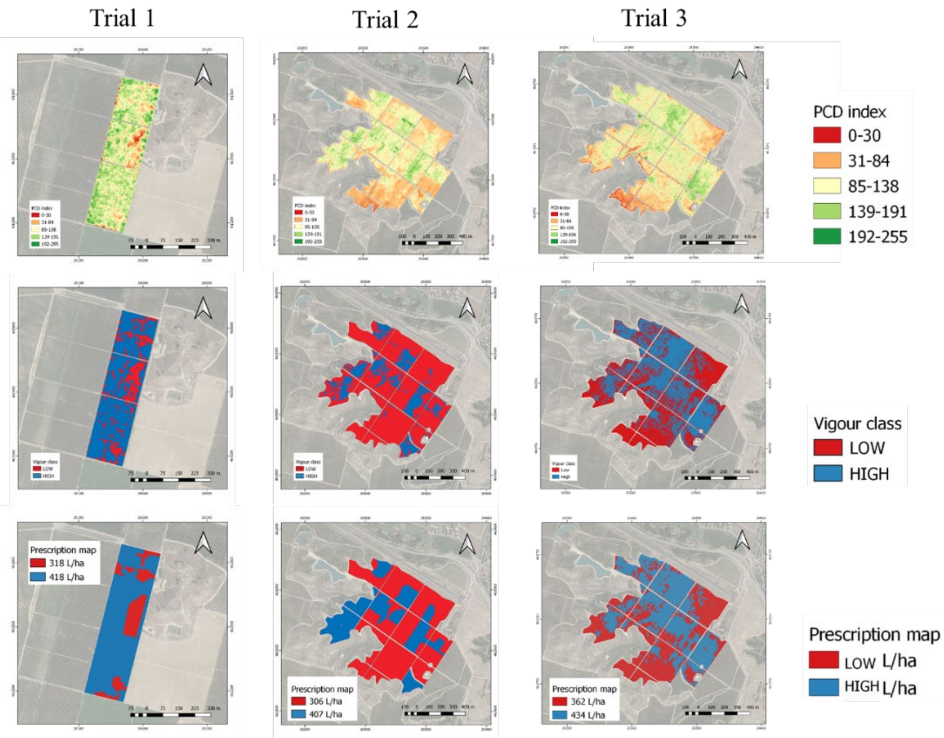

Figure 2. Interpolated Plant Cell Density (PCD) index maps, classified maps in low and high vigour, and volume rate prescription maps for trials 1, 2 and 3.

2.3 Pest monitoring and economic damage threshold

In trials 1 and 2, YSM was monitored in three different locations within each vigour class, specifically on the dates August 8, 2016 and August 5, 2017, respectively. The methodology, although more simplified, was based on the recommendations suggested by Baillod et al. (1979). In each location, 20 leaves were observed with a 10x magnifying glass to detect the presence or absence of YSM. The leaves were taken randomly from the middle part of the shoot by random sampling of non-contiguous vines from two adjacent rows. Presence or absence of the mite on leaves was recorded and expressed as the percentage of leaves bearing YSM. The economic damage threshold (EDT) was established in 60% of leaves bearing YSM by Baillod et al., (1979). However, this threshold was undoubtedly too risky given the current incidence of the YSM in the wine-growing region under study. So in order to avoid pest control problems, a threshold adjustment was adopted. In this case, the EDT was adjusted according to vineyard phenology following the BBCH scale, now being the thresholds of 10% of leaves occupied by YSM in BBCH 11-75; 20% in BBCH 75-89; and 30% in BBCH 91-97 (Planas and Román, 2020).

In trial 3, number of LHs (nymphs or adults) on five leaves were scouted in five different sites for each vigour class and for each treatment condition. The sampling date was July 12, 2019. The EDT in the IPM guide for grapevines in Spain is an average of 2 insects per leaf (Martín Gil et al., 2014). It is also true that other authors have proposed 0.5-2.0 insects per leaf (Decante and van Helden, 2006; Fornasiero et al., 2016). In 2018, the ripening of berries was highly delayed due to the high incidence of LHs, lowering grapes quality at harvest time. So advisers decided to establish in 0.5 insects per leaf the new EDT value as best adapted for the year 2019 (field test).

2.4 Pesticides and spraying settings

All treatments were performed when the corresponding EDT was exceeded at least in one of the vigour classes. The pesticides used in each trial are shown in Table 3. For trial 1, a wide-spread adulticide against YSM was used, while a plant fortifier authorized for organic farming with pesticide effect against some pests (Sannino and Piro, 2015) was used in trial 2 and finally, in trial 3, a natural pyrethrin was applied.

Table 3. Pesticide doses (LV: low vigour; HV: high vigour) and tracers used in each trial.

Trial	Pest	Product	Cost (€ l^{-1})	Tank concentration (%)	LV dose ($l\ ha^{-1}$)	HV dose ($l\ ha^{-1}$)	Tracer	Tank concentration ($g\ l^{-1}$)	LV Dose ($g\ ha^{-1}$)	HV Dose ($g\ ha^{-1}$)
1	Yellow spider mite	Apache® [a]	12.5	0.05	0.16	0.21	Mn^{2+}	2.02	642	844
2	Yellow spider mite	Boundary® [b]	23.6	0.75	2.30	3.05	Mn^{2+}	1.92	587	781
3	Leafhoppers	Pirecris® [c]	54.3	0.25	0.91	1.09	Tartrazine (E-102)	1.12	405	486

[a] a.i. 18 g abamectin l^{-1} (Industrias Afrasa, Spain)

[b] a.i. Extract of shrubby sophora (*Sophora flavescens*), brown algae and vegetal oil (International Company Agro-Science, Spain)

[c] a.i. 20 g pyrethrins l^{-1} (Seipasa, Spain)

The sprayer used in all trials was a two-row IRIS sprayer (Ilemo Hardi, S.A.U., Lleida, Spain) equipped with four vertical booms and a tangential-flow fan (540 mm diameter) (Figure 3). The PTO speed was 430 min^{-1} for all treatments. The hydraulic circuit of the sprayer was modified to spray two volume rates by modifying the working pressure by means of a bypass electrovalve activated by a switch embedded on the tractor dashboard (Román et al., 2020). Sprayer settings for each trial are shown in Table 4.

Prescription maps were uploaded to the on-board monitor using the software PixelMaps 1.0.3 (Agropixel SL, Lleida, Spain). The monitor showed the sprayer location within the maps through Global Navigation Satellite System indications (±2m) and, therefore, the operator changed the working pressure when the zone border was crossed.

The treatment day temperature and relative humidity were recorded each hour with a portable weather station ((Model 8910, AZ Instrument Corp., Taichung City, Taiwan) and showed in Table 5.

Figure 3. Back and partial view of IRIS vertical boom spraying in trial 3.

Table 4. Spraying settings for each trial.

Trial	Nozzle model (number)	Forward speed (km h^{-1})	Vigour	Working pressure (bar)	Volume rate (l ha^{-1})
1	Albuz ATR yellow (24)	6.5	Low	8.0	318
			High	14.0	418
2	Albuz ATR brown (4) + yellow (12) + orange (4)	6.5	Low	5.9	306
			High	10.7	407
3	Albuz ATR yellow (20)	6.3	Low	7.9	362
			High	11.4	434

Table 5. Temperature and relative humidity conditions of each trial.

		Hour		Temperature (ºC)		Relative humidity (%)	
Trial	Date	*begining*	*end*	*min*	*max*	*min*	*max*
1	25/08/2016	11:40	14:40	27.8	31.0	38	45
2	09/08/2017	8:00	11:00	26.6	32.6	39	54
3	12/07/2019	10:30	13:30	27.7	32.9	36	62

2.5 Evaluation of on-target spray deposit

Treatments against YSM and LHs were applied over the entire vineyard. Tracer leaf deposition was measured in order to assess differences between vigour classes and to understand the effect of vigour on pesticide distribution within the canopy. However, since the plots were large, the tracer was only applied consuming a fully sprayer tank (2000 L) for each trial, being the resulting tracer concentrations in the tank, measured in laboratory, those shown in Table 3. Thus, tracer deposition on leaves was assessed within the tracer treated area containing two vigour classes (low and high). The sampling methodology was adapted from ISO 22522:2007. Specifically, leaf deposition was measured in 6 vines (trials 1 and 2) or 3 vines (trial 3) for each vigour class. In each vine, nine different canopy zones (three heights and three depths) were sampled. And, for each sampling position, 3 to 5 leaves were collected, introduced in a zip-lock bag and stored in dark conditions until laboratory extraction and analysis. For trials 1 and 2, Mn^{2+} was determined by means of atomic absorption spectrometry (AAnalyst 400, Perkin Elmer, Waltham, USA). Instead, for trial 3, tartrazine (E-102) was analysed by optical absorbance with a spectrophotometer at 427 µm wavelength (Spectronic 301, Milton Roy, Philadelphia, PA, USA). Tracer deposits in each sample were quantified in µl, and then were related to sample surface area to be expressed as µl cm^{-2}. Blank samples were also taken before treatments and analyzed in order to avoid cross-contamination or residues from previous treatments.

For each trial, data were statistically analyzed using a linear four-factor model with mixed effects (LMM). Vigour was considered as a fixed factor and the sampled vines within each vigour area and deposition zones within the vines (height and depth) as nested random factors. A total of nine mean deposition values from each vine were obtained depending on the location (deposition zone) sampled within the canopy, being the model finally applied the one shown below:

$$y_{ijklm} = \mu + \alpha_i + B_{j(i)} + C_{k(j(i))} + D_{l(j(i))} + CD_{kl(j(i))} + e_{ijklm} \quad \text{Eq. 2}$$

where, for trials 1 and 2 (as an example), i = 1,2, j = 1,…,6, k = 1,2, l = 1,…,3, m = 1 for k = 1 and m = 2 for k = 2, with y_{ijklm} the tracer deposition value m obtained within the canopy at height l (top, middle or bottom) and depth k (inside or outside of the canopy) for the vine j within the vigour class i (low or high), μ the general average, α_i the effect of level i of the fixed factor A (vigour class), $B_{j(i)}$ the random effect of vine factor nested in each vigour class, $C_{k(j(i))}$ and $D_{l(j(i))}$ the effects of positional factors 'depth' and 'height' nested within the random factor B (vine), $CD_{kl(j(i))}$ the interaction between the two previous positional factors, and e_{ijklm} the error term.

Because of the random character of nested factor B (vine) and, consequently, also for the nested canopy factors 'depth' and 'height', significant variation within these factors was assessed by applying different contrasts arranged, for example, for factor B as follows:

$$H_0: \sigma_B^2 = 0$$

$$H_1: \sigma_B^2 > 0$$

As it was possible to obtain the variance components, the relative contribution of each significant random factor on the variation of deposition values was then quantified. To meet the assumptions of homogeneity of variances (Bartlett test) and normality (Shapiro-Wilk test), square root transformation of data from trials 2 and 3 was needed. Tukey's honest significant difference (HSD) was used for pairwise multiple comparisons to search for specific differences. Open source R software (RStudio 1.2.1335 using R 3.3.2) was used for data analysis.

In addition to the previous analysis, Coefficient of Variation (CV), leaf recovery (equivalent to the spraying efficiency) and penetrability (expressed as the ratio between inside and outside deposits) were calculated for each trial and for the two vigour classes. Finally, percentage of leaf samples with depositions fulfilling several deposit criteria (thresholds) were calculated.

2.6 Evaluation of biological efficacy

In order to assess the biological efficacy to control YSM and LHs, pests' incidences were monitored after the treatment at the same sites where the pests were monitored initially to decide, according to the EDT, to carry out the application of the pesticide based on a prescription map. The follow-up dates were, for the YSM, September 5, 2016 (trial 1), that is, 13 days after treatment (DAT), and August 15, 2017 for trial 2 (8 DAT); in the case of LHs in trial 3, the efficacy of the treatment was verified on July 22, 2019 (10 DAT).

In trials 1 and 2, to assess differences between pre and post-treatment for each vigour class, a *t*-test was performed with the assumption of paired data and unequal variances. Moreover, since it was not possible to maintain an untreated area, the biological efficacy was evaluated in a relative way as the percentage of reduction of leaves occupied by YSM between the two sampling dates and for each vigour class. To evaluate differences on relative efficacy comparing vigour classes, a *t*-test was also done under the same assumptions but considering independent samples.

In trial 3, because an untreated (control) area was kept, a two-way ANOVA was carried out with treatment (*treated and untreated*) and vigour (*low and high*) as fixed factors. Data was transformed using natural logarithms of original data plus 0.5 to meet the assumption of homogeneity of variances (Bartlett test). Tukey's honest significant difference (HSD) was used for pairwise multiple comparisons. Efficacy for each vigour class was calculated through the Abbott's formula (Abbott, 1925), and a *t*-test was performed to compare low and high vigour efficacies.

3. Results

3.1 On-target spray deposition

Main results are reported in Table 6. According to data analysis (LMM ANOVA), there were no significant differences between vigour classes in none of the trials performed (Table 7). This result confirms the suitability of adjusting the dose of pesticides based on vine vigour. However, the Coefficient of Variation (CV), which indicates the homogeneity of tracer deposits, was higher in high vigour classes compared to low vigour classes (Table 6). Also, LMM analysis confirmed the heterogeneity of on-leaf deposits showing a significant variability in all trials due to the effects of both canopy height and depth (with also significant interaction height x depth in trial 1). Specifically, in trial 1, the height factor accounted for 16.1% of the variability of tracer deposits, the depth factor for 36.8% (being the factor that represents the greatest variation), and their interaction (height x depth) for 19.0%. In trials 2 and 3, both height and depth also accounted for a significant percentage of deposition variability, 15.2% and 24.2%, respectively for trial 2, and 26.9% and 35.5%, respectively for trial 3. Figure 4 shows the different deposition patterns for each trial and for each vigour class, being clear the greater variation gradient produced in canopy depth than in canopy height.

Concerning leaf recovery (global efficiency), in trial 2 lower values could be expected compared to trial 3 since 40% more volume was applied to control YSM, having the lower LAI and overdosing made could have increased losses.

Table 6. Leaf deposition values (mean ± SE), Coefficient of Variation (CV), leaf recovery (LR) and penetrability (P) for each trial and vigour class.

Trial	Vigour	Tracer leaf deposition (µl cm^{-2})	CV (%)	LR (%)	P (%)
1	Low	1.74 ± 0.08	37.1	53,7	69.0
	High	1.55 ± 0.09	43.7	53,7	61.6
2	Low	1.35 ± 0.08	47.2	34,7	66.2
	High	1.38 ± 0.09	49.3	43,4	64.7
3	Low	1.45 ± 0.11	39.0	56,4	69.4
	High	1.34 ± 0.12	47.3	61,4	54.1

Table 7. Linear mixed model (LMM) analysis of variance of leaf deposition for trials 1, 2 and 3.

				LMM ANOVA	
Trial	Source of variation	DF	Sum Sq	F-value	p-value
1	Vigour (V)	1	1.03	0.9	0.3663^{ns}
	Vine [V] *random*	10	11.52	0.96	0.5099^{ns}
	Vine [V] [Height] *random*	24	11.15	1.86	0.0685*
	Vine [V] [Depth] *random*	12	11.8	3.93	0.0021**
	Vine [V] [H x D] *random*	24	6.01	2.01	0.0278**
	Residuals	36	4.47	-	-
2	Vigour (V)	1	0.001	0.02	0.8790^{ns}
	Vine [V] *random*	10	0.61	0.31	0.9681^{ns}
	Vine [V] [Height] *random*	24	2.182	1.97	0.0521*
	Vine [V] [Depth] *random*	12	1.837	3.31	0.0060**
	Vine [V] [H x D] *random*	24	1.109	0.78	0.0736^{ns}
	Residuals	36	2.135	-	-
3	Vigour (V)	1	0.04	2.36	0.1996^{ns}
	Vine [V] *random*	4	0.06	0.06	0.9913^{ns}
	Vine [V] [Height] *random*	12	1.25	2.85	0.0412*
	Vine [V] [Depth] *random*	6	1.02	4.66	0.0114**
	Vine [V] [H x D] *random*	12	0.144	1.62	0.1773^{ns}
	Residuals	17	0.38	-	-

DF: degrees of freedom; Sum Sq: sum of squares; ns: not significant; * : significant at p = 0.1; ** : significant at p = 0.05; *** : significant at p ≤0.001.

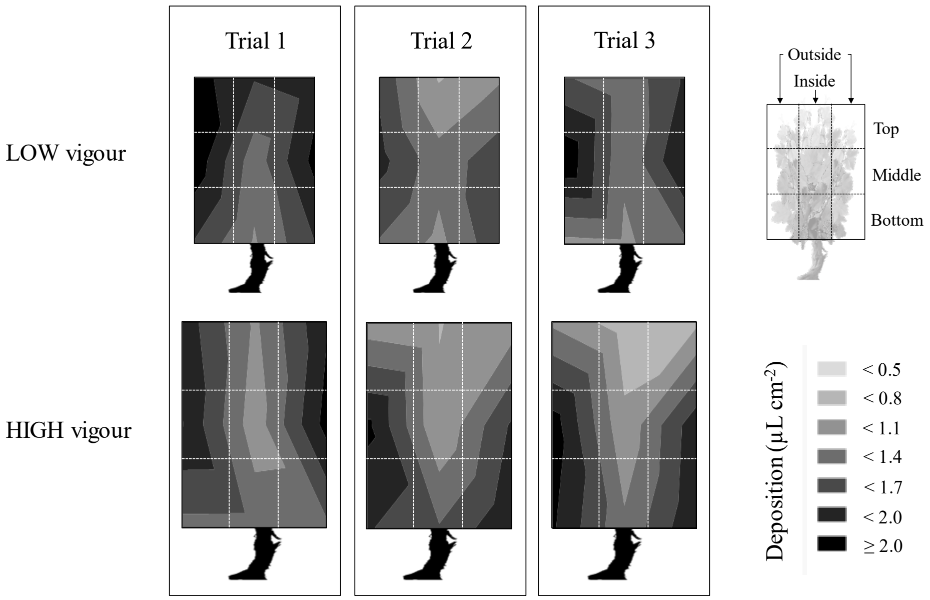

Figure 4. Contour plots of mean depositions within the vines (µl cm-2) by vigour class (low and high) for each trial.

Although no significant differences in leaf deposition appeared between vigour zones in all trials (Table 7), a deep analysis should be carried out because mean values could hide relevant misinformation influencing the efficacy at canopy zone level. This concerns to the minimum deposition required to achieve the acceptable biological efficacy.

To obtain an optimal coverage of the leaf area to be protected, Planas et al. (2013) recommend reaching a minimum deposition value of 1.2 µl cm^{-2}. Figura 5 shows the percentage of samples that fulfilled this requirement according to the vigour class and for each of the field trials (1, 2 and 3).

The proportion of deposits under the threshold tends to be higher in high vigour vines (Figure 5). This fact is clearly expressed in trial 1 where beyond the lower percentage of samples achieving the threshold in high vigour zones, a non-negligible proportion of sites achieve very low deposits (6.5 % under quarter part of the proposed threshold value). The accurate analysis of data deposits in Figure 5 allows to predict a lower efficacy in high vigour zone in Trial 1. Moreover, low vigour vines reached the minimum safety threshold in a greater number of samples in each trial. So dose reduction in low vigour areas resulting from a zonal treatment does not present any negative effect, even seems to be a positive effect

Rather, an upward adjustment of volume rates in both low and high vigour areas would be necessary to overcome the aforementioned deposition threshold in most of the canopy.

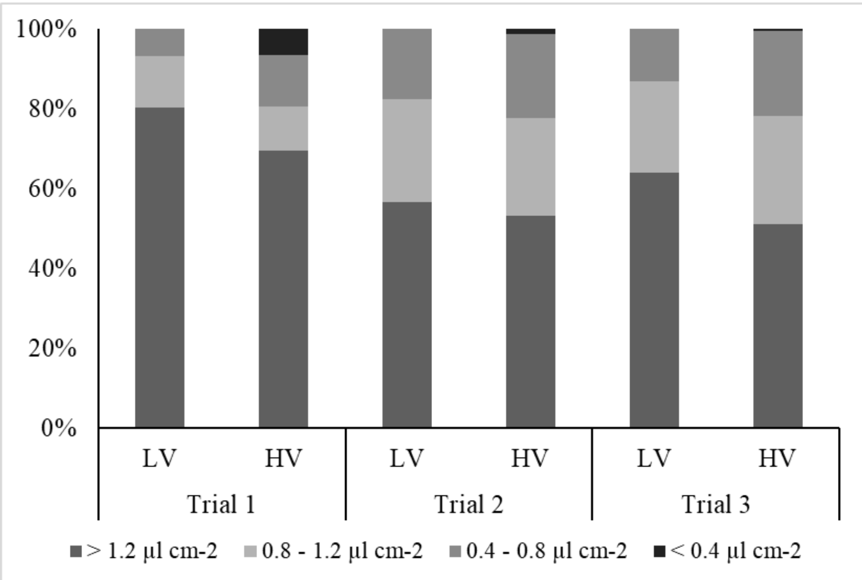

Figure 5. Percentage of leaf samples with depositions fulfilling a deposit criterion by trial (T1: trial 1; T2: trial 2; T3: trial 3) and vigour classes (HV: high vigour; LV: low vigour).

3.2 Biological efficacy of zonal-dose treatments

By inspection before treatment in both trials 1 and 2 YSM population density was 20% higher in vines within areas of high vigour compared to those of low vigour (Figure 6). But, having inspected the vines after treatment (13 DAT and 10 DAT for trials 1 and 2 respectively), the percentage of leaves occupied by YSM dropped significantly in both low and high vigour vines, reaching values below the corresponding EDT (Figure 6). As for the relative efficacy, significant difference was observed between low and high vigour in trial 1, being the efficacy 14.4 % higher in the LV zone (Table 8). The relative efficacy in trial 2 was only 8.2 % higher in the LV zone, resulting in a similar treatment effect to that obtained in HV. These results allowed YSM control based on a zonal treatment to be confirmed, despite a greater difficulty (less efficacy) found in vines with more foliar development (high vigour zones). Nevertheless, some doubts appear on the efficacy for high vigour zones. Data results (Figure 6) allows for forecasting in high vigour zones the pest density will overcome early the EDT, expressly in trial 1, being probably necessary a subsequent treatment, but it was not the case because the date of the trial was close to the harvest.

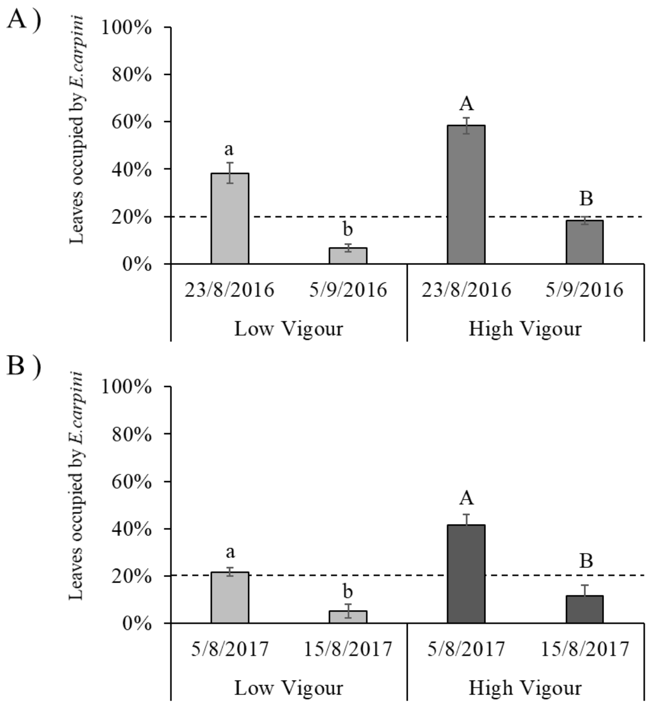

Figure 6. Percentage of leaves occupied by Eotetranychus carpini before and after the acaricide treatment in A) trial 1 (+13 days after treatment) and B) trial 2 (+8 days after treatment) by vigour classes. Dot lines indicate the economic damage threshold (EDT). In each vigour class, different letters between the monitoring date are significantly different (t-test, $p < 0.05$).

Table 8. Relative efficacies against Eotetranychus carpini (trials 1 and 2) Abbott's insecticide efficacy against leafhoppers (trial 3).

Trial	Low Vigour	High Vigour	prob > t
1	82.9% ± 2.8%	68.5% ± 2.6%	0,0104*
2	78.3% ± 11.7%	70.1% ± 13.8%	0,3368ns
3	100% ± 0.0%	75.0% ± 11.2%	0,0445*

ns: not significant; * : significant at p = 0.1; ** : significant at p = 0.05; *** : significant at p ≤0.001.

Figure 7 shows the monitoring results in trial 3 (untransformed data). In the first monitoring date (spraying date), as in YSM occurs, LHs population density was 77% higher in vines from high vigour areas, this factor having a clearly significant effect ($p < 0.0001$). In the second monitoring date (10 DAT), LHs population decreased significantly in the treated area but only for those vines of high vigour (interaction of treatment and vigour factors with $p = 0.0107$). Probably, the low initial presence of LHs in low vigour vines would explain the non-significant effect of the treatment in this area. The efficacy result is related to the above. As there was a low initial population of insects in low vigour vines, no LHs were found after treating and hence the result of 25% more efficacy in this zone (Table 8). Anyway, efficacy against LHs in high vigour zones could be considered as acceptable because the final pest density is far under the EDT, so no subsequent treatment is predictable at a short term.

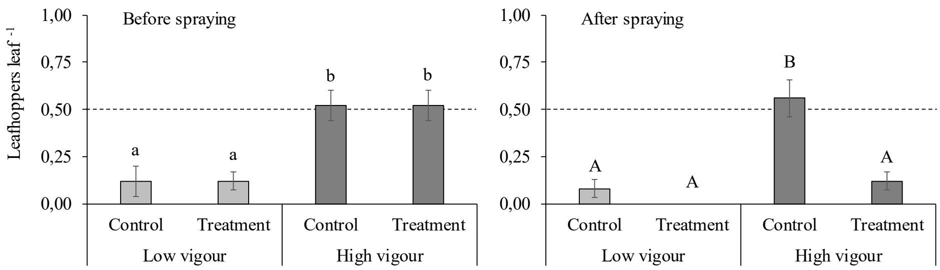

Figure 7. Leafhoppers (adults and nymphs) per leaf counted just before and 10 days after the insecticide spraying (control plot remained untreated) by vigour class. Dot lines indicate the economic damage threshold. In each monitoring date, different letters are significantly different (HSD Tukey test, p < 0.05).

3.3 Savings from treatments based on vigour maps

Table 8 shows the savings derived from using zonal doses according to vigour maps for the three trials that have been assessed. In terms of pesticide amount, dose reduction in low vigour areas allowed dosage savings of 23.9%, 24.8% and 16.6% to be achieved in trials 1, 2 and 3, respectively. Product cost per hectare is shown for each trial and vigour class, taking in account the unitary pesticide cost (Table 3), then weighting by area to obtain the total product cost for the zonal treatment (Table 9). The savings were computed taking as a reference a uniform treatment over the entire trial area at the same dose as that applied to high vigour vines. Final savings values were respectively 1.3€, 780€ and 303€ for the total area covered by the trials 1, 2 and 3.

Table 9. Sprayed area, product cost and savings assessment for trials 1, 2 and 3.

Trial	Vigour	Total area (ha)	Low vigour surface (%)	Cost (€ ha^{-1})	LV savings (%)	Cost of zonal application (€ ha^{-1})	Total cost Savings (%)
1	Low High	2,6 10,4	20.0	2,0 2,6	23.9	2,5	4,8
2	Low High	43,8 21,2	67.3	54,2 72,0	24.8	60,0	16,7
3	Low High	30,3 35,5	46.0	49,4 59,3	16.6	54,7	7,6

4. Discussion

4.1 On-target deposition and efficacy

The objective and the dosage recommendation of DOSA3D system, whatever the vigour, is to reach the minimum deposition threshold of 1.2 µl cm^{-2} leaf area. DOSA3D DSS has shown to be useful to adjust volume rates in case of applying pesticides based on a map discriminating low and high vigour areas. However, this work has also shown that this objective is not always achievable even after adjusting volume rates with well-reasoned criteria, in some zones within the canopy (Figure 5).

Variability of deposition within the canopy (measured as coefficient of variation) was always higher in high vigour vines. Much of this variability is produced by the barrier effect of canopy leaves, significantly reducing deposition as the spray penetrates into the interior parts of the vines. So it is not surprising that the lower penetrability values are found in more vigorous vines, due to their wider and denser canopy (Table 5 and Figure 4).

This relationship between the dimension of the vines and canopy variability of deposition would also explain why the deposition threshold of 1.2 µl cm^{-2} was reached less frequently in high vigour vines (Figure 5). In short, the higher the vigour, the greater the variability of deposition within the canopy. This is also linked to an increase in the number of samples that do not reach the minimum required deposition, more frequently placed in the inner parts of the canopy as the penetrability of the spraying droplets is lower.

All the trials showed results in the same order of magnitude in terms of penetrability (Table 6). Values range from 54% to 69% meaning 31% to 46% lower deposits in the inner than outer zones of the canopy. In trial 3 the lowest penetrability ratio corresponds to the high vigour zone where the LAI and canopy width achieves the highest values. This is an effective demonstration of the barrier effect or difficulty for the spray penetration into the inner parts of the vine canopy. This has been described by various authors, being necessary adjusting volume rates to the characteristics of the canopy to improve penetration (Gil et al., 2007; Llorens et al., 2010; Román et al., 2020). Nevertheless, more conservative ways to improve deposition level in the internal part of the canopy should be adopted as using sprayers capable to remove the leaves facilitating the penetration of the droplets or modifying the conduction system and/or the pruning or defoliating interventions through the season.

All of this is consubstantial to any spraying treatment. It must be underlined that canopy zones where the deposits are low (under the therapeutic dose) could constitute a pest reservoir giving most probable the EDT recovery in the dates next to chemical application. High vigour zone in trial 1, where very low deposits and lower efficacy were observed, could be a practical example (Figure 5). In an ideal treatment, leaf deposition in each canopy zone should be as much as possible approximated to the threshold (1.2 µl cm^{-2}), minimizing the proportion of under and over dosed canopy zones.

4.2 Yellow spider mite

The spatial distribution of YSM within a field is poorly studied. As already mentioned, trials carried out in this work showed that the percentage of leaves occupied were 20% higher in areas of high vigour compared to those of low vigour. This could be due to aspects related to the mite's feeding patterns. Tetranychid mites feed on the content of mesophyll cells by introducing a retractile stylet between epidermal cells or through open stomata (Santamaria et al., 2020). Soil properties in areas of low vigour influence the vegetative development of vines by affecting the availability of water and nutrients (Weber et al., 2013), resulting in vines that oppose a certain physical barrier to the entrance of the stylet since the stomata under stress are closed (Conesa et al., 2016). Likewise, Lorenzon et al.(2018) found a higher occurrence of YSM in vineyards with more vigorous formation systems. They also noted that more research is needed on the ecology of the mite, such as the effect that canopy management has on it.

4.2.1 Trial 1

Abamectin is a neurotoxic acaricide with high efficacy against several mites, including tetranychids (Kumari, et al., 2017; Marcic, 2012). In trial 1, treatment with Apache® reduced YSM occupation below EDT by applying a dose of 0.16 and 0.21 l ha^{-1} in low and high vigour zones, respectively (Table 3). The relative efficacy achieved in these respective zones were 82.9 and 68.5% (Table 8). The authors have found no references about pesticide treatments to control YSM. However, the achieved efficacy was similar to that shown by Kumari, Reddy, & Vijaya (2019), reaching a value of 72% against other tetranychid that damages grapevines (*Tetranychus urticae* Koch) 10 DAT, with application of abamectine 1.9% EC at the similar concentrations (0.03% and 0.05%). However, dose (l ha^{-1}, derived from the applied volume rate) and spraying technology were not described in the paper making impossible a robust efficacy comparison with the trial 1 results. Also, Duchovskienė (2007) achieved 83-100% efficacy against *T. urticae* applying Vermitex (abamectin 1.8% EC) at doses ranged from 0.50 – 1.20 l ha^{-1}, in this case in cucumber under greenhouse conditions. With all the reserves since the target species are different (*E. carpini* and *T. urticae*), the efficacy results were similar when similar doses were applied and lower efficacies when the dose was lower.

At the time of the trial, the official register in Spain indicated that Apache® should be applied at doses between 0.05% and 0.10% (maximum 1.3 l ha^{-1}). After reviewing the current dose informed in the register (valid until 2022) it has been modified to 0.25-1.00 l ha^{-1} applied at volume rate ranging from 500 to 1000 l ha^{-1} (MAPA, 2020). This volume rate recommendation is well above the volume rates commonly used in Spain viticulture.

Even so, leaf volumetric deposition provided an optimal coverage in both vigour classes, although product concentration was not enough to achieve the minimum effective dose that would have properly controlled YSM. But, certainly, it was possible to keep YSM below the EDT until harvest. Moreover, as shown in Figure 5 and commented before, at high vigour zones, 6.5% of the samples did not achieve a deposition of 0.4 µl cm^{-2}. The consequences of applying doses below those recommended are known, namely, i) to reduce the effectiveness of the product, especially in the area of high vigour, since the deposition may be less homogeneous, with a higher number of samples below the threshold, even increase the possibility of reappearance of pests at levels above the EDT, ii) the appearance of resistance, which has been widely described in the case of *T. urticae* caused by abamectin (Monteiro et al., 2015), although no literature has been published on *E. carpini*, and iii) abamectin is no longer recommended for IPM programs due to its toxicity on natural enemies (Biondi et al., 2012; Silva et al., 2019). However, its application at lower doses may reduce this negative impact while maintaining good efficacy. It would be very interesting that the chemical industry provided the therapeutic doses in terms of on target deposition on the target.

4.2.2 Trial 2

Winegrowers are currently very interested in using biopesticides and other EBPM practices instead of chemical control, but much more research is still needed to make these practices reliable and affordable (Wilson and Daane, 2017).

In trial 2, the Boundary product was applied at doses of 2.29 and 3.05 l ha^{-1} in low and high vigour areas, respectively, achieving efficacies of 78.3% and 70.1%. According to the recommendation on the product label, dosage should be done under concentrations between 0.025-0.040% and applying the product through a reference volume of 1000 l ha^{-1}. In any case, crop protection advisers recommend using a dose of 3.00 l ha^{-1}, without specifying further adjustments to the canopy characteristics. The only study dealing with this product (Sanninano & Piro, 2015), compared the efficacy between Boundary (5 l ha^{-1}) and Vertimec (abamectin 1.8% EC, 1.2 l ha^{-1}) against *T. urticae* in eggplant under greenhouse. An efficacy of 98.9% and 99.1% was achieved for both products, respectively, in both cases being greater than that achieved in trials 2 and 1 of this work but applying lower doses. However, it has been shown in trial 2 that by applying Boundary at a lower dose (in low vigour areas), the pest level can be reduced below the corresponding EDT. One of the compounds derived from *Sophora flavescens*, is the oxymatrine, which has an antifeedant action on insects and mites Marčić & Međo (2014). These authors. showed that this bio-product has no ovicidal action, which must be taken into account when establishing control strategies because a second application when several generations of YSM coexist may be needed.

4.3 Leafhoppers

In the same tendency as happened with YSM, also for trial 3 and before treatment, 77% more LHs were monitored in high vigour zones. This is in consonance to Fornasiero et al. (2012) who observed a positive effect of irrigation on the population density of *E. vitis*, while in vineyards where negative values of stem water potential were measured, LHs population density was clearly affected. On the other hand, LHs spatial distribution within a vineyard follows an aggregate pattern. Del-Campo-Sanchez et al. (2019) quantified the effect (symptoms) of *J. lybica* using RGB images obtained by an unmanned aerial vehicle (UAV). They found greater damage in high vigour zones within the vineyard.

As mentioned before, the differences in vigour could influence the content of nutrients and other metabolites within the grapevine tissues, being the areas of more vigor mainly preferred by insect (Wilson et al., 2015). Moreover, cover crops and surrounding landscape also influence the LHs dynamics (Decante and van Helden, 2006). So LHs sampling to decide the right time for treatment (based on EDTs) could be improved by integrating factors as vineyard vigour variability and LHs population dynamics. As seen before, this is a very frequent situation observed for pests when affecting non uniform vigour vineyards.

4.3.1 Trial 3

In trial 3, Pirecris was applied at 0.905 and 1.085 l ha^{-1} in low and high vigour areas, respectively, achieving efficacies of 100% and 75.0% (Table 8). By using the Pirecris product, Nácher et al. (2014) reported efficacy results against *E. vitis* on a vineyard cv Carignan (BBCH: 79-81). *E.vitis* density average was 0.80 insects per leaf before treatment. They studied low, medium and high doses (1.0, 1.5 and 2.5 l ha^{-1}) applied by means of a portable sprayer. Authors no provide information on volume rates nor canopy dimensions. Pirecris achieved efficacies ranged between 50 to 70% depending on the dose applied (low to high) 7 DAT, when they carried out a second treatment efficacies increased up to 80-90%. Results presented in this paper showed higher efficacies just in one treatment at a lower dose. This could be due to the higher efficiency of the spraying technology. Efficiency refers to the percentage of product that is recovered from the leaves compared to the total sprayed. Román et al. (2019) showed that applying with a two-row IRIS sprayer (the same as used in this trial) it was possible to recover on leaves 41.2% more product than using a motorized knapsack sprayer, typically used in biological assessment trials. However, as pyrethrin have low persistence (Fornasiero et al., 2012), LHs population increased again after the first treatment in trial 3, being necessary subsequent treatments on two more occasions to ensure control (data not shown). This study represents just one specific trial of each pesticide, more work should be done for understand how they act. Special caution must be taken with the use of pyrethrins on vineyards since a detrimental effect on natural enemies, especially on predatory mites of the Phytoseiidae family, may occur. (Tacoli et al., 2017; Zehnder et al., 2006). In any case, the use of pyrethrins should be done in a rational way

4.4 Pesticide savings

Regarding to savings in precision crop protection, a first strategy to reduce the amount of pesticides is to adjust the dosage spraying a constant (non-variable) volume rate for the entire area under treatment. That is, to adjust the dose to the representative characteristics of the canopies, taking also into account the sprayer efficiency and in some cases the additional requirements of the pest to be controlled. A second, more refined strategy, is to adjust the dosage by varying volume rates and adapting them to different vigour zones within the vineyard. To assess the total savings, the adjusted dose rates at high vigour zone have been used as reference dose (this adjustment could be considered as equivalent to the first strategy in precision crop protection).

As some authors have shown, savings obtained with this second strategy (zonal dosage) can be similar to those obtained in uniform applications with the first strategy (optimal dosage adjustment to the canopy characteristics and sprayer efficiency) (del-Moral-Martínez et al., 2020; Román et al., 2020).

Figure 8 shows the potential pesticide savings from using this second strategy (on the understanding that two kinds of vigour are basically differentiated, low and high). Dosage reductions in low vigour areas were near 20% in the assessed trials (dark gray line). Therefore, in order to save more than 10% in pesticide, the low vigour area should cover at least 50% of the vineyard area (as happened in trial 3). These results are similar to those obtained by Takács-György et al. (2014) which also indicate the importance of competitiveness and environmental protection when reducing doses. Related to the latter, note that decreasing volume rates also reduces the number of sprayer tanks refills and, therefore, the fuel and time consumption.

From an economic point of view, savings evaluation should include the costs of the aerial images and their interpretation (25-50 € ha^{-1}), also the incurred when boarding new technology that allows different and adapted volume rates to be applied (between 1000-5000€). In addition, electronics mounted on a sprayer require maintenance and further revision to prevent reliability extra cost. According to Tona et al. (2018), advanced technologies only could be affordable for large-area farms (> 100 ha). However, given the higher prices of the pesticide used in EBPM, the use of these technologies could be used in medium-sized farms (10-100 ha).

Finally, spatial distribution pattern of the pest is also relevant. It is known that LHs are spatially aggregated. For its control, low vigour areas could not be treated (dot line in Figure 8) as its not exceeding the EDT (González Andújar et al., 2005). By adopting this strategy, in trial 3 almost 50% of pesticides could have been saved, achieving the objectives of the F2F strategy.

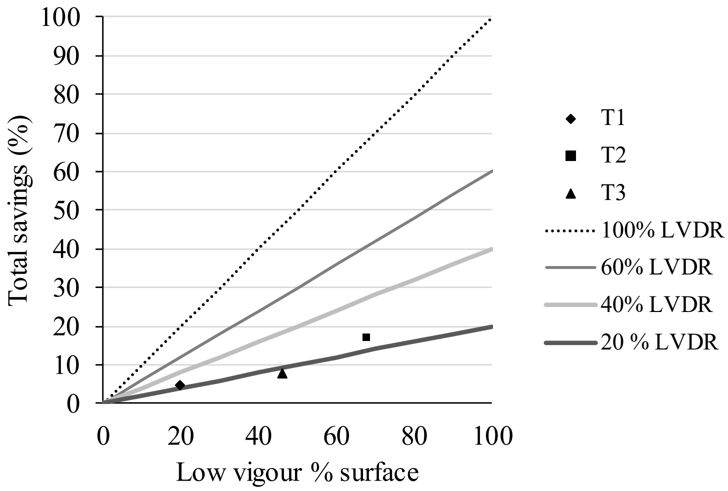

Figure 8. Total product savings (%) of trials (T) 1, 2 and 3 depending on low vigour surface within the vineyard (%). Lines indicate totals savings by different low vigour dose reductions (LVDR: low vigour dose reduction).

5. Conclusions

Pesticide map-based applications shown in this paper are fully in line with the demand of the F2F strategy, allowing considerable pesticide savings.

Mean leaf deposition values can hide certain differences between vigour areas. Thus, the required deposition threshold is not met in some canopy zones of high vigour vines, with also greater variability in deposition within the canopy due to the poor spraying penetrability. The assessment of the quality of the application should be complemented through parameters such as the deposition threshold (1.2 µl cm^{-2}), the coefficient of variation, the penetrability, and the percentage of samples under the mentioned threshold. Additionally, for a robust efficacy assessment, the pesticide minimum effective dose expressed in l ha^{-1}, should be related to a deposition per target surface (µg cm^{-2}) and should be included on the labels.

Spatially variable vineyards make possible to differentiate between vigour classes and to adjust doses in each class while maintaining efficacy to control YSM and LHs. In addition, reducing the dose in low vigour areas is justified due to the lower presence of YSM and LHs. Consequently, a feasible strategy to start applying precise crop protection in vineyards would be to use prescription maps where dosage is adjusted especially in low vigour areas, where the pressure of pests is lower, thus limiting the use of pesticides within a more sustainable use.

Furthermore, significant savings of the product are achieved without compromising the efficacy of the treatment. In general terms, the more expensive the pesticide used, the higher the proportion of low vigour zone and the higher greater the reduction of dose to be applied in low vigour area, more feasible the zonal application will be (from en economic point of view).

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CAPÍTULO 8

Discusión general

Discusión general

En la presente tesis se valida el sistema de ajuste de dosis DOSA3D para cultivos tridimensionales (3D) o arbóreos, específicamente en frutales de pepita y viñedo. Los objetivos marcados y seguidos a lo largo del documento han permitido aportar evidencias científico-técnicas en la validez a escala productiva del ajuste de las dosis de los productos fitosanitarios (PF) en tratamientos a dosis uniforme y en tratamientos a dosis zonal. El ajuste de la dosis aporta como principales efectos beneficiosos la reducción de los costes de producción y de los riesgos tanto ambientales y como para la salud humana.

Los ahorros obtenidos en los ensayos de ajuste de dosis en viñedo mediante el sistema DOSA3D se sitúan entre el 0 y el 60% (Figura 1) sin menoscabo de la eficacia de los tratamientos para el control de las plagas y enfermedades. Estos resultados están en concordancia con los obtenidos anteriormente en los trabajos realizados en frutales (Planas et al. 2013; Solanelles et al. 2013) y, también en frutales de hueso y pepita, con la constatación a escala productiva de tratamientos ajustados que vienen realizándose en el marco del programa FruitNet desarrollado en Cataluña (Planas y Román 2020).

En viñedo, únicamente, la eficacia biológica se ha visto disminuida en pequeña proporción en tratamientos en los que la reducción de dosis supera el 40% y, a su vez, concurren circunstancias meteorológicas muy favorables al desarrollo del organismo a controlar (períodos prolongados de lluvia, especialmente).

Los resultados alcanzados sintonizan por completo con los objetivos de la Directiva de Uso Sostenible de los Productos Fitosanitarios (Directiva 2009/128/CE) y los recientemente establecidos en la estrategia europea “de la granja a la mesa” para el año 2030 consistentes en reducir en un 50% el uso y el riesgo generado por los productos fitosanitarios en la agricultura y el uso de las substancias activas de mayor riesgo (EC, 2020). Por lo tanto, además habrá que reducir el número de tratamientos, y en consecuencia mejor la gestión integrada de plagas, optimizando el momento de intervención a los estrictamente necesarios de acuerdo, por ejemplo, a modelos de predicción y utilizando medidas de control alternativas como la confusión sexual.

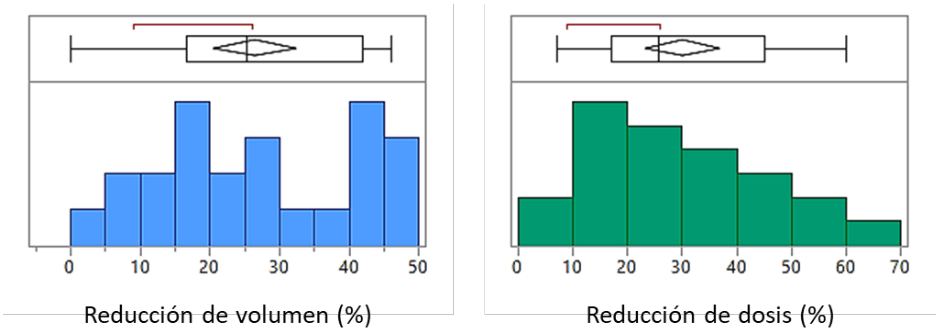

Figura 1. Resumen de reducciones de volumen y dosis (%) obtenidas en los trabajos presentados en la tesis (n=23)

En este apartado se discuten los resultados referidos en los cinco capítulos centrales (capítulos del 3 al 7) y los condicionantes identificados para la aceptación o rechazo de las cinco hipótesis de partida.

Hipótesis 1. El índice de área foliar (parámetro más relevante para el ajuste de la dosis) es estimado correctamente a partir de la geometría de la vegetación y del estado fenológico del viñedo.

El índice de área foliar (LAI) es un parámetro adimensional que se define como la cantidad de área foliar por unidad de área de superficie cultivada. A partir de la revisión bibliográfica realizada en el capítulo 3, se deduce que el LAI es el mejor descriptor del objetivo a tratar (Hislop, 1987; Pergher and Petris, 2008; Planas et al., 2016; Rüegg et al., 2001; Siegfried et al., 2007; Viret et al., 2005). Sin embargo, algunos autores abogan por descriptores como el Leaf Wall Area (LWA) o el Tree Row Volume (TRV) argumentando la dificultad para determinar el LAI en campo (Pergher and Petris, 2008). En realidad, todos los parámetros que permiten caracterizar la vegetación a tratar (altura y anchura), porosidad y densidad foliar son difíciles de medir de manera precisa sin el uso de sensores (Gil et al., 2014).

Se ha demostrado que al LAI tiene una baja relación en con el LWA (principalmente porque no tiene en cuenta la anchura de la vegetación) y una relación aceptable con el TRV (Planas et al., 2016; Rüegg et al., 2001). Sin embargo, como se ha explicado en los capítulos 4 y 5, el sistema DOSA3D permite de una manera simplificada, sin necesidad de recurrir a sensores, estimar el LAI en frutales y viñedo a partir de la altura, la anchura, la distancia entre filas y el estado fenológico, a partir del descriptor designado por *Canopy Solid Housing (CSH)*. La Figura 1 muestra la relación entre el LAI real, determinado por defoliación, con el LWA (R^2=0.48), TRV (R^2=0.68) y LAI estimado por el método CSH en frutales y viñedo (R^2=0.86). El sistema DOSA3D tiende a sobreestimar el LAI al utilizar el valor superior en cada uno de los rangos establecidos para cuantificar la altura y anchura de la vegetación a tratar. Sin embargo, minimiza los riesgos de infradosificación debidos a la variabilidad intraparcelaria y decanta los resultados hacia el lado seguro *(safety side)* en términos de eficacia de los tratamientos fitosanitarios. No obstante, se ha observado que el modelo de DOSA3D puede subestimar el LAI en viñedos de anchura superior a 1.25 m, situación excepcional, pero existente en la fase vegetativa avanzada en algunos sistemas de conducción de alta productividad. En esta situación se recomienda incrementar la recomendación establecida. En consecuencia, la primera hipótesis queda validada con la limitación mencionada.

Como se ha visto en el capítulo 4, el ajuste de la dosis mediante el sistema DOSA3D permite alcanzar deposiciones medias más uniformes a medida que el LAI incrementa. Con excepción de las deposiciones obtenidas a inicio de vegetación, por lo que área foliar total es el parámetro más importante en el ajuste de dosis, pero influyen otros factores cómo la geometría de la vegetación.

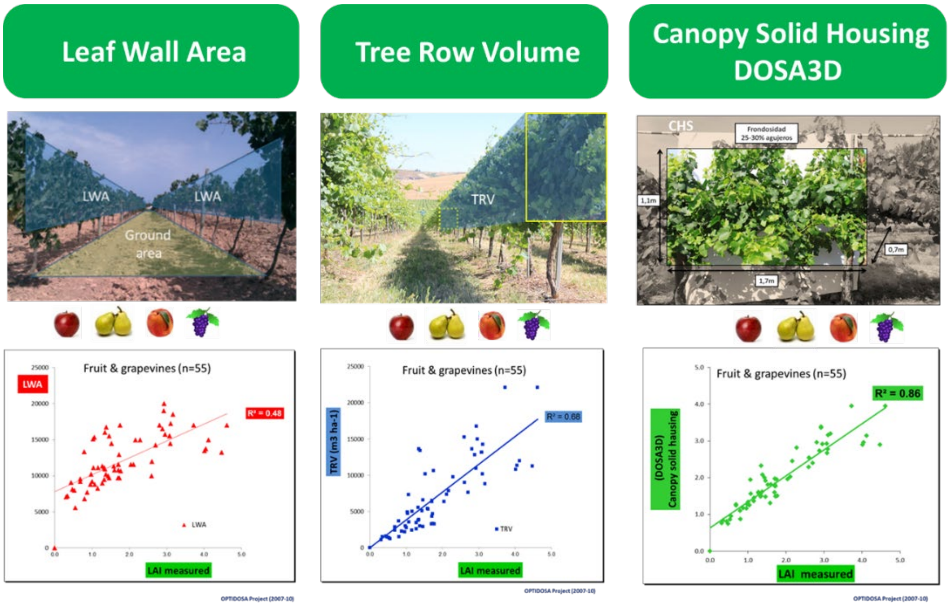

Figura 2. Relación del índice de área foliar (LAI) medido en frutales y viñedo con el LWA (Leaf Wall Area), el TRV (Tree Row Volume) y el LAI estimado con DOSA3D (Fuente: Planas et al. 2016).

Hipótesis 2. La eficiencia del pulverizador calculada mediante el sistema DOSA3D se ajusta a la realidad operativa de los tratamientos.

En la actualidad, en España, el tipo de pulverizador hidroneumático más ampliamente utilizado sigue siendo el estándar (equipado con un ventilador de flujo axial) para frutales y viñedo y los equipos con deflectores para frutales. No obstante, empieza a ser común el uso de pulverizadores de nueva generación mejor adaptados a la geometría del cultivo como es el caso de los equipos de flujo tangencial en frutales y los pulverizadores multibocas o los de bajantes en viñedo y, de forma incipiente, el túnel de recuperación. En el capítulo 3 se revisan numerosos estudios en los que se demuestra que los nuevos equipos pulverizadores mejoran la eficiencia de la aplicación, en términos de porcentaje de producto aplicado que se deposita sobre el objetivo tratado, reduciendo las pérdidas al suelo o por deriva (Balsari y Sciencia, 2003). El aumento de la eficiencia y la mejor distribución de la pulverización en el conjunto de la vegetación tratada alcanzadas por los equipos de nueva generación permiten conseguir la misma deposición que la de un equipo estándar y, consecuentemente, reducir las dosis.

No obstante, más allá del pulverizador, la eficiencia global alcanzada por la pulverización depende de la geometría, la aerodinámica del cultivo y de los parámetros operativos del pulverizador. Por ello DOSA3D calcula la eficiencia teniendo en consideración el tipo de pulverizador, la altura y la anchura de la vegetación (capítulo 4). Con la combinación de estos 3 factores para el tipo de pulverizador multibocas (*multi-spout*) se asignan eficiencias entre el 56% y el 64%, para el de bajantes (*vertical booms*) entre el 60-64% y para el túnel de recuperación (*tunnel*) 63-72%. La Figura 3 muestra las eficiencias globales obtenidas en diferentes ensayos de deposición en hojas en viñedo siguiendo la norma ISO 22522:2007 (ISO, 2007) con volúmenes ajustados con DOSA3D (capítulo 5). Se puede observar que las eficiencias propuestas están dentro del rango de las eficiencias reales obtenidas, por lo que la segunda hipótesis se acepta.

No obstante, el número de ensayos, especialmente con los pulverizadores multibocas y túnel es bajo para llegar a una conclusión definitiva, por lo que a partir de más experiencias las eficiencias propuestas por DOSA3D podrían modificarse. Sin embargo, cabe destacar que este trabajo es totalmente pionero ya que no existen aportaciones con un volumen de información similar sobre eficiencia en condiciones operativas reales.

En el caso de frutales, las eficiencias calculadas por DOSA3D han sido validadas en trabajos anteriores al desarrollo de la presente tesis (Proyecto Pulvexact).

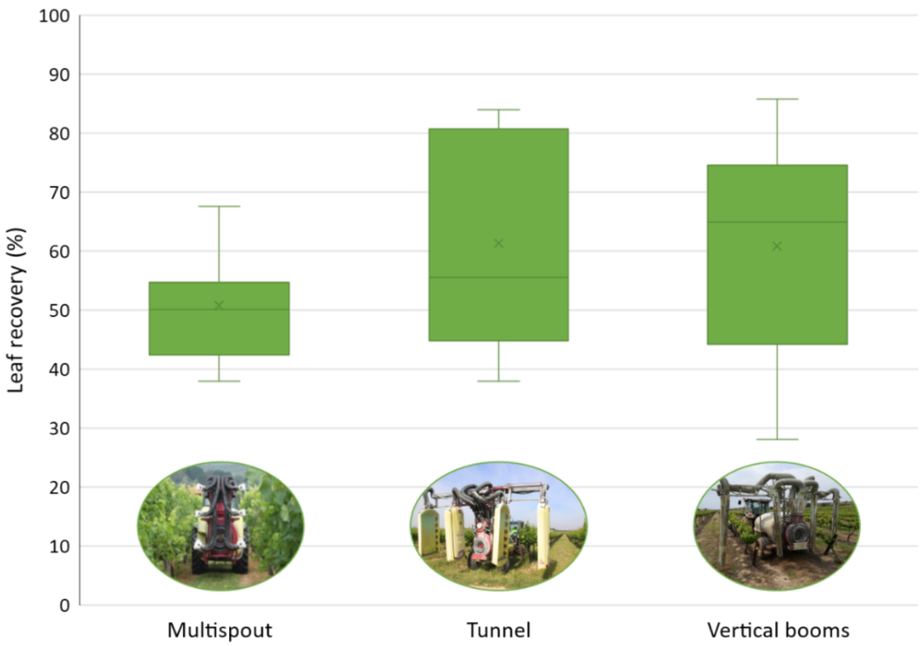

Figura 3. Recuperación en hojas de los diferentes para diferentes tipos de pulverizadores: Multispouts (n=7) Tunnel (n=5) y Vertical booms (n=22). Los extremos de las barras indican los valores máximo y mínimo. Los extremos de las cajas el percentil 25 (inferior) y 75 (superior). La cruz interior representa la media y la barra interior la mediana. Las imágenes son representan un ejemplo del tipo de pulverizador. Datos procedentes del capítulo 4.

Hipótesis 3. La deposición en hojas es un parámetro que se relaciona bien con la eficacia biológica del tratamiento.

El sistema no diferencia entre tipo de producto utilizado (fungicidas, insecticidas, biopesticidas, etc.), pero aumenta un 40% el volumen de aplicación cuando se tratan plagas y enfermedades de difícil control cómo el ácaro amarillo, tal como se justifica en el capítulo 4.

En el capítulo 7 se analizan las deposiciones de trazador y la eficacia de tres tratamientos contra plagas de la viña aplicando dosis zonal a partir de mapas de vigor. En la Figura 4 se muestra la correlación de las deposiciones normalizadas (ng dm^{-2} por cada g ha^{-1} de trazador aplicado) y la eficacia resultante de estos ensayos. Se puede observar una relación positiva entre ambos parámetros.

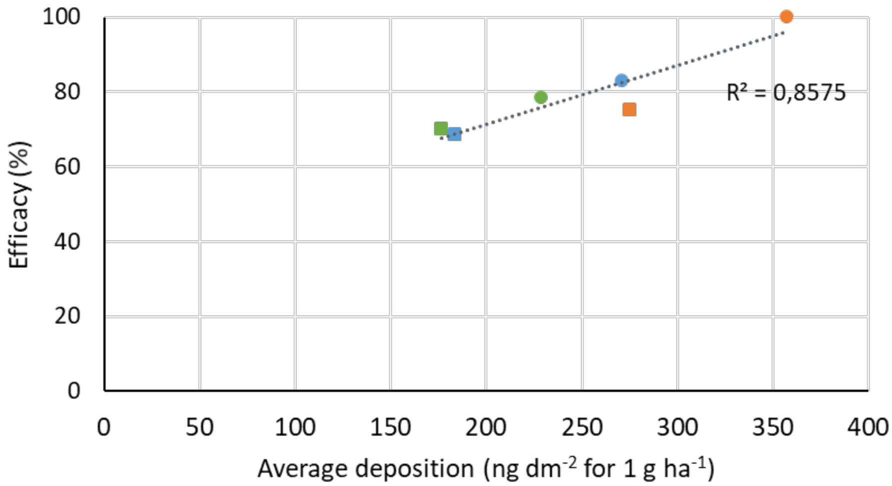

Figura 4. Relación entre eficacias obtenidas (relativa o por Abbot's) y la deposición media normalizada para los ensayos del capítulo 6 (Tral 1: azul; Trial 2: verde; Trial 3: naranja). Los puntos cuadrados hacen referencia al alto vigor y los circulares al bajo vigor.

En este sentido, Viret et al. (2003) también demostraron que una mayor deposición de trazador se correlaciona con una mayor eficacia, pero que la homogeneidad de la distribución también es un factor clave. En su estudio analizaron las deposiciones en dos alturas de la planta (hojas de la mitad superior de la vegetación y hojas a la altura del racimo), observando mayor severidad de oídio (*Erysiphe necator* Schw.) cuando la aplicación no se distribuía homogéneamente en las dos alturas.

Por ello son muy importantes los análisis de variabilidad de la deposición mediante criterios como los que se introducen en esta tesis a partir de ensayos realizados en base a la norma ISO 22522:2007 (ISO, 2007). Esta norma, cuando se aplica en función de las zonas de vegetación (diferentes alturas y profundidades), permite analizar la homogeneidad de la aplicación. En la presente tesis se proponen dos indicadores de calidad que complementan la media de la deposición y el coeficiente de variación, tradicionalmente utilizados en la evaluación de pulverizadores. Estos son la penetrabilidad y el porcentaje de muestras alcanzando el umbral terapéutico propuesto. Ambos parámetros de evaluación son fundamentales para evaluar la calidad del tratamiento puesto que los valores medios de deposición enmascaran posibles zonas de la vegetación infradosificadas que pueden constituir reservorios de plagas y enfermedades.

La densidad de plaga antes del tratamiento también tiene influencia sobre la eficacia esperada. A más densidad inicial se necesitará aumentar los efectos de control del tratamiento al objeto de asegurar que la densidad de plaga se sitúa por debajo del umbral económico de daños. Esta cuestión abre el interrogante sobre la necesidad de dosis adicionales en escenarios de alta densidad de plaga o sobre la monitorización y la toma de decisiones en GIP.

Otros indicadores de la calidad de la distribución que no se han estudiado en esta tesis son el tamaño y distribución de las gotas en las hojas y el porcentaje que se deposita en el haz y el envés de las hojas. Todos los ensayos se han realizado con boquillas de cono hueco estándares (Albuz ATR). Cuando se pulveriza con boquillas de reducción de deriva, el tamaño de gota es superior y por lo tanto el recubrimiento y deposición total aumenta (Garcerá et al., 2017), no obstante, la distancia entre impactos también es superior pudiendo resultar en problemas de eficacia (Doruchowski et al., 2016), especialmente en productos cuyo modo de acción sea por contacto (como el cobre o el azufre) o por asfixia (como los aceites). En cuanto a la distribución de la deposición entre el haz y el envés de las hojas, Pergher et al. (2013) estudiaron esta variabilidad mediante el ratio deposición en el envés/media total, observando que la deposición en el envés era inferior. Esto puede tener implicaciones en el control de plagas que se localicen en esta parte de las hojas con poca movilidad, cómo es el caso del ácaro amarillo, justificando así el aumento de volumen de caldo que propone DOSA3D.

A pesar de estas objeciones, se acepta la tercera hipótesis ya que, como se ha visto, la deposición foliar se relaciona bien con la eficacia biológica.

Hipótesis 4. El volumen de caldo establecido por el sistema DOSA3D permite obtener deposiciones similares al objetivo umbral (1.2 $\mu L\ cm^{-2}$) y, consecuentemente, conseguir la eficacia adecuada.

En viñedo, al comparar la deposición en hojas entre el volumen de aplicación establecido por el agricultor y el volumen ajustado con el sistema DOSA3D (capítulos 5 y 6) no se han encontrado diferencias significativas. Además, en la serie de ensayos realizados en viñedo con volúmenes ajustados se logra mantener la deposición por encima del umbral propuesto por el sistema (1.2 $\mu L\ cm^{-2}$) en el 93% de los casos, por lo que cabría esperar una eficacia aceptable cuando se aplica la recomendación de DOSA3D.

La EPPO define eficacia aceptable de un PF en base a dos criterios: el principal es que el producto debe mostrar resultados significativamente superiores a los registrados en el control no tratado, y el secundario la eficacia del PF a evaluar debe ser similar a la obtenida con el de un PF de referencia (EPPO, 2017). Aplicando esta definición a la estrategia del ajuste de dosis mediante el sistema DOSA3D, el criterio principal se cumple en todos los casos estudiados en los que se ha dispuesto de una zona testigo sin tratar (capítulo 5). En cuanto al criterio secundario, en general la estrategia DOSA3D ha mantenido eficacias equivalentes a la estrategia seguida por el agricultor (capítulo 5).

En consecuencia, la cuarta hipótesis se acepta siempre y cuando se mantenga como mínimo la misma concentración de PF en el depósito que se utiliza en los tratamientos estándar.

El único caso en el que la severidad del oídio es superior en la estrategia DOSA3D a la observada en la seguida por el agricultor, aunque muy inferior a la del testigo (ensayo 2.3 descrito en el capítulo 5), puede explicarse por el hecho de que se practicó una reducción adicional a la establecida por DOSA3D para no exceder la dosis máxima admitida por registro de PF en un año con condiciones meteorológicas favorables al desarrollo de oídio. Lo que apunta a que, en general, en estas condiciones (como 2018 y 2020) el ajuste de dosis se debe realizar con precaución. Justamente, para el caso del oídio en manzano Doruchowski et al. (2016) también apunta que en los años con condiciones climáticas favorables al desarrollo de la enfermedad y una presión de infección extremadamente alta controla mejor utilizando boquillas de pulverización fina y volúmenes de caldo más alto. Esta conclusión sería probablemente extrapolable al caso del viñedo.

Hipótesis 5. El tratamiento zonal en viñedo a partir de mapas de vigor, ajustando la dosis mediante el sistema DOSA3D, permite alcanzar deposiciones óptimas y la eficacia biológica esperada en los distintos vigores.

En la tesis se han presentado dos capítulos (6 y 7) en los que se utilizan mapas de vigor para diferenciar dos zonas de manejo dentro de la parcela. Estas zonas, con dos vigores diferenciados (alto y bajo) recibieron dosis ajustadas a cada vigor. La evaluación de la deposición de trazador en las hojas fue superior al umbral de DOSA3D y no mostró diferencias significativas entre clases de vigor, por lo que se debería esperar la misma eficacia biológica al aplicar dosis zonales. Siempre se redujo la población por debajo del umbral económico de daños, pudiendo ser calificados de eficaces todos los tratamientos si se adopta este criterio (capítulo 7). Por lo tanto, se acepta la quinta hipótesis.

Además, en los ensayos realizados se ha comprobado que la densidad inicial de las plagas estudiadas (ácaro amarillo y mosquito verde) está relacionada con el vigor, siendo siempre superior en las zonas de alto vigor. Esto podría explicar que la eficacia alcanzada en las zonas de alto vigor fuese siempre inferior a la del bajo vigor. Otras enfermedades del viñedo, no estudiadas en esta tesis, como el mildiu (*P. viticola*) y la botrytis (*Bortrytis cinerea*) también parecen tener más incidencia en las zonas de alto vigor (Bramley et al 2011; Ferrer et al 2019). Un mayor conocimiento de la relación entre el vigor y la densidad de plaga o enfermedad debería llevar a un mejor ajuste de las dosis para cada binomio (plaga-cultivo).

No obstante, cabe remarcar el coste de la tecnología para la aplicación zonal. La tecnología utilizada en estos capítulos (regulador de presión manual) tiene un coste relativamente bajo consiguiendo ahorros entre el 4.8 y el 25.3%, similares a los considerados por Petrović et al. (2018). Con tecnologías más automatizadas el ahorro y la precisión de la aplicación aumentan (Campos et al., 2020), pero también los costes y el mantenimiento del equipo.

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CAPÍTULO 9

Conclusiones

Conclusiones generales de la tesis

A partir de los objetivos planteados en esta tesis y los resultados obtenidos bajo las condiciones ensayadas, se pueden dilucidar las siguientes conclusiones:

Objetivo 1. Profundizar en las evidencias científicas disponibles relacionadas con la expresión y el ajuste de la dosis, tales como los parámetros que mejor caracterizan la vegetación o la influencia del pulverizador.

- El índice de área foliar (LAI) cuantifica la superficie a tratar, siendo el parámetro más importante en el ajuste de las dosis en frutales y viñedo.
- El tipo de pulverizador, la geometría del cultivo y la plaga a controlar son también factores clave en el ajuste de dosis.

Objetivo 2. Comparar los diferentes sistemas de ayuda a la decisión disponibles para el ajuste de dosis en frutales y viñedo.

- DOSA3D es el único sistema de ayuda a la decisión disponible hasta ahora que integra los cuatro factores (LAI, pulverizador, geometría del cultivo y plaga o enfermedad a controlar), facilitando el cálculo del volumen de aplicación y la dosis óptima para diferentes tipos de pulverizadores hidroneumáticos equipados con boquillas de cono hueco.
- DOSA3D es el sistema de ayuda a la decisión más conservador, proporcionando volúmenes de caldo y dosis superiores al resto. Esto implícitamente conlleva una mayor garantía en la eficacia biológica de los tratamientos fitosanitarios.

Objetivo 3. Mejorar el sistema DOSA3D, simplificando la interfaz del usuario.

- El sistema DOSA3D ha sido perfeccionado en lo referente a la estimación del volumen de caldo, dosis y expresión de la misma, así como su usabilidad.

Objetivo 4. Validar el modelo de estimación del LAI utilizado en DOSA3D en viña.

- El modelo de estimación del LAI es válido para viñedos en espaldera de hasta 1.25 m de anchura de copa, lo que supone la práctica totalidad de los viñedos existentes en España. En viñedos excediendo este límite deben considerarse dosis adicionales a las establecidas por el sistema DOSA3D.

Objetivo 5. Validar técnicamente el sistema DOSA3D en tratamientos uniformes a dosis ajustadas y el control de plagas y enfermedades en frutales y viñedo.

- El estudio de las deposiciones en las diferentes zonas de la vegetación mediante la norma ISO 22522:2007, con los factores de calidad propuestos (penetrabilidad, número de muestras por encima del umbral 1.2 $\mu L\ cm^{-2}$ y distribución de las muestras por debajo del umbral) permite relacionar la deposición de la pulverización con la eficacia.

- Entre los diferentes tipos de pulverizador considerados por el sistema DOSA3D, el túnel de recuperación Hardi Optimus 55 es el pulverizador que mayores ahorros de producto consigue en viñedo, mejorando, además, la distribución de la deposición sobre el objetivo tratado.
- El sistema DOSA3D se ha validado en el control de las principales plagas y enfermedades de frutales y viñedo.
- Mediante el ajuste de dosis, DOSA3D permite reducir riesgos ambientales y de salud humana derivados del uso de productos fitosanitarios en frutales y viñedo.

Objetivo 6. Validar técnica y económicamente los tratamientos zonales, basados en mapas de vigor, y el control de plagas en parcelas de viñedo a gran escala.

- En viñedos espacialmente variables, el índice de vigor PCD (*Plant Cell Density*) permite clasificar de forma robusta las zonas en relación al vigor de las cepas. Para ajustar la dosis en tratamientos zonales mediante el sistema DOSA3D, se propone caracterizar en campo las cepas correspondientes al cuartil 80 del PCD para tratamientos uniformes y al cuartil 70 de cada clase de vigor en tratamientos zonales.
- El ajuste de dosis zonal mediante el sistema DOSA3D en viñedo mejora las deposiciones y permite controlar adecuadamente el ácaro amarillo y el mosquito verde en las zonas correspondientes a las diferentes clases de vigor.

Recomendaciones

A partir de los resultados obtenidos se derivan una serie de recomendaciones dirigidas a los usuarios finales (técnicos, aplicadores, agricultores) en el ajuste de las dosis de productos fitosanitarios en cultivos 3D:

1. Utilizar sistemas de ayuda a la toma de decisión para ajustar las dosis de fitosanitarios a los diferentes escenarios, especialmente el sistema DOSA3D ya que es el único que establece el volumen y la dosis en base a la superficie foliar a partir de la estimación del LAI en cultivos 3D.
2. Para conseguir incrementar la uniformidad de las deposiciones y minimizar las pérdidas la calibración previa del pulverizador es un factor clave en la correcta aplicación de fitosanitarios. Se debe potenciar la formación de los aplicadores y las ayudas para adquirir equipos de tratamientos mejor adaptados a la geometría del cultivo.
3. En años con condiciones meteorológicas especialmente favorables al desarrollo de plagas y enfermedades, se debe tomar especial precaución en alcanzar la deposición necesaria en toda la vegetación. Posiblemente se deba incrementar la concentración del caldo en estos casos.
4. Utilizar las tecnologías de aplicación variable para la realización de tratamientos zonales de productos fitosanitarios en el control de plagas y enfermedades del viñedo.
5. Substituir los equipos de tipología convencional por equipos más eficientes como es el caso de los pulverizadores con deflectores y los de flujo tangencial en frutales y los de bajantes o el túnel de recuperación en viñedos.

A la industria química, en los ensayos de eficacia de los productos fitosanitarios, se le recomienda facilitar la dosis mínima efectiva en función de la superficie a tratar ($\mu g\ cm^{-2}$), la caracterización de la vegetación objeto del tratamiento, la aportación de datos sobre las deposiciones y el empleo de equipos de tratamientos similares a los operativos en la agricultura productiva.

Por último, a las autoridades evaluadoras y reguladoras, el establecimiento de la obligatoriedad de proporcionar los citados informes como parte de la información contenida en el dosier de evaluación de eficacia conforme al Reglamento CE 1107/2009 relativo a la comercialización de productos fitosanitarios y por el que se derogan las Directivas 79/117/CEE y 91/414/CEE del Consejo.

Futuros trabajos

1. Las autoridades deberían intensificar sus actuaciones destinadas a promover el uso de sistemas de ajuste de dosis como DOSA3D para minimizar los riesgos asociados al uso de productos fitosanitarios, dar cumplimiento a las disposiciones vigentes en la materia y contribuir a la consecución de los objetivos de la estrategia europea Farm to Fork de reducción de uso de los productos fitosanitarios.
2. DOSA3D está diseñado para aplicaciones con pulverizadores hidroneumáticos equipados con boquillas de cono hueco, que son el tipo de boquillas más utilizado en los tratamientos de cultivos 3D. No obstante, las boquillas de reducción de deriva constituyen una alternativa técnica debido a las ventajas medioambientales que conlleva su uso, siendo incluso obligatorias en algunos países europeos, entre ellos Holanda. El patrón de distribución de la pulverización con estas boquillas es diferente. Por lo tanto, se debería ampliar el conocimiento existente sobre la eficacia de los tratamientos realizados con estas boquillas en el control de las plagas y enfermedades que suponen mayor presión sanitaria y mayor dificultad de control y, si procede, adaptar el sistema DOSA3D a los condicionantes de estas boquillas.
3. Igualmente, el sistema DOSA3D debe seguir divulgándose al objeto de que se vea ampliada su utilización entre los productores de cultivos 3D. Asimismo, a partir de nuevas experiencias del sistema DOSA3D a escala productiva en el control de plagas y enfermedades, deberá perfilarse su motor de cálculo y mejorar la interfaz de uso.
4. En tanto en la prescripción de los tratamientos se continúen empleando formas de expresión de la dosis no relacionadas con la vegetación a tratar (concentración, kg ha^{-1}), se recomienda establecer las cantidades de producto a aplicar mediante la vía verde (*Green Way*). Esta metodología debe seguir siendo objeto de validación en campo para determinar la dosis mínima eficaz en diferentes escenarios y, siempre, en sintonía con los criterios de mejores prácticas fitosanitarias propias de cada región y los principios de la GIP.
5. Mediante el empleo de sensores LiDAR deberán caracterizarse los modelos de conducción del viñedo que exceden al límite admisible por el sistema DOSA3D (espaldera de 1.5 m de anchura de copa) y las nuevas formas de conducción en frutales y almendro que actualmente conforman las nuevas tendencias de intensificación sostenible de la producción.
6. En viñedos espacialmente uniformes y también en los variables, el túnel de recuperación puede jugar un papel importante en el ahorro de producto. Se debe profundizar en la hipótesis de que la recuperación del túnel se relaciona bien con el vigor (superficie de la planta expuesta).
7. Si bien ya disponemos de antecedentes válidos, para la elaboración de mapas de prescripción en tratamientos zonales y la detección temprana de zonas de afectación, debe profundizarse en el uso de imágenes multiespectrales como las proporcionadas por el sistema Sentinel-2.
8. El método de generación de los mapas de prescripción debe mejorarse, por ejemplo, formando una cuadrícula de rectángulos paralelos a las filas del viñedo, teniendo como base de cada rectángulo el ancho de trabajo del pulverizador y como longitud mínima la distancia requerida para que la presión de trabajo de las boquillas se

adapte a las condiciones de la nueva zona (transitoriedad). En este escenario, los equipos dotados de sistema selectivo de boquillas o la pulverización pulsante aparecen como soluciones tecnológicas de elevado interés para acortar el tiempo de respuesta.

9. Como se ha visto, la distribución de las plagas estudiadas es heterogénea dentro de parcelas con vigor variable, lo que puede conducir a tratamientos selectivos en los que se dejen sin tratar las zonas de menor densidad (generalmente las de bajo vigor) o las que presentan ausencia del agente causal. Todo ello debe asociarse a la mejora de los procedimientos de monitoreo y al análisis de riesgos derivados de la existencia de zonas sin tratar.
10. Tanto para la práctica de los tratamientos zonales como de los selectivos, son necesarias otras mejoras del sistema de control de la pulverización, geolocalización e interpretación de mapas digitales de prescripción.
11. Finalmente apuntar que en un futuro próximo los pulverizadores deberán ser equipados con sensores adicionales para monitorizar los riesgos generados durante la aplicación. Las bases de estos sistemas se encuentran en la futura norma internacional *ISO 4444 Agricultural sprayers — Recording of Spray Drift Parameter*