Volume application rate adapted to the canopy size in greenhouse tomato crops

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ABSTRACT: The application rate of plant-protection products is indicated as a concentration or amount of product per area. Greenhouse crops grow swiftly, and an application rate based on a fixed amount of product per hectare can result either in large losses and overdoses when the plants are small or to be insufficient when the plants are fully developed. To solve these problems, the application rates of plant-protection products need to be adapted to the plant mass present in the greenhouse when the spray is applied. Two models were developed to estimate the leaf area based on easily measured geometric data of the vegetation in a greenhouse tomato crop. The model based on the PRV (Plant Row Volume) had that best results. The calculation of the volume application rate from the PRV has resulted in a reduction of more than 30 % of the quantity of plant protection product sprayed, without decreasing yield. The PRV of a greenhouse tomato (*Lycopersicon esculentum* Mill.) is an easily measured parameter that enables the estimation of the leaf area index and the use of application strategies adapted to the changes in the plant canopy, saving major amounts of plant protection product used, compared to the conventional system.

Introduction

Quantifying vegetation and its subsequent relation to the spray-application rate are the basis for techniques of crop adapted spraying (CAS) used by researchers (Sutton and Unrath, 1988; Giles et al., 1989; Rüegg et al., 1999; Gil et al., 2007; Pergher and Petris, 2008) for applying plant protection products in different crops. The goal is to achieve a more rational use of sprays according to the real needs of the crop while seeking to protect the environment and human health.

Different methods have been developed to solve the problems of adjusting the application rate to the level of crop development. One method is the "Tree-Row Volume" (TRV) (Byers et al., 1971), whereby the application rate is determined by comparing the crop canopy volume per surface-area unit with the rate applied to a standard crop. This method specifies the application rates in a more methodical way and has rendered good results in orchards (Sutton and Unrath, 1988; Rüegg et al., 1999; Gil et al., 2007; Siegfried et al., 2007). A simpler system was proposed by Furness et al. (1998), called "Unit Canopy Row" (UCR), in which the application rate was determined by each unit of 100 m^3. Barani et al. (2008) used the UCR in vineyards to determine the application rates and obtained good results.

To match application rates and spray volume, Weisser and Koch (2002) proposed the "treated area" concept, defined as the area that is sprayed and oriented between nozzles and targets. Therefore, for high crops the application rate is to be expressed in terms of the "leaf wall area" (LWA) (Koch, 2007).

Another way of establishing the application rate as a quantity of spray product per unit of leaf surface area is from the measurement of the LAI (Leaf Area Index). This parameter is used to determine the application rates (Dammer et al., 2008; Pergher and Petris, 2008; Gil and

Escolà, 2009). However, the use of the LAI to adjust the application rate is not very practical because its value is difficult to determine for the farmer under field conditions.

This study describes a model to estimate the leaf area based on easily measured geometric data of the vegetation in a greenhouse tomato crop, such as the canopy height or the Plant Row Volume (PRV), and its use to calculate the volume application rate of plant protection product from the average foliar deposit.

Materials and Methods

Measurement of geometric parameters of the canopy

This study was conducted with the geometric data from greenhouse tomato plants (*Lycopersicon esculentum* Mill.), measured at three locations from various commercial cultivars and in different types of greenhouses, from 2007 to 2010. Table 1 lists the locations of the greenhouses, cultivars, and planting pattern of the crop. In all cases, the crop was planted in twin-rows (two plants per position) on a perlite substrate. In the greenhouses, the geometric parameters of height and width of the canopy as well as the foliar surface area were recorded using the methodology detailed below. These parameters were measured periodically (every 15-20 days) according to the crop cycle, development, and cultivation tasks.

Determination of the Plant Row Volume

The TRV is defined as the volume of vegetation per unit of surface area cultivated. In the present study, this is called Plant Row Volume (PRV), as this refers to annual plants and not to the trees, with the implications that this involves. The geometric variables needed to determine this index are height and width of the canopy,

391

Sánchez-Hermosilla et al.   Volume application rate in greenhouse crops

Table 1 – Geographical coordinates, season, and cultivar at the locations.

Locations	Geographical coordinates WGS84	N° of greenhouses	Area (m²)	Seasons	Cultivar	Planting pattern (m)	N° of samplings
1	Lat. 36.84° Long. -2.41°	1	8,000	Spring-Summer 2007-2008	Beel	1.8 × 0.5	9
2	Lat. 36.79° Long -2.72°	2	1,780	Spring-Summer 2007-2008	*Divine*	2 × 0.5	11
				Autumn-Winter 2008-2009	*Divine*	2 × 0.5	12
				Spring-Summer 2008-2009	*Divine*	2 × 0.5	17
				Autumn-Winter 2009-2010	*Racimo*	2 × 0.5	10
				Spring-Summer 2009-2010	*Racimo*	2 × 0.5	4
3	Lat. 36.78° Long -2.71°	2	1,920	Spring-Summer 2009-2010	*Delicia*	2 × 0.4	12

and the distance separating the plant rows. Because the width of the canopy varies with plant height, PRV was calculated considering the volume of the vegetation corresponding to each of the three heights defined to measure the width (Figure 1). Thus, the PRV was calculated according to Eq. 1.

$$PRV = \frac{10000 \cdot H \cdot \left[(B_1 + B_2) + (M_1 + M_2) + (A_1 + A_2) \right]}{3 \cdot D} \quad (1)$$

where PRV is the Plant-Row Volume (in m³ ha⁻¹), H is the canopy height (in m), B_1 and B_2 are the width of the plants at 1/6 the height (in m), M_1 and M_2 width of the plants at 1/2 the height (in m), A_1 and A_2 width of the plants at 5/6 the height (in m) and D is the distance between the rows (in m).

The height of the canopy was measured perpendicular to the soil. In the first stages total height was considered. After the different clearing of leaves closest to the soil during the crop cycle, usual in cultivation tasks, this measurement refers only to the zone with the foliar mass. The canopy height was measured in four randomly assigned pairs of plants representative of the rest of the greenhouse.

As the plants were paired, the width was the mean length parallel to the soil, from the lateral exterior of the right-hand plant to the lateral exterior of the left-hand plant, discounting the space between them, but without overestimating this geometric parameter (Figure 1).

Determination of the leaf area index

The surface area of the leaflets comprising the leaves was measured, using a destructive method, which consisted of cutting off all the leaves of the individual, measuring their surface area with the use of a planimeter (WinDias, Delta-T Devices Ltd. Cambridge). Thus, this method involves the destruction of the studied sample. This parameter was measured on six plants assigned
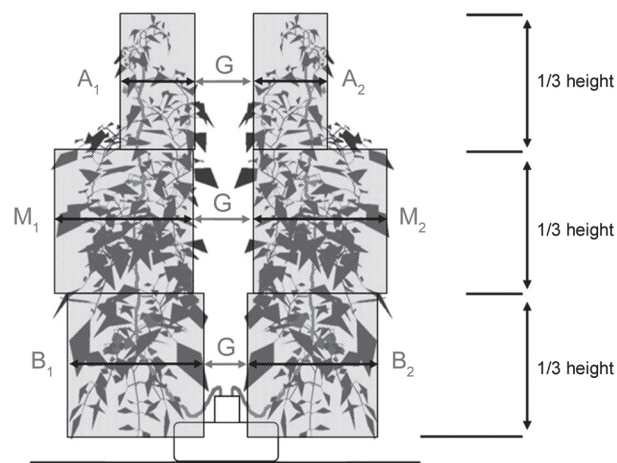

Figure 1 – Measurement of width; B low width (B_1+B_2) (1/6 height), M middle width (M_1+M_2) (1/2 height), and A high width (A_1+A_2) (5/6 height).

at random from among the four pairs of plants used to measure the height and width. Because of the destruction involved over the crop cycle, this parameter was not measured on all the plants.

Development of the model to estimate the LAI

Models were developed to relate the canopy height, PRV, and LAI, with the aim of finding a correlation between them, and to be able to estimate LAI from the canopy height or from the PRV. For the development of these models, the mean values of H, PRV, and LAI were used for each greenhouse and day sampled, and were measured according to the methodology described above. Correlation and regression analyses were calculated with the software SPSS v15.0 (SPSS Inc., an IBM Company, Chicago, IL, USA).

The accuracy of the developed models was determined by measuring the height of the canopy and quantifying the LAI and PRV, according to the methodology

described above, in a tomato crop at 11 times over the crop cycle (Table 2). The tomato cultivar was *Divine*, cultivated in a greenhouse in El Ejido, Almería, Spain (36° 48′ N, 2° 43′ W and 151 m elevation), during the autumn-winter season 2010-2011. For each of the developmental stages of the crop in which the data were taken, the LAI was estimated according to models established previously, and the prediction residual sum of squares (PRESS) was calculated using Eq. 2.

$$PRESS = \sum_{j=1}^{N}\left(LAI_j - L\hat{A}I_j\right)^2 \qquad (2)$$

where N is the total number of data (11); LAI_j the known LAI for the j-th data and $L\hat{A}I_j$ the estimated LAI of LAI_j. The PRESS values provide a measure of how well the models predict the LAI. The prediction error of a LAI was calculated as the relative standard error (RSE) of the LAI prediction (Eq. 3).

$$RSE(\%) = 100 \cdot \left(\frac{\sum_{j=1}^{N}\left(LAI_j - L\hat{A}I_j\right)^2}{\sum_{j=1}^{N} LAI_j^2} \right)^{\frac{1}{2}} \qquad (3)$$

Estimation of the volume application rate

Pergher and Petris (2008) proposed Eq. 4 to estimate the product application rate (Q, in g ha^{-1}) based on LAI, the average foliar deposit (d, in μg cm^{-2} leaf area) and the spray fraction deposited on the canopy (ε).

$$Q = 2 \cdot 10^2 \cdot d \cdot LAI/\varepsilon \qquad (4)$$

The use of Eq. 4 to adjust the product application rate is not very practical because the values of LAI, d and ε are difficult to determine by the farmer under field conditions. In the present study, the d value corresponds to the mean deposition achieved by farmers in their routine practice, consisting of spray gun applications at high pressures and volumes. Taking into account the value

of average foliar deposition in μL cm^{-2} leaf area (d$_v$) the volume application rate (V, in L ha^{-1}) can be determined by Eq. 5.

$$V = 2 \cdot 10^2 \cdot d_v \cdot LAI/\varepsilon \qquad (5)$$

The value of ε depends on sprayer type, crop structure, and weather conditions. In several studies the values of d$_v$ and ε have been calculated in a greenhouse tomato crops (Cerruto et al., 2009a, b; Sánchez-Hermosilla et al., 2011, 2012), as indicated in Table 3. In consideration of these values, our proposal is to use a value of 1.5 μL cm^{-2} d$_v$ and, for the spray fraction deposited on the canopy (ε) 0.50 for spray-gun applications or 0.75 for spray boom applications.

The value of LAI in Eq. 5 can be calculated with the model for estimating LAI as a function of geometric parameters of the crop, developed under the previous point.

Evaluation of the method to determine the volume application rate

To evaluate the method to determine the volume application rate, two greenhouses of 960 m^2 (24 m × 40 m) were selected in La Mojonera, Almería, Spain, (36°48′ N, 2°41′ W and 142 m elevation) for a field experiment during two seasons (spring-summer 2011 and autumn-winter 2011-2012). The crop used was tomato grown in perlite and planted in a twin-row system. Each twin-row was 2 m apart and had 50 pairs of plants spaced on 0.4 m (2.5 plants m^{-2}).

Every greenhouse was divided into two blocks following a randomized block design with four blocks and two treatments (two application strategies). The treatments were the "conventional (CON)" and "estimated (EST)" application rate. The CON treatment involved spraying throughout the season according to the farmer's criteria (application rate, pressure, travel speed, etc.). The EST treatment meant spraying according to the volume application rate calculated using the Eq. 5. During the application of the sprays, the concentration

Table 2 – Data used to validate the models.

Assay	dat[a]	PRV[b] m^3 ha^{-1}
1	36	4,397.27
2	42	5,761.67
3	56	8,810.33
4	63	8,212.83
5	70	8,463.00
6	77	10,923.00
7	88	10,106.42
8	95	9,990.13
9	102	10,098.83
10	108	10,063.17
11	112	9,656.33

[a]dat = days after transplanting; [b]Plant Row Volume.

Table 3 – Values of average foliar volume deposit (d$_v$) with spray gun and the spray fraction deposited on the canopy (ε) for greenhouse tomato crop in different studies.

	LAI[a]	d$_v$ (μL cm^{-2})[b]	ε	
			Spray gun	Vertical boom
Sánchez-Hermosilla et al. (2011)	3.31	1.55	0.49	0.75[c]
Sánchez-Hermosilla et al. (2012)	2.64	1.22	0.51	0.86
Beulke et al. (2011)	3	–	–	0.75
Beulke et al. (2011)	2	–	0.67	–
Cerruto et al. (2009a)	5.80	1.43	–	–
Cerruto et al. (2009a)	2.09	1.16	–	–
Cerruto et al. (2009b)	2.99	1.21	–	–

[a]Leaf area index; [b]Mean deposition by farmers in their routine practice; [c]Value calculated from the data published in Sánchez-Hermosilla et al., 2011.

of the active ingredient (a.i.) in the tank was the same for the CON as for the EST treatment and was determined following the recommendations indicated on the product label, using the volume application rate selected by the farmer (V_{CON}) as a reference.

Each treatment was applied in an experimental plot measuring 10 m × 24 m, 4-5 crops lines and separated by plastic sheets (Figure 2). The spray equipment used in this study was a manually pulled trolley with two vertical spray booms (Carretillas Amate S.L., Almería, Spain), which was connected through a 25-m long hose (diameter 17 mm) to a wheelbarrow with a tank of 100 L and a membrane pump (M-30, Imovilli Pompe s.r.l., Reggio Emilia, Italy) that provided a maximum pressure of 3000 kPa and a maximum flow of 33 L min^{-1}. Each boom had four standard flat fan nozzles (XR 110 03) inserts spaced 0.50 m apart and the nozzles were fitted at an offset angle of 7° and oriented 15° upwards. The vertical distance between the lowest nozzle and the ground was 0.27 m. Table 4 shows the working parameter for the applications.
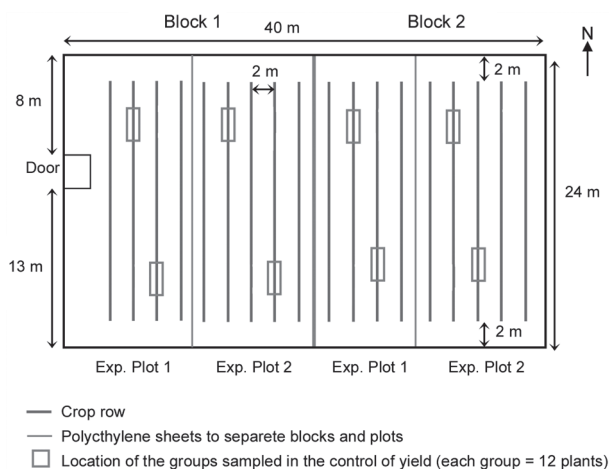

Figure 2 – Greenhouse plant with the compartmentalization in experimental blocks and plots.

Yield evaluation

To quantify yield, two groups of 12 plants were selected from each experimental plot (Figure 2). One was situated in the northern half of the greenhouse and the other in the southern half in order to avoid the effects of orientation. In each harvest, the fruits from each group were weighed using a scale (HW-100KV WP, A&D Company Ldt., Japan).

Results and Discussion

Development of the model to estimate the LAI

The correlations between LAI and canopy height were analysed (Figure 3), as well as between LAI and PRV (Figure 4), the results being significant in both cases at a confidence level of 95 %, with determination coefficients (R^2) of 0.91 and 0.94, respectively. Easily measured parameters in the plant mass of the tomato crop permit the estimation of an index as complex as LAI. This is because the normal development of the tomato plant has regular node distribution and leaf development. However, the LAI has a closer relationship with PRV than with canopy height, since the PRV value, apart from taking into account canopy height also takes into account the development of the leaves in an indirect way from the width of the vegetation. The model relating LAI with PRV corresponds to a power equation, similar to
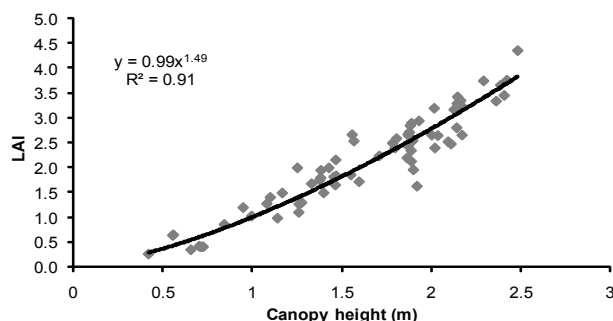

Figure 3 – Canopy height- Leaf area index (LAI) regression curve.

Table 4 – Working parameters for the applications.

Season	Applications	PRV	Conventional application			Estimated application			
			Pressure	Speed	V_{CON} [b]	V_{EST} [c]	Pressure	Speed	V_F [d]
		m^3 ha^{-1}	kPa	m s^{-1}	——————— L ha^{-1} ———————		kPa	m s^{-1}	L ha^{-1}
Spring-summer 2011	1	6442.09	1185	1.22	1277.89	808.00	758	1.58	790.76
	2	6314.20	1179	1.25	1246.34	788.00	653	1.42	817.16
	3	5978.60	1178	1.36	1149.42	736.00	593	1.42	779.88
	4	6467.59	1159	1.20	1284.20	812.00	604	1.29	862.50
Autumn-winter 2011/12	1	7047.46	1188	1.10	1426.19	904.00	581	1.15	954.37
	2	8221.40	1211	0.91	1732.26	1096.00	623	1.01	1121.64
	3	8532.00	1201	0.87	1814.29	1148.00	592	0.95	1168.09
	4	8674.40	1235	0.86	1852.16	1172.00	654	0.99	1173.34

[a]Plant Row Volume V_{CON}; [b]application rate calculated with the farmer's criteria; [c]V_{EST}, application rate calculated with Eq. 6; [d]V_F, application rate calculated under field conditions.
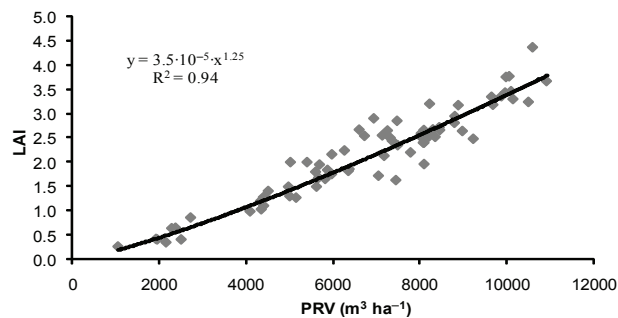
Figure 4 – Plant row volume (PRV)- Leaf area index (LAI) regression curve.

Table 5 – Values of the prediction residual sum of squares (PRESS), the relative standard error (RSE) and equation for each model.

Models to estimate LAI	PRESS	RSE (%)	Model equation	R^2
Based on the canopy height	0.78	8.73	$LAI = 0.99 \cdot (H)^{1.49}$	0.91
Based on PRV	0.30	5.44	$LAI = 0.35 \cdot 10^{-4} \cdot (PRV)^{1.25}$	0.94

Table 6 – Relative errors in estimating the leaf area index (LAI) with each of the models.

Assay	dat	PRV	Canopy Height	LAI	Relative Error (%)[b]	
					RE_H[c]	RE_{PRV}[d]
		$m^3 ha^{-1}$	m			
1	36	4397.27	1.08	1.27	12.01	6.32
2	42	5761.67	1.35	1.60	3.27	6.14
3	56	8810.33	1.93	2.94	10.23	1.73
4	63	8212.83	2.09	2.52	18.14	8.14
5	70	8463.00	2.17	2.65	18.41	6.84
6	77	10923.00	2.39	3.66	1.22	8.68
7	88	10106.42	2.41	3.45	6.06	3.95
8	95	9990.13	2.29	3.74	9.13	5.66
9	102	10098.83	2.36	3.49	1.99	2.71
10	108	10063.17	2.42	3.76	1.71	5.10
11	112	9656.33	2.36	3.33	6.65	1.20

[a]Plant Row Volume; [b]Relative error (%) = |LAI-LÂI|/LAI·100; [c]Relative error with the model "height of plant mass-LAI"; [d]Relative error with the model "PRV-LAI".

the model reported by Siegfried et al. (2007) to relate LAI and VRV (Vine Row Volume) in grapevine.

To determine which of the models offered the best estimation of the LAI, a calculation was made of the Relative Standard Error (RSE) from the data (11 data in total) of a series of plants sampled (Table 2), which were not included in the models developed. For each model used to estimate LAI, Table 5 shows the PRESS, the RSE, and the equation. These models to estimate LAI were validated only for greenhouse tomato crops with normal vegetative development (internodes of c. 5-16 cm, depending on the growth stage), cultivated with adequate irrigation and nutrients as well as proper management (leaf thinning, branch thinning, and tip pinching).

The analysis of the LAI values estimated for each datum used for validation (Table 6) indicated that the model based on the canopy height had greater relative errors between tests 3 and 5, with values higher than 10 %. This was because just at 56 dat (days after transplanting) the plants were leaf thinned. The thinning, i.e. clipping off the lower leafs of the plants, decreased the leaf surface area, reducing the LAI by 14 % from assay 3 to 4. However, leaf thinning did not lower the canopy height, which between assay 3 and 4 increased 8 %, resulting in errors of more than the 10 % indicated above. On the other hand, the canopy height was shortened when tip pinched, which consisted of removing the tip of the main stem, limiting plant growth. Tip pinching was performed at 88 dat, although this operation did not lead to major errors in estimating the LAI with the canopy height, (all were under 10 %) because the loss in leaf area was minor, since new leaves were located at the tip of the stem, representing minor surface-area development.

For the model used to estimate LAI based on the PRV, all the errors were lower than 9 % (Table 6), even after leaf thinning and tip pinching, which prompted major changes in plant architecture. Nevertheless, major errors (c. 8 %) also arose just after leaf thinning.

The two models enabled a good estimation of the LAI with relative standard errors lower than 9 %. Nevertheless, the model that offered the best estimation of the LAI was the one based on the PRV with a RSE of 5.44

%. Taking into account the PRV-LAI relationship, Eq. 5 enabled the volume application rate to be determined as a function of PRV (Eq. 6.):

$$V = 7 \cdot 10^{-3} \cdot d_V \cdot PRV^{1.25}/\varepsilon \qquad (6)$$

Evaluation of the method to determine the volume rate for spraying

An evaluation was made of the plant protection achieved over two seasons (spring-summer 2011, autumn-winter 2011-12). Table 7 lists the products applied in each season and the dose applied for the CON and EST strategies, calculated on the basis of the volume shown in Table 4 for each strategy. The aim of these assays was to compare two strategies to calculate the application volumes: the CON rate, calculated with the criteria of the farmer (V_{CON}), and the EST rate, calculated from the PRV using Eq. 6 (V_{EST}). For this, the yield corresponding to each treatment was compared for possible differences.

Table 7 shows the percentage of savings of the chemical when Eq. 6 was used to estimate the volume application rate. The savings in both seasons consistently exceeded 30 %, with mean values of 34.39 % and 35.15 % in the first and second season, respectively.

In terms of yield, Table 8 shows the mean values calculated in the areas where each control strategy was evaluated. The two strategies gave similar yield in both seasons. There were no differences ($p < 0.05$) with

395

Sánchez-Hermosilla et al.   Volume application rate in greenhouse crops

Table 7 – List of plant protection product applied in each season. Applied dose for the conventional and estimated strategies and savings.

Season	Applications	Active ingredients	Conventional rate	Estimated rate	Savings (%)
Spring-summer 2011	1	Cyprodinil 37.5 % + Fludioxonil 25 %	1277.89 g ha^{-1}	790.76 g ha^{-1}	38
		Dimethomorph 7.5 % + Mancozeb 66.7 %	1659.00 g ha^{-1}	1026.59 g ha^{-1}	38
	2	Indoxacarb 30 %	249.27 g ha^{-1}	163.43 g ha^{-1}	34
	3	Chlorantraniliprole 35 %	126.44 g ha^{-1}	85.79 g ha^{-1}	32
	4	Chlorantraniliprole 35 %	141.26 g ha^{-1}	94.88 g ha^{-1}	33
		Spiromesifen 24 %	770.52 mL ha^{-1}	517.50 mL ha^{-1}	33
Autumn-winter 2011/12	1	Cyazofamid 40 %	186.00 mL ha^{-1}	124.47 mL ha^{-1}	33
	2	Cyazofamid 40 %	193.00 mL ha^{-1}	124.97 mL ha^{-1}	35
	3	Fenhexamid 50 %	1189.00 g ha^{-1}	765.51 g ha^{-1}	36
		Chlorothalonil 50 %	4535.72 mL ha^{-1}	2920.23 mL ha^{-1}	36
	4	Mefenoxam 2.5 % + Copper oxychloride 40 %	463.04 g ha^{-1}	293.34 g ha^{-1}	37
		Spiromesifen 24 %	1111.30 mL ha^{-1}	704.00 mL ha^{-1}	37

Table 8 – Commercial yield in each season.

Application strategy	spring-summer 2011	autumn-winter 2011/12
	———————— kg m^{-2} ————————	
Conventional application rate	8.8	9.0
Estimated application rate	8.9	8.9

respect to the main factors (control strategy, block and greenhouse) or between their interactions. The similarity of the yield in both treatments, V_{CON} and V_{EST}, means that the crop was suitably protected despite the decrease in volume applied. If the volume application rates in V_{EST} had not been enough to control the pest attack, there would have been reduction in the yield.

Conclusions

The model that offered the best results was based on the PRV. The errors in estimating the LAI were relatively low even after leaf thinning and tip pinching, which alter the plant architecture. The estimation of LAI from the PRV defined a strategy by which volume application rate could be matched to the characteristics of the crop. This strategy presented satisfactory results, providing a reduction of more than 30 % with respect to the conventional volume application rate.

Acknowledgements

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