Thresholds for Management of *Phorodon humuli* (Hemiptera: Aphididae) on Hops[1]

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Abstract The hop aphid, *Phorodon humuli* (Schrank), is one of the main hop, *Humulus lupulus* L. (Cannabaceae), pests in the world. The aim of this work was to determine (1) the yield loss function in hops based on the pest density of *P. humuli*, (2) and the economic injury level (EIL), economic threshold (ET), environmental economic injury level (EEIL) and environmental economic threshold (EET). Different densities of *P. humili* were applied to hop plants in the form of several aphid treatments over time. A negative correlation was found between yield and the number of aphids per square meter of canopy in accordance with the formula: $y = [0.047 \bullet x] / [1 + (0.047 \bullet x) / 54.385]$, where: y = percentage of yield lost, and x = annual maximum number of aphids per square meter of canopy. Based on this formula, the economic injury level (EIL) was calculated as follows: $[54.385 \bullet C] / [2.556 \bullet V \bullet P_0 \bullet K - 4.7 \bullet C]$, where: C = total insecticide cost per hectare, V = hop price per kilogram, P_0 = yield per hectare of a minimum pest level orchard, and K = reduction of injury due to treatment. The economic threshold (ET) obtained from the population dynamics of *P. humuli* was, on average, 0.7 EIL. The EEIL and the EET also were calculated: EEIL ≅ 1.66EIL and EET ≅ 1.66 ET ≅ 1.16 EIL. Other formulae relating the number of aphids per square meter with other simpler indices expressing these thresholds were calculated: aphids per leaf, percentage of infested leaves, infested leaves per frame, index of infestation, percentage of frames occupied, aphids per dm^2 of leaf, aphids per 20 cm high volume and aphids per hop bine.

Key Words *Phorodon humuli*, *Humulus lupulus*, alpha-acids, economic injury level, economic threshold

The cones or flowers of the hop, *Humulus lupulus* L., are an essential raw material for brewing beer. This is because the lupulin that they contain provides the bitterness and other characteristic organoleptic or sensorial properties of this beverage (Neve 1991). Alpha-acids are the principal component of lupulin. In Spain, hops are typically sold by kilogram of dried cones but at rates that vary according to alpha-acid content.

Today, Spain is the seventh most important producer of hops in the European Union following Germany, the Czech Republic, the United Kingdom, France, Poland and Slovenia. The USA and China are also among the top four producers worldwide. Most of the Spanish plantations are situated in the Province of León, occupying a total land surface of 497 ha in 2007 (The Barth Report 2007/2008). These, together with a

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further 5 ha in the region of La Rioja, represent the total farmland dedicated to hops in Spain. The most common cultivar in Leon is "Nugget" (98%); others grown are "Magnum" (1%) and "Columbus" and "Perle" (jointly accounting for 1%).

The hop aphid, *Phorodon humuli* (Schrank), is a serious pest in most areas where hop, its secondary host (Blackman and Eastop 2000), is grown. *Phorodon humuli* is responsible for both direct and indirect damage. Direct damage is due to sap absorption and saliva injection. Indirect damage is caused by associated fungi and the transmission of viruses. Both direct damage and fungal infection inhibit growth and reduce the number of flowers (Tsvetkov 1962). Moreover, aphids and fungi inside the cones of a plant can reduce the value of the crop and, in some cases, cause total crop loss (Campbell 1978, Thomas et al. 1983). Viruses also cause serious problems in hops; however, few studies on the diagnosis of viruses or on their transmission by the hop aphid have been conducted in Spain.

The extent of the damage caused by *P. humuli* has led to the use of aphicides for their control. These are only applied, however, when the density of the pests surpasses a threshold level at which it becomes economically viable to intervene within an integrated pest management system.

Economic thresholds for *P. humuli* in hop have always been calculated in an approximate way and vary considerably from one growing region to another. In León, 2-3 insecticide treatments are applied while the crops are growing, depending on how frequently the aphids appear. In the USA, an insecticide is applied when aphid numbers reach 15-20 per leaf during June or July or, if a sufficient number of aphid predators are active during these months, when aphid numbers reach 25-30 per leaf (D. G. James, pers commun). In Germany, the insecticide treatment is recommended when aphid numbers reach 50-100 per leaf, usually near the end of June or the beginning of July (Rossbauer 1983). In Portugal and France, treatment is recommended at Infestation Level 3, which is equivalent to 80 aphids per leaf (Ilharco et al. 1979, Trouve et al. 1997). In England, individual hop growers follow their own criteria (C. A. M. Campbell, pers commun). Such variability indicates the need for systematic research evaluating economic injury levels and economic thresholds for *P. humuli* on hop.

The parameters for calculating economic injury level (EIL) and its derivative, economic threshold (ET), as defined by Stern et al. (1959), are treatment cost, price obtainable for the crop, insecticide efficacy and yield loss, these being a function of pest density (Higley and Pedigo 1996). Related to these thresholds, we likewise have the environmental EIL (EEIL) and the environmental economic threshold (EET) (Higley and Wintersteen 1996). These parameters consider the ecological cost of applying each of the insecticides. Thus, the aim of this work was to determine the yield loss function in hops, based on the pest density of *P. humuli*, and to determine the EIL, ET, EEIL and EET for this aphid pest.

Materials and Methods

Experiments were conducted in 2002, 2003 and 2004 in the Province of León in northwest Spain on a 0.72-ha hop field where the Nugget cultivar was planted in rows 3 m apart (running north to south), with a separation of 1.5 m between plants within rows. The height of the wirework trellis on the field was 6 m with 2 strings per rootstock and 3 hop bines were typically trained to each string. We worked with only the cultivar Nugget because, as it's said in the introduction, this cultivar occupies the majority of the hop surface in Spain.

To determine the relationship between pest density and yield loss, an essential component in calculating economic injury level (EIL), we needed to establish plant groups with varying pest densities and then analyze how crop yield and quality were affected at each of these levels of infestation. To achieve this, over the 3 yrs of the study aphicide treatments were applied at different times. In 2002 and 2003, the treatments were applied systematically on set dates, whereas in 2004 they were adjusted for the various groups over the growing season with the intention of attaining the desired range of aphid densities. Furthermore, in this last year aphids were deliberately introduced into one of the groups.

In 2002, eight groups of 3 plants each were selected randomly from the field (outside the experimental trial) for the purpose of determining yield uniformity among plants in these groups. That same year the last 9 rows on the western side of the plot (except the last 2 plants at the ends of the rows, which were not included) were chosen for the trials. Six groups of plants were established in these rows. The treatments in the 3 yrs are listed and described in Table 1.

All plants were treated with imidacloprid (0.008 L of imidacloprid/16 L of water per repetition) using a back-pack sprayer to avoid contamination among treatments.

Table 1. Treatments of plants in 2002 and 2003 (without treatment (A) or with an aphid treatment at different time (B, C, D, E, F)) and in 2004 (without treatment and with introduction of aphids (A), without treatment (B, C, F) or with an aphid treatment at different time (D, E))

Treatment	Years 2002 and 2003	Year 2004
A	Untreated	Untreated and aphids introduced deliberately once in June and twice in July
B	0.008 L imidacloprid /16 L water /243 m^2 in 21st of August (2002) and 20 of August (2003)	Untreated with an initial population of 936 aphids/m^2 in 21st of June
C	0.008 L imidacloprid /16 L water /243 m^2 in 25th of July (2002) and 24th of July (2003)	Untreated with an initial population of 1262 aphids/m^2 in 21st of June
D	0.008 L imidacloprid /16 L water /243 m^2 in 18th of June (2002 and 2003)	Necessary treatments to maintain the level of pests as close as possible to zero (One in 14th of June, one in sixth of July and one in 23rd of August)
E	Necessary treatments to maintain the level of pests as close as possible to zero (One in June, one in July and one in August in the same days as B, C and D)	0.008 L imidacloprid /16 L water /243 m^2 in 14th of June
F	Treatments given as standard to the remainder of the field (One in 18th of June)	Untreated with an initial population of 584 aphids/m^2 in 21st of June

Aphids were deliberately introduced into treatment "A" three times in 2004—once in June and twice in July—by placing 4-5 aphid-infested leaves (100 - 200 aphids/leaf) on each bine of the treatment plants at a height of 2-3.25 m.

Treatments B, C and F were not treated during the year 2004 because they had different aphid population throughout the sampling. In this way, the treatment B had 936 aphids/m^2, C had 1262 aphids/m^2 and F had 584 aphids/m^2 in the first date of sampling.

Treatments were arranged in a randomized complete block with 3 repetitions. Therefore, each experimental block contained 18 plants distributed on 3 rows.

Only the 3 central plants in each treatment plot were sampled. For each of the 54 plants (3 plants within each repetition × 3 repetitions × 6 treatments), counts were taken weekly (from late May-early June to late August-early September during the 3 yrs) as follows: on the surface of one of the plant bines, a wooden frame measuring 20 × 30 cm was placed at heights of 2, 3.25, and 6 m from the ground. Within the area enclosed by this frame, counts were taken of the total number of leaves, the number of leaves with aphids, the total number of aphids and the average number per leaf. The following indices were calculated from these data for each treatment: number of aphids per m^2 of bine surface, number of aphids per leaf, number of aphids per dm^2 of leaf, number of aphids per volume of 20 cm of bine, number of aphids per bine, percentage of leaves attacked, number of leaves attacked per framed area, attack index (0, 1, 2, or 3 according to whether the number of leaves attacked in the framed area was none, one, two, or more than two), and percentage of framed areas occupied (those areas with at least one leaf attacked).

In all 3 yrs, after the cones of the plants had been harvested and dried (7-8 h at temperatures of 60°C to 65°C), a sample from each of the repetitions of each treatment was taken to analyze alpha acids content. The alpha acids were analyzed by means of a technique for determining the lead conductance value, adapted from the E.B.C. (European Brewery Commission) method 7.4 (Anonymous 1998) and expressed as a percentage of dried hops.

The annual yield of the 5 treatments with aphids was subtracted from the yield of the near-zero level treatment (control). A calculation was then made of the percentage of the control treatment production which this deduction represented. Subsequently, a formula relating that percentage of yield loss with the maximum number of aphids per square meter of bine for each treatment in the weekly counts made during the year was established. To this end, Cousens (1985) rectangular hyperbola formula developed to express the effect of weed density on yield loss was adapted for our purposes (because its graph fit the points that were obtained):

$$Y_L = \frac{I \bullet d}{1 + \frac{I \bullet d}{A}} \tag{1}$$

where Y_L = percentage yield loss; d = plants/m^2; A = Y_L value as $d \to \infty$ = horizontal asymptote; $I = Y_L / d$ value as $d \to 0$ = slope of the straight line $Y_L = I \cdot d$. In this case: Y_L = y = percentage of yield lost; d = x = annual maximum number of aphids per square meter of canopy.

To calculate the EIL, the value of the loss is matched to treatment cost (Higley and Pedigo 1996, Higley and Wintersteen 1996):

$$C = V \cdot D' \cdot K \tag{2}$$

where C = total insecticide cost per ha (= application cost + product cost); V = crop price per kilogram; K = reduction of injury due to treatment (= product efficacy between 0 and 1); D'= yield loss per pest unit and it is equal to:

$$D' = \frac{P_0}{100} \cdot y$$

where P_0 = yield per ha of a hop crop with the minimum level of pests.

The ET value was considered as the density of pests on the day before EIL was reached, so as to allow a 24-h period to prepare the treatment. The formulae relating the number of aphids per square meter (y) with time (days in the year) (x) were calculated by regression, for those years and plant treatments with a sufficient number of aphids, by using a normal type of distribution defined by the following general equation:

$$y = \frac{4\,a\,e^{\frac{b-x}{c}}}{\left(1 + e^{\frac{b-x}{c}}\right)^2} \tag{3}$$

The goodness of fit for these models is expressed through the asymptotic standard error for the same reasons mentioned in respect of the regression used in Eq. 1.

The corresponding environmental thresholds were determined based on EIL and ET. Higley and Wintersteen (1996) determined the EET (and the EEIL) by adding an environmental impact cost to the price of insecticide and its application. They calculated this environmental cost for every insecticide studied by assigning a dollar value to each of the effects insecticides could have on water, animals and humans. They deduced this value by polling farmers to find out how much they would pay to avoid these risks. They used the sum of the price of the insecticide and these environmental costs as the value for C in Eq. 2. Equations relating the number of aphids per square meter to each of the indices described were calculated by regression, so as to allow calculation of the 4 thresholds by these simplified methods.

The price of the dried hops used in the formula of the EIL is subject to variation depending on alpha-acid content. It was uncertain whether the alpha-acid content was inversely proportional to the number of aphids. To determine whether such an aphid-related decrease actually occurred, the values for alpha-acid content were correlated by regression with the figures for the annual maximum number of aphids per m^2 of hop bine surface, the general formula being $y = a + bx$.

Results and Discussion

Yield from plants outside the experimental trial receiving no differentiated aphid treatments in 2002 appeared to be homogeneous, as shown in Table 2. Conversely, in the case of plants treated with different aphicides in 2002-2004, a trend was observed toward a more pronounced decline in yield as the number of aphids on the plants increased (Table 3). Treatment B in 2002 and treatments B and C in 2003 were not

Table 2. Yield of eight groups of plants in 2002

Group	Fresh hops (kg)	Dried hops (kg)
1	8.94	2.84
2	7.44	2.44
3	7.94	2.94
4	7.44	2.44
5	8.94	3.34
6	8.44	2.94
7	8.97	3.18
8	8.97	2.73

considered in determining the relationship between pest density and yield loss due to a number of problems encountered during processing in the hop picker. To corroborate this trend, yield loss percentage values were correlated with figures on the

Table 3. Yield and number of aphids of each hop plants treatment

		Yield (kg)		Yield loss (in relation to dried hops)		
Year	Treatment	Fresh hops	Dried hops	Kg	%	Max. number of aphids/m^2
2002	A	6.81	2.44	0.43	14.98	379.67
	C	8.11	2.84	0.03	1.04	473.22
	D	7.94	2.77	0.1	3.48	86.11
	E*	7.77	2.87	0	0	6.11
	F	7.27	2.67	0.2	6.97	41.56
2003	A	8.02	2.85	2.25	44.12	4395.37
	D	10.67	4.17	0.93	18.23	838.89
	E*	9.1	5.1	0	0	379.17
	F	8.64	3.89	1.21	23.72	619.45
2004	A	7.11	2.12	1.49	41.27	937.04
	B	10.77	3.28	0.33	9.14	936.11
	C	9.36	2.74	0.87	24.1	1262.04
	D*	11.97	3.61	0	0	19.75
	E	8.86	2.66	0.95	26.32	65.43
	F	7.54	2.24	1.37	37.95	589.82

* Control (treatment with minimum pest level).

maximum number of aphids per square meter of hop bine, using Eq. 1. In this case the following details were recorded: y = percentage of yield lost; x = annual maximum number of aphids per square meter of canopy; A = 54.385 ± 22.934; I = 0.0469 ± 0.022 (± asymptotic standard error).

The following formula was established from the foregoing:

$$y = \frac{0.047\,x}{1 + \frac{0.047\,x}{54.385}}$$

Or:

$$y = \frac{2.556\,x}{54.385 + 0.047\,x} \tag{4}$$

This function 4 is represented in relation to the points observed (as in Table 3) in Fig. 1.

To calculate the EIL, Eq. 2 must be used. In this equation, D´ is

$$D' = \frac{P_0}{100} \cdot y = \frac{P_0}{100} \cdot \frac{2.556\,x}{54.385 + 0.047\,x} \tag{5}$$

Incorporating Eq. 5 into Eq. 2, the value of x is found to be:

$$x = \frac{54.385 \cdot C}{2.556 \cdot V \cdot P_0 \cdot K - 4.7 \cdot C} = \mathrm{EIL}(\text{aphids/m}^2) \tag{6}$$

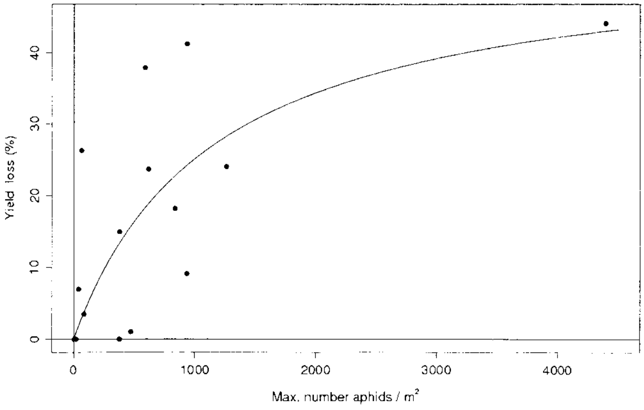

Fig. 1. Relationship of yield loss percentage in hop plants as annual maximum number of *Phorodon humuli* per square meter of canopy on the observed values.

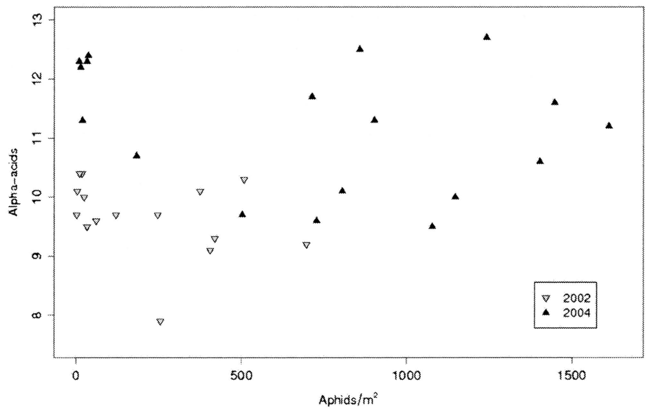

Fig. 2. Alpha-acids with respect to the annual maximum figure for *Phorodon humuli* per m^2 of bine surface.

By way of example, some current values can be assumed: C = 65 euro/ha; V = 2 euro/kg; K = 1; P_0 = 2100 kg dried hops/ha. In this case, EIL = 35 aphids/m^2.

Alpha-acids with respect to the annual maximum figure for *P. humuli* per m^2 of bine surface are given in Fig. 2. It would appear that the extent of pest infestation did not affect alpha-acid contents because the graph shows a line that is virtually horizontal. This is confirmed with the results of the regression, which are presented in Table 4. In all cases, the significance level (p) of the test for b was higher than 0.05. Since b = 0, the number of pests has no influence on alpha acid content. This implies that the yield loss associated with high aphid-density is due to a reduction in dry weight and not to a decrease in alpha-acid content.

To obtain the ET, the number of aphids per square meter was correlated with the time factor by means of Eq. 3. The results are presented in Table 5 and Fig. 3. If the EIL value obtained in the previous example (y = 35) is applied to each of these equations and the value of x is found, the y value corresponding to x – 1 will be the ET. In this way, the following figures are obtained for the ET and for the ET to EIL ratio. In 2003-A, 22 and 0.63 respectively and in the case of 2003-B 24 and 0.69. Thus, ET = 0.7 of EIL on average, which is similar to the ET used by Higley and Wintersteen (1996) who established ET at 0.8 of EIL. In this specific case, ET = 23 aphids/m^2.

Table 4. Regression coefficients and standard errors of the formula (y = a + bx) that relates alpha-acids (y) with the maximum number of aphids/m^2 (x)

	Coefficient value ± standard error		
Coefficients	Year 2002 (R^2 = 0.1020)	Year 2004 (R^2 = 0.0805)	Grouped years (R^2 = 0.0202)
a	9.8620** ± 0.2292	11.6012** ± 0.4198	10.3419** ± 0.2927
b	–0.0009 ± 0.0008	–0.0006 ± 0.0005	0.0003 ± 0.0004

* α = 5%; ** α = 1%; *** α = 0.1%

Table 5. Nonlinear regression analysis of the evolution in time of *P. humuli* number per m² of hop canopy, on the real observations, in the treatments A3 and B3 of the year 2003

Treatment	Parameter	Parameter value ± standard error
A3	a	5653.6 ± 1449.5
	b	168.8 ± 0.5949
	c	2.1640 ± 0.5433
B3	a	4503.3 ± 811.8
	b	168.5 ± 0.5333
	c	2.6249 ± 0.5564

Higley and Wintersteen (1996) obtain a figure for EEIL, and then for EET, representing a pest density higher than that of ET. The average ratio of EET to ET for all the insecticides reported by those authors was 1.66. In this work, the environmental costs of the different aphicides which could be used were not calculated due to their complexity. However, it does seem necessary to account for them in some way. Hence, whereas in-depth studies are pending, we propose that an approximate figure for environmental thresholds based on the Higley and Wintersteen (1996) results be used. Such figures could be used as approximate values for each insecticide:

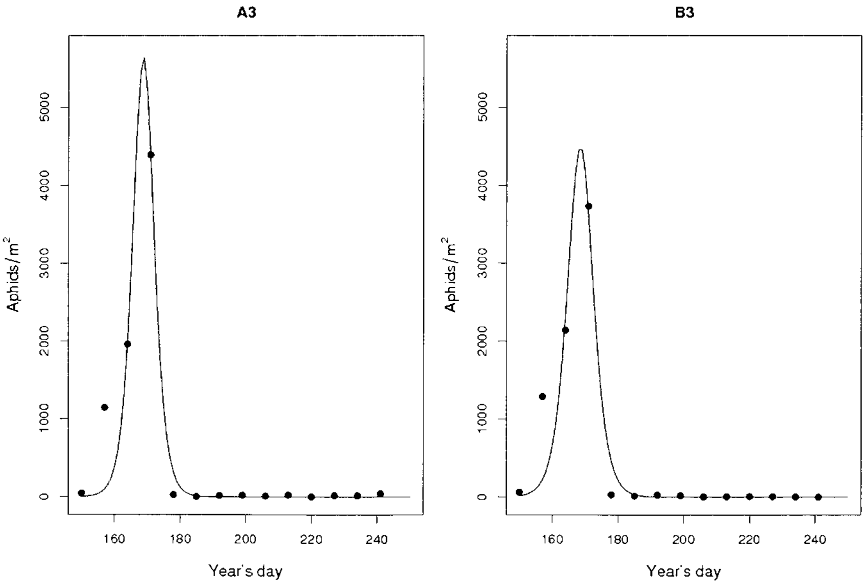

Fig. 3. Theoretical graphs according the Eq. [3] for evolution in time of *Phorodon humuli* number per m² of hop canopy, on the real observations in the treatments A3 and B3 of the year 2003.

Table 6. Economic thresholds for *P. humuli* on hop obtained through different methods in an example case*

Index	Formula	EIL	EEIL (1.66 EIL)	ET (0.7 ET)	EET (1.16 EIL)
Aphids/m^2	x	35	58	23	38
Aphids/leaf	$x_1 = 0.016\ x$	0.56	0.93	0.37	0.61
% attacked leafs	$x_2 = 0.297\ x$	10.4	17.23	6.83	11.29
Attacked leafs/frame	$x_3 = 0.012\ x$	0.42	0.7	0.28	0.46
Index of attack	$x_4 = 0.011\ x$	0.39	0.64	0.25	0.42
% occupied frames	$x_5 = 0.663\ x$	23.21	38.45	15.25	25.19
Aphids/dm^2 leaf	$x_6 = 0.015\ x$	0.53	0.87	0.35	0.57
Aphids/20 cm high volume	$x_7 = 0.274\ x$	9.6	15.9	6.3	10.41
Aphids/hop bine	$x_8 = 7.333\ x$	256.66	425.31	168.66	278.65

* Insecticide cost = 65 €/ha. Hop price = 2 €/kg dried hops. Insecticide efficacy = 1. Yield with minimum pest = 2100 kg/ha.

EET ≅ 1.66 ET ≅ 1.16 EIL; EEIL ≅ 1.66 EIL. In the example, this would lead to figures of EEIL ≅ 58 aphids/m^2; EET ≅ 38 aphids/m^2.

All thresholds are expressed as the number of aphids per square meter given that this is considered the most accurate way of expressing pest density. However, the simplified methods mentioned in the introduction, perhaps easier to apply in the field, use other types of units. The values obtained for each method have been correlated by regression with the corresponding values of number of aphids per square meter up to 100. This is because up to that figure the functions behave as straight lines and, as has already been demonstrated, the thresholds in this work did not exceed 70 aphids per square meter. The equations derived and the 4 thresholds obtained by each of the different methods in the case of the example proposed earlier are given in Table 6 (x_1 to x_8).

Consequently, growers should follow the following 4 steps: (1) apply Eq. 6 to their figures for total insecticide costs, the price of hops, product efficacy and production per ha of hop garden to obtain the EIL; (2) multiply the EIL by 1.16 to get the EET, expressed as the number of *P. humuli* per square meter of hop bine; (3) if growers prefer using a measurement index which is simpler than number of aphids per m^2, they could apply the EET value to the equation from Table 6 which relates the number of aphids per m^2 with the selected index, and (4) when pest density reaches the EET, treat within 24 h to prevent this density from exceeding EEIL.

Finally, it is important to stress that the EIL and ET values in this project should not be considered static because a large number of variables are involved in their calculation. These include phenology, geographic zone, presence and abundance of natural enemies, variety, climate factors, features of agriculture and expected crop price. Strictly speaking, the thresholds for each place and year should be calculated individually. However, the relativity of the thresholds proposed should not take away from their utility as they constitute a key element in integrated pest management in hops.

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