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Re-evaluating the Economic Injury Level for Alfalfa Weevil (Coleoptera: Curculionidae) Control in Low Desert Irrigated Alfalfa

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Abstract

Alfalfa (*Medicago sativa* L.) dominates cropping systems in the Western United States and is first in terms of acreage planted in Arizona. The alfalfa weevil, *Hypera postica* (Gylenhall) and/or *Hypera brunneipennis* (Boheman), respectively, is the most destructive pest in terms of yield loss in low desert-grown alfalfa hay. The current economic threshold of 15–20 larvae per sweep, established in California in 1975, is currently not suitable or adopted by growers in the western U.S. low desert. Here, we conducted 4 yr of field trials to re-evaluate this economic threshold. Supporting observations of agricultural growers and professionals in the region, our results indicate that the economic threshold established in 1975 is too high. Specifically, one to three large larvae often cause a significant decrease in yield justifying weevil control based on current hay prices and costs of insecticide application. These results are discussed in the context of sustainable alfalfa production in the western U.S. low desert.

Key words: Alfalfa weevil, economic threshold, integrated pest management, economic injury level

Alfalfa (*Medicago sativa* L.) is the third most valuable field crop produced in the United States after corn and soybean (USDA National Agricultural Statistics Service (USDA NASS) 2019). Alfalfa is an important commodity for dairy and livestock enterprises and dominates the cropping systems in the Western United States. In the low desert of southwestern Arizona, over 280,000 acres of irrigated alfalfa is grown annually, producing on average 9–10 cuttings and over 10 tons/acre/yr (Murphree 2016, USDA NASS 2019). Due to the slow growth of the crop from November to February, the longest period between harvests is before the first cut of the year. After the first cut, warmer temperatures generally promote quick regrowth after cuttings and many growers begin to cut every 28 d for contracts (personal communication with growers accounting for over 100,000 acres).

The alfalfa weevil and Egyptian alfalfa weevil denote two separate, morphologically identical species, *Hypera postica* (Gyllenhal) and *Hypera brunneipennis* (Boheman), respectively, with the former species comprising at least two strains (Bundy et al. 2005, Godfrey et al. 2017). There is uncertainty about the distribution of *H. postica* and *H. brunneipennis* in the Western United States. Here, following Pellissier et al. (2017), we refer to these species collectively as 'alfalfa weevil'. Alfalfa weevil is not native to the United States and there have been three identified introductions; Utah (Titus 1910), Arizona (Wehrle 1940), and Maryland (Poos and Bissell 1953). It is a pest in all regions where alfalfa is grown in the United States, although populations in the northeastern states are often maintained below economic threshold by a complex of parasitic wasps (Kuhar et al. 2000, Tooker 2018).

The alfalfa weevil is the most destructive arthropod in terms of yield loss in low desert-grown alfalfa hay in the first cut of the year and depending on altitude may also be present in the second and third cuttings (Mostafa 2019). Alfalfa weevil larvae feed on leaves, quickly leading to skeletonizing of the plant. Adults also feed on leaves, but larvae cause most damages (Radcliffe and Flanders 1998, Pierce and Marsalis 2013, Rim et al. 2020). In the low desert regions of the southwestern United States, the alfalfa weevil often completes a single generation per year during the cooler temperatures that coincide with the first cutting (Godfrey et al. 2017). As temperature increases, weevils enter estivation to avoid mortality at temperatures close to 35°C (Hsieh and Armbrust 1974). On average, the low desert growing regions of Arizona reach high temperatures of 30°C in April and 34.4°C in May (NOAA 2020).

An economic threshold (ET) refers to the pest density that justifies population control actions to avoid economic yield loss (Pedigo et al. 1986). The economic threshold (ET) is often set at 50–75% of the economic injury level (EIL), which is the lowest pest density that causes an economic yield loss equal to the cost of actions taken to reduce the pest population (Pedigo et al. 1986, Plant 1986, Diane 2011). Koehler and Rosenthal (1975) analyzed the EIL of the alfalfa weevil in Tulare, Yolo, and Siskiyou counties of California. These counties are in central, north central, and northern California, respectively. The environmental conditions most similar to the low desert regions of Arizona occur in Tulare. From the analysis in Koehler and Rosenthal (1975), an ET of 15–20 larvae per 180° sweep was adopted in the low desert region of the Southwest United States (Evans 1989; Blodgett 1996; Knowles 1998; UC IPM 2017, 2018, 2019; Long et al. 2017; Pellissier et al. 2017).

Interaction with growers and pest control advisors (PCAs) in Arizona indicated a concern that the ET of 15–20 larvae per sweep for the alfalfa weevil is too high (personal communication). Indeed, alfalfa weevil densities lower that 15–20 larvae per sweep currently result in significant yield losses in the low desert southwest region (personal communication with growers accounting for over 100,000 acres). This ET may be too high at least in part because the monetary value of alfalfa has increased since 1975 and current alfalfa varieties yield more than old ones (Long 2017). The goal of this study was to reevaluate the EIL for the alfalfa weevil in low desert irrigated alfalfa grown in Arizona. We conducted 4 yr of trials, which indicates that an EIL of one to three large larvae per sweep is more appropriate under current agronomic conditions for alfalfa cultivation.

Materials and Methods

Alfalfa Crop

Four years of trials were conducted at the Maricopa Agricultural Center (MAC) in Maricopa, Arizona. Years of trials were 2014, 2015, 2017, and 2018. In all years, one alfalfa field was subdivided into 24 plots of 7.6 × 6.1 m separated by 3-m alleys. The fields were unfertilized and flood irrigated with 4.65 m/ha of water per year in accordance with recommendations from the Arizona Forage and Grain Crops Information (Ottman 2020). There was one irrigation event during each trial. The 2014 and 2015 trials were conducted on a second and third year stand of the CUF101 variety sourced from Fertizona (Fertizona, Casa Grande, AZ). The 2017 trial was conducted on a second year stand of 'Saltbuster' also marketed by Fertizona (Fertizona, Casa Grande, AZ). The 2018 trial was conducted on a second year stand of Alforex PGI 908-S (Alforex Seeds, Woodland, CA). All trials were conducted on the first cut of the season. Insecticide treatments were applied on 5 February in the 2014 trial, 28 January for the 2015 trial, 26 January for the 2017 trial, and 2 March for the 2018 trial. Alfalfa was harvested approximately 4–5 wk later (see below) when the crop had ca.10% bloom to align with regional standards.

Experimental Design

In each year, six different insecticide treatments including untreated (control) plots were applied in a randomized complete block design with four replications (4 plots per treatment; 24 plots per trial) to generate variation in alfalfa weevil density (Supp Table 1 [Online only]). Hereafter, we refer to plots receiving different insecticide treatments as plot types. The specific insecticides and rates were chosen based on knowledge of their efficacy in the southwest region (Mostafa and Natwick 2015). The insecticides used in the trials have broad spectrum activity and cause acute nerve poisoning. These insecticides have low persistence times in the environment and result in quick mortality with the longest product re-entry interval of 24 h. Thus, individuals still alive a few days following the insecticide treatments are unlikely to have suffered sublethal effects affecting their damaging potential to alfalfa. Insecticides were applied using a modified John Deere 6500 tractor with a multi boom spray implement. TeeJet 8003 twin fan nozzle tips spaced 50.8 cm apart applied the insecticides at a carrier rate of 187 L/ha. Weekly pretreatment sampling was conducted by separating the whole field into four sections (i.e., quadrants) and taking five sweeps from each quadrant. A single insecticide application was applied as soon as larvae were detected in each quadrant. In 2014 and 2015, plots treated with insecticides and control plots were simultaneously treated with Transform (active ingredient sulfoxaflor), a selective insecticide used to control aphids that can reduce alfalfa yield. In 2017 and 2018, all plots were similarly treated with Sivanto (active ingredient flupyradifurone), a selective insecticide used for aphid control.

Weevil Sampling

Following insecticide treatments, plots were sampled for 5 wk at weekly intervals taking five 180° sweeps (0.4-m diameter sweep net) per plot. Samples were placed in plastic re-sealable bags in coolers for transportation to the lab where they were stored in a −20°C freezer. For each sample, weevil larvae were sorted as 'small' (first and second instars), 'large' (third and older instars), or 'adults' (Supp Figs. 1 and 2 [Online only]).

Yield Estimation at Harvest

Plots were harvested with a Carter self-propelled flail harvester with a 0.9-m wide harvesting path. The 2014 trial was harvested on 12 March, the 2015 trial on 24 February, the 2017 trial on 9 March, and the 2018 trial on 4 April. The Carter harvester had a free-floating calibrated basket scale where the harvested alfalfa was transferred via a chute. One pass from the middle of each plot spanning the entire 7.6 m of the plot was used to capture the fresh weight of the 7 m^2 sampled. Fresh yields were converted into hay yield (tons/acre) with 12% moisture content. The 7 m^2 of fresh cut was converted into pounds (lbs) per acre. From Orloff et al. (1997), alfalfa moisture content in the field ranges from 75 to 80% moisture (or 25 to 20% dry matter). We assumed that the dry matter content was 20%, as the fields were harvested in the cooler growing season when most moisture is retained by plants. We estimated weight of hay (tons per acre) with 12% moisture for each sample using the equation: (fresh weight per acre in lbs.) (0.2/(2,000 × 0.88)).

Data Analysis

For each life stage (i.e., small larvae, large larvae, adults), a covariance analysis was used to evaluate the association between the mean density of weevils and mean yield. The response variable in these analyses was mean yield for each plot type, and explanatory variables were mean density of a life stage for each plot type, year, and the density × year interaction. Mean yield for the plot types was calculated by averaging yield of the four replicates. Mean density of the life stages for the plot types were calculated in two steps. First, for each life stage and plot type, weekly averages of the four replicates were calculated. Second, for each life stage and plot type, the mean of the weekly averages (*n* = 5 across the sampling period) was calculated. For each year, we used linear regression to evaluate the association between mean density of the life stages and mean yield. Because the slope of the association between density of large larvae and yield was consistent across years (see Results), we also used linear regression to evaluate the association between mean density of large larvae and mean yield for data pooled across the 4 yr. Statistical analyses were performed in JMP (version 14.2, SAS Institute Inc. NC).

Decision Tables

We used the slope of the linear association between the mean density of the large larvae and mean yield for the pooled data, as well as the 95% CI associated with this slope, to build decision tables (e.g., Cronholm et al. 2007, Reza Hassani et al. 2009, Porter et al. 2010). These tables indicate whether application of an insecticide is justified based on the sampled density of large larvae, cost of the insecticide treatment and value of alfalfa. EIL's for these tables were calculated using Microsoft Excel (Version 16.0.1 Microsoft Corporation, WA), using equation 1 in Diane (2011) modified from Pedigo et al. (1986):

$$EIL = \left(\frac{C}{V}\right)\left(\frac{I}{L}\right),$$

where *EIL* is the density of large larvae causing a loss of value equal to the cost of treatment, *C* is the cost of an insecticide treatment ($USD per acre), *V* is the market value of hay ($USD per ton), and *L* the yield loss corresponding to a one unit increase in the density of large larvae (tons / acre × 1 /density of larvae). *L* was estimated by the slope (and 95% CI) from the above linear association for pooled data. For each combination of *L*, *C*, *V*, and *EIL*, the decisions tables indicate whether application of an insecticide is economically justified (i.e., EIL smaller than the sampled density of large larvae), not justified (i.e., EIL greater than the sampled density of large larvae), or equivocal (i.e., EIL equal to the sampled density of large larvae).

Results

Means and associated standard errors for density of each life stage and yield of the plot types are shown in Supp Tables 2–5 (Online only). In analyses of effects of density, year, and the interaction between these factors on yield for each life stage, yield varied significantly among years (Table 1, *P*-values < 0.0001). The association between density and yield was negative for each life stage (Table 1, *P*-values ≤ 0.0005). The slope (SE) of this general association was −0.302 (0.084), −0.076 (0.015), and −1.04 (0.315) for small larvae, large larvae and adults, respectively (Table 1). The slope of the negative association between density and yield was similar across years for large larvae (Table 1, density × year interaction, $P = 0.087$) and adults ($P = 0.15$), but not for small larvae ($P = 0.011$).

For both small and large larvae, a significant negative association occurred between density and yield in 2015 and 2017, although the negative associations for 2014 and 2018 were not significant (Table 2, Fig. 1; Supp Fig. 3 [online only]). For adults, the negative association between density and yield was not significant in any years (Table 2; Supp Fig. 4 [online only]).

The negative slope between density and yield was more consistent across years for large than small larvae (Tables 1 and 2). Furthermore, for specific years, the association between density and yield was stronger for large larvae than adults, as shown by the larger coefficient of determination (R^2) for large larvae than adults in each year (Table 2). Accordingly, we used the slope of the association between density and yield for large larvae to estimate L (see Materials and Methods, Decision Tables). For data pooled over the four years, there was a significant negative association between density of the large larvae and yield ($P < 0.0001$, $R^2 = 81\%$). The slope (SE) of this association was −0.060 (0.012). The 95% CI for this slope had lower and upper limits of −0.084 and −0.036, respectively. Based on this, we used 0.060 as the most likely value of L, although we also considered 0.036 and 0.084 as plausible lower and upper values for the rate of decline in yield when constructing decision tables.

Decision tables based on $L = 0.060$ and a number of sampled large larvae ranging from 1 to 3 per sweep are presented in Figs. 2–4. As the number of sampled larvae increases from 1 to 3, application of an insecticide for alfalfa weevil control becomes economically justified for and increasing number of combinations of crop values (*X*-axis) and insecticide costs (*Y*-axis). The decision table based on $L = 0.60$ and a number of sampled large larvae of 4 indicates that application of an insecticide is justified for all but 3 combinations of low crop values (i.e., $150, 160, and 170/ton) and high insecticides cost (i.e., $40 per acre) (table not shown). Thus, decisions tables based on a sampled density of 1–3 large larvae (Figs. 1–3) are adequate to evaluate the need for application of an insecticide under current agronomic conditions for alfalfa cultivation.

For a given number of sampled large larvae from 1 to 3, decision tables based on $L = 0.036$ reduce the number of cases justifying use of an insecticide (Supp Tables 6–8 [Online only]), whereas decision tables based on $L = 0.084$ increase the number of cases justifying use of an insecticide (Supp Tables 9–11 [Online only]). Importantly, for

Table 1. Results from covariance analysis assessing association between yield (tons/acre at 12% moisture) and year, density of each life stage, and the interaction between these factors

Life stage	Effect	df	*F*	*P*	R^2(%)
Small larvae	Year	3	51.3	<0.0001	82
	Density	1	12.9	0.0005	
	Year × Density	3	4.0	0.011	
Large larvae	Year	3	65.3	<0.0001	83
	Density	1	24.0	<0.0001	
	Year × Density	3	2.3	0.087	
Adults	Year	3	43.6	<0.0001	80
	Density	1	10.9	<0.0001	
	Year × Density	3	1.8	0.150	

Table 2. Result for simple regression analyses assessing the association between yield (tons/acre at 12% moisture) and density of each life stage for trial years 2014, 2015, 2017 and 2018

Year	Slope	SE	Upper 95% CI	Lower 95% CI	*P*	R^2 (%)
Small Larvae						
2014	−0.09	0.05	0.05	−0.22	0.14	46
2015	−0.07	0.02	−0.02	−0.13	0.02	76
2017	−0.17	0.04	−0.07	−0.26	0.01	85
2018	−2.17	1.061	0.78	−5.11	0.11	51
Large Larvae						
2014	−0.04	0.02	0.01	−0.08	0.08	57
2015	−0.14	0.02	−0.08	−0.21	0.004	90
2017	−0.12	0.03	−0.04	−0.20	0.01	82
2018	−0.10	0.07	0.09	−0.28	0.23	33
Adults						
2014	−1.54	0.82	0.73	−3.80	0.13	47
2015	−1.48	1.31	2.16	−5.12	0.32	24
2017	−2.40	1.66	2.21	−7.02	0.22	34
2018	−0.46	0.47	0.86	−1.77	0.39	19

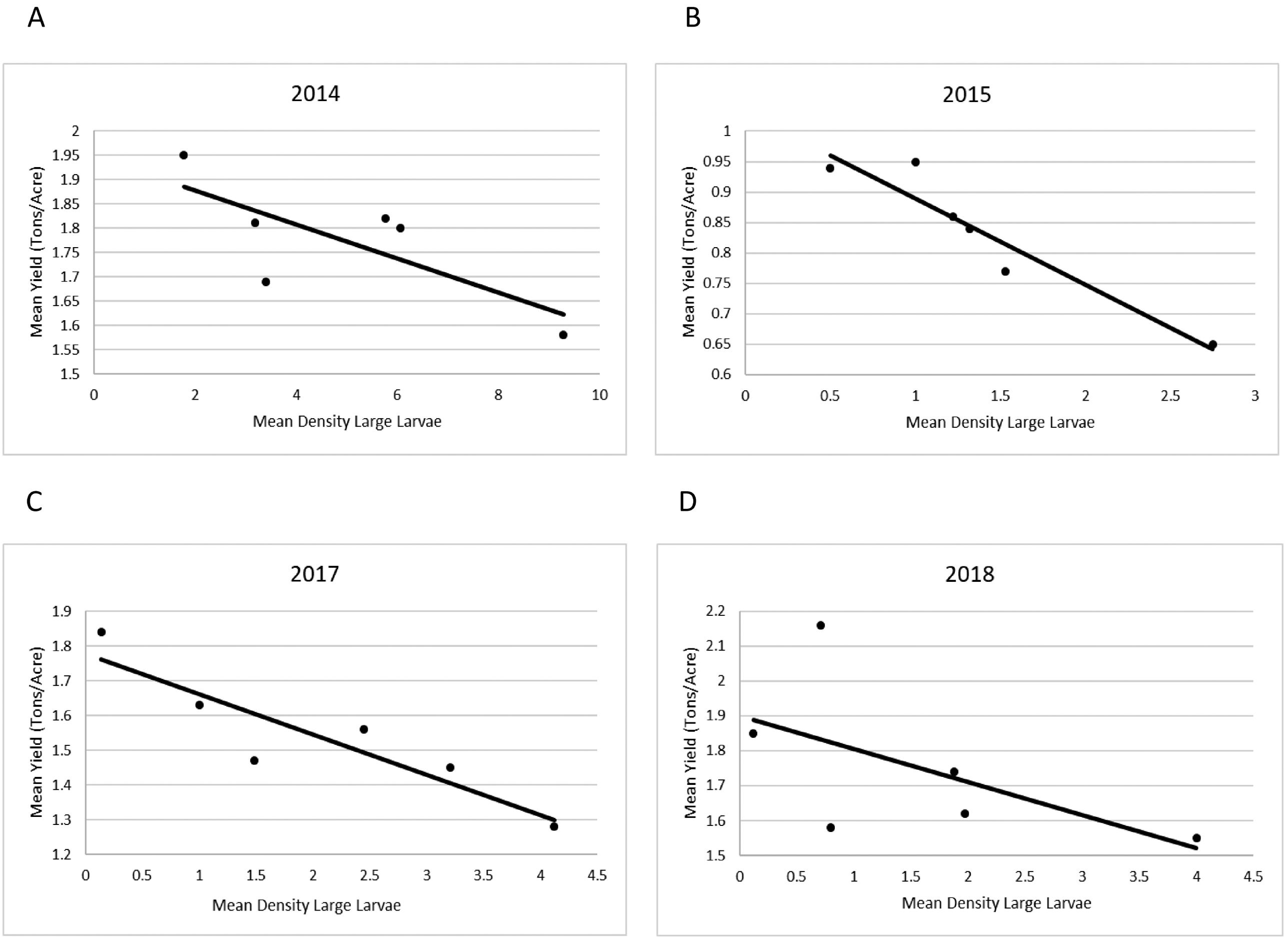
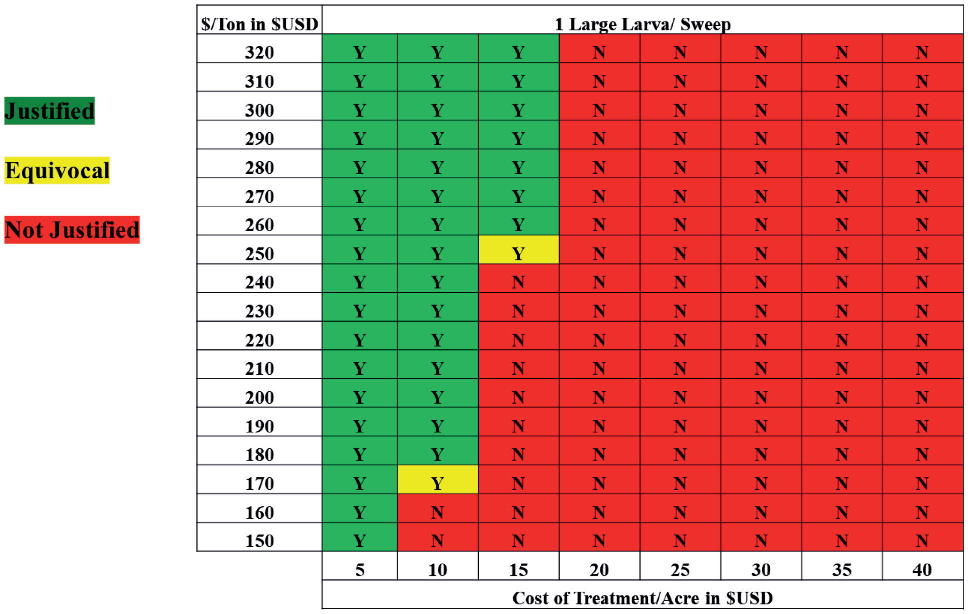


Fig. 1. Association between mean density of large larvae and mean yield in 2014 (A), 2015 (B), 2017 (C), and 2018 (D). Each point corresponds to the mean yield and seasonal average of larval density for each plot type (see Supp Table S1 [online only] for plot type labels). Note that the scale of the X and Y axis differ among figures. The regression lines are shown even if the slope was not significantly different from 0 (see Table 2 for significance of the slopes).



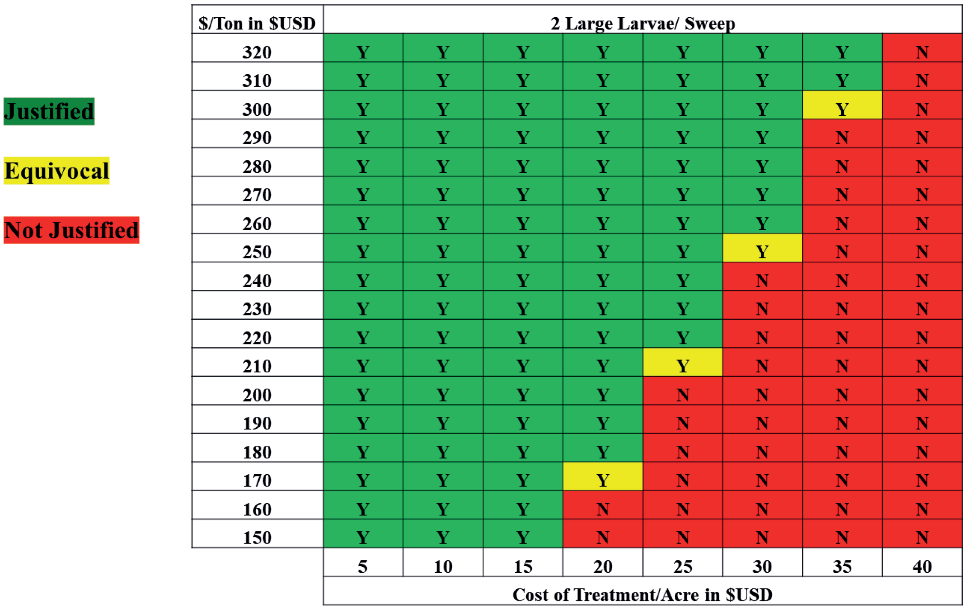
🟩 Justified

🟨 Equivocal

🟥 Not Justified

$/Ton in $USD	1 Large Larva/ Sweep							
320	Y	Y	Y	N	N	N	N	N
310	Y	Y	Y	N	N	N	N	N
300	Y	Y	Y	N	N	N	N	N
290	Y	Y	Y	N	N	N	N	N
280	Y	Y	Y	N	N	N	N	N
270	Y	Y	Y	N	N	N	N	N
260	Y	Y	Y	N	N	N	N	N
250	Y	Y	🟨 Y	N	N	N	N	N
240	Y	Y	N	N	N	N	N	N
230	Y	Y	N	N	N	N	N	N
220	Y	Y	N	N	N	N	N	N
210	Y	Y	N	N	N	N	N	N
200	Y	Y	N	N	N	N	N	N
190	Y	Y	N	N	N	N	N	N
180	Y	Y	N	N	N	N	N	N
170	Y	🟨 Y	N	N	N	N	N	N
160	Y	N	N	N	N	N	N	N
150	Y	N	N	N	N	N	N	N
	5	10	15	20	25	30	35	40
	Cost of Treatment/Acre in $USD							

Fig. 2. Decision table for estimated density of large weevil larva per sweep close to 1, when L used in calculation of the EIL was 0.060, the best estimate of the slope of the association between mean density of large larvae and mean yield (see Results). Value of hay ($USD per ton) is shown on the *X* axis and cost of the insecticide treatment ($USD per acre) on the *Y* axis. GREEN signifies that a treatment is justified because the EIL is smaller than 1 larva per sweep, YELLOW indicates an equivocal decision because the EIL is equal to 1, and RED denotes that a treatment is not justified because the EIL is greater than 1 larva per sweep. Estimated value of hay is $180 per ton (USDA, NASS).



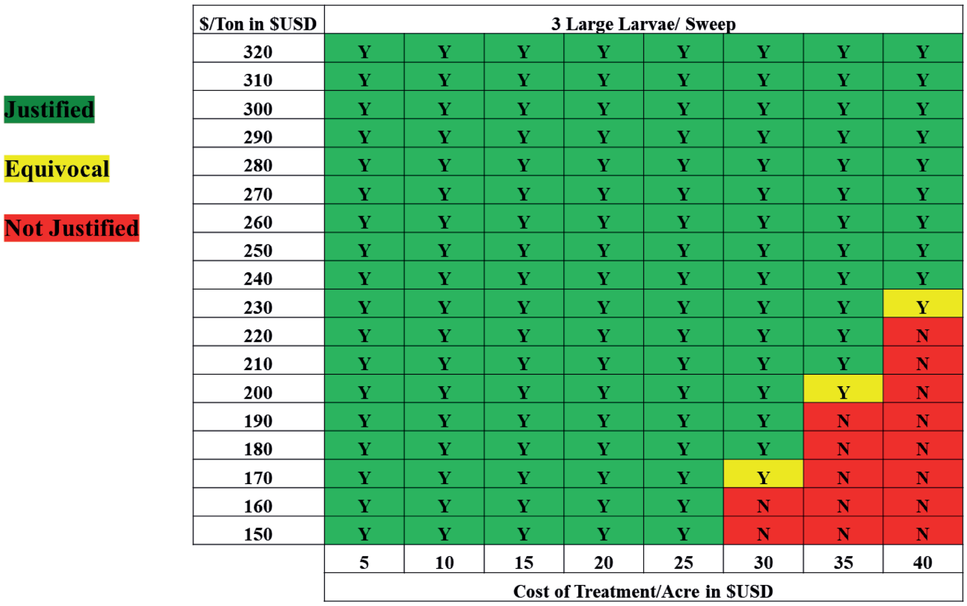
🟩 **Justified**

🟨 **Equivocal**

🟥 **Not Justified**

$/Ton in $USD	2 Large Larvae/ Sweep							
320	Y	Y	Y	Y	Y	Y	Y	N
310	Y	Y	Y	Y	Y	Y	Y	N
300	Y	Y	Y	Y	Y	Y	🟨 Y	N
290	Y	Y	Y	Y	Y	Y	N	N
280	Y	Y	Y	Y	Y	Y	N	N
270	Y	Y	Y	Y	Y	Y	N	N
260	Y	Y	Y	Y	Y	Y	N	N
250	Y	Y	Y	Y	Y	🟨 Y	N	N
240	Y	Y	Y	Y	Y	N	N	N
230	Y	Y	Y	Y	Y	N	N	N
220	Y	Y	Y	Y	Y	N	N	N
210	Y	Y	Y	Y	🟨 Y	N	N	N
200	Y	Y	Y	Y	N	N	N	N
190	Y	Y	Y	Y	N	N	N	N
180	Y	Y	Y	Y	N	N	N	N
170	Y	Y	Y	🟨 Y	N	N	N	N
160	Y	Y	Y	N	N	N	N	N
150	Y	Y	Y	N	N	N	N	N
	5	10	15	20	25	30	35	40
	Cost of Treatment/Acre in $USD							

Fig. 3. Decision table for estimated density of large weevil larva per sweep close to 2, when L used in calculation of the EIL was 0.060, the best estimate of the slope of the association between mean density of large larvae and mean yield (see Results). Value of hay ($USD per ton) is shown on the *X* axis and cost of the insecticide treatment ($USD per acre) on the *Y* axis. GREEN signifies that a treatment is justified because the EIL is smaller than 2 larva per sweep, YELLOW indicates an equivocal decision because the EIL is equal to 2, and RED denotes that a treatment is not justified because the EIL is greater than 2 larva per sweep.



🟩 **Justified**

🟨 **Equivocal**

🟥 **Not Justified**

$/Ton in $USD	3 Large Larvae/ Sweep							
320	Y	Y	Y	Y	Y	Y	Y	Y
310	Y	Y	Y	Y	Y	Y	Y	Y
300	Y	Y	Y	Y	Y	Y	Y	Y
290	Y	Y	Y	Y	Y	Y	Y	Y
280	Y	Y	Y	Y	Y	Y	Y	Y
270	Y	Y	Y	Y	Y	Y	Y	Y
260	Y	Y	Y	Y	Y	Y	Y	Y
250	Y	Y	Y	Y	Y	Y	Y	Y
240	Y	Y	Y	Y	Y	Y	Y	Y
230	Y	Y	Y	Y	Y	Y	Y	🟨 Y
220	Y	Y	Y	Y	Y	Y	Y	N
210	Y	Y	Y	Y	Y	Y	Y	N
200	Y	Y	Y	Y	Y	Y	🟨 Y	N
190	Y	Y	Y	Y	Y	Y	N	N
180	Y	Y	Y	Y	Y	Y	N	N
170	Y	Y	Y	Y	Y	🟨 Y	N	N
160	Y	Y	Y	Y	Y	N	N	N
150	Y	Y	Y	Y	Y	N	N	N
	5	10	15	20	25	30	35	40
	Cost of Treatment/Acre in $USD							

Fig. 4. Decision table for estimated density of large weevil larva per sweep close to 3, when L used in calculation of the EIL was 0.060, the best estimate of the slope of the association between mean density of large larvae and mean yield (see Results). Value of hay ($USD per ton) is shown on the *X* axis and cost of the insecticide treatment ($USD per acre) on the *Y* axis. GREEN signifies that a treatment is justified because the EIL is smaller than three larva per sweep, YELLOW indicates an equivocal decision because the EIL is equal to 3, and RED denotes that a treatment is not justified because the EIL is greater than three larva per sweep.

the range of L values used in decision tables, an insecticide treatment was economically justified for many realistic combinations of crop values and insecticide costs, indicating that an EIL of one to three large larvae per sweep is appropriate under current agronomic conditions for alfalfa cultivation.

Discussion

Analyses of data considering year, alfalfa weevil density and the interaction between these factors show that increased density of small larvae, large larvae or adults was associated with reduced yield. However, contrary to large larvae and adults, the slope of the association between density and yield varied significantly across years for small larvae. Larvae cause more plant skeletonization than adults (Radcliffe and Flanders 1998, Pierce and Marsalis 2013, Rim et al. 2020). A weaker association between density and yield occurred for adults than small or large larvae in individual years. Based on these results, we used the slope of the association between density of large larvae and yield to estimate *L* (i.e., the yield loss corresponding to a one unit increase in density) and build decision tables for alfalfa weevil management. Another reason for using the density of large larvae for decision making is that large larvae are easier to count than small larvae in sweep nets. Decision tables based on numbers of sampled large larvae from 1 to 3 larvae per sweep and plausible estimates of *L* (i.e., the above-mentioned slope and its associated lower and upper 95% CI) show that an insecticide treatment was economically justified for several reasonable combinations of crop values and insecticide costs. Thus, we conclude that an EIL of one to three large larvae per sweep is appropriate for alfalfa weevil management in low desert-grown alfalfa hay under current agronomic conditions.

Our results demonstrate that fewer than 15–20 alfalfa weevil larvae per sweep can significantly reduce alfalfa yield. Using the most likely estimate of the slope for the association between density of large larvae and yield (i.e., $\beta = -0.060$), we find that each unit increase in the density of large larvae per sweep reduced yield by 120 lb/ton/acre at 12% moisture. The limits of the 95% CI for this slope (i.e., −0.036 and −0.084) indicate that such decrease in yield could vary between 72 and 168 lb/ton/acre at 12% moisture, respectively.

While the ET is typically set lower than the EIL, we propose here to use an ET equal to our estimated EIL (i.e., 1–3 large larvae per sweep) for decision making, as this new ET is considerably lower than the previously-proposed ET of 15–20 larvae. Using and ET of 1–3 large larvae rather than 15–20 larvae may ultimately increase use of insecticides applied for alfalfa weevil control. Nevertheless, if fields are treated with effective insecticides, a single treatment could be sufficient to protect all vulnerable alfalfa stands. Because weevils only complete their life cycle under relatively cool temperatures (Hsieh and Armbrust 1974), they are a threat primarily for the first and possibly second and third cuts of the year in the low desert Southwest United States (Godfrey et al. 2017). Three classes of insecticides (organophosphates, pyrethroids/pyrethrins, and an oxadiazine) are currently labeled and efficacious for alfalfa weevil control. While oxadiazine insecticides are semiselective (Michaud and Grant 2003), organophosphates and pyrethroids/pyrethrins have broad-spectrum activity, which may negatively impact pollinators and natural enemies that are common in alfalfa and important for pest control in other crops (Summers 1998, Godfrey et al. 2017, Wang et al. 2019). In regions where the alfalfa weevil in abundant, insecticides could be needed in most years in some fields to protect the first cuts. In this context, it will be important to rotate the insecticide modes of action across years to reduce the risk of evolution of resistance (Orloff et al. 2016, Walsh and Forrence 2019) and develop tactics other than chemical control for reducing weevil populations (Ouayogode and Davis 1981, Bryan et al. 1993, Brewer et al. 1997, Rand 2013). Cutting early when weevils are abundant is a cultural practice that may be used in place of chemical treatments. However, weevil larvae can move under the windrows and continue feeding on alfalfa, which further reduces yield and impedes regrowth (Hutchins et al. 1990, Godfrey et al. 2017).

Many alfalfa varieties are nondormant and suitable for low desert conditions. Extending our trials to other varieties could be useful to refine use of the ET proposed here. Our study only considered the first cut of second- and third-year stands. Without application of a fertilizer at the time of planting, the first cut of the year for a first-year stand is delayed and typically has low yield at our study site. Because application of fertilizers is recommended and economical (Jung and Smith 1959; Berg et al. 2005, 2007), further work considering the ET of first-year stands fertilized at planting is warranted. Our trials were performed on flood irrigated alfalfa. More research is required for farms utilizing subsurface drip and above ground linear or center pivot irrigated technologies. Above ground linear and center pivot irrigations simulate 'rainfall', which perhaps could disrupt larval feeding as the system passes over the crops. The ET for alfalfa irrigated with an above ground irrigation system could thus be higher than for flood irrigated alfalfa.

The alfalfa weevil comprises two separate morphologically identical species, *Hypera postica* and *Hypera brunneipennis*, with the former species including an eastern and western strain (Erney et al. 1996, Godfrey et al. 2017). There is also at least one undescribed strain (possibly *Hypera postica*) that was discovered in New Mexico in 2005 (Bundy et al. 2005). Each species and strains have different behavioral, ecological, and physiological characteristics, including differences in location of estivation (i.e., inside or outside alfalfa fields) (Bundy et al. 2005, Böttger et al. 2013). It is currently unknown whether these species and strains have similar impacts on yield. A better characterization of the impact of these species and strains on yield and of potential regional variation in the composition of alfalfa weevil populations could help refine decisions about applications of insecticides to avoid economic yield loss.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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