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Author(s): Kelly Hamby, Ling Wang Gao, Bruce Lampinen, Thomas Gradziel, and Frank Zalom

Source: Journal of Economic Entomology, 104(3):965-969.
Published By: Entomological Society of America
DOI: http://dx.doi.org/10.1603/EC10396
URL: http://www.bioone.org/doi/full/10.1603/EC10396

Hull Split Date and Shell Seal in Relation to Navel Orangeworm (Lepidoptera: Pyralidae) Infestation of Almonds

KELLY HAMBY,[1,2] LING WANG GAO,[3] BRUCE LAMPINEN,[4]
THOMAS GRADZIEL,[4] AND FRANK ZALOM[1]

J. Econ. Entomol. 104(3): 965–969 (2011); DOI: 10.1603/EC10396

ABSTRACT Hull split date, shell seal, and navel orangeworm, *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), infestation data for 19 varieties of almonds, *Prunus dulcis* (Mill.) D.A.Webb, were analyzed to determine the relationship of shell seal and hull split date on *A. transitella* infestation. Data for all varieties were collected from three University of California regional almond variety trials from 2003 to 2005, with a total of 8,550 nuts evaluated. A significant negative relationship was found between percentage of shell seal and percentage of navel orangeworm infestation, with lower percentage of shell seal correlating to higher percentage of infestation. Similarly, hull split date was negatively correlated with percentage of infestation, with later splitting varieties trending toward lower percentage of infestation. Although there are outlying varieties, hull split and shell seal are indeed significant components in varietal differences in almond navel orangeworm infestation. Understanding such factors gives insight into both the predictive value of almond characteristics related to navel orangeworm damage as well as other potential indicators.

KEY WORDS navel orangeworm, *Amyelois transitella*, almonds, hull split, shell seal

First found in California in the late 1940s (Michelbacher and Davis 1961, Wade 1961) the navel orangeworm, *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), became devastating to the California almond, *Prunus dulcis* (Mill.) D.A.Webb, industry in the late 1970s (Higbee and Siegel 2009). Although control measures were developed to lessen economic damage by navel orangeworm (Curtis and Clark 1979, Engle and Barnes 1983, Zalom et al. 1984, Welter et al. 1987), damage tolerance is lower presently due to reduced thresholds for aflatoxin and industry price structures (Higbee and Siegel 2009). This has led to renewed research interest in *A. transitella* (Burks et al. 2008, Higbee and Burks 2008, Palumbo et al. 2008, Beck et al. 2009, Higbee and Siegel 2009, Liu et al. 2010).

Almond shell seal and hull split have been implicated in varietal susceptibility to *A. transitella* damage (Crane and Summers 1971, Curtis and Barnes 1977, Soderstrom 1977). Crane and Summers (1971) first reported a relationship between hard and soft shell almonds and navel orangeworm damage, which was further investigated in terms of shell seal by Soderstrom (1977) who developed quantitative measurement of shell seal by using an air probe that assessed the permeability of the shell. He reported seal quality as the airflow (cubic centimeters per minute) through the shell for nine varieties of almonds and determined that there was a relationship between percentage of almond rejects and seal quality. This has not become a widely accepted method for measuring percentage shell seal owing to inconsistent data measurements. For the past 20 yr, almond phenologists have measured percentage of shell seal as the percentage of almonds that have a split >0.5 mm wide.

Soderstrom (1977) also suggested that *A. transitella* infestation increases dramatically after hull split as the navel orangeworm attacks the almond at or near hull split (Curtis and Barnes 1977). Although varieties used in the 1970s are now a minor portion of overall almond production (other than 'Nonpareil') (Anonymous 2010), shell seal and hull split date continue to be regarded as significant in almond navel orangeworm susceptibility despite a lack of validation and correlation analysis with current varieties. Eighty percent of current California almond production can be attributed to five varieties (Nonpareil, 'Monterey', 'Carmel', Butte', and 'Padre'). This study aims to validate individually the commonly used indicators of almond navel orangeworm susceptibility (hull split date and shell seal) across the mosaic of growing conditions and varietal characteristics present in current California almond cultivation.

Therefore, to determine the significance of shell seal and hull split date on *A. transitella* infestation in the cultivation of California almonds, we analyzed

[1] Department of Entomology, University of California, Davis, One Shields Ave., Davis, CA 95616.

[2] Corresponding author, e-mail: kahamby@ucdavis.edu.

[3] China Agricultural University College of Agriculture and Bio-Tech, China Agricultural University, Beijing 100094, People's Republic of China.

[4] Department of Plant Sciences, University of California, Davis, One Shields Ave., Davis, CA 95616.

shell seal, hull split date, and *A. transitella* damage data for 19 almond varieties in three University of California regional almond variety trials, each representing a distinct almond production region for 2003–2005.

Materials and Methods

Regional Variety Trials. The University of California Regional Almond Variety Trials (RAVTs) were established in 1993 and designed to evaluate yield and additional production variables of newer varieties in a semicommercial (20–40 trees per variety) manner representative of the three major almond production regions of California. The industry standard varieties, Nonpareil (for the early- to mid-blooming varieties) and 'Mission' (for the late-blooming varieties), were planted 1:1 with new varieties and the "new standard" varieties 'Butte', 'Carmel', Monterey, Padre, 'Price', and 'Sonora', as points of comparison and to ensure adequate pollination. In total, >30 varieties were planted with similar orchard composition at each RAVT. Nineteen of these varieties, chosen for their presence at each location and wide range of *A. transitella* damage, were selected for the current study. The varieties were 'Aldrich', Butte, Carmel, 'Jiml', 'Johlyn', 'Kapareil', 'Livingston', Mission, Monterey, Nonpareil, Padre, 'Plateau', Price, 'Rosetta', 'Ruby', Sonora, 'Winters', 'Wood Colony', and 'Yokut'.

The RAVTs were located in Butte County at the California State University at Chico farm (CSU-Chico), in San Joaquin County at the Delta College farm (Delta College, Delta) near Manteca, and in Kern County at a Paramount Farming Company orchard (Kern) located south of Shafter and just off of seventh Standard Road. Although all sites were maintained to approximate commercial standards, winter mummy sanitation at the Paramount site was more stringent than at either of the other two locations, although natural mummy drop tends to be greater in more northern growing regions. The distance between the northernmost (CSU-Chico) and southernmost (Kern) orchards was ≈580 km, and southern sites would be expected to be exposed to greater annual navel orangeworm pressure, on average. Varieties were planted on 'Lovell' rootstock for those at CSU-Chico and on 'Nemaguard' rootstock for trees at Delta College and in Kern County. In the Kern and Delta College trials, varieties were planted as a full row of 29–38 trees. The rows at CSU-Chico were longer so each row had three different variety sections, with 21–25 trees per section.

The trial at CSU-Chico was planted on a Vina loam soil and was irrigated with solid-set sprinklers. The Delta College orchard is on a Delhi loamy sand soil and is flood irrigated. Probably as a result of the coarse textured soil and flood irrigation, the trees at Delta College were generally somewhat smaller than those in the other two RAVTs. In 2004, a microsprinkler irrigation system was installed at the Delta site. The Kern site was planted on a Milham sandy loam soil and irrigated with a drip system (it was irrigated with microsprinklers before 1999). Insecticides were not applied for *A. transitella* control during the period of our study.

Data. Hull split date was recorded when 90–100% of nuts on the trees showed an open suture for each variety. Hull split was assessed every 3–4 d at a height approximately half-way up the tree canopy. A 1.81-kg sample of almonds of each variety was collected at each of the three locations for 2003–2005 to evaluate nut variables. Samples were taken from the stream of nuts coming off the harvester into the receiver cart at the Chico and Paramount sites. A bucket was passed into the stream of nuts approximately every 10 s manually at Chico and with an autosampler at the Paramount site. At the Delta College site, samples were taken from the elevator belt as the nuts were being loaded onto the trucks for transport to the huller so that they were mixed in the receiver trailer with a random sample taken every 10 s from the belt. After mixing, the 1.81-kg sample was taken and 50 nuts were randomly selected to assess shell seal and damage infestation. Percentage of shell seal was assessed as a proportion of the 50 nuts with a >0.5-mm split. *A. transitella* damage was assessed as the proportion of the subsample that was found to be infested. Over the 3 yr of the study this amounts to a total number of 8,550 nuts inspected.

Statistical Methods. The value of hull split date and proportion shell seal as predictors across California almond cultivation was examined individually over a representative subsample of California almond-growing locations and the full spectrum of varietal characteristics to validate their predictive utility. To this end, a separate linear regression analyses were performed on arcsine-transformed proportion *A. transitella* damage (averaged over years and sites for each variety) for Julian hull split date and average proportion shell seal in JMP version 8.0.2 (SAS Institute 2009). For Julian hull split date, normality of residuals was tested using Shapiro–Wilk ($W = 0.933$, $P<W$ 0.2003), and variances were found to be homogenous using Levene's test. Similarly, proportion shell seal data also met the assumption for normality ($W = 0.960$, $P<W$ 0.5718) as well as homogeneity of variance. A regression analysis of variance was used to determine the significance of these relationships.

Results and Discussion

Table 1 presents mean percentage of *A. transitella* damage, Julian hull split date, and percentage of shell seal for the 19 varieties and three locations for the 3 yr of this study ($n = 450$). The levels of damage observed in this study would be considered high in today's industry, because tolerances have dropped to 1–2% infestation. The orchards used in this study were unsprayed, allowing for comparison of variability in infestation due to varietal characteristics such as hull split date and percentage of shell seal rather than management practices. The commercial varieties Padre and Mission had the lowest percentage of *A. transitella* damage, with means of 0.29 and 0.31%, respectively. The greatest damage was found in the varieties

Table 1. Mean ± SE percentage of *A. transitella* damage, Julian hull split date, and percentage of shell seal for each variety across the three locations (Chico, Delta College, and Kern) for 2003–2005 (n = 450)

Variety	% damage	Julian hull split	% shell seal
Kapareil	14.29 ± 15.34	187.57 ± 6.16	10.57 ± 5.86
Johlyn	10.22 ± 9.97	209.00 ± 5.48	27.56 ± 21.40
Plateau	7.43 ± 9.71	218.71 ± 8.65	64.86 ± 29.57
Sonora	6.00 ± 6.16	207.56 ± 7.49	45.33 ± 9.06
Butte	5.25 ± 5.23	230.50 ± 8.26	67.50 ± 17.94
Winters	5.11 ± 5.01	224.33 ± 5.68	58.00 ± 22.41
Jiml	5.11 ± 3.89	206.70 ± 8.12	63.33 ± 16.73
Livingston	4.67 ± 3.93	223.00 ± 6.42	33.00 ± 18.19
Yokut	4.44 ± 4.45	215.67 ± 7.05	45.11 ± 21.82
Nonpareil	4.30 ± 4.70	193.16 ± 4.81	22.54 ± 13.71
Monterey	4.29 ± 3.73	234.00 ± 13.17	55.14 ± 27.69
Carmel	4.00 ± 4.81	233.50 ± 9.13	72.60 ± 21.71
Aldrich	4.00 ± 2.82	221.50 ± 7.62	33.50 ± 11.50
Price	2.44 ± 3.28	211.89 ± 8.27	46.44 ± 17.94
Ruby	2.22 ± 1.86	232.56 ± 7.42	84.67 ± 17.69
Wood Colony	2.00 ± 2.14	221.00 ± 8.23	45.50 ± 25.34
Rosetta	1.33 ± 2.65	213.00 ± 10.10	91.33 ± 14.32
Mission	0.31 ± 0.89	237.36 ± 9.50	98.57 ± 5.93
Padre	0.29 ± 0.76	227.00 ± 5.48	98.00 ± 2.83

Kapareil (14.29%) and Johlyn (10.22%), which have not become widely planted, but were selected for this study because of greater anticipated damage. The most widely planted variety (Nonpareil) representing 39% of California production (Anonymous 2010) had a mean *A. transitella* damage of 4.30%. Kapareil and Nonpareil had the earliest mean hull split dates of 187.57 and 193.16, respectively, and Mission (237.36) and Monterey (234.00) the latest. Mission and Padre had the tightest mean shell seal of 98.57 and 98.00%, respectively. Kapareil had by far the lowest percentage of sealed nuts at 10.57%.

Both hull split date ($F_{1, 17}$ = 8.2126; P = 0.0107) (Fig. 1) and proportion shell seal ($F_{1, 17}$ = 21.2169; P = 0.0002) (Fig. 2) for the almond varieties were found to have significant negative linear relationships with *A. transitella* damage. The hull split relationship with *A. transitella* damage was expressed by the equation: arcsine NOW = 0.2301x + 0.3363 (R^2 = 0.559) (Fig. 1). The proportion shell seal relationship with *A. transitella* was expressed by the equation arcsine NOW = −0.003413x + 0.9477 (R^2 = 0.325) (Fig. 2).

It is not surprising that almond phenology influences the amount of *A. transitella* damage. *A. transitella* larvae overwinter in mummy nuts, with the first moths emerging in April, depending on location, and reinfest remaining mummies (Curtis and Barnes 1977, Seaman and Barnes 1984, Zalom et al. 1984). Moths from this generation usually emerge in late June and July (Julian date ≈170–200) and are the first generation that oviposits directly on new crop nuts (Curtis and Barnes 1977, Seaman and Barnes 1984, Zalom et al. 1998). The *A. transitella* infestation develops rapidly after dehiscence begins (Curtis and Barnes 1977), so a variety's hull split date might be expected to influence *A. transitella* infestation. Indeed, early harvest has been proposed as a cultural control method to avoid infestation by the third seasonal *A. transitella* generation (Connell et al. 1989). Therefore, varieties with hull split that overlap peaks of *A. transitella* egg laying would be expected to have greater damage. Our data suggest a significant negative trend in *A. tran-*

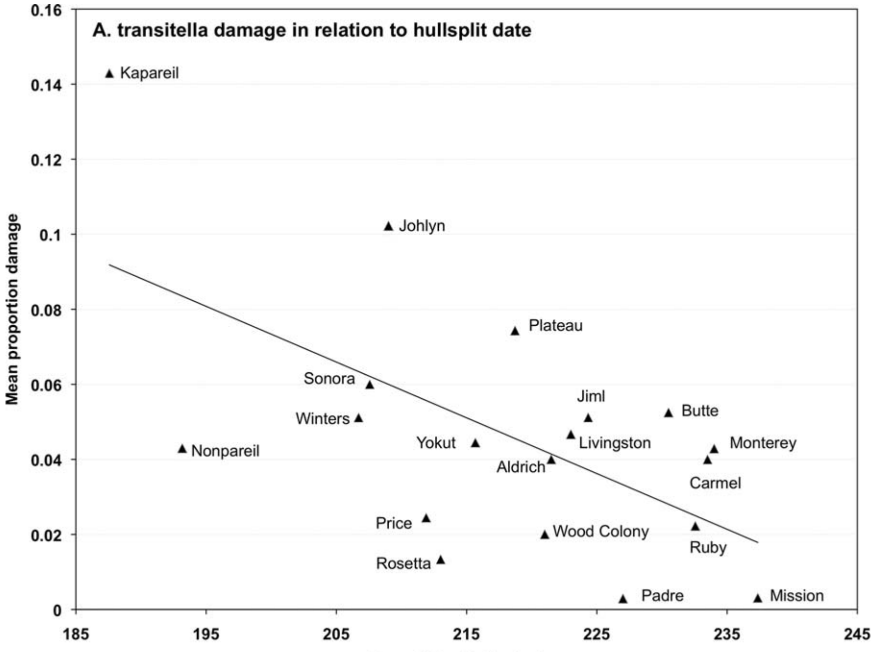

Fig. 1. Linear regression [arcsine NOW = 0.2301x + 0.3363 (R^2 = 0.559)] of proportion *A. transitella* damage and date of hull split for 19 almond varieties, averaged across three locations and years 2003–2005.

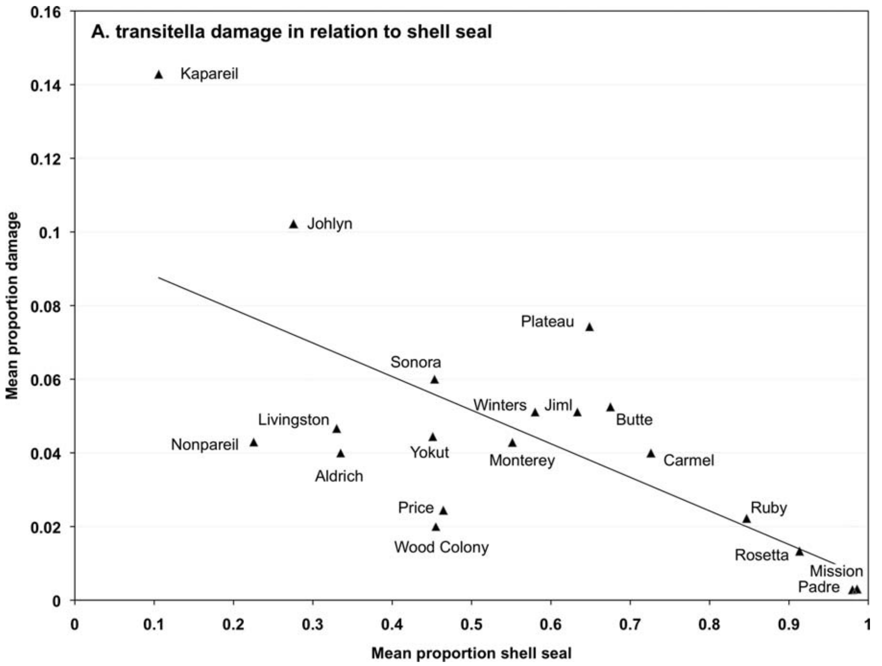

Fig. 2. Linear regression [arcsine NOW = −0.003413x + 0.9477 (R^2 = 0.325)] of proportion *A. transitella* damage and proportion shell seal for 19 almond varieties, averaged across three locations and years 2003–2005.

sitella damage as hull split becomes later from a Julian date of ≈187 (well within the range for the emergence of the first spring generation) to ≈237.

An even stronger negative relationship was found between *A. transitella* damage and proportion shell seal. Larvae are thought to penetrate to the nutmeat through cracks in the shell (Soderstrom 1977). It has been proposed that larvae become established faster and with less energy expenditure if they tunnel into the nutmeat, reducing their exposure to allelochemicals in the shell and hull (Siegel et al. 2010). Therefore, it would be expected that more tightly sealed almonds would be less amenable to infestation and require more energy expenditure for larval establishment.

In conclusion, almond varieties with later hull split and greater percentage of shell seal tend to have significantly less *A. transitella* damage. A particularly interesting outcome of this study is that some varieties seem to be outlying from the trend lines for both the hull split date and shell seal, suggesting that there may be other important factors that contribute to the observed damage levels for these genotypes. Further analysis of potential factors (such as allelochemical composition, preference, and ease of infestation) for these varieties could yield valuable insight into future *A. transitella* control tactics and almond varietal selection.

Acknowledgments

We thank the University of California Cooperative Extension Farm advisors Joseph Connell, Mario Viveros, and Paul Verdegaal for collecting the field data on hullsplit date. We acknowledge the Almond Board of California for supporting this research; and Paramount Farming Company, Delta Community College, and California State University Chico for providing land, equipment, and labor needed to establish and maintain the RAVTs.

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Received 22 October 2010; accepted 20 March 2011.