Diel Activity and Behavior of *Bagrada hilaris* (Hemiptera: Pentatomidae) on Desert Cole Crops

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**ABSTRACT** Patterns of diel activity and behavior of the Bagrada bug, *Bagrada hilaris* (Burmeister) (Hemiptera: Pentatomidae), were investigated in a series of field and greenhouse experiments in Yuma, AZ. Adults of *B. hilaris* were monitored by on-site direct observation on broccoli and cauliflower plants in large-block experimental plots at various intervals throughout consecutive 24-h periods. In the field trials, mean number of *B. hilaris* adults differed among sampling times, with peak abundance observed consistently between 1300 and 1800 hours. There was a positive correlation between temperature and numbers of *B. hilaris* adults in all fields, and a negative relationship between humidity and adult numbers in 7 of 12 fields. Significant relationships between temperature and *B. hilaris* numbers were revealed in regression models for all trials. Slopes were not significantly different among all broccoli blocks or in three of the four cauliflower fields. In greenhouse studies, mating occurred throughout the day but peaked between 1000 and 1600 hours. Females of *B. hilaris* caused more feeding damage than males on the first true leaf of broccoli, and additional differences in behavior between sexes were observed. Our results suggest that higher temperatures increase field activity and influence the behavior of adult *B. hilaris*, and temperature is a more reliable indicator to predict the activity of *B. hilaris* than other environmental parameters measured. The implications of these findings for developing monitoring and management programs for *B. hilaris* in cruciferous crops are discussed.

**KEY WORDS** diel activity, stink bug, pest management, broccoli, cauliflower

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*Bagrada hilaris* (Burmeister) (Hemiptera: Pentatomidae), commonly referred to as the Bagrada bug or Painted bug, is an invasive stink bug species that has recently become established in the desert southwest of the United States (http://cisr.ucr.edu/bagrada/bug.html). It is now considered a serious economic pest of a variety of cruciferous vegetable crops grown during fall and winter months in the desert agricultural valleys of Arizona and southern California (Palumbo and Natwick 2010). Seedling crops are highly susceptible to direct feeding damage on cotyledons, newly emerged leaves, and apical meristems. Excessive feeding damage to apical meristems can result in destruction of the terminal growing points, leading to either adventitious bud break (e.g., cabbage plants with multiple unmarketable heads) or plants with no productive head being formed (e.g., broccoli with no crowns) (Palumbo and Natwick 2010). A recent survey of growers from Yuma, AZ, and the Imperial Valley, CA, estimated that >90% of broccoli acreage planted in 2010 and 2011 was infested with *B. hilaris* at some point in the growing season, and on average, this resulted in stand losses and plant injury exceeding 5 and 10% in cauliflower and broccoli crops, respectively (http://ag.arizona.edu/crops/vegetables/advisories/more/insect59.html). The potential economic impact of *B. hilaris* on the Western vegetable industry could be significant, considering that the production of cruciferous crops in Arizona and California was collectively valued at >US$1 billion in 2011 (CDFA 2012, U.S. Department Agriculture, NASS 2012).

Limited information is available on *B. hilaris* biology (Singh and Malik 1993, Rajpoot et al. 1996, Halbert and Eger 2010), behavior (Guarino et al. 2008), host range (Gupta and Gupta 1970, Rawat and Singh 1950, Risvi et al. 1986, Lal and Singh 1993), or management practices (Ahuja et al. 2008; Nyabuga 2008; Palumbo 2012a, 2012b). Most recently, field and laboratory observations demonstrated the damage potential of *B. hilaris* infesting broccoli in Arizona (Palumbo and Natwick 2010). However, scientific information is lacking on the field-scale ecology of this pest, particularly in high-value broccoli and cauliflower crops destined for the fresh market. The seasonal population dynamics of *B. hilaris* have been examined on mustard and *Brassica* seed crops (Joshi et al. 1989, Verma et al. 1993, Nyabuga 2008, Saitoh et al. 2010), but these studies were conducted in India and Africa under growing conditions distinctly different from the desert cropping systems of the southwestern United States. Furthermore, these studies did not investigate the influence of environmental variables on *B. hilaris* diel activity or feeding behavior. Diel activity patterns on
flight or feeding have been studied for other related pentatomids (Shearer and Jones 1996, Krupke et al. 2006, Huang and Toews 2012). A clear understanding of factors that influence population abundance and associated feeding injury on host crops is essential for the development of a sustainable management approach for this new pest (Kogan 1988). Therefore, the main objectives of this study were to determine if diel activity and abundance of B. hilaris were related to temperature and other environmental parameters, and to evaluate temporal patterns of B. hilaris feeding and mating behaviors by direct observation in the field and greenhouse.

Materials and Methods

Field Plot Description. Several large-block experimental field trials were conducted in 2010 and 2012 at the Yuma Agricultural Center (32° 42′44″ N, 114° 42′14″ W) operated by the University of Arizona in Yuma, AZ. In 2010, two experimental field sites of direct-seeded broccoli (evaluated at the 2–3-leaf stage) and two field sites of transplanted cauliflower (transplanted on 31 August and 23 September) were established. The size of experimental sites varied by crop, with the two nontreated blocks of cauliflower in 2010 being 0.20 and 0.24 ha in area. One broccoli block (treated with an at-planting, soil application of imidacloprid, Admire Pro at 280 g active ingredient [AI]/ha, Bayer CropSciences, Raleigh, NC) was imbedded within an efficacy trial and was 0.04 ha in size. The other nontreated broccoli block was in a separate planting and was 0.20 ha in size. In 2012, experiments were conducted on four large experimental field sites of direct-seeded broccoli (cotyledon = 5-leaf stage) and one field site of transplanted cauliflower (transplanted on 5 September) in September; and two of directed-seeded broccoli (cotyledon and 4-leaf stage) and one field site of transplanted cauliflower (transplanted on 24 September) in October. Block size varied by crop from 0.2 to 0.4 ha. No insecticides were applied on any of the experimental blocks in 2012. Fertilization, irrigation, tillage, and crop management followed University of Arizona Cooperative Extension recommendations for each crop (http://ag.arizona.edu/crops/vegetables/vegetables.html). Emerald Crown (Sakata America, Morgan Hills, CA) was the variety of direct-seeded broccoli each year, and Minuteman (Seminas Vegetable Seeds, Inc., Oxnard, CA) was the variety used for cauliflower transplants.

Data Collection. Sampling was conducted by counting all B. hilaris adults present on 10 plants in eight randomly selected areas of each experimental block (n = 80 plants per experimental field site) during each sampling interval. Adult counts were observational, and no insects or plants were removed from the experimental field sites during the course of the study. The sample unit consisted of a single whole plant where all leaf blades and petioles, stems, and the soil surface immediately below and adjacent to each sampled plant were examined carefully for the presence of adults. To minimize disruption, leaves were turned gently by using a 10-cm metal ruler and plants were not shaken. In 2012 only, numbers of mating pairs in each sampled field site were recorded for analysis of diel mating activity. In 2010, sampling intervals were irregular and varied by day and field site, but generally included sampling conducted during the coolest (pre-sunrise) and warmest (afternoon) times of the day during a 24-h period. In 2012, sampling for the first trial was conducted six times daily from 25 to 29 September at regular intervals (0600, 0900, 1300, 1800, 2400, and 0300 hours). In the second trial, sampling was conducted every 3 h (eight sampling intervals daily) from 22 to 26 October. Sampling conducted at night was done with the assistance of a fluorescent head lamp (Princeton Tec, Trenton, NJ). Environmental conditions were recorded hourly for ambient air temperature, soil temperature (10 cm in depth), humidity, dew point, solar radiation, and wind speed from the on-site AZMET weather station located within 0.4–0.8 km of each experimental field site (http://cals.arizona.edu/azmet/).

Greenhouse Observations. Three separate trials designed to measure adult behavior and diel activity were conducted on 26 September, 5 October, and 19 October in a greenhouse at the Yuma Agricultural Center in 2012. Broccoli with one true leaf (direct-seeded on a 5 by 5-cm² pot) was transferred into an 8.5-cm-diameter plastic cup and then caged with individuals of B. hilaris (single male, single female, or one pair). The top of the plastic cup was covered by a 9-cm-diameter petri-dish cap drilled with 15–20, 0.2-cm-diameter round holes for ventilation. Five replicates of males, females, and pairs of B. hilaris were observed in the first trial, and 10 replicates of males, females, and pairs were observed in the second and third trials (n = 25 total replicates). No adults were caged on the control group plants. All adult insects were obtained from a B. hilaris colony maintained at the Yuma Agricultural Center where all life stages were supplemented with organic broccoli heads (Earthbound Farm, Salina, CA) and sweet alyssum plants. Diel activity patterns of B. hilaris were observed every 3 h (eight observation intervals). Each trial was recorded over a 48-h period. Behavior (feeding, resting, walking, or mating) and location (on plant, soil surface, or cage) of B. hilaris were recorded. Nighttime observations were conducted with the assistance of a fluorescent head lamp. Temperature was measured hourly by using a data logger (HOBO Pendant, Onset Computer Corp., Cape Cod, MA). Feeding of B. hilaris was determined by observing the probing/penetrating behavior of the mouthparts (styles) into the plant tissue with the aid of magnification, when needed. At the end of the 48-h period, each first true leaf was detached from the plant by using a sterile disposable scalpel (Ted Pella, Inc., Redding, CA). Feeding damage by B. hilaris was photographed by using a USB digital microscope (Dino-Lite, AnMo Electronics Corp., New Taipei City, Taiwan) and measured by using Dino Capture 2.0 graphic software. The proportion of feeding damage was calculated by the total feeding area per original leaf area. Symptoms of
feeding damage used to assess feeding area were characterized as small visible white patches starting on the edge of leaves (Palumbo and Natwick 2010).

Statistical Analyses. The field experiments were organized as a one-way arrangement of treatments in a randomized complete block design. As there were differences in crop variety, plant stage, soil quality, treatment, and the surrounding habitat among each experimental field site, each trial and field site were sorted and analyzed separately by using a one-way analysis of variance (ANOVA) (PROC GLIMMIX; SAS Institute 2009). Sampling time-of-day (treatment) was modeled as a fixed effect, and each observation day was modeled as a random effect. Treatment means were separated by using the LSMEANS test ($P < 0.05$). The response variable, number of $B. hilaris$, was subjected to a logarithmic transformation (Zar 1999) before each analysis, and means for each sampling date at each field were obtained by using PROC MEANS (SAS Institute 2009). Regardless of transformations, actual numbers of $B. hilaris$ counts per 10-plant sample on each experimental field site are presented in the text and figures. Analysis of diel mating activity was performed by the same model as previously described. Linear relationships between environmental variables and numbers of $B. hilaris$ counted on each experimental field site were quantified separately by using regression analysis (PROC REG). The $B. hilaris$ counts were subjected to a logarithmic transformation before analysis (Zar 1999). Regardless of sampling date, slopes (between environmental variables and numbers of $B. hilaris$) from all broccoli fields or cauliflower fields were pooled and compared within each crop by using an analysis of covariance (PROC GLM; SAS Institute 2009) to determine that the slopes were consistent among fields.

Because the spatial dimension and orientation were identical in the greenhouse diel activity trials, data from all three trials were pooled and analyzed by using a two-way ANOVA (PROC GLIMMIX; SAS Institute 2009). Observation time and sex were modeled as fixed effects, and replicates were modeled as a random effect. The response variables, such as percentage of feeding (male and female groups) or percentage of mating (pair group only), were subjected to arcsine transformation before analysis. Treatment means were separated by using the LSMEANS test ($P < 0.05$) and the slice option (SAS Institute 2009), if there was a significant interaction. Relationship between greenhouse temperature and percentage of mating $B. hilaris$ pairs was quantified by using regression analysis (PROC REG). The percentage of mating pairs was subjected to arcsine transformation before analysis. Analysis of leaf feeding damage by $B. hilaris$ was performed by using a one-way ANOVA (PROC GLIMMIX; SAS Institute 2009). The proportion of feeding area (response variable) was subjected to arcsine transformation before analysis, and treatment means were separated by using the LSMEANS test ($P < 0.05$). Sex (male, female, or pair) was modeled as a fixed effect and replicates were modeled as a random effect to determine whether the sex of the adult affected the amount of feeding.

Results

Diel Activity in the Field. In 2010, 1,294 adults of $B. hilaris$ were recorded from 22 to 28 September in the four experimental field sites. The mean number of $B. hilaris$ was significantly different among sampling times in the nontreated broccoli ($F = 19.53; df = 5, 4; P = 0.0065$), but not in the imidacloprid-treated field site ($P = 0.0689$; Fig. 1). On cauliflower plants, the mean number of $B. hilaris$ was significantly different among sampling times at both the $3 \approx 4$-leaf-stage field ($F = 7.73; df = 6, 5, P = 0.0202$) and $4 \approx 5$-leaf-stage field ($F = 70.05; df = 3, 2, P = 0.0014$) (Figs. 2 and 3). In 2012, 1,705 adults of $B. hilaris$ were counted from 25 to 29 September from the five sites and 1,682 were observed from 22 to 26 October from three field sites. In September, $B. hilaris$ counts differed significantly among sampling times at all broccoli field sites: cotyledon-stage field ($F = 28.68; df = 5, 15; P < 0.0001$), $2 \approx 3$-leaf-stage fields ($F = 11.26; df = 5, 15; P < 0.0001$), and in the $5 \approx 6$-leaf-stage cauliflower field ($F = 15.38; df = 7, 21; P < 0.0001$) (Fig. 4). In October 2012, the mean number of $B. hilaris$ was significantly different among sampling times in the two broccoli field sites: cotyledon-stage field ($F = 2.94; df = 7, 21; P = 0.0262$) and $3 \approx 4$-leaf-stage field ($F = 11.59; df = 7, 21; P < 0.0001$), and in the $5 \approx 6$-leaf-stage cauliflower field site ($F = 15.38; df = 7, 21; P < 0.0001$) (Fig. 5). In general, regardless of year and field site location, $B. hilaris$ was found to be most abundant at 1300–1800 hours and least abundant at 0300–0600 hours on both broccoli and cauliflower (Figs. 1–5). Mating pairs were recorded only in 2012, and the percentage of mating pairs among all $B. hilaris$ counts was significantly different among sampling times in three of the eight field sites. Among these sites, the percentage of mating pairs was greatest at 1900 hours for the cotyledon-stage broccoli field ($F = 19.51; df = 5, 13; P < 0.0001$) and was greatest at 1800 hours for the 2 $\approx 3$-leaf-stage broccoli field ($F = 3.48; df = 5, 13; P = 0.0325$) in September, and was greatest at 1500 hours for the $3 \approx 4$-leaf-stage broccoli field ($F = 2.66; df = 7, 21; P = 0.0391$) in October. In most cases, the highest occurrence of mating pairs coincided with peak adult abundance that was recorded during the warmest part of the day for each of the three field sites.

Regression analyses showed significant positive relationships between ambient air temperatures at each sampling time and numbers of $B. hilaris$ in all fields. Linear relationships were shown to fit the regression models between temperatures at each sampling time and numbers of $B. hilaris$ (Figs. 6 and 7). Covariance analyses showed that there were no significant differences among the slopes relating temperatures to $B. hilaris$ counted at all broccoli field sites ($P = 0.1891$), but a significant difference was observed among cau-
lißower Þelds where the slope of the 3 ≈ 4-leaf-stage field site in 2010 was signiÞcantly different from the other three cauliflower fields (F = 6.49; df = 1, 3; P = 0.0006).

Seven of the twelve Þeld sites showed a negative relationship between humidity and B. hilaris counts (r² range: 0.28 ÷ 0.76), whereas 9 of the 12 Þeld sites showed a positive relationship between soil temperature (10 cm in depth) and B. hilaris counts (r² range: 0.28 ÷ 0.95). Only 2 of 12 Þelds showed a positive relationship between dew point and B. hilaris counts (r² = 0.20 and 0.26). Eleven of the twelve Þelds showed a positive relationship between solar radiation and B. hilaris counts (r² range: 0.23 ÷ 0.77). Six of twelve Þelds showed a positive relationship between wind speed and B. hilaris counts (r² range: 0.34 ÷ 0.89).

Diel Activity and Behavior in the Greenhouse. There were no interactions between sex and observation time when examining feeding behavior during each trial (F = 0.72; df = 7, 75; P = 0.6515). Conversely, there were obvious differences between ßxed effects for sex (F = 65.08; df = 1, 75; P < 0.0001) and among observation times (F = 5.14; df = 7, 75; P < 0.0001). Peak male feeding activity occurred around 1900 hours, which is the approximate time twilight occurs in Yuma during late September and early October. The fewest numbers of females were observed feeding at 0700 hours, and there were no differences in feeding activity at other times of night and day (Fig. 8). There were no interactions between sex and observation time when examining statistical analyses for resting behavior (F = 0.71; df = 7, 75; P = 0.6663). However, there were signiÞcant differences between ßxed effects for sex (F = 60.96; df = 1, 75; P < 0.0001) and among observation times (F = 13.16; df = 7, 75; P < 0.0001). A greater percentage of B. hilaris males engaged in resting behavior than females, and both sexes displayed a higher resting behavior at 0700 hours than at any other observation time (Fig. 8). Although no signiÞcant difference between sexes in walking behavior was observed (F = 0; df = 1, 75; P = 0.989), both sexes showed signiÞcant differences in the timing of their walking behaviors (F = 58.16; df = 7, 75; P < 0.0001) that occurred only between 1000 and 1600 hours (Fig. 8).

There were no interactions between sex and observation time when examining statistical analyses for...
location of B. hilaris ($F = 0.4; \text{df} = 7, 75; P = 0.8997$). However, there were differences between fixed effects for sex ($F = 31.45; \text{df} = 1, 75; P < 0.0001$) and among observation times ($F = 7.15; \text{df} = 7, 75; P < 0.0001$). A greater percentage of females inhabited plants than males, and both sexes inhabited plants more often during scotophase (1900 ~ 0400 hours) than photophase (0700 ~ 1600 hours) (Fig. 9). Con-
versely, a significantly greater percentage of males stayed on the cage than females ($F = 17.83; df = 1, 75; P < 0.0001$), but there was no difference among observation times ($F = 2.06; df = 7, 75; P = 0.0578$) (Fig. 9). When examining soil-inhabited preference, there was a significant interaction between sex and observation times ($F = 2.52; df = 7, 75; P = 0.0219$). Further analyses of the interaction (sliced by sex) showed that there were differences among observation times by sex (male: $F = 11.48; df = 7, 75; P < 0.0001$) (female: $F = 3.37; df = 7, 75; P = 0.0035$). Further analyses of the interaction (sliced by time) showed that there were no differences between sexes among observation times at 0100, 0400, 0700, 1000, 1900, and 2200 hours ($F = 0.35 = 0.72; df = 1, 75; F = 0.3981 = 0.5572$), but there were differences between sexes at 1300 hours ($F = 12.07; df = 1, 75; P = 0.0009$) and 1600 hours ($F = 7.63; df = 1, 75; P = 0.0072$) (Fig. 9).

There was a significant difference when mating pairs were examined among observation times. The percentage of mating pairs was higher between 1000 and 1600 hours than at other observation times ($F = 5.34; df = 7, 35; P = 0.0003$; Fig. 10). Regression analysis showed that there was a quadratic relationship between temperature and percentage of mating pairs ($r^2 = 0.56$, model: $y = 1.87315 - 0.10074x + 0.00219x^2$; $P < 0.0001$). There was a significant difference in leaf feeding among sexes (males, females, and pairs). Females caused significantly more feeding damage than males, and mating pairs of *B. hilaris* fed on a significantly greater area of leaf tissue than females ($F = 88.94; df = 2, 48; P < 0.0001$) (Table 1). The proportion of leaf-feeding damage by the pair groups (67.52%) was greater than the combined leaf damage by male and female groups (56.70%).

**Discussion**

Results of these experiments have important implications for understanding the population dynamics and behavior of this new invasive stink bug, *B. hilaris*, and for developing management strategies in cruciferous crops under arid desert growing conditions. The direct experimental observations on the diel activity of naturally occurring *B. hilaris* populations made during this study provide the most accurate and reliable information currently available on the field-scale ecology of this pest. These field experiments were initiated.
in September 2010, when outbreaks of *B. hilaris* first occurred on commercial cole crops in the Yuma Valley, AZ. In 2011, *B. hilaris* population levels were low and precluded further observations, but during the fall of 2012, large outbreaks allowed the continuation of these field trials. Populations of *B. hilaris* were widespread on fall plantings of broccoli, cauliflower, and cabbage throughout western Arizona and southern California in 2012, comparable with outbreak levels experienced by growers in the fall of 2010. Furthermore, the abundance of *B. hilaris* sampled from the experimental field sites in this study is representative of the infestation levels experienced by local growers (http://ag.arizona.edu/crops/vegetables/advisories/more/insect59.html).

Field trials in both years indicated that ambient temperature was an important factor affecting the activity and abundance of *B. hilaris* on young cole crop plants. In essence, relative numbers of *B. hilaris* adults on broccoli and cauliflower plants fluctuated according to ambient temperature, with peak abundances occurring during the warmest period of the day. These data were consistent in all 12 experimental field sites. Temperatures during these peak periods often exceed 32°C in late September, and reached as high as 42°C. In contrast, *B. hilaris* was consistently least abundant on plants or the soil beneath plants during the coolest part of the day (≈0600–0700 hours), when temperatures often fell below 20°C. Although the adult numbers varied by field site, the lack of significant differences in the regression slopes between temperature and *B. hilaris* counts from the eight independent broccoli field sites suggests that population density, crop stage, and field location do not affect the diel activity patterns of this insect. This was true in three of four cauliflower fields as well, where the only exception was the 3–4-leaf-stage cauliflower field site in 2010, when the *B. hilaris* infestation was light. Patterns in flight and feeding activities driven by temperature have been documented in other hemipteran studies (Bellows et al. 1988, Feil et al. 2000, Son et al. 2012).

Fig. 5. Mean ± SEM numbers of adult *B. hilaris* in a single cauliflower field and two broccoli fields and ambient temperatures during late October 2012.
We were not surprised when large numbers of *B. hilaris* adults were recorded on the imidacloprid-treated plants in the 2010 experiment (Fig. 1). The imidacloprid-treated block, which had been imbedded within a separate efficacy trial, was much smaller (0.04 ha) and contained fewer plants than the larger nontreated broccoli blocks (0.2 ha) used in these studies. Furthermore, field efficacy trials have shown that soil systemic applications of imidacloprid and other neonicotinoid insecticides do not effectively control *B. hilaris* or protect emerging broccoli seedlings from adult feeding damage (Palumbo 2011, J.C.P., unpublished data). It is also possible that the treated plants were more attractive to *B. hilaris* adults because of the lack of feeding damage by another important pest, the sweetpotato whitefly, *Bemisia tabaci* (Gennadius), that had been effectively controlled with the systemic imidacloprid treatment on broccoli plants in the treated block.

Other environmental parameters such as soil temperature (10 cm in depth) and solar radiation were shown to be correlated with *B. hilaris* counts in most of the fields, but this would be expected because these two factors are closely related to ambient air temper-

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**Fig. 6.** Linear relationships between mean number of *B. hilaris* counts and ambient temperature from all broccoli fields and the regression model for each slope. (A): (2010, September) Imidacloprid-treated, 2 ≈ 3 leaf; (B): (2010, September) Nontreated, 2 ≈ 3 leaf; (C): (2012, September) Nontreated, cotyledon; (D): (2012, October) Nontreated, cotyledon; (E): (2012, September) Nontreated, 2 ≈ 3 leaf; (F): (2012, September) Nontreated, 2 ≈ 3 leaf; (G): (2012, September) Nontreated, 4 ≈ 5 leaf; (H): (2012, October) Nontreated, 3 ≈ 4 leaf.
Fig. 7. Linear relationships between mean number of *B. hilaris* counts and ambient temperature from all cauliflower fields and the regression model for each slope. (A): (2010, September) Nontreated, 3 ÷ 4 leaf; (B): (2010, September) Nontreated, 4 ÷ 5 leaf; (C): (2012, September) Nontreated, 5 ÷ 6 leaf; (D): (2012, October) Nontreated, 5 ÷ 6 leaf.

Fig. 8. Mean ± SEM percentage of adult males and females of *B. hilaris* showing various types of behavior in periodicity pattern in the greenhouse. Means within each behavior type followed by the same letter are not significantly different (*P* < 0.05).

Fig. 9. Mean ± SEM percentage of adult males and females of *B. hilaris* showing various location preferences in periodicity pattern in the greenhouse. Means followed by the same letter are not significantly different (*P* < 0.05).
atures under desert growing conditions. Correlations between adult *B. hilaris* numbers on plants and other parameters such as humidity, dew point, and wind speed were less consistent and suggest that these environmental factors were not reliable indicators of adult activity. This is not surprising because humidity and wind are often influenced by seasonal monsoon activity in the desert southwest during September, where strong thunderstorms can occur unexpectedly.

The greenhouse studies showed that a higher percentage of mating, walking (only between 1000 and 1600 hours), and activity (i.e., not resting) occurred daily during the warmest hour of a day for both sexes. This further indicates that *B. hilaris* is a daytime-active temperature-triggered insect. This pattern is similar to the results from a pitfall trap study, which reported that phytophagous hemipterans were strongly diurnal, with activity concentrated from 1100 to 1600 hours (Dondale et al. 1972). In addition, Huang and Toews (2012) reported two pentatomids, the brown stink bug, *Euschistus servus* (Say), and the southern green stink bug, *Nezera viridula* (L.), moved more frequently among cotton bolls during photophase than scotophase. In contrast, Krupke et al. (2006) reported a nocturnal attribute of *E. conspersus* (2006) reported a nocturnal attribute of *B. hilaris* females inhabited and fed on the broccoli plants than did the males at each observation time suggests the females may require more plant nutrients for vitellogenesis. The fact that mating pairs of *B. hilaris* caused greater feeding damage on leaves than the groups of single males and females combined further supports this hypothesis.

There may be additional factors that interact with temperature to influence the behavior and activity of *B. hilaris* adults that were not directly measured in these studies. Although numbers of *B. hilaris* varied field-by-field, adults were often found to aggregate on a few select plants within experimental field sites. Preliminary observations of mean to variance ratios of adult counts from the sampling data indicated that populations were spatially aggregated among plants, particularly during the afternoon and early evening (J.C.P., unpublished data). In addition, it was unusual to find three or more mating pairs on a single plant during these periods, suggesting that mate location could be facilitated by pheromone attraction. Adult males of several agriculturally important stink bug species are known to produce pheromones to attract conspecific males and females, as well as natural enemies (Aldrich 1988, Mcbrien et al. 2001, Millar et al. 2002). Furthermore, based on laboratory bioassays, De Pasquale et al. (2007) and Guarino et al. (2008) identified volatile and contact compounds from male *B. hilaris* adults that they suggested might be attractant pheromones for mating, aggregation, or both. Thus, pheromone attraction, along with temperature, may play an important role in the mating and aggregation behavior of *B. hilaris* in cruciferous crops. Further research is needed to determine whether these or similar volatile pheromones can attract *B. hilaris* and influence their activity under arid desert field conditions.

When conducting nighttime observations of *B. hilaris* adults in the greenhouse and field, the use of the fluorescent head lamp did not disturb them or alter their behavior. Detection of the insects at night with the high-intensity lights actually seemed easier than

Table 1. Mean percentage (±SEM) feeding damage by adult *B. hilaris* on one-leaf broccoli in a no-choice test in the greenhouse

<table>
<thead>
<tr>
<th>Sex</th>
<th>Replicates (n)</th>
<th>Mean percentage of feeding damage ± SEM (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>25</td>
<td>9.58 ± 0.01a</td>
</tr>
<tr>
<td>Female</td>
<td>25</td>
<td>47.12 ± 0.04b</td>
</tr>
<tr>
<td>Pair</td>
<td>25</td>
<td>67.52 ± 0.03c</td>
</tr>
</tbody>
</table>

* Means followed by the same letter are not significantly different (*P < 0.05; LSMEANS test).
during mid-day under bright diffused sunlight. Furthermore, black light trapping was conducted bi-weekly at the Yuma Agricultural Center in September and October 2012 near several of the experimental field sites, but no *B. hilaris* were caught in any traps. These observations suggest that the behavior of *B. hilaris* differs from other pentatomids. For example, the daytime-active green stink bug, *Chinacia hilaris* (Say), *Haltomorpha halys* (Stål), as well as other pentatomids were found to be attracted to a light source at night (Lee et al. 2002, Kamminga et al. 2009, Nielsen and Hamilton 2009, Kamminga et al. 2012). However, most *B. hilaris* we observed while sampling fields were sensitive to leaf movements and vibrations if plants were intentionally shaken. When plants were disturbed, adults of *B. hilaris* often fell to the soil surface at night, or immediately flew or walked away from plants during the daytime when temperatures were high (>30°C).

Phytophagous stink bugs are reported to disperse from host-to-host at the farm scale level, depending on the availability of food sources (Kiritani et al. 1966, Jones and Sullivan 1982, Ehler 2000, Tillman et al. 2009). Although the flight activity of *B. hilaris* is unclear, it is likely to actively disperse from field-to-field based on its capacity to adapt to different environments (from lower desert to mountainous regions) and its rate of invasion (3 yr from California to New Mexico) (Bundy et al. 2012, D. A. Reed et al., unpublished data). As our studies clearly demonstrated that ambient temperature was strongly correlated with diel activity of *B. hilaris*, other observations during the field trials suggest that flight activity and dispersion may also be influenced by temperature. It was not unusual to observe adults taking flight for short distances (3–6 m) during the warmer periods of the day (i.e., 1000–1800 hours), whereas flight behavior was never observed during scotophase or in the morning before 1000 hours. Furthermore, one broccoli field sampled during October 2012 had an unusually high number of adults suddenly occur on a single sample period (Figs. 5 and 6D). This resulted from heavy adult immigration into the newly established broccoli stand (cotyledon stage) that coincided with peak afternoon temperatures. Investigations of *Bagrada cruciferae* Kirkaldy (now considered taxonomically synonym with *B. hilaris*; Rider et al. 2002) infestation patterns on cauliflower seed crops in India showed that adults appeared on the crop soon after an increase in temperature, and weekly infestation levels were positively correlated with maximum temperature (Verma et al. 1993). Thus, a better understanding of the factors that influence the movement of this insect pest between cole crops and alternative host plants is needed and will be important for developing long-term management strategies. Research examining the flight and dispersal activity of *B. hilaris* under different environmental conditions is presently being conducted.

This study provides useful information for growers and pest control advisors (PCAs) that can be applied to their current management programs for *B. hilaris* on desert cole crops. Presently, PCAs tend to scout fields and monitor insect pest activity, beginning at dawn. Based on the results in this study, scouting for *B. hilaris* on desert cruciferous crops in September and October during the coolest part of the morning (0600 ÷ 0900 hours) will likely result in inaccurate low estimates of population density. Although an action threshold has yet to be established for *B. hilaris*, preliminary research suggests that significant stand losses and plant damage can occur when populations exceed one adult per row m on seedling cole crops (J. C. Palumbo et al., unpublished data). Thus, monitoring fields and obtaining reliable estimates of *B. hilaris* densities are critical for making accurate control decisions; failure to do so properly may result in unacceptable plant damage or improper insecticide use. Recently developed pest management guidelines for *B. hilaris* have incorporated this temperature-density relationship and recommend that PCAs scout fields for *B. hilaris* adults when temperatures are near or above 30°C before making management decisions (http://ag.arizona.edu/crops/vegetables/advisories/more/insect67.html). Furthermore, because growers presently rely on contact foliar insecticide applications for controlling *B. hilaris* infestations, sprays applied when the insect are most active on plants during the afternoon and early evening are likely to provide more effective knockdown control than during the early morning hours.

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