

Influence of Abiotic Factors on Flight Initiation by Asian Citrus Psyllid (Hemiptera: Liviidae)

Xavier Martini^{1,2,3} and Lukasz L. Stelinski²

¹Entomology and Nematology Department, North Florida Research and Education Center, University of Florida, 155 Research Rd., Quincy, FL 32351 (xmartini@ufl.edu), ²Entomology and Nematology Department, Citrus Research and Education Center, University of Florida, 700 Experiment Station Rd., Lake Alfred, FL 33850 (stelinski@ufl.edu), and ³Corresponding author, e-mail: xmartini@ufl.edu

Subject Editor: Melody Keena

Received 26 October 2016; Editorial decision 5 January 2017

Abstract

Predicting the emergence and arrival of insect pests is paramount for integrated pest management. To achieve this goal, it is important to understand how abiotic factors influence pest dispersal behavior. We investigated the effects of abiotic conditions on flight initiation by the Asian citrus psyllid, *Diaphorina citri* Kuwayama. We first explored the effect of barometric pressure changes on flight initiation. We used a custom-made barometric chamber and observed the activity of *D. citri* as measured by the number of psyllids captured on yellow cardboard panels coated with adhesive. We found that psyllid flight initiation changed in response to variations in barometric pressure rather than to differences in stable pressures. *Diaphorina citri* were equally active at 1,009 mbar and 1,022 mbar. However, *D. citri* dispersed more as barometric pressure increased, and less when barometric pressure decreased. In a subsequent experiment, we manipulated temperature and relative humidity and observed how *D. citri* dispersed between citrus plants. Psyllids dispersal increased linearly with temperature. Changes in humidity did not affect dispersal of *D. citri*. Less than 1% of psyllids dispersed at 15 °C, compared with 7.7% at 21 °C and 27% at 25 °C. The minimal threshold for *D. citri* to initiate flight is estimated to be 16.5 °C. Collectively, our results provide an initial step toward developing predictive models of *D. citri* movement as influenced by abiotic factors.

Key words: citrus greening, dispersal behavior, abiotic factor, phytopathogen vector

The Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Liviidae), is the vector of bacterial pathogens (*Candidatus Liberibacter* sp.) that cause citrus greening disease, also called huanglongbing (HLB). Huanglongbing is considered the most destructive disease of citrus crops worldwide. All known citrus cultivars are susceptible to HLB (Folimonova et al. 2009), and prevention of disease spread has proven difficult (Grafton-Cardwell et al. 2013). Infected mature trees produce small and misshapen fruit with uneven color development and suffer from significant fruit drop (Bassanezi et al. 2009). Juice from infected fruit tastes bitter and unbalanced owing to low soluble solids and high acid contents (Gottwald 2010). Trees often die within 5–10 yr of infection if they are not nursed with supplemental nutrition (Spann and Schumann 2012), owing to symptoms of HLB or because of secondary infections to the weakened trees (Bové 2006). It is estimated that the HLB-infection rate in Florida is ~80% and that the average yield loss experienced by growers owing to HLB is ca. 41% (Singerman and Useche 2016).

Given the near complete infection of the citrus tree inventory with *Candidatus Liberibacter asiaticus* in Florida (Singerman and

Useche 2016), replanting young, uninfected trees has become both a necessity and a major challenge. One of the major pillars of HLB management continues to be vector management with insecticides (Qureshi et al. 2014, Boina and Bloomquist 2015). However, aggressive use of insecticides has resulted in cases of decreased insecticide susceptibility among populations of *D. citri* in Florida (Tiwari et al. 2011). Potential impacts on nontarget insects and possible contamination of water and soil (Bonmatin et al. 2015) should be concerns in areas where citrus is grown in Florida. Also, insecticide efficacy is limited by the short residual life of foliar sprays onto citrus against *D. citri* following applications (Serikawa et al. 2010). This is of particular concern in Florida where growers are experiencing continuous influx of *D. citri* flying in from untreated or marginally managed neighboring blocks (Tiwari et al. 2010, Lewis-Rosenblum et al. 2015). For example, abandoned groves comprised 52,653 ha of citrus in Florida in 2015 (US Department of Agriculture 2015) and serve as an unmanaged reservoir of infected vector populations (Tiwari et al. 2010). Also, mobile *D. citri* commonly invade well-managed (9–13 insecticide sprays per year)

commercial citrus from neighbouring groves where owners manage the vector less rigorously (3–4 insecticide sprays per year; Pelz-Stelinski et al. 2017). Consequently, even if repeated application of insecticides with different modes of action can readily decrease localized populations of *D. citri* (Qureshi et al. 2014), consistent reinfestations by adults from unmanaged areas render area-wide management of this phytopathogen vector vastly difficult. For instance, despite intensive insecticide sprays and absence of associated insecticide resistance, growers from Central Florida found it nearly impossible to manage *D. citri* in 2016 (L. Stelinski, pers. observation).

Relative to its size, the dispersal capability of *D. citri* is relatively robust. Martini et al. (2014) found that *D. citri* perform long-distance flights covering 320 m on average, with maximum flight distance up to 2.4 km on flight mills. In the field, dispersal distance by *D. citri* up to 2 km has been documented with mark–recapture investigations (Lewis-Rosenblum et al. 2015). Furthermore, *D. citri* adults were captured year round in a forest lacking citrus hosts and 2.3 km away from the nearest abandoned citrus grove (Martini et al. 2013). There is mounting evidence that *D. citri* routinely disperse between citrus groves on the order of m to km in distance (Boina et al. 2009, Tiwari et al. 2010, Lewis-Rosenblum et al. 2015) and their dispersal capabilities without wind assistance should not be underestimated. Additionally, it has been suggested that *D. citri* could have dispersed up to 470 km, throughout the Okinawan islands, mediated by lower jet airstreams (Sakamaki 2005).

Predicting when *D. citri* disperse and the associated risk of infestation should benefit grower management programs. For instance, some insecticides, such as soil-applied neonicotinoids, require several days of uptake before becoming effective against feeding psyllids, and are considered more preventive rather than completely effective. Among these insecticides are some of the more effective compounds against *D. citri*, such as imidacloprid, thiamethoxam, or clothianidin. These active ingredients disrupt the feeding behavior of *D. citri* by reducing the phloem salivation phase and therefore decreasing bacterial inoculation into the plant (Serikawa et al. 2012, Miranda et al. 2016). To predict when *D. citri* will invade groves, it is important to understand how abiotic

factors, including temperature, relative humidity, and barometric pressure, affect vector movement. Each of these factors impacts insect behavior. For instance, barometric pressure has been found to affect courtship behavior and foraging activity of a wide range of insects, including thrips, Coleoptera, Lepidoptera, and Hemiptera (Fournier et al. 2005, Pellegrino et al. 2013, McFarlane et al. 2015). Also, tephritid flies move to cooler locations within host trees as temperature increases and their movement is inhibited at high temperature extremes (Roitberg et al. 2009). Here, we investigated short-range dispersal of *D. citri* adults as influenced by barometric pressure, temperature, and humidity.

Materials and Methods

Insect Rearing

Adult *D. citri* used in behavioral bioassays were obtained from a laboratory culture maintained at the University of Florida, Citrus Research and Education Center, Lake Alfred, USA). The culture was established in 2000 from field populations collected in Polk Co., FL, USA (28.0° N, 81.9° W), prior to the discovery of HLB in Florida. The culture was maintained without exposure to insecticides on curry leaf plants (*Berbera koenigii* (L.)) and ‘Valencia’ *Citrus sinensis* in an air-conditioned greenhouse at 26–28 °C, 60–65% relative humidity (RH), and a photoperiod of 14:10 (L:D) h. Illumination in the greenhouse was supplemented with linear fluorescent 54-W lights (F54W/T5/865/ECO, GE lighting, Nela Park, OH). Monthly testing of randomly sampled nymphs and adults by quantitative PCR assays was conducted to confirm that psyllids and plants in this culture were free of *Candidatus Liberibacter asiaticus*. *Candidatus*

Dispersal of *D. citri* as Influenced by Barometric Pressure

We developed a pressure chamber to measure changes in dispersal by *D. citri* adults as influenced by controlled changes in pressure (Fig. 1). Our pressure chamber consisted of a cylindrical glass dome (54 cm tall by 20 cm ID). The glass chambers were sealed by glass lids with metal rings and a 5-cm-wide Parafilm band (Pechiney,

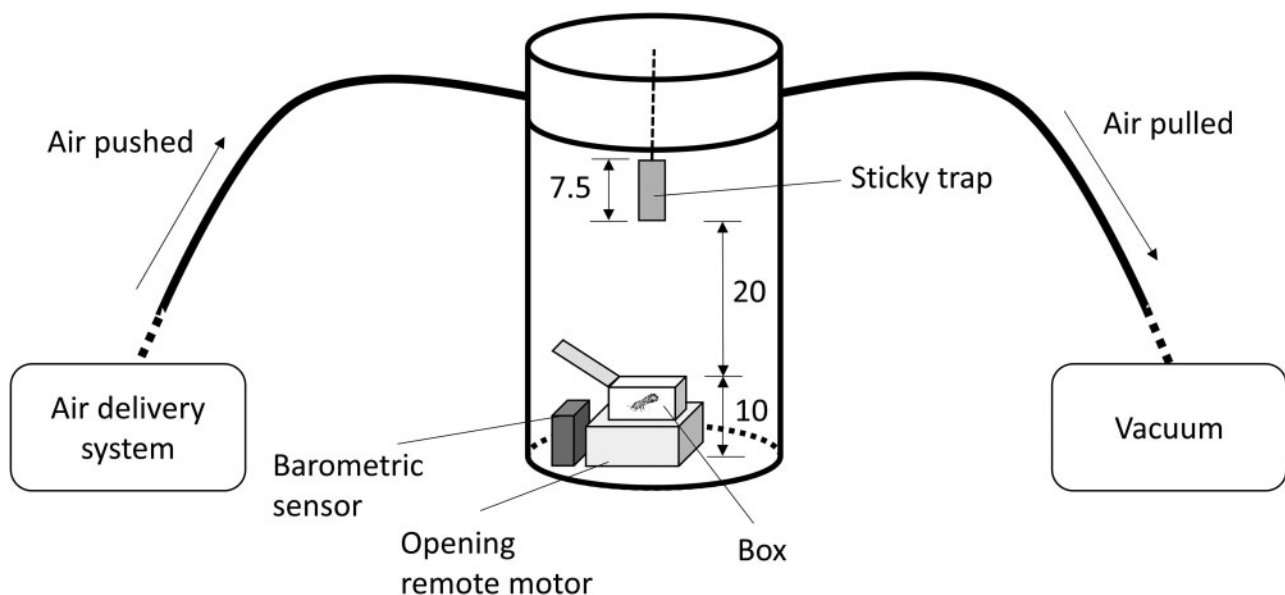


Fig. 1. Graphic representation of the pressure chamber used to investigate the effect of barometric pressure changes on *D. citri* dispersal behavior. The measurements in the diagram are presented in cm (the diagram is not to scale).

Chicago, IL). To ensure chemical-free ambient air supply, the chamber received charcoal purified and humidified air from a custom-made air delivery system (ARS, Gainesville, FL). Pushed airflow was controlled just before entering the pressure chamber with a flowmeter (Varian, Walnut Creek, CA) and was set at a constant rate between 0.27 to 0.35 liter/min. Pulled air flow was set at a constant rate of 0.3 liter/min. The changes in barometric pressure within the chamber were calibrated by the difference between airflow entering the chamber and the air pulled out. A digital barometer (Digi-sense, Cole-Parmer, Vernon Hills, IL) within the chamber directly measured pressure. Light was provided by two lamps positioned 1.35 m above the pressure chamber; luminosity measured with a luxmeter (Foot Candle Lux, Extech Instruments, Nashua NH) within the pressure chamber was 829 lux. Room temperature was $24.8 \pm 1.5^\circ\text{C}$, humidity $40 \pm 10\%$, and all replicates were conducted between 0900 to 1200 hours.

Diaphorina citri adults were placed into a homemade Plexiglas box (4 by 5.5 by 2 cm) that was opened by a remote control. When closed, the box was not sealed to allow air exchange without allowing *D. citri* to escape. A rectangle (7.5 by 2.5 cm) of yellow sticky card (ISCA technologies, Riverside, CA) was hung 20 cm above the box, so that flying psyllids were captured upon release (Fig. 1). At the onset of the experiment, 25 *D. citri* of mixed sex (from a colony of ~50:50 sex ratio) were enclosed within the release box. The initial ambient pressure was recorded and the box was placed into the chamber with the barometer. The push flow was set at a chosen rate to obtain the desired pressure. The pressure was allowed 90 min to stabilize. After 90 min, the box containing the psyllids was opened by electronic remote control, without affecting the internal pressure within the chamber, and the number of *D. citri* captured on the sticky trap was counted every 15 min for 2 h. There were a total of 16 replications that compared psyllid response at initial pressure inside the chamber, with varying pressures between -5.42 mbar/h and $+4.57$ mbar/h during the 3.5-h total duration of the experiment. In Central Florida, most of the daily barometric pressure variations occur between $+2.00$ to -2.00 mbar/h. However, more extreme variations can occur during severe weather events.

Dispersal of *D. citri* as Influenced by Temperature and Relative Humidity

Effects of temperature on *D. citri* dispersal were investigated by establishing treatments in environmental chambers. Humidity was controlled by the coupled use of a dehumidifier (General Electric, Fairfield, CT) and of a humidifier (Essick Air Product, Little Rock, AR). Fifty *D. citri* adults of mixed sex (50:50 sex ratio) from our HLB-free colony were enclosed within mesh bags on nonflushing seedling 'Swingle' *Swinglea glutinosa* (Blanco) citrus plants. These plants were placed in a mesh cage (34 by 34 by 61 cm) in the environmental chamber set to default conditions of 25°C and 70% RH for an acclimation period of 3 d. Thereafter, temperature and humidity were set at the desired treatment for 2 h. There were three humidity levels: 35, 65, and 95%, and six temperature levels: 15, 18, 21, 25, 30, and 33°C . All the 18 humidity and temperature combinations were replicated three times, except for 21°C at 65% that were replicated six times. Humidity and temperature were chosen to fall in a range that is in accordance with conditions observed in Florida during spring, when dispersal of *D. citri* occurs with greatest frequency (Lewis-Rosenblum et al. 2015). Four newly flushing 'Swingle' citrus seedlings were introduced into the cage 10 cm away from the infested plant, and the mesh bags were removed, as well as, all *D. citri* that did not settle on plants during the acclimation

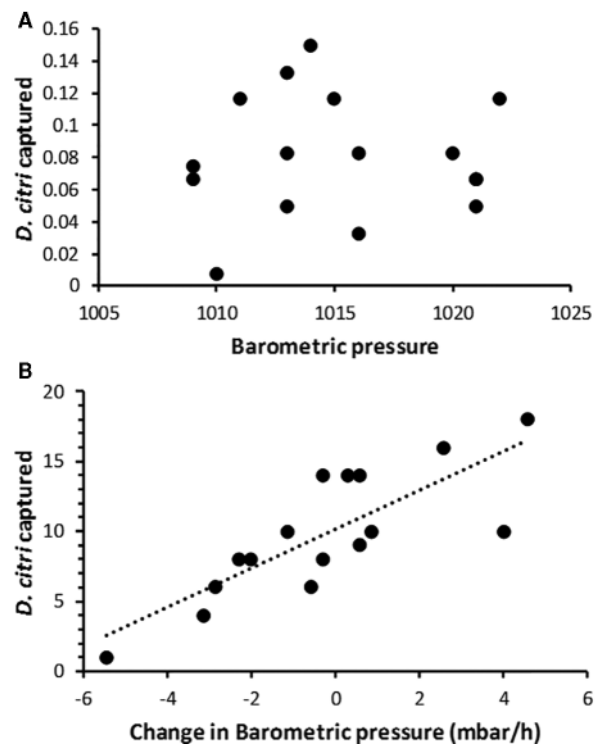


Fig. 2. Number of *D. citri* captured after 2 h on an 18.75-cm^2 sticky trap placed within a pressure chamber depending on (A) the ambient pressure at the start of the experiment, (B) the variation of the barometric pressure during the experiment (linear regression: $y = 1.401x + 10.150$, $R^2 = 0.65$).

period. This allowed those *D. citri* that had settled the ability to move between plants within the cages. We counted the number of *D. citri* that dispersed to introduced plants 24 h after initiating the experiment. Subsequently, all adults were removed from each plant, counted, and their sex and abdominal color were determined. There are three color morphs in *D. citri*: blue-green, gray-brown, and orange (Wenninger and Hall 2008), and these color morphs have been correlated with differences in flight behavior (Martini et al. 2014).

Statistical Analysis

Analyses were performed with the statistical software SigmaPlot (Systat Software, San Diego, CA) and R v3.02 (The R Foundation for Statistical Computing, Vienna, Austria). All analyses were performed after assuring the requirements of normal distribution and equal variance among treatments were met. The numbers of *D. citri* captured on sticky traps after 2 h within the pressure chamber were analyzed with multiple linear regression of the initial barometric pressure and changes in barometric pressure during the experiment. Initial barometric pressure and changes in barometric pressure were computed as linear variables.

The proportion of psyllids that dispersed in each cage depending on temperature and humidity was first analyzed with multiple linear regression by using the proportion of psyllids that effectively moved onto introduced plants after 24 h as the response variable and temperature, humidity, and their interaction as the dependent variables. Subsequently, this maximal model was simplified by stepwise deletion. Interaction and parameters were removed from the model at the $\alpha = 0.10$ threshold in order to obtain the minimal adequate model (Crawley 2009). We also applied a generalized additive model (GAM) to generate a more precise visual description of the relationship between dispersal and temperature.

Once we determined that temperature was the main driver of *D. citri* dispersal (see results), we tested the hypothesis that color morph and sex could influence short-distance dispersal behavior. We built a matrix with the number of *D. citri* that did or did not disperse after 24 h. Afterward, we ran a GLM with binomial distribution, with temperature, sex, and color as independent variables. We started by analyzing the more complex model that included all of the interactions, and then removed the nonsignificant interactions by stepwise deletion until obtaining the minimal adequate model. Additional GAMs were used to obtain a more precise visual description of the relationship between dispersal and temperature for each color morph and sex.

Results

Dispersal of *D. citri* as Influenced by Barometric Pressure

Ambient pressure varied between 1,009 to 1,022 mbar (average: 1015.25 ± 5.15 mbar). There was no significant interaction between the initial pressure and the change in barometric pressure in the chamber on psyllid dispersal ($F_{1,12} = 2.85$, $P = 0.117$). Similarly, the ambient pressure at the initiation of the experiment did not influence

Table 1. Multiple and simple linear model of *D. citri* dispersal among citrus plants, depending on temperature and humidity

	df	Coefficient	SE	<i>t</i>	<i>P</i>
Maximal model (AIC: -89.87)					
Constant		-0.413	0.1586	-2.609	0.0118
Temperature	1	0.0258	0.0065	3.994	<0.001
RH	1	0.0006	0.0023	0.291	0.772
RH × Temp	1	<0.0001	<0.0001	-0.497	0.621
Residual	53				
Minimal adequate model (AIC: -92.97)					
Constant		-0.3700	0.0543	-6.822	<0.001
Temperature	1	0.0228	0.0022	10.313	<0.001
Residual	55				

The maximal model contains temperature and humidity as variables, along with their interaction. The minimal adequate model was determined after stepwise deletion and only contains the significant variable (temperature).

the dispersal behavior of *D. citri* (multiple linear regression, $F_{1,12} = 0.032$, $P = 0.836$, Fig. 2A). Therefore, initial pressure and the interaction with pressure change were removed from the model (Crawley 2009), and we pursued a simple linear regression between barometric change and the number of *D. citri* captured. The maximal model and the simple linear regression model had similar Akaike information criteria (AICs; 82.41 vs. 82.04, respectively), justifying model simplification. There was a significant positive relationship between the change in barometric pressure within the pressure chamber and the number of *D. citri* captured on the sticky trap ($F_{1,14} = 25.86$, $P < 0.001$, Fig. 2B). The lowest capture occurred when the pressure dropped at the rate of -5.42 mbar/h when a single psyllid was captured, whereas a maximum of 18 psyllids were captured when the pressure increased at a rate of 4.57 mbar/h. When the pressure was steady (between -0.3 mbar to 0.3 mbar/h variation), 12 psyllids (48% of introduced psyllids) were captured on average. Overall, when the barometric pressure was decreased within the chamber, *D. citri* were less mobile and fewer were captured per sticky trap than when barometric pressure was increased.

Dispersal of *D. citri* as Influenced by Temperature and Relative Humidity

Dispersal of *D. citri* increased linearly as temperature was increased within the range of temperatures tested and independently of relative humidity level (Table 1, Fig. 3B). However, changes in relative humidity alone or humidity interacting with temperature had no significant effect on dispersal of *D. citri* (Table 1, Fig. 3A). Removal of humidity and of the humidity × temperature interaction improved the model as demonstrated by the lower AIC obtained for the simplified model (Table 1). Similarly, the best GAM only included temperature as the predictor (estimate = 0.0227, SE = 0.002, $P < 0.001$, Fig. 3B). Based on the linear regression, the estimated threshold for *D. citri* to initiate flight was $16.464 \pm 0.864^\circ\text{C}$. Female *D. citri* dispersed more than males (Table 2, Fig. 4B), and there was a significant interaction between temperature and abdominal color (Table 2, Fig. 4A). Dispersal of gray-brown *D. citri* was significantly higher than of the blue-green and orange color morphs at 30°C ($P < 0.05$), but not at the other temperatures investigated (Table 2, Fig. 4A).

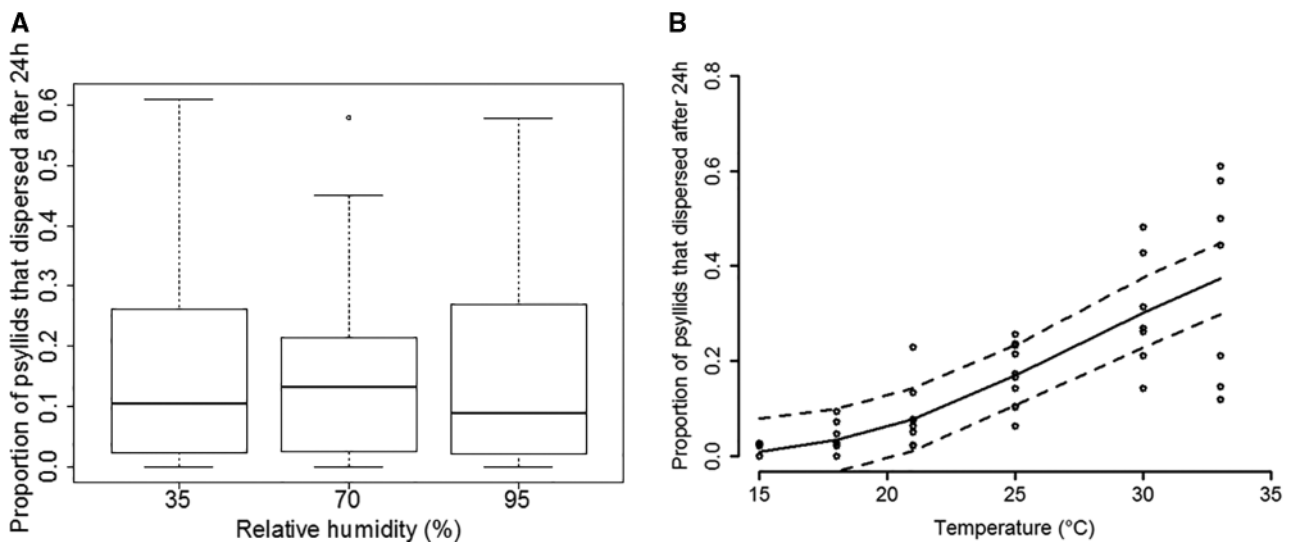


Fig. 3. Proportion of *D. citri* that dispersed after 24 h depending on (A) relative humidity and (B) temperature: Predicted dispersal of *D. citri* depending on temperature based on a generalized additive model (dotted lines indicate 95% confidence interval).

Discussion

Understanding flight initiation and dispersal behavior of an insect pest could help in predicting the risk of serious pest attack and developing better and more customized management responses. Predictive models are important to help growers make decisions regarding pest management. Several models have been developed to predict pest dispersal rate depending on abiotic factors. Hodges et al. (2003) predicted trap catches of the beetle, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae), in Ghana depending on temperature and humidity from field data. The spread of the processionary moth, *Thaumetopoea pityocampa* Denis and Schiffermüller, was modeled based on submodels including growth, survival, and dispersal parameters of the insect (Robinet et al. 2014). We believe that a similar tool may help to better manage *D. citri* and HLB. In order to develop predictive models for *D. citri* migrations, it is important to know how abiotic factors influence dispersal behavior of this insect.

We found that barometric pressure changes and temperature influenced the activity and flight initiation of *D. citri*. These findings could help predict movement of *D. citri* across landscapes based on predominantly occurring abiotic conditions. In our cage experiments, females dispersed more than males. *Diaphorina citri* were released onto plants without new shoot growth, while the newly introduced plants had new shoots. *Diaphorina citri* females only lay eggs on young shoots because nymphs cannot develop on mature citrus leaves (Hall and Albrigo 2007), which likely explains the greater movement by females observed in this experiment.

Table 2. Generalized linear model with binomial distribution of *D. citri* dispersal depending on ambient temperature, sex, and color morphotype

	df	χ^2	P
Temperature	1	312.98	<0.001
Color	2	4.26	0.119
Sex	1	20.97	<0.001
Temperature \times color	2	7.124	0.028

Color morphotype did not affect the proportion of *D. citri* that made short-distance flights between plants at the lower temperatures tested, but at 30°C, gray-brown colormorphs of *D. citri* dispersed more than the other colormorphs. These results slightly differ from those observed previously for long-distance flight behavior. For instance, previous results suggested that both sexes have the same flight capacity (Arakawa and Miyamoto 2007, Martini et al. 2014). Also, Martini et al. (2014) demonstrated that blue-green *D. citri* exhibited more long-distance flights than gray-brown colormorphs. In those experiments, only blue-green colormorphs performed “long” duration flights (>1 min), but there was no difference in the activity among morphs performing short-duration flights (<1 min; Martini et al. 2014). In the current investigation, each color morph tested displayed similar dispersal capacity at each temperature tested, with the exception of 30°C, where gray-brown colormorphs dispersed more than the other colormorphs. This seems to indicate that the optimal flight temperature for this colormorph is lower than the other morphs. Further experiments are needed to determine if long-range flight behavior and performance is influenced by temperature and barometric pressure in the same way as we observed in these microscale experiments.

Increased movement with increasing temperature is not necessarily a general rule among insects, depending on temperature extremes. For example, flight capabilities of the olive fly, *Bactrocera oleae* Rossi, are reduced after exposure to temperatures ranging between 35–37°C (Roitberg et al. 2009). Other insects can change their movement behavior with temperature. For instance, the plum curculio will walk until 20°C, but will start flying above this temperature threshold (Prokopy et al. 1999). It is possible that *D. citri* are less mobile at temperatures above the 33°C extreme tested here. Even if our data suggest there may be an optimum beyond 33°C (Fig. 3B), they also demonstrate that *D. citri* is active and perfectly willing to fly at temperature and humidity conditions typical of Florida field conditions.

The effects of barometric pressure on behavior of *D. citri* were similar to those found in other insect species. Notably, exposure to a steady barometric pressure value (low or high) did not affect behavior, but rather a change in barometric pressure prior to flight

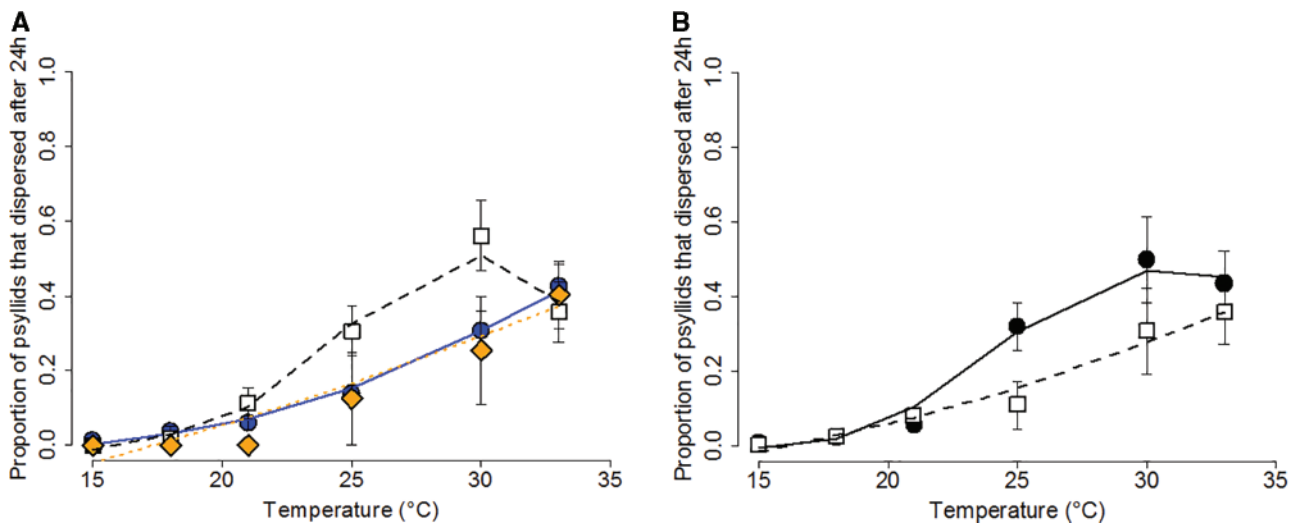


Fig. 4. (A) Proportion of *D. citri* that dispersed after 24 h depending on temperature and color morph (blue: blue-green morph, orange: orange morphs, black: gray-brown morph), (B) and sex (black: females, white: males). Curves represent predicted dispersal of *D. citri* depending on temperature based on a generalized additive models ran for each sex and color morph.

initiation affected behavior. Similarly, flight initiation by *Trichogramma pretiosum* Riley and *Trichogramma evanescens* Westwood (Hymenoptera: Trichogrammatidae) were both reduced with rapid changes in barometric pressure, but were not affected by stable or slow changes in barometric pressure (Fournier et al. 2005). Similarly, the thrips, *Franklinella schultzei* Trybom, exhibits decreased mating activity and will actively forage for shelter during barometric pressure drops (McFarlane et al. 2015). Pellegrino et al. (2013) compared the courtship behavior of three taxonomically unrelated insects: the curcubit beetle, *Diabrotica speciosa* Germar, the true armyworm moth, *Pseudaletia unipuncta* (Haworth), and the potato aphid, *Macrosiphum euphorbiae* (Thomas), at various barometric pressures. When barometric pressure dropped, these insects exhibited reduced courtship activity as compared with that observed during stable barometric pressure (Pellegrino et al. 2013). In *Drosophila*, the effect of barometric changes on courtship and mating decreased in some population strains, while other strains were not affected by pressure changes (Austin et al. 2014). Overall, it appears that insects demonstrate ability to forecast weather and adapt their behavior to maximize survival during severe weather events. In our case, this response to rapid drops in barometric pressure is likely linked to an imminent threat of rain or a storm event. Our data suggest that *D. citri* is able to anticipate inclement weather conditions by inhibiting flight initiation. Interestingly, Zagvazdina et al. (2015) investigated the long-term effect (3–48 h before experiment) of barometric pressure changes on *D. citri* behavior and found contrasting results. For instance, increased phototaxis occurred when pressure decreased 24 h prior to testing (Zagvazdina et al. 2015). In contrast, mating and mate-seeking behavior were reduced following a pressure drop (Zagvazdina et al. 2015). Collectively, our experiment and this previous research demonstrate that *D. citri* is affected by decreases in barometric pressure; however, psyllid response to pressure drops (increasing or decreasing activity) will depend on the behavior involved.

In addition to temperature, humidity, and barometric pressure, flight behavior of *D. citri* is influenced by several other factors. *Diaphorina citri* exhibit strong phototaxis and tend to aggregate where light is most intense (Sétamou et al. 2011). This behavior can be exploited to develop windbreaks that provide shade and reduce density of *D. citri* on border rows of citrus groves (Martini et al. 2015) or reflective mulches that disorient host seeking by *D. citri* (Croxtan and Stansly 2014). Abundance of *D. citri* also decreases with increasing elevation (Bové 2006, Jenkins et al. 2015). This may explain why citrus groves in Puerto Rico do not appear to support infestations by *D. citri* (Jenkins et al. 2015). Wind likely plays a role in long-distance transfer of *D. citri* within lower jet streams between islands (Sakamaki 2005); however, mark–recapture investigations thus far have failed to demonstrate that *D. citri* movement is aided by wind within an agricultural landscape (Lewis-Rosenblum et al. 2015). Other abiotic factors, such as habitat heterogeneity or drought, could also potentially influence movement behavior (Mazzi and Dorn 2012, Martini et al. 2015) and remains to be investigated for *D. citri*. Overall, our data indicated that *D. citri* is well adapted for movement in Florida and likely remains sessile directly prior to major events of inclement weather.

Acknowledgments

We thank the Citrus Research and Development Foundation for funding (Grant 15-024). We thank Eric Linder and Angeliqye Hoyte for help during laboratory experiments.

References Cited

- Arakawa, K., and K. Miyamoto. 2007. Flight ability of Asiatic citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera; Psyllidae), measured by a flight mill. Res. B. Plant Prot. Serv. Jpn. 43: 23–26.
- Austin, C. J., C. G. Guglielmo, and A. J. Moehring. 2014. A direct test of the effects of changing atmospheric pressure on the mating behavior of *Drosophila melanogaster*. Evol. Ecol. 28: 535–544.
- Bassanezi, R. B., L. H. Montesino, and E. S. Stuchi. 2009. Effects of Huanglongbing on fruit quality of sweet orange cultivars in Brazil. Eur. J. Plant Pathol. 125: 565–572.
- Boina, D. R., and J. R. Bloomquist. 2015. Chemical control of the Asian citrus psyllid and of Huanglongbing disease in citrus. Pest Manag. Sci. 78: 808–823.
- Boina, D. R., W. L. Meyer, E. O. Onagbola, and L. Stelinski. 2009. Quantifying dispersal of *Diaphorina citri* (Hemiptera: Psyllidae) by immunomarking and potential impact of unmanaged groves on commercial citrus management. Environ. Entomol. 38: 1250–1258.
- Bonmatin, J. M., C. Giorio, V. Girolami, D. Goulson, D. P. Kreutzweiser, C. Krupke, M. Liess, E. Long, M. Marzaro, E.A.D. Mitchell, et al. 2015. Environmental fate and exposure; neonicotinoids and fipronil. Environ. Sci. Pollut. Res. Int. 22: 35–67.
- Bové, J. 2006. Huanglongbing: A destructive, newly-emerging, century-old disease of citrus. J. Plant Pathol. 7–37.
- Crawley, M. J. 2009. The R book. John Wiley & Sons Ltd, Chichester, United Kingdom.
- Croxtan, S., and P. Stansly. 2014. Metalized polyethylene mulch to repel Asian citrus psyllid, slow spread of Huanglongbing and improve growth of new citrus plantings. Pest Manag. Sci. 70: 318–323.
- Folimonova, S. Y., C. J. Robertson, S. M. Garnsey, S. Gowda, and W. O. Dawson. 2009. Examination of the responses of different genotypes of citrus to Huanglongbing (citrus greening) under different conditions. Phytopathology 99: 1346–1354.
- Fournier, F., D. Pelletier, C. Vigneault, B. Goyette, and G. Boivin. 2005. Effect of barometric pressure on flight initiation by *Trichogramma pretiosum* and *Trichogramma evanescens* (Hymenoptera: Trichogrammatidae). Environ. Entomol. 34: 1534–1540.
- Gottwald, T. R. 2010. Current epidemiological understanding of citrus Huanglongbing. Annu. Rev. Phytopathol. 48: 119–139.
- Grafton-Cardwell, E. E., L. L. Stelinski, and P. A. Stansly. 2013. Biology and management of Asian citrus psyllid, vector of the Huanglongbing pathogens. Annu. Rev. Entomol. 58: 413–432.
- Hall, D. G., and L. G. Albrigo. 2007. Estimating the relative abundance of flush shoots in citrus with implications on monitoring insects associated with flush. HortScience 42: 364–368.
- Hodges, R. J., S. Addo, and L. Birkinshaw. 2003. Can observation of climatic variables be used to predict the flight dispersal rates of *Prostephanus truncatus*? Agric. For. Entomol. 5: 123–135.
- Jenkins, D. A., D. G. Hall, and R. Goenaga. 2015. *Diaphorina citri* (Hemiptera: Liviidae) abundance in Puerto Rico declines with elevation. J. Econ. Entomol. 108: 252–258.
- Lewis-Rosenblum, H., X. Martini, and S. Tiwari. 2015. Seasonal movement patterns and long-range dispersal of Asian citrus psyllid in Florida citrus. J. Econ. Entomol. 208: 3–10.
- Martini, X., T. Addison, B. Fleming, I. Jackson, K. Pelz-Stelinski, and L. L. Stelinski. 2013. Occurrence of *Diaphorina citri* (Hemiptera: Liviidae) in an unexpected ecosystem: The lake Kissimmee State Park Forest, Florida. Florida Entomol. 96: 658–660.
- Martini, X., A. Hoyte, and L. Stelinski. 2014. Abdominal color of the Asian citrus psyllid (Hemiptera: Liviidae) is associated with flight capabilities. Ann. Entomol. Soc. Am. 842–847.
- Martini, X., K. S. Pelz-Stelinski, and L. L. Stelinski. 2015. Absence of windbreaks and replanting citrus in solid sets increase density of Asian citrus psyllid populations. Agric. Ecosyst. Environ. 212: 168–174.
- Mazzi, D., and S. Dorn. 2012. Movement of insect pests in agricultural landscapes. Ann. Appl. Biol. 160: 97–113.
- McFarlane, D. J., M. A. Rafter, D. T. Booth, and G. H. Walter. 2015. Behavioral responses of a tiny insect, the flower thrips *Frankliniella schultzei*

- Trybom (Thysanoptera, Thripidae), to atmospheric pressure change. *J. Insect Behav.* 28: 473–481.
- Miranda, M., P. Yamamoto, R. Garcia, J. Lopes, and J. Lopes. 2016. Thiamethoxam and imidacloprid drench applications on sweet orange nursery trees disrupt the feeding and settling behaviour of *Diaphorina citri* (Hemiptera: Liviidae). *Pest Manag. Sci.* 72: 1785–1793.
- Pellegrino, A. C., M.F.G.V. Peñaflores, C. Nardi, W. Bezner-Kerr, C. G. Guglielmo, J.M.S. Bento, and J. N. McNeil. 2013. Weather forecasting by insects: Modified sexual behaviour in response to atmospheric pressure changes. *PLoS ONE* 8: e75004.
- Pelz-Stelinski, K., X. Martini, H. Gibbard, and L. L. Stelinski. 2017. Overwintering habitat use of the Asian citrus psyllid, *Diaphorina citri*, vector of a major phytopathogen. *Agric. For. Entomol.* Available at: <http://onlinelibrary.wiley.com/doi/10.1111/afe.12197/full>, DOI: 10.1111/afe.12197. In Press.
- Prokopy, R. J., C. B. Wirth, and T. C. Leskey. 1999. Movement of plum curculio adults toward host trees and traps: Flight versus walking. *Entomol. Exp. Appl.* 91: 3985–3392.
- Qureshi, J. A., B. C. Kostyk, and P. A. Stansly. 2014. Insecticidal suppression of Asian citrus psyllid *Diaphorina citri* (Hemiptera: Liviidae) vector of Huanglongbing pathogens. *PLoS One* 9: e112331.
- Robinet, C., J. Rousselet, and A. Roques. 2014. Potential spread of the pine processionary moth in France: Preliminary results from a simulation model and future challenges. *Ann. For. Sci.* 71: 149–160.
- Roitberg, B. D., C. R. Lauzon, S. B. Opp, and D. R. Papaj. 2009. Functional and behavioural ecology of tree-fruit pests: The four Fs of fruit flies (Diptera: Tephritidae), pp. 56–84. *In* M. Aluja, T.C. Leskey, and C. Vincent (eds.), *Biorational tree-fruit pest manag.* CABI, Cambridge, United Kingdom.
- Sakamaki, Y. 2005. Possible migration of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae) between and within islands. *Occas. Pap. Kagoshima Univ. Res. Cent.* 42: 121–125.
- Serikawa, R. H., M. E. Rogers, E. A. Backus, and L. L. Stelinski. 2010. Can insecticide protect citrus from HLB infection? *Citrus Indus.* 91: 6–9.
- Serikawa, R., E. A. Backus, and M. E. Rogers. 2012. Effects of soil-applied imidacloprid on Asian citrus psyllid (Hemiptera: Psyllidae) feeding behavior. *J. Econ. Entomol.* 105: 1492–1502.
- Sétamou, M., A. Sanchez, J. M. Patt, S. D. Nelson, J. Jifon, and E. S. Louzada. 2011. Diurnal patterns of flight activity and effects of light on host finding behavior of the Asian citrus psyllid. *J. Insect Behav.* 25: 264–276.
- Singerman, A., and P. Useche. 2016. Impact of citrus greening on citrus operations in Florida. *Univ. Florida Ext.* (<http://edis.ifas.ufl.edu/fe983>)
- Spann, T., and A. Schumann. 2012. Using good horticultural practices to maintain yield of HLB-affected groves. *Citrus Ind.* 6–11.
- Tiwari, S., H. Lewis-Rosenblum, K. Pelz-Stelinski, and L. L. Stelinski. 2010. Incidence of *Candidatus Liberibacter asiaticus* infection in abandoned citrus occurring in proximity to commercially managed groves. *J. Econ. Entomol.* 103: 1972–1978.
- Tiwari, S., R. S. Mann, M. E. Rogers, and L. L. Stelinski. 2011. Insecticide resistance in field populations of Asian citrus psyllid in Florida. *Pest Manag. Sci.* 67: 1258–1268.
- US Department of Agriculture. 2015. Citrus abandoned acres. (http://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Citrus/aban/CitAA15.pdf)
- Weninger, E. J., and D. G. Hall. 2008. Daily and seasonal patterns in abdominal color in *Diaphorina citri* (Hemiptera: Psyllidae). *Ann. Entomol. Soc. Am.* 101: 585–592.
- Zagvazdina, N. Y., T. M. Paris, B. J. Udell, M. Stanislauskas, S. McNeill, S. A. Allan, and R. W. Mankin. 2015. Effects of atmospheric pressure trends on calling, mate-seeking, and phototaxis of *Diaphorina citri* (Hemiptera: Liviidae). *Ann. Entomol. Soc. Am.* 108: 762–770.