Attraction of Rhagoletis indifferens (Diptera: Tephritidae) to White Light in the Presence and Absence of Ammonia

Author: Yee, Wee L.

Source: Florida Entomologist, 100(1) : 21-28

Published By: Florida Entomological Society

URL: https://doi.org/10.1653/024.100.0105

Attraction of *Rhagoletis indifferens* (Diptera: Tephritidae) to white light in the presence and absence of ammonia

*Wee L. Yee**

Abstract

Attraction of tephritid fruit flies to light and its role in fly biology and management have received little attention. Here, the objective was to show that western cherry fruit fly, *Rhagoletis indifferens* Curran (Diptera: Tephritidae), is attracted to white light in the presence and absence of ammonia, an olfactory cue used with traps. Laboratory tests were conducted inside a 0.23 m^3 cage with a halogen or light-emitting diode (LED) bulb hung ~2 cm above a trap with or without an ammonium carbonate lure; flies were released in the cage opposite from the light. Fly captures on yellow or clear traps with white light from both bulb types were greater than on controls, and greater at higher than lower light intensities whether ammonia was present or not. Adding heat without additional light near traps did not increase captures, indicating light rather than heat from bulbs attracted flies. In the field, light from LED and halogen bulbs did not enhance fly captures on ammonia-baited yellow traps, but light from halogen bulbs did enhance captures when there was no ammonia, although captures were lower than when ammonia was added. Results show that bright white light is attractive to *R. indifferens* and suggest orientation towards it may induce behaviors that positively affect fly fitness, such as mating and foraging. However, stronger light-associated stimuli than those used here may be needed to enhance fly captures on ammonia-baited traps under field conditions.

Key Words: western cherry fruit fly; positive phototaxis; halogen bulb; light intensity; ammonium carbonate

Resumen

La atracción de las moscas de la fruta tefrítidas a la luz y su papel en la biología y el manejo de las mismas ha recibido poca atención. Aquí, el objetivo fue mostrar que la mosca de la fruta del cerezo occidental, *Rhagoletis indifferens* Curran (Diptera: Tephritidae), es atraída por la luz blanca en presencia y ausencia de amonio, una señal olfativa usada con las trampas. Se realizaron pruebas de laboratorio dentro de una jaula de 0,23 m^3 con una bombilla halógena o de diodo emisor de luz (LED) colgada ~2 cm por encima de una trampa con o sin señuelo de carbonato de amonio; las moscas fueron liberadas en la jaula opuesta a la luz. Las capturas de moscas en trampas amarillas o claras con luz blanca de ambos tipos de bulbo fueron mayores que en los controles, y mayores en intensidades de luz más altas que bajas, si el amonio fuera presente o no. La adición de calor sin luz adicional cerca de las trampas no incrementó las capturas, lo que indica que la luz y no el calor de los bulbos atrajo las moscas. En el campo, la luz de las bombillas LED y halógenas no mejoró las capturas de moscas en las trampas amarillas con amoníaco, pero la luz de las bombillas halógenas mejoró las capturas cuando no había amonio, aunque las capturas fueron menores que cuando se agregó amonio. Los resultados muestran que la luz blanca brillante es atractiva para *R. indifferens* y sugieren que la orientación hacia ella puede inducir comportamientos que afectan positivamente la aptitud de la mosca, como el apareamiento y el forrajeo. Sin embargo, los estímulos asociados a luces más fuertes de las que fueron utilizados aquí pueden ser necesarios para mejorar las capturas de moscas en las trampas con amonio en condiciones de campo.

Palabras Clave: mosca de la fruta de la cereza occidental; fototaxis positivas; bombilla halógena; intensidad de luz; carbonato de amonio

Positive phototaxis or attraction to light is a well-known behavior in adults of crepuscular and nocturnal insects. Much work has focused on responses to artificial light by moths (e.g., Robinson 1952; Baker & Sadovy 1978; Garris & Snyder 2010), mosquitoes (Hoel et al. 2009), sand flies (Cohnstaedt et al. 2008), and *Drosophila* (e.g., Parsons 1975; Markow & Fogleman 1981; Rieger et al. 2007) in order to understand physiological mechanisms underlying orientation responses and ways to use light for pest management. However, attraction to lights, whether ultraviolet (UV), white, or others, in most diurnal insects and its role in basic biology and pest management has received little attention. Responses to various types of light have been studied in some muscid and calliphorid flies (Zablocka 1972; Meyer 1978; Pickens 1989; Smallegange 2004), but have not been well studied in diurnal Diptera, including in the economically important family Tephritidae. In contrast, many studies have been done on responses of tephritids to color and other visual cues, especially as they relate to traps (e.g., Prokopy 1968, 1986; Greany et al. 1977; Owens & Prokopy 1984, 1986; Yee 2014, 2015).

Western cherry fruit fly, *Rhagoletis indifferens* Curran (Diptera: Tephritidae), is a major quarantine pest of cherries (*Prunus* species; Rosaceae) in western North America that is diurnal as far as known. Peak activity times for flies occur between 1000 and 1700 h during Jun when adults are most abundant (Yee 2002). Observations of the fly in the field strongly suggest it is positively phototactic, as during mornings more flies are usually seen at sunlit than shady sides of trees (Frick et al. 1954; Yee 2002). Sunlight comprises white light along with UV and other components. UV light (10–400 nm) is more attractive than white light to other insects (e.g., Smallegange 2004; Jeraldo et al. 2012), but it is uncertain whether it is attractive to *R. indifferens*. Eyes of the related apple maggot, *R. pomonella* (Walsh), are insensitive to wavelengths <330 nm (Owens 1982) and are most sensitive to 400–530 nm within the visible light range (Agee 1985), suggesting flies may be more attracted to the white light component. Also, *R. indifferens* flies

United States Department of Agriculture, Agricultural Research Service, Yakima Agricultural Research Laboratory, 5230 Konnowac Pass Road, Wapato, WA 98951, USA
*E-mail: wee.yee@ars.usda.gov

inside colony cages often congregate in the area closest to white light from bulbs outside cages in the absence of any other obvious stimuli (W. L. Y., personal observations). As yet, however, experiments showing *R. indifferens* is attracted to white light have not been done.

Showing that *R. indifferens* is attracted to white light is important for several reasons. It could help explain fly behaviors such as fly movements toward optimal mating or foraging sites, and reveal selection pressures for evolution of these behaviors. It can also potentially be used to improve fly detection, which is critical for managing the pest. Traps for detecting the fly are typically baited with ammonia, a highly attractive olfactory cue (Frick 1952). Sunlight transmitted through translucent yellow panel traps baited with ammonia has been shown to increase fly captures (Yee 2014), suggesting light from bulbs near traps could be used to increase trap efficacy. Despite this observation, whether light associated with traps with or without ammonia can increase fly captures in the field is unknown.

In this study, the main objective was to show that *R. indifferens* is attracted to white light, as opposed to heat from light, in the presence and absence of ammonia. A secondary objective was to compare results with halogen and light-emitting diode (LED) bulbs. A third objective was to test the hypothesis that white light attracts flies independent of the trap color. Studies were first conducted in the laboratory to show that the fly is attracted to white light. Studies were then conducted in the field to determine whether white light can enhance fly captures on ammonia-baited and non-baited sticky yellow traps.

Materials and Methods

Flies used in laboratory experiments were reared from larvae collected in infested sweet cherries from central Washington State, USA, in Jun to Jul 2014 and 2015. Larvae exited cherries placed on hardware cloth suspended in tubs and pupated in the tubs. Pupae were held at 3 to 5 °C for 6 to 8 mo before transfer to 23 to 24 °C for adult emergence and aging for experiments. Sets of 30 males and 30 females were held upon emergence in 1.9 L (16.2 cm diameter, 10.5 cm high) paper containers covered with a tulle fabric (1 mm^2 openings) and with dry sucrose–yeast extract food on a paper strip and a water wick under a 16:8 h L:D photoperiod. Flies were 12 to 16 d old and reproductively mature at the start of experiments.

DESIGN OF LABORATORY EXPERIMENTS

Eight similar experiments (experiments 1–8) were conducted in 1 aluminum frame cage set up in a room at 26 to 27 °C and 20 to 30% RH with slowly circulating air. The cage was 0.23 m^3 (61 cm by 61 cm) with an aluminum floor and was set 1.7 m below fluorescent lights. The cage remained in the same location in all experiments. The sides of the cage were covered with black poster board to eliminate visual cues, and its front and back were fitted with plain brown cardboard. The top was covered with gray window screen of 1.6 mm openings to allowing entry of overhead light. Experiments were conducted with one of several types of halogen or LED white light bulbs at a time. Information on lights used in these experiments is presented in Table 1. Light intensities were controlled with a rheostat (Staco Energy Products Co., Dayton, Ohio) set to 120 volts. One bulb was hung ~2 cm above a sticky rectangle trap. Except in experiment 5, the trap was a 14 by 23 cm sticky yellow plastic sheet covered with a pressure sensitive adhesive (AgriSense-BCS Limited, South Wales, United Kingdom) that is highly attractive to *R. indifferens* in the field (Yee 2014). In experiment 5, the trap was a 14 by 23 cm clear styrene plastic sheet (Plastruct, Industry, California) covered with a thin layer of Tanglefoot® adhesive (Contech Enterprises, Inc., Victoria, British Columbia, Canada). This trap was used to test if a clear sticky sheet alone could catch flies in the presence of light from bulbs.

All 8 laboratory experiments were conducted with a no-choice design. Experiments either had or did not have an ammonia lure placed ~1 cm above the trap. The lure was a clear vial with 10 g of ammonium carbonate (Keystone Universal, Melvindale, Michigan) and two 1 mm holes in the lid. A light meter (model 941, Fluke Corp., Everett, Washington) was used to measure light intensity (lm/m^2 or lx). Light treatments (see below for specifics) were average intensities at 15 cm (an arbitrary distance) from the bulbs based on 3 readings. Light readings from bulbs were made with the sensor facing the side of the bulb. With the sensor facing this direction, light intensities at the top, center, and bottom of the cage were 250, 140, and 90 lx, respectively; with the sensor up, they were 500, 390, and 240 lx, respectively. For each light treatment, temperatures on the surface of the side of the bulb and 2.5 and 5 cm away were recorded by a digital thermometer probe set in place until temperatures stabilized after 5 to 10 min.

For each replicate in all experiments, 30 males and 30 females were held in a 473 mL paper carton for 1 to 2 h before being moved into the cage and released. The carton was placed on the floor of the cage ~60 cm away from the bulb/trap. Releases occurred between 4 and 9 h after lights had been turned on. Light gradients facing the bulb between the fly release point and the bulb/trap were 50 to 5,000 lx, depending on the test. Flies caught on the trap were counted 2.5 h later. Five replicates of the control and all treatments were conducted in light experiments 1 to 4, and 4 replicates in experiment 5. For heat experiments 6 to 8, 5 replicates were performed. Each replicate comprised a different set of 30 male and 30 female flies; each set of flies was used only once.

Laboratory Experiments 1 and 2: Halogen or LED Bulbs, with Ammonia

Ammonia was used in these 2 experiments. In these and laboratory experiments 3 to 7, the control was a bulb turned off, with light intensity of 140 lx at 15 cm away. In test 1A of experiment 1, a 60 W halogen bulb was set to 210, 660, and 1,971 lx, the maximum for the bulb. In test 1B, a 75 W halogen bulb was set to 2,020 lx and the maximum of 2,200 lx. To reduce the amount of heat emitted from bulbs and thus conserve energy use for potential field application, in test 2A of experiment 2, a 60 W LED bulb was set to 320, 720, and 2,280 lx. In test 2B,

Table 1. Light bulbs used in experiments, along with their specifications according to the manufacturers.

Experiment	Equivalent W energy bulb	Actual energy used	Light appearance	Brightness	Color temperature	Dimensions (cm)
1, 3, 5	60 W halogen[a]	43 W	soft white	750 lm	2,920 K	8.8 long; 5.5 diameter
1, 6, 7, 9, 10	75 W halogen[b,c]	53 W	soft white	1,050 lm	2,950 K	8.0 long; 5.5 diameter
2, 4	60 W LED[d]	9 W	soft white	800 lm	3,000 K	4.7 long; 5.5 diameter
6, 9	45 W LED[e]	3 W	warm white	400 lm	3,000 K	4.0 × 1.9 × 1.9

Manufacturer or distributor: [a, b]Ecosmart™, Home Depot, Atlanta, Georgia, USA; [c]for experiments 6 and 7, black or white paint applied on bulb. [d]Thinklux Lighting, EarthLED, Golden, Colorado;[e]1000Bulbs.com, Garland, Texas. No bulb was used in experiment 8.

a 60 W LED bulb was set to 2,280 lx and the maximum of 3,210 lx. The original intent was to compare the same light intensities from halogen and LED bulbs, but it was determined after testing that the rheostat settings used gave different intensities for the 2 bulb types.

Laboratory Experiments 3 and 4: Halogen or LED Bulbs, no Ammonia

These 2 experiments were a subset of experiments 1 and 2, but no ammonia lure was used. In experiment 3, a 60 W halogen bulb was set to 210 and 1,970 lx. In experiment 4, a 60 W LED was set to 320 and 2,280 lx.

Laboratory Experiment 5: Halogen Bulb with Clear Plastic Trap, no Ammonia

For testing the hypothesis that white light attracts flies independently of the trap color, a test with no ammonia lure was conducted with a 60 W halogen bulb set to 210, 660, and 1,970 lx placed above a sticky and clear styrene plastic sheet trap.

Laboratory Heat Experiments 6 to 8: Effect of Heat near Traps on Fly Captures

To determine whether heat from bulbs affected fly captures, 3 experiments were performed. All used yellow traps with or without an ammonia lure. In all experiments, the control had no added heat source. Experiment 6 had an ammonia lure and a painted 75 W halogen bulb as a heat source. The bulb was painted to prevent light from escaping the bulb while allowing it to produce heat as from the unpainted 75 W halogen bulb in experiment 1. The bulb was painted either black (tests 6A, 6B) or white (tests 6C, 6D). The bulb was hung ~2 cm above a trap next to a 45 W LED bulb that provided 1,200 lx at 15 cm from the trap. Paints were high heat enamels (Rust-oleum Corp., Vernon Hills, Illinois). For the white bulb, white paint was applied over the black paint, as light passed through the white paint alone.

Experiment 7 used the same heat source as test 6B, but had no ammonia lure and room light was the only illumination source. In experiment 8, to eliminate the possibility of enamel paint odors affecting fly responses, a 10.2 cm long by 1.3 cm diameter soldering iron was used as the heat source in place of a painted bulb. There was no ammonia lure and only room light was used.

FIELD EXPERIMENTS (9 AND 10)

Two field experiments (experiments 9 and 10) were conducted in Jun to Jul 2015, both with the same sticky yellow trap as in the laboratory. Experiments were set up to determine whether 45 W LED or 75 W halogen bulbs in the presence and absence of ammonia can enhance fly captures on traps in sweet cherry trees (*Prunus avium* [L.] L.; Rosaceae). Experiment 9 tested traps with the same ammonia lure as in the laboratory and consisted of 2 tests (9A, 9B). Experiment 10 tested traps with no ammonia lure and consisted of 2 tests (10A, 10B). All tests compared a trap with light from a bulb versus a trap without light in a paired design. Field sites were Moxee, an experimental sweet ('Bing') cherry orchard at the United States Department of Agriculture, Agricultural Research Service, Research Farm in Yakima County, Washington, and Roslyn, a rural site with sweet cherry trees in Kittitas County, Washington. Trees at Moxee were ~3.7 m tall and wide and those at Roslyn were ~5 to 7 m tall and wide. Light levels ~15 cm around traps were measured with a light meter, with the sensor facing towards the sun's direction.

Test 9A was conducted at Moxee from 3 to 16 Jun using 2 LED bulbs housed inside a 7.6 cm diameter clear plastic sphere (bulbs were not weatherproof) ~2 cm above a trap. Bulbs were connected by cord to a timer that kept light on from 0500 to 2100 h; electricity was supplied by car batteries. Traps were hung in trees 2 to 2.5 m above ground beneath the south side of the canopy. Four tree pairs were arranged in 2 adjacent rows, with 1 trap per tree. Trees were 6.7 m apart within and between rows. Within a row, control and lighted traps were placed in alternate trees. Trap positions were switched within a pair every 1 to 3 d, at which time traps were replaced and captured flies counted. There were 9 sample dates. Light intensity between 1000 and 1300 h measured beneath the tree canopy around traps averaged 23,000 lx.

Test 9B was conducted at Roslyn from 14 to 23 Jul with 75 W halogen bulbs. Electricity was supplied to bulbs by car batteries as at Moxee. Four trees were used, each with a paired lighted and control trap spaced 1.5 m apart. Traps were deployed for 3 h between 0900 and 1300 h each test day at Roslyn (also in Test 10B below) instead of continuous exposure because of the threat of batteries being stolen if left overnight, unlike at Moxee, which is an experimental farm inaccessible to the public. Treatment and control trap positions within a pair on different test days were switched. Traps were removed after 3 h and flies were counted. There were 6 sample dates. Mean light intensity around traps was 22,300 lx.

Experiment 10 used 75 W halogen bulbs. Test 10A was conducted at Moxee from 23 to 25 Jun and followed the methods of test 9A. Test 10B was conducted at Roslyn from 30 Jun to 15 Jul and from 24 to 29 Jul and followed the methods of test 9B, for 12 sample dates in total. In Roslyn, average light intensities between 1000 and 1300 h measured around traps were 21,800 and 28,800 lx. Light intensities were not recorded during test 10A.

STATISTICAL ANALYSES

Fly counts were square-root transformed and analyzed for normality and equal variances, which were met in all laboratory and field experiments based on Shapiro–Wilk and Brown–Forsythe tests. All experiments were designed to test for light-induced fly responses, rather than to determine light intensity–fly response relationship curves using regression. Thus fly responses in experiments 1 to 5 were subjected to 2-way analysis of variance (ANOVA), testing for sex, light intensity, and interaction effects (SAS Institute 2010). When there were no interaction and no sex differences, a 1-way ANOVA was conducted on light treatments, followed by Tukey's HSD test at $\alpha = 0.05$. In experiments 6 to 8, pooled *t*-tests were conducted (TTEST; SAS Institute 2010), as control and treatment samples were independent and variances were equal. In experiments 9 and 10, paired *t*-tests were conducted, as control versus treatment traps were deployed simultaneously in adjacent trees or 1.5 m apart within the same trees and could be considered choice tests. Data across all sample dates were combined.

Results

TEMPERATURES ON OR NEAR BULBS

Temperatures on the surfaces of and near bulbs increased with greater light intensity. For example, in test 1A, surface temperatures of the halogen bulb in the 140, 210, 660, and 1,970 lx treatments were 26.6, 37.4, 44.1, and 55.7 °C, respectively. Heat from halogen bulbs was greater than from the 60 W LED bulb (data not shown). Despite greater heat with increased light intensity, temperatures 2.5 and 5 cm away from halogen bulbs were never >35 °C and most were close to the ambient 27 °C. For example, in test 1A, temperatures 2.5 cm away from the bulb in the 140, 210, 660, and 1,970 lx treatments were 26.6, 28.3, 30.4, and 32.2 °C, respectively. This indicated heat from bulbs

dissipated quickly at short distances. Heat on painted bulb surfaces, especially the black surface, was higher than that on unpainted bulbs, at 105.8 °C, but temperatures 2.5 and 5 cm from these bulbs were similar, at 27.9 to 30.6 °C. No flies were found dead underneath a bulb, so flies were not killed by landing on a bulb that was too hot.

GENERAL RESULTS OF LABORATORY LIGHT EXPERIMENTS

No sex × light treatment interactions and sex differences were detected in light experiments 1 to 5 ($P > 0.05$), so results for the sexes were summed and light treatment effects analyzed by 1-way ANOVA. Fly captures among light treatments differed in every experiment, with higher light intensities generally inducing greater fly responses.

LABORATORY EXPERIMENTS

Laboratory Experiments 1 and 2: Halogen and LED Bulbs, with Ammonia

In test 1A with the 60 W halogen bulb, fly captures in light treatments were higher than in the control, with captures in 210, 660, and 1,970 lx treatments progressively increasing ($F = 129.54$; df = 3, 6; $P < 0.0001$) (Fig. 1A). In test 1B with the 75 W halogen bulb, fly captures in light treatments were greater than in the control ($F = 372.54$; df = 2, 12; $P < 0.0001$), whereas 2,020 and 2,200 lx treatments did not differ (Fig. 1B).

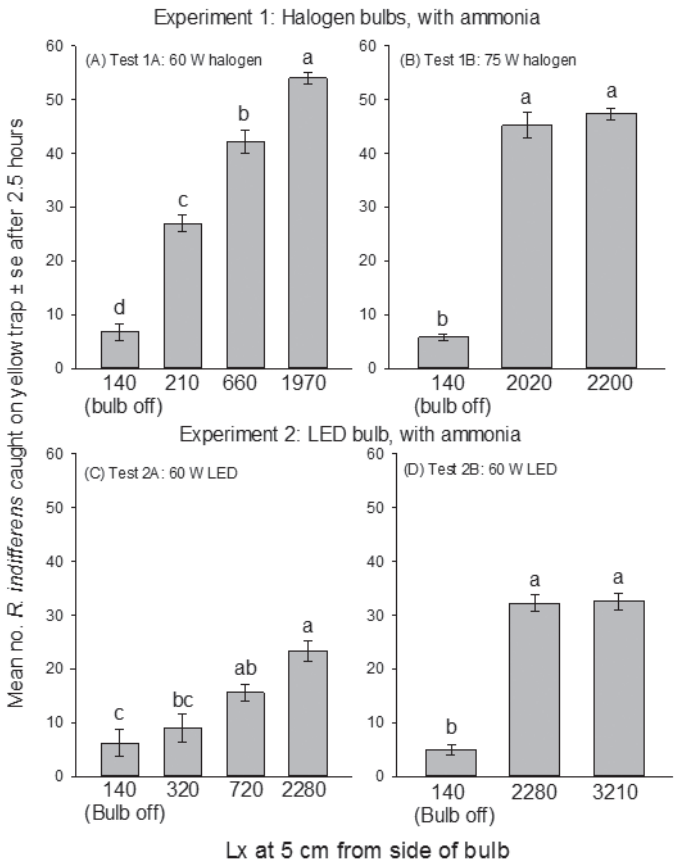

Fig. 1. Mean numbers **± SE** of *Rhagoletis indifferens* flies caught on sticky yellow traps with ammonia lure at different light intensities (lx) shown along the x-axis: experiment 1: (A) test 1A, 60 W halogen bulb; (B) test 1B, 75 W halogen bulb; experiment 2: (C) test 2A, 60 W LED bulb; (D) test 2B, 60 W LED bulb. Light intensities inside test cage were 90 to 250 lx. Maximum number of flies was 60. Means with same letters are not significantly different ($P > 0.05$, Tukey's HSD test).

In test 2A with the LED bulb, fly captures in 720 and 2,280 lx treatments were greater than in the control ($F = 10.10$; df = 3, 16; $P = 0.0006$) (Fig. 1C). In test 2B with the LED bulb, fly captures in light treatments were also greater than in the control ($F = 82.26$; df = 2, 12; $P < 0.0001$), whereas 2,280 and 3,210 lx treatments did not differ (Fig. 1D). More flies were captured with the halogen bulb than the LED bulb even when light intensity for the LED bulb was greater (Fig. 1A–D), although data were not statistically compared due to unequal light intensities produced from the 2 bulb types.

Laboratory Experiments 3 and 4: Halogen and LED Bulbs, No Ammonia

When ammonia was absent, fly captures in 60 W halogen bulb light treatments were also greater than in the control, with numbers greater in the 1,970 than 210 lx treatment ($F = 560.66$; df = 2, 12; $P < 0.0001$) (Fig. 2A). Similarly, fly captures in the 60 W LED bulb light treatments with no ammonia were greater than in the control, with more flies caught in the 2,280 than 320 lx treatment ($F = 61.25$; df = 2, 12; $P <$

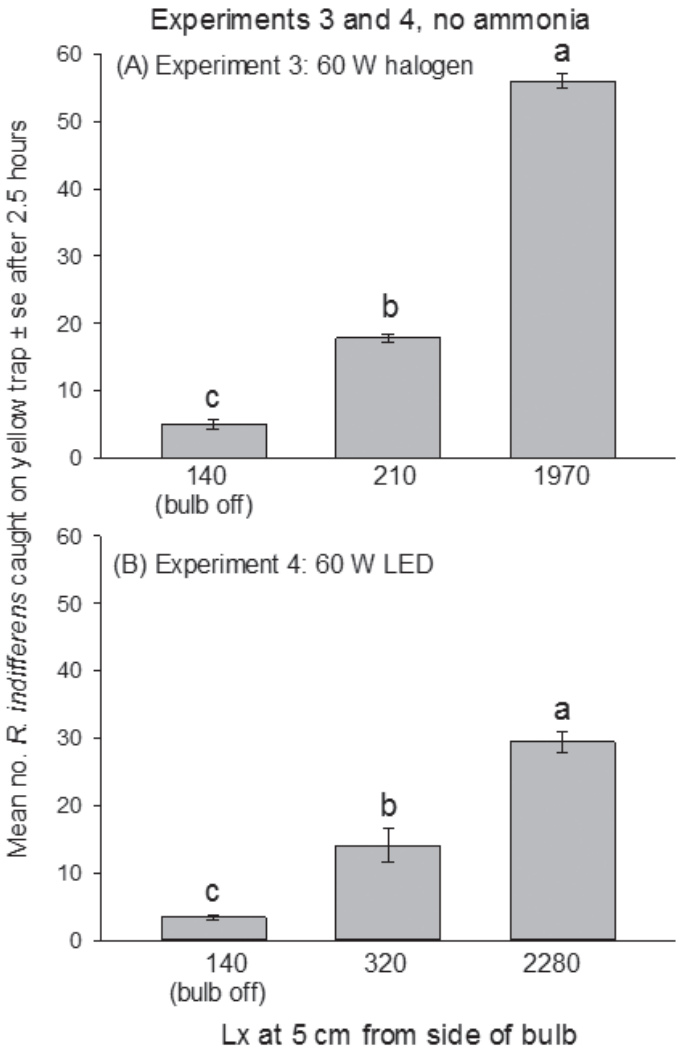

Fig. 2. Mean numbers **± SE** of *Rhagoletis indifferens* flies caught on sticky yellow traps with no ammonia lure at different light intensities (lx) shown along the x-axis: (A) experiment 3, 60 W halogen bulb and (B) experiment 4, 60 W LED bulb. Light intensities inside test cage were 90 to 250 lx. Maximum number of flies was 60. Means with same letters are not significantly different ($P > 0.05$, Tukey's HSD test).

0.0001) (Fig. 2B). As in experiments 1 and 2, more flies were caught with the halogen than LED bulbs.

Laboratory Experiment 5: Halogen Bulb with Clear Plastic Trap, no Ammonia

Fly captures on the clear plastic trap with 60 W halogen bulb light treatments were higher than on the control (F = 51.51; df = 3, 12; P < 0.0001). Also, the 1,970 and 660 lx treatments caught more flies than the 210 lx treatment (Fig. 3), indicating white light does not need to be near a yellow trap to enhance fly captures.

Laboratory Heat Experiments 6 to 8: Effect of Heat near Traps on Fly Captures

In experiment 6, fly captures on traps next to painted bulbs that were turned on and produced heat were lower than on control traps (Fig. 4). In tests 6A and 6B, numerically fewer flies were caught on traps near the 76.3 and 105.8 °C black bulbs, respectively, than on control traps, with statistically more in test 6A (Fig. 4A) although not test 6B (Fig. 4B). Statistically fewer flies were caught on traps near the 65.0 and 90.5 °C white bulbs than on control traps in tests 6C (Fig. 4C) and 6D (Fig. 4D), respectively. Similar results were obtained in experiments 7 and 8, in that heat treatments using the black bulb and the soldering iron, respectively, did not capture more flies than controls (Fig. 5).

FIELD EXPERIMENTS (9 AND 10)

Fly captures in field experiment 9 on ammonia-baited yellow control and lighted traps with LED (Moxee) or halogen bulbs (Roslyn) did not differ (Moxee, mean ± SE: control: 534.5 ± 35.6 flies; light treatment: 543.2 ± 32.8 flies; t = −0.48; df = 3; P = 0.6655; Roslyn, control: 150.5 ± 17.7 flies; light treatment: 164.0 ± 27.3 flies; t = −0.69; df = 3; P = 0.5389). In contrast, when there was no ammonia lure in experiment 10, fly captures were higher on yellow traps with 75 W halogen bulbs than on control traps, numerically in test 10A and statistically more in test 10B (Table 2). Combining both no-ammonia tests, there were 1.9 times more flies caught in the light treatment than control. However, total fly captures in no-ammonia tests were lower than in ammonia tests. The ratios of males to females in unbaited control (299 total flies) and treatment traps (570 total flies) were 1.2 to 1 and 1.1 to 1, respectively, for the 2 tests combined in experiment 10.

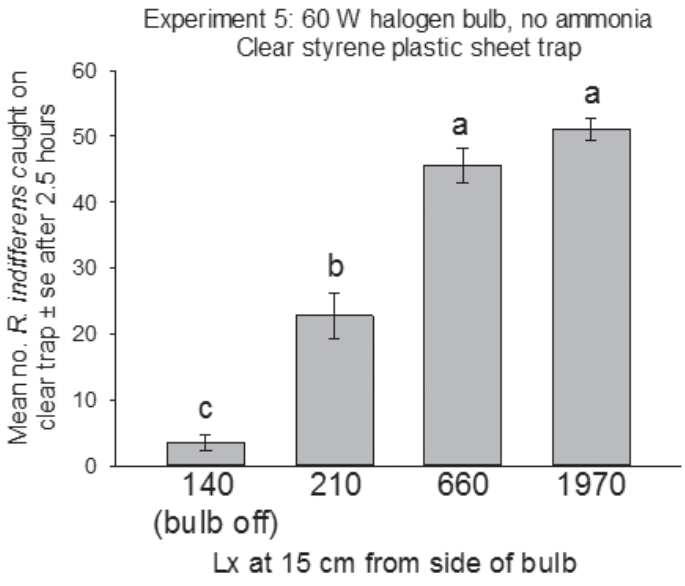

Fig. 3. Mean numbers **± SE** of *Rhagoletis indifferens* flies caught on clear styrene trap with 60 W halogen bulb and no ammonia lure at different light intensities (lx) shown along the x-axis. Light intensities inside test cage were 90 to 250 lx. Maximum number of flies was 60. Means with same letters are not significantly different (P > 0.05, Tukey's HSD test).

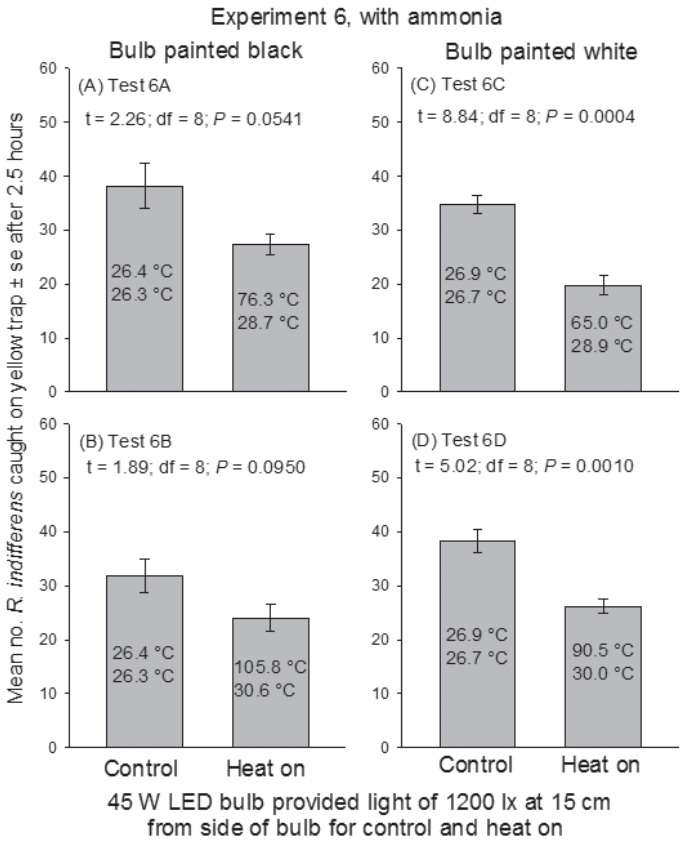

Fig. 4. Mean numbers **± SE** of *Rhagoletis indifferens* flies caught on sticky yellow traps with ammonia lure in control (no heat) and heat treatments, using a painted 75 W halogen bulb: (A) 76.3 °C black bulb; (B) 105.8 °C black bulb; (C) 65.0 °C white bulb; (D) 90.5 °C white bulb. Light was provided to each trap by using a 45 W LED. Top temperature inside bar is that on the bulb surface; lower temperature is that at 2.5 cm from the bulb. Light intensities inside the test cage were 90 to 250 lx. Maximum number of flies was 60.

Discussion

Results show that white light from halogen and LED bulbs was attractive to female and male *R. indifferens* adults whether ammonia was present or not under laboratory conditions. Although greater heat was generated at higher light intensities, several results indicate flies were mostly, if not only, attracted to white light and not the heat from the bulbs. First, even when little heat was generated at lower light intensities, more flies were caught on the lighted than control traps. Second, even when the lighted bulb surface temperatures were high (e.g., 65 °C), temperatures 2.5 to 5 cm away were relatively low, so flies probably first detected and oriented towards the light. Third, greater heat near bulbs did not result in greater fly captures. In fact, some data suggested greater heat near bulbs (30 vs. 27 °C at 2.5 cm away) could deter flies from landing on traps. One possible explanation for these results is that brighter light from bulbs formed a stronger contrast with the 90 to 200 lx surroundings than dimmer light, similar to dark traps forming a strong contrast against a light background that is stimulating to *R. pomonella* (Owens & Prokopy 1984, 1986).

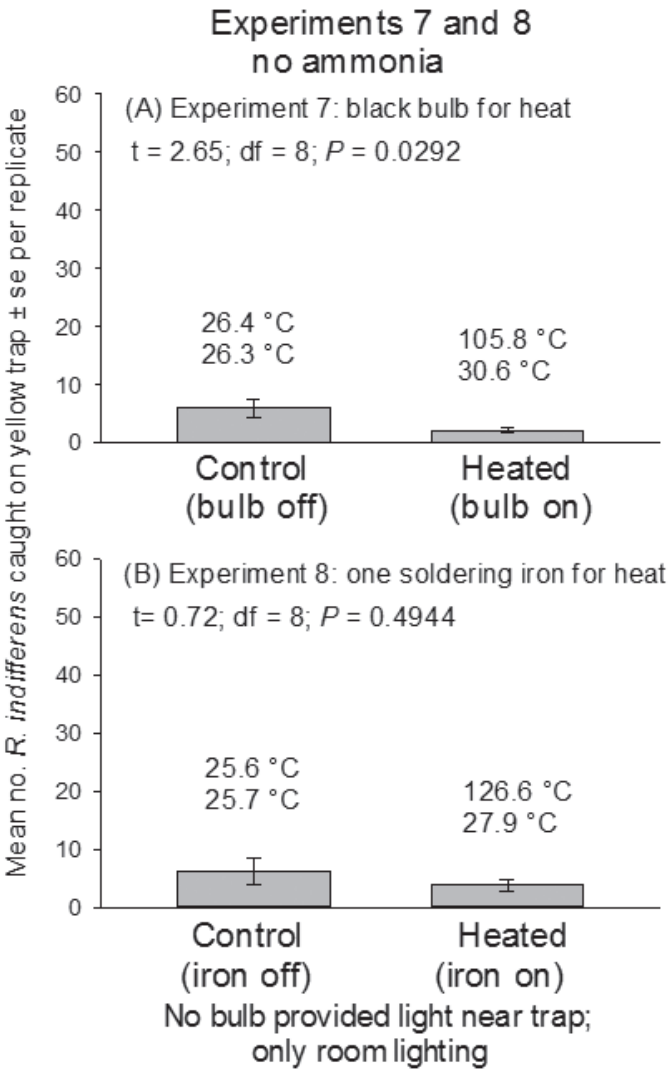

Fig. 5. Mean numbers **± SE** of *Rhagoletis indifferens* flies caught on sticky yellow traps with no ammonia lure: (A) experiment 7 using a black bulb: control (light off) and heated (light on); (B) experiment 8 using an iron: control (iron off) and heated (iron on). No bulb light was provided in either experiment. Top temperature above bar is that on the surface; lower temperature is that at 2.5 cm from the heat source. Light intensities inside the test cage were 90 to 250 lx. Maximum number of flies was 60.

Results with the clear styrene trap show that high fly captures did not depend on light shining on the yellow color or on the trap type itself, suggesting flies were attracted only to the light in the laboratory. This is consistent with *Drosophila* (Diptera: Drosophilidae) flies that are attracted to light that is not associated with any trap color (Parsons 1975; Rieger et al. 2007). Observations showed that regardless of trap color, *R. indifferens* flies first flew to the brown cardboard at the opposite side of the cage ~5 cm from the bulb and rested there. The flies then took a short, hoppy flight onto the trap. These could be undirected flights in the sense that light stimulated flight, and captures were an incidental result due to the trap's close proximity to the light bulb. Some flies also flew directly to the bulb and briefly landed on it (in the case of the 60 W LED, resting for up to 5 min) while others glanced off.

Table 2. Mean numbers ± SE of *Rhagoletis indifferens* flies caught on yellow traps per replicate in 75 W halogen bulb, no ammonia field experiment 10 at Moxee and Roslyn, Washington, in Jun and Jul 2015.

Test	Site	Control	Light treatment	*t*	df	*P*-value
10A	Moxee[a]	3.8 ± 1.1	9.0 ± 2.3	−2.12	3	0.1242
10B	Roslyn[b]	71.0 ± 9.7	133.5 ± 15.3	−11.77	3	0.0013

Four replicates. [a]23 to 25 Jun . [b]Twelve sample dates between 30 Jun and 29 Jul ; 3 h test periods on each of the dates.

In the laboratory, white light from the LED bulb attracted flies, but in lower numbers than from halogen bulbs. Greater heat output from the halogen bulbs was probably not responsible for this attraction because flies did not respond positively to heat alone. However, the white LED bulb had a 50 or 80 K higher color temperature than halogen bulbs (Table 1), suggesting that even though white light is a mix of wavelengths, particular white lights that have more of some wavelengths could be especially attractive to flies. Studies comparing identical light intensities, LEDs with different color temperatures (e.g., 3,000 vs. 5,000 K), and fly physiological responses would be needed to pinpoint causes for any differences.

Results suggest flies were not responsive to ammonia in the test cage while they were responsive to bright white light. This is consistent with results from light shone through translucent yellow traps with no ammonia (Yee 2015). These results are unlike those in the field, where ammonia increases captures on traps (Frick et al. 1954). The apparent lack of response to ammonia could have been caused in part by the small test arena size: ammonia odors overwhelmed the small cage and flies were unable to detect differential odor gradients, whereas in the field there is a detectable gradient. In addition, laboratory flies may have been unaffected by ammonia because they were fed yeast extract and sugar before tests and had no need to seek ammonia as a signal for proteinaceous food.

Based on the laboratory results, it was predicted that light near ammonia-baited traps would attract *R. indifferens* in the field. However, unlike flies in the laboratory, when ammonia was present, flies in the field appeared to bypass the white light from the bulbs in favor of the ammonia and/or yellow trap. The ammonia release rate from the lures was ~4 mg/h (W. L. Y, unpublished data) and apparently overrode any light stimulus. *Rhagoletis pomonella* flies locate host fruit visually if fruit are apparent, and by host odor if fruit are not apparent (Aluja & Prokopy 1993). It is unclear if ammonia-baited traps are similarly located, i.e., by using vision if traps are unobstructed from view, but this seems possible because traps of certain colors or shapes catch more flies than other traps despite the same ammonia stimulus (Burditt 1988; Yee 2014). If they are, then the bulb light stimulus may be weaker than both yellow color and ammonia stimuli in the field. Another possible cause for the results is that field flies were hungrier for protein than laboratory flies, explaining the overwhelming response to ammonia.

In contrast to when ammonia was present, white light in the field did enhance captures of *R. indifferens* on yellow traps when ammonia was absent, as predicted based on the laboratory results. However, responses were lower than expected based on those results and much lower than when ammonia was present in the field. In the field, captures on the no-ammonia traps were only about 2 times greater than on the control, versus 8 times greater in the laboratory, so white light effects in the field were weaker. One possible explanation is that light from bulbs competed against sunlight, at ~22,000 lx around traps, unlike in the laboratory, where lit bulbs were in relatively dim surroundings of ~250 to 500 lx, allowing for strong light contrast. Also, the color temperatures of white light and sunlight differ, at 2,950 and 5,800 K, respectively (NASA 2016), possibly affecting fly orientation. Age structure could also be a factor for the discrepancy between the field and laboratory results, as only reproductively mature flies were tested in the laboratory.

The group of field flies attracted to white light associated with the unbaited yellow traps may have been more sensitive to differences between artificial and natural light than the majority of field flies. This sensitivity could be genetically based. Any increased sensitivity was probably due to flies being stimulated first by the yellow of the traps and then by the light. That yellow color was the stronger stimulus was suggested by the relatively small catch enhancement using white light. After the yellow color brought flies in close to the trap, light from the bulb apparently stimulated the sensitive flies to fly more around the bulb, resulting in captures.

Combined laboratory and field results indicate *R. indifferens* is photophilic, unlike *D. melanogaster* Meigen, which prefers dim light (Rieger et al. 2007). This is consistent with *R. indifferens* (Frick et al. 1954; Yee 2002) and other *Rhagoletis* species (Prokopy & Papaj 2000) being most active on bright, sunny days. The photophilic nature of both sexes of *R. indifferens* may have several possible benefits in nature. One is that it could concentrate male and female flies during cool mornings in sunny, warm sites in trees where mating and foraging are optimized. Another is that light can be used by flies as an indicator of open space as suggested for moths (McGeachie 1989), resulting in dispersal, advantageous for spreading eggs among trees that may not fruit yearly. Dispersal in different *Drosophila* species has been linked to differential light responses (McDonald & Parsons 1973; Parsons 1975). As a caveat to the benefits of being photophilic, the phototactic responses of *R. indifferens* may be overridden by high temperatures: during sunny and hot days ≥38 °C, flies seek shade (Yee 2002), almost certainly to avoid overheating and desiccation. The photophilic nature of the fly also indicates that light intensity and direction are factors to consider when interpreting results of any laboratory experiment on fly behaviors.

The lack of enhancement in *R. indifferens* captures with light bulbs with ammonia-baited traps indicates light as used in this study has no benefit for fly detection in the field. However, here only 1 light deployment method was tested. Furthermore, as stated earlier, ammonia odor alone does not make all yellow traps equally effective at catching flies (Yee 2012, 2014), so improving the efficacy of ammonia-baited traps is possible. Some possibilities to explore with light include deploying different white color temperatures and stronger lights that cover a larger area, using lights with a different yellow trap, and changing the position of the bulb relative to the trap and sun. For instance, a bulb placed on 1 side of the trap would transmit light through and create a bright yellow that flies may find attractive (Yee 2014).

In summary, results show that bright white light was consistently attractive to *R. indifferens* in relatively dim conditions in the laboratory; however, it was attractive with traps under brighter field conditions in the absence of ammonia. Orientation towards light may induce behaviors that positively affect fly fitness. Because ammonia is such a powerful attractant, stronger light-associated stimuli than those used here may be needed to enhance fly captures on ammonia-baited traps under field conditions.

Acknowledgments

I thank Pete Chapman and Janine Jewett (United States Department of Agriculture, Agricultural Research Service) for laboratory assistance, and Diane Alston (Utah State University, Logan, Utah), Juan Rull (PROIMI biotecnologia-CONICET, Tucuman, Argentina), and 2 anonymous reviewers for helpful comments on previous versions of the manuscript. This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or a recommendation by the United States Department of Agriculture for its use.

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