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Research Paper

Measurement of semiochemical release rates with a dedicated environmental control system

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Insect semiochemical dispensers are commonly deployed under variable environmental conditions over a specified period. Predictions of their longevity are hampered by a lack of methods to accurately monitor and predict how primary variables affect semiochemical release rate. A system was constructed to precisely determine semiochemical release rates under environmentally-controlled conditions. Three dissimilar types of solid matrix, passive emission semiochemical dispensers (P339 Sirex, Beetleblock-MCH, W230 terpinolene) were selected to verify the system capabilities. The rate of mass loss for each semiochemical was measured inside a 0.11 m^3 air sealed reservoir. Each product was tested at five ambient temperatures and three values of relative humidity. Temperatures were maintained at their set points within ±1.0 °C and relative humidity within ±0.4%. Mass losses for the relatively large P339 Sirex dispensers were linear over the test period; losses for the smaller Beetleblock-MCH and W230 terpinolene dispensers fell sharply over the first 10 h of exposure and then fell linearly with exposure time. Test results demonstrated that release rates of the three semiochemicals at the linear fall stage increased exponentially as ambient temperature increased, and those rates were not apparently affected by relative humidity. Compared to release rates measured under field conditions, determination of semiochemical release rates was more precise and consistent with this dedicated, controlled environmental system. Semiochemical release rates measured with this system should provide a baseline for predicting performance and useful lifetime of semiochemical devices deployed for pest management in agriculture and forestry.

1. Introduction

The use of conventional pesticides has raised concerns over potential contamination of the environment. Consequently, bio-pesticides, which are considered safer and have minimal non-target impacts, have been integrated with other disciplines to provide reliable and eco-friendly pest management tools for effective pest control (Wall, 1989). Applications of semiochemicals to attract or repel insects in specific areas, or

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to disrupt their mating have increased rapidly as a pest management strategy (Clarke et al., 1999; Holsten, Shea, & Borys, 2003). For example, the control of codling moth via mating disruption in apple orchards of the north-western United States increased from 1000 ha in 1991 to 45,000 ha in 2000 (Brunner et al., 2002; Thomson, 1997).

Semiochemicals are chemicals emitted by living organisms that induce a behavioural or physiological response in other individuals. Due to their reduced environmental impacts and non-target effects, semiochemicals are used in a variety of scenarios for insect pest management (Heuskin, Verheggen, Haubruge, Wathelet, & Lognay, 2011). They are used to capture insects that spread diseases, determine the timing and necessity of insecticide applications, track pest population and dispersal, detect and monitor economically important pests (attractants or synergists), and protect tree resources in areas of particularly high value (anti-aggregants or disruptants) (Baker, 2008; Oehlschlager, Chinchilla, Castillo, & Gonzalez, 2002; Ridgway, Inscoe, & Dickerson, 1990; Wall, 1990). For instance, insect chemical attractants are regularly used to monitor flight activity and dispersal for efficient timing of insecticide applications, detecting non-native species, disrupting mate-finding capabilities, and attracting beneficial insects for the biological control of pestiferous insects (Baker, 2008; Heuskin et al., 2011; Oehlschlager et al., 2002; Ridgway et al. 1990).

Efforts are also underway to identify repellent compounds as alternatives to the more indiscriminate conventional pesticides for pest management purposes (Wall, 1989). Repellents can be integrated with attractants as part of a 'push–pull' strategy, whereby they are used to 'push' insect pests away from a crop and attractants are simultaneously used to 'pull' them into traps or areas where they can be killed (Cook, Khan, & Pickett, 2007).

A variety of devices and formulations have been developed for releasing semiochemicals that essentially fall into three main categories, namely, solid matrix dispensers, liquid formulations, and reservoirs of formulations (Heuskin et al., 2011). Pest management applications demand that devices be inexpensive and rugged, leading to the development of solid matrix passive dispensers (or first-order emitters) (Holsten et al., 2003). Solid matrix dispensers release their contents by evaporation through a permeable membrane that encapsulates a chemical reservoir (e.g., bubble cap or pouch) (Hayes, Strom, Roton, & Ingram, 1994; Ross, Daterman, & Gibson, 2002).

However, one of the limitations of solid matrix dispensers is the difficulty in maintaining a constant release rate (i.e., zero-order release kinetics) (Heuskin et al., 2011). Krüger and Tolmay (2002) noted that release rates from dispensers are heavily dependent on the diffusion speed of the compound through the matrix and the evaporation rate of the compound into the air. Diffusion speed is influenced by a variety of characteristics associated with the dispenser, including type, size, and shape of the matrix, along with the distribution of the semiochemical in the matrix (Golub, Weatherston, & Benn, 1983; Heuskin et al., 2011; Hofmeyr & Burger, 1995). Evaporation rate of the compound is mainly influenced by abiotic parameters such as air temperature, relative humidity, wind speed, and the physical properties of the semiochemical (Alfaro-Cid et al., 2009). Among those parameters, temperature might be one of the most important abiotic factors (Atterholt, Delwiche, Rice, & Krochta, 1999; Bradley, Suckling, McNaughton, Wearing, & Karg, 1995; Johansson et al., 2001; Shem, Shiundu, Gikonyo, Ali, & Saini, 2009; Van der Kraan & Ebbers, 1990). These devices characteristically release less chemical with time and release rates are influenced by heat, ventilation, humidity, membrane permeability and contact area with the liquid in the dispenser.

It is a goal of pest management programs to optimise dispenser performance, thereby promoting predictable and efficient use of semiochemicals with minimally adequate release rates for controlling a specific insect population and activity over a specified time frame. However, dispensers are often exposed to large environmental variations with many uncertainties, which leads to unpredictable performance and uncertain replacement schedules (Progar, 2005). Release rates of commercial semiochemical dispensers are usually provided by the manufacturer, having been determined in a laboratory setting at a single temperature point in the product lifetime. The utility of these measurements for predicting field performance is uncertain, depending on many factors, some intrinsic to the device (e.g., stability of release as the reservoir empties) and some meteorological. Less frequently, field evaluations have been made by investigators to estimate *in situ* performance. This approach is time-consuming and results are affected by many uncontrollable environmental variables (Doane, 1999). Consequently, test results are not well understood despite providing estimates of the useful life of dispensers under the observed field conditions (Strom & Clarke, 2011).

Because there is not a quantified target for the optimal release of semiochemicals against most insects, practitioners are primarily interested in knowing the useful lifetime of a semiochemical product in order to develop an efficient replacement schedule under local field conditions (Shorey, Sisk, & Gerber, 1996). Therefore, a greater understanding of the processes at work in semiochemical release rates with an accurate measurement under controlled conditions and field deployment is needed. Once primary factors are better understood, development of predictive models for the performance of different devices under different field conditions can proceed.

The primary goal of this research was to develop an understanding of the meteorological mechanisms affecting the release rates of solid matrix, passive emission semiochemicals from dissimilar, commercially available dispensers. The specific objective was to develop an environmentally-controlled system that maintained constant and precisely-controlled ambient air temperature and relative humidity, thereby allowing an accurate description of their effects on semiochemical release rates.

2. Materials and methods

A dedicated system was constructed to measure semiochemical release rates under controlled ambient temperature and relative humidity conditions. Primary components of

the system were a controlled environmental chamber (Model 5503-00, Electro-Tech Systems, Inc., Glenside, PA, USA), an analytical balance (Mettler-Toledo AG Laboratory & Weighing Technologies, Greifensee, Switzerland), a data acquisition unit and a computer monitoring system (Fig. 1).

The controlled environmental chamber was a 0.11 m^3 rectangular air sealed reservoir (610 mm long, 460 mm wide and 380 mm high) fabricated from a 10 mm thick, clear acrylic sheet. Access to the chamber was through a 0.093 m^2 square opening. A 12 mm thick, clear acrylic door, secured by a single half-turn latch, along with a compression gasket for an airtight seal provided an access entry into the chamber. A 32 mm diameter pass-through opening was provided for passing cables and/or tubing through the chamber wall and sealed with a pliable reusable sealer. The access door and all fittings were located on one end of the chamber.

Consistent air temperature inside the chamber was maintained with a 500 W heating unit and a 150 W solid-state thermoelectric cooling unit, and consistent relative humidity was achieved using an ultrasonic humidification unit and a desiccant-pump dehumidification unit. These units were mounted inside the chamber and were controlled with a temperature-humidity controller.

The ultrasonic humidification unit created a fine, room temperature mist on demand for humidification of the air within the chamber. An air-moving device in the unit evacuated the mist out of the humidifier through a 25 mm diameter plastic tube into the chamber. The desiccant dehumidification unit was a closed loop system, and it was used to reduce the relative humidity of the air within the controlled environmental chamber. A clear plastic column filled with 1.13 kg of renewable calcium sulphate desiccant was mounted to the top of the unit. The desiccant absorbed moisture from the air into the column, and this dried air was then forced back into the environmental chamber with a small quiet linear pump inside the dehumidification unit.

Air temperature and relative humidity inside the environmental chamber were measured with a resistance temperature detector (RTD) probe and a capacitive humidity sensor, respectively. The RTD probe contained a resistor that changed resistance as the temperature changed. The temperature measurement accuracy was ±1.0 °C. The relative humidity sensor measured relative humidity over the entire 0–100% range with an accuracy of ±2%. In addition, the electronics incorporated within the humidity sensor utilised the air temperature information to compensate the humidity reading for changes in air temperature. This capability improved the accuracy of measuring relative humidity values when the air temperature was significantly above or below 23 °C which was the standard calibration point. Temperature and relative humidity values measured from the sensors were fed back to the air temperature-humidity controller to maintain the constant air temperature and relative humidity at their set points.

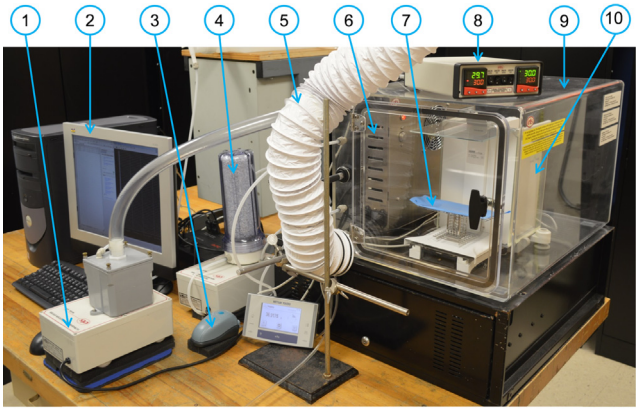


Fig. 1 – Controlled environmental system for measurements of semiochemical release rates.

The air temperature-humidity controller provided a proportional, integral and derivative control of air temperature and relative humidity inside the environmental chamber. Electricity to the temperature and relative humidity control units was pulsed at a rate of 1 s to either power on or off the two units when the air temperature and relative humidity were beyond ±0.2 of their set points. The controller was connected to a desktop computer with a cable through a 9-pin RS-232 serial communication port. The communication between the controller and the computer was through a Windows™ based CAL graphic program (CALGrapix Version 3.1.0 Professional Version, Long Beach, CA, USA). The program recorded the air temperature and relative humidity detected by the temperature and humidity probes every minute and then plotted these measurements to a chart displayed on the computer monitor and stored daily in a spreadsheet file.

The dual range analytical balance (Model XS205DU, Mettler-Toledo, LLC., Columbus, OH, USA) was placed inside the environmental chamber to measure mass changes during the evaporation process of the semiochemical dispenser samples at the temperature and relative humidity test parameters. The balance had the weighing capability of 220 g, readability of 0.1 mg and stabilisation time of 6 s. The balance was factory-calibrated with an accuracy of 0.1 mg. The dimensions of the balance were 263 mm wide, 453 mm deep and 322 mm high. A universal serial bus (USB) to serial RS-232 adapter was used to connect a USB port on the computer to the 9-pin RS-232 port on the balance. Semiochemical dispenser mass losses were recorded and stored in the computer every 15 min and charted on the computer monitor screen with a recording program (BalanceLink version 4.0.2, Mettler-Toledo, LLC., Columbus, OH, USA). The program communicated with the balance and downloaded the mass measurements of a semiochemical sample along with a date time stamp directly into an open and active Microsoft Excel spreadsheet in the computer.

The CAL graphic program and the BalanceLink mass recording program did not communicate with each other. However, both programs used the same real-time clock in the desktop computer to synchronise the recorded air temperature, relative humidity, and semiochemical sample mass measurements.

In addition to the above instruments, a small fan was mounted inside the chamber to agitate the air to maintain

Fig. 2 – Three different semiochemicals used for experiments: (a) P339 Sirex lure (150-mm long and 77-mm wide bag), (b) Beetleblock-MCH (30-mm in diameter and 4-mm high bubble cap), (c) W230 terpinolene (23-mm in diameter and 47-mm high bottle).

uniform temperature and humidity levels. A 160 l h^{-1} capacity, 110 V AC vacuum pump exhausted the air inside the chamber to prevent the build-up of semiochemical vapours and continuously drew fresh air into the chamber. At settings of low air temperature and high relative humidity, condensation might form and drip to the bottom of the environmental chamber. To solve this problem, a stainless steel panel was attached on the wall behind the cooling unit inside the chamber to guide the condensation flow. A V-shaped stainless steel drip pan was placed at the bottom inside the chamber to collect the accumulated condensation from the panel, and a small fish tank pump was used to remove the condensation in the drip pan.

To test the capability and accuracy of the system in measuring release rates, three different types of semiochemicals were used. These samples were a P339 Sirex lure, anti-aggregation pheromone Beetleblock™-MCH dispensers, and W230 terpinolene (Fig. 2). They all were manufactured by Synergy Semiochemicals Corp. (Burnaby, BC, Canada). These three semiochemicals were chosen for testing the system because they presented three different dispensers used in forest pest management with very different shapes, reservoir sizes and target elution rates. They were also tested under outdoor conditions (http://www.fs.fed.us/foresthealth/technology/elutionrate/lure.htm accessed on March 31, 2014).

The P339 Sirex lure was formulated with 70% blended alpha-pinene and 30% beta-pinene used as a host component synergist to attract southern pine beetles (*Dendroctonus frontalis* Zimmermann). The lure was stored in a blue bag (Fig. 2a). It had an effective release surface area of 2.31×10^{-2} m^2, and had a mass of about 90 g full and 6.5 g empty.

The BeetleBlock™-MCH repellant was an anti-aggregation pheromone to repel bark beetles that attack pine and Douglas-fir trees. The repellent was composed of the beetles naturally occurring pheromones and stored in a plastic bubble cap (Fig. 2b). The dispenser was 4 mm high and 30 mm in diameter with a release surface of 7.57×10^{-4} m^2, and a mass of about 1.52 g when full and 1.16 g when empty.

The W230 terpinolene dispenser was formulated to be a component of an attractive lure for the mountain pine beetle, *Dendroctonus ponderosae* Hopkins. The lure compound was loaded in a 15 ml polyethylene bottle which was loosely stored inside a white plastic bag (Fig. 2c). Its surface area was 3.72×10^{-3} m^2 for the 15 ml bottle, and 1.54×10^{-2} m^2 for the plastic bag. The entire unit had a mass of about 18.83 g full and 6.29 g empty.

The test variables for each semiochemical sample were five ambient air temperatures ranging from 20 to 40 °C and three values of relative humidity ranging from 30% to 80% (Table 1). To verify the system repeatability, the release rate for each semiochemical was measured three times with three fresh samples at 30 °C ambient temperature and 50% relative humidity. To determine the effect of ambient temperature on the evaporation rate, each semiochemical was tested at 20, 25, 30, 35, and 40 °C ambient temperature and 50% relative humidity. To determine the effect of relative humidity on the release rate, each pheromone was tested at 30%, 50%, and 80% relative humidity and 30 °C ambient temperature. The mass of each sample was measured for at least 140 h of exposure.

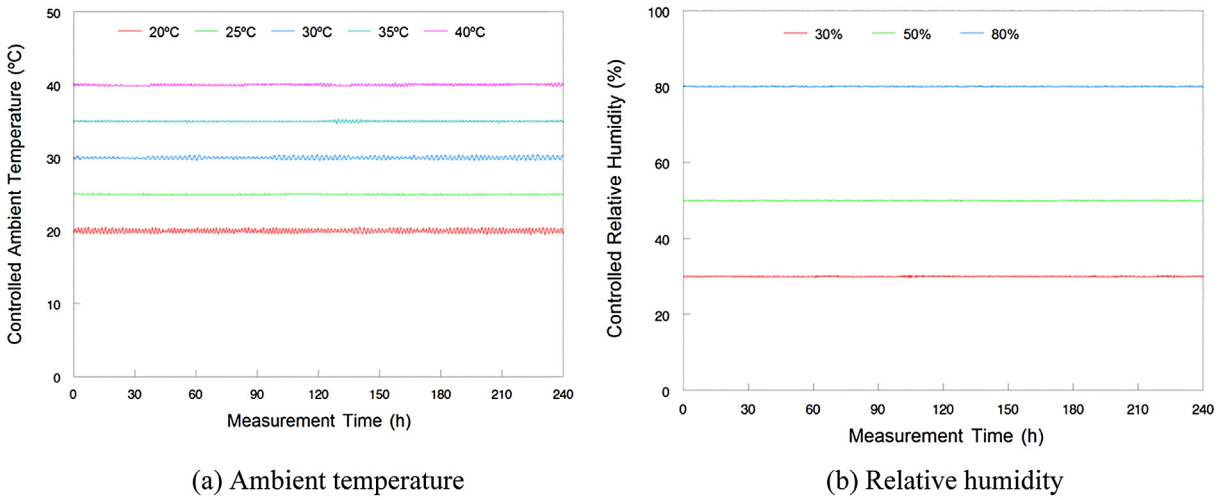
For each treatment, one sample at a time was placed on the balance inside the controlled environmental chamber. Measurements of the mass of each sample, ambient temperature and relative humidity were saved at 15 min intervals in the computer.

3. Results and discussion

The ambient temperature inside the controlled environmental chamber at each set point of 20, 25, 30, 35 and 40 °C had

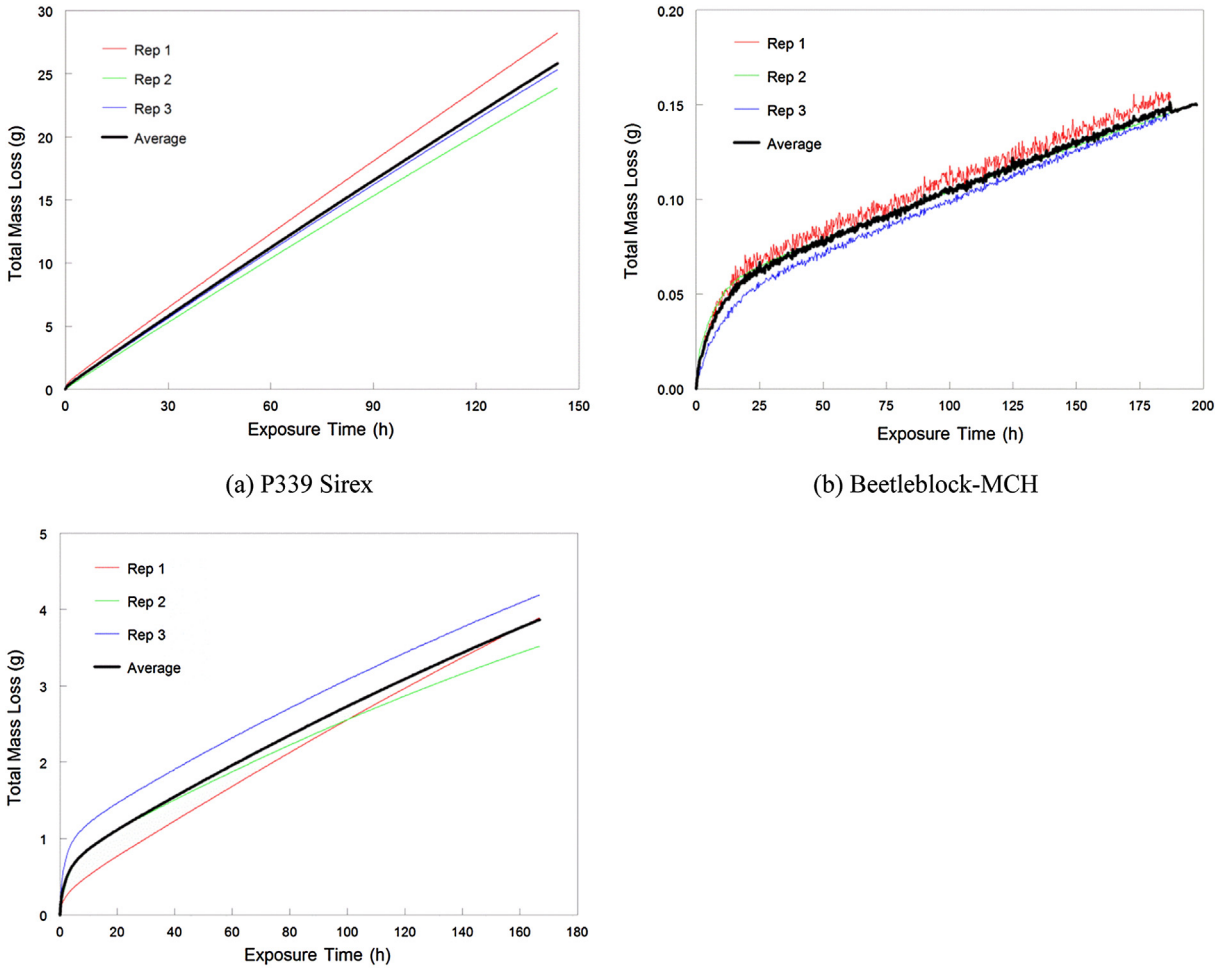
Table 1 – Three semiochemicals (P339 Sirex, Beetleblock-MCH and W230) and their initial masses tested in the controlled environmental chamber at different set points of ambient temperature and relative humidity.

Tested samples	Mass (gram)		Test set points		Note
	Initial	Empty	Ambient temperature (°C)	Relative humidity (%)	
P339 Sirex	88.95 ± 3.36	6.478	20, 25, 30, 35, 40	50	For tests at 30 °C temperature and 50% relative humidity, they were repeated 3 times.
			30	30, 50, 80	
Beetleblock-MCH	1.538 ± 0.050	1.159	20, 25, 30, 35, 40	50	
			30	30, 50, 80	
W230 Terpinolene	18.67 ± 0.56	6.290	20, 25, 30, 35, 40	50	
			30	30, 50, 80	



(a) Ambient temperature (b) Relative humidity

Fig. 3 – Variations of ambient temperature and relative humidity measurements at their set points inside the controlled environmental chamber. (a) Set points for temperature were 20, 25, 30, 35 and 40 °C at 50% relative humidity, and (b) set points for relative humidity were 30%, 50% and 80% at 30 °C ambient temperature.



(a) P339 Sirex (b) Beetleblock-MCH

(c) W230

Fig. 4 – Total mass loss over exposure time with three replications at 30 °C temperature and 50% relative humidity for three semiochemicals: (a) P339 Sirex, (b) Beetleblock-MCH, and (c) W230.

little variation during the 240 h measurement period (Fig. 3a). At these temperature set points with 50% relative humidity, the maximum measured temperatures were 20.5, 25.1, 30.5, 35.3 and 40.3 °C, the minimum measured temperatures were 19.5, 24.9, 29.6, 34.7 and 39.8 °C, and coefficients of variation around their averages were 1.2, 0.2, 0.6, 0.2 and 0.2%, respectively.

Similarly, the measured relative humidity at each set point of 30%, 50% and 80% also fluctuated little during the 240 h measurement period (Fig. 3b). At these relative humidity set points with the ambient temperature at 30 °C, the maximum measured relative humidity was 30.2%, 50.2% and 80.2%, the minimum measured relative humidity was 29.8%, 49.8% and 79.8%, and coefficients of variations around their averages were 0.2%, 0.1% and 0.1%, respectively. For the five temperatures the maximum difference was 1.0 °C and for the three values of relative humidity the maximum difference was 0.4% which was lower than the factory specification of ±2%. Thus, the controlled environmental chamber was able to maintain constant ambient temperature and relative humidity at the specified set points.

The maximum difference for the mass losses among the three replications for each semiochemical sample at 30 °C ambient temperature and 50% relative humidity increased slightly as the exposure time increased (Fig. 4). After a 10 h exposure, this difference was 0.5687 g for P339 Sirex, 0.0034 g for Beetleblock-MCH and 0.5142 g for W230 while the difference increased to 3.0152 g for P339 Sirex, 0.0075 g for Beetleblock-MCH and 0.5165 g for W230 after a 120 h exposure. After the 10 h exposure, the average sample mass was 87.71 g for P339 Sirex, 1.475 g for Beetleblock-MCH and 17.972 g for W230 while after the 120 h exposure it was 68.0407 g for P339 Sirex, 1.4041 g for Beetleblock-MCH and 15.7386 g for W230. Compared to the sample masses, these differences were negligible. Therefore, the measurements of total mass losses due to the chemical release for all three semiochemicals with the controlled environmental system were repeatable.

Relative humidity from 30% to 80% did not apparently influence release rates of the three semiochemicals (Fig. 5). For example, after a 10 h exposure at 30%, 50% and 80% relative humidity and an ambient temperature of 30 °C, total mass losses were 2.0211, 2.0898 and 2.1740 g for P339 Sirex (Fig. 5a),

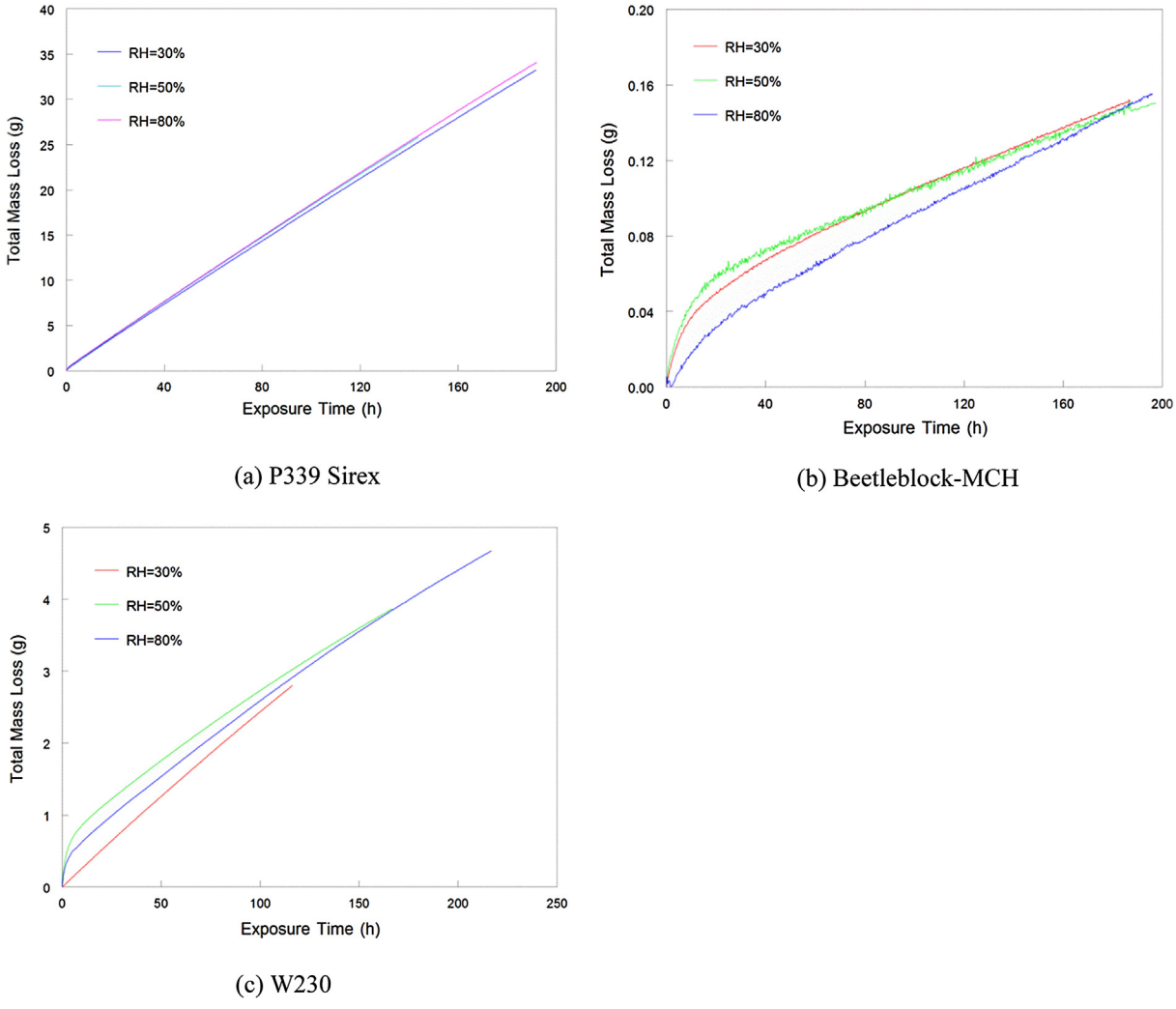


Fig. 5 – Total mass loss over exposure time at 30%, 50%, and 80% relative humidity (RH) and 30 °C temperature for three semiochemicals: (a) P339 Sirex, (b) Beetleblock-MCH, and (c) W230.

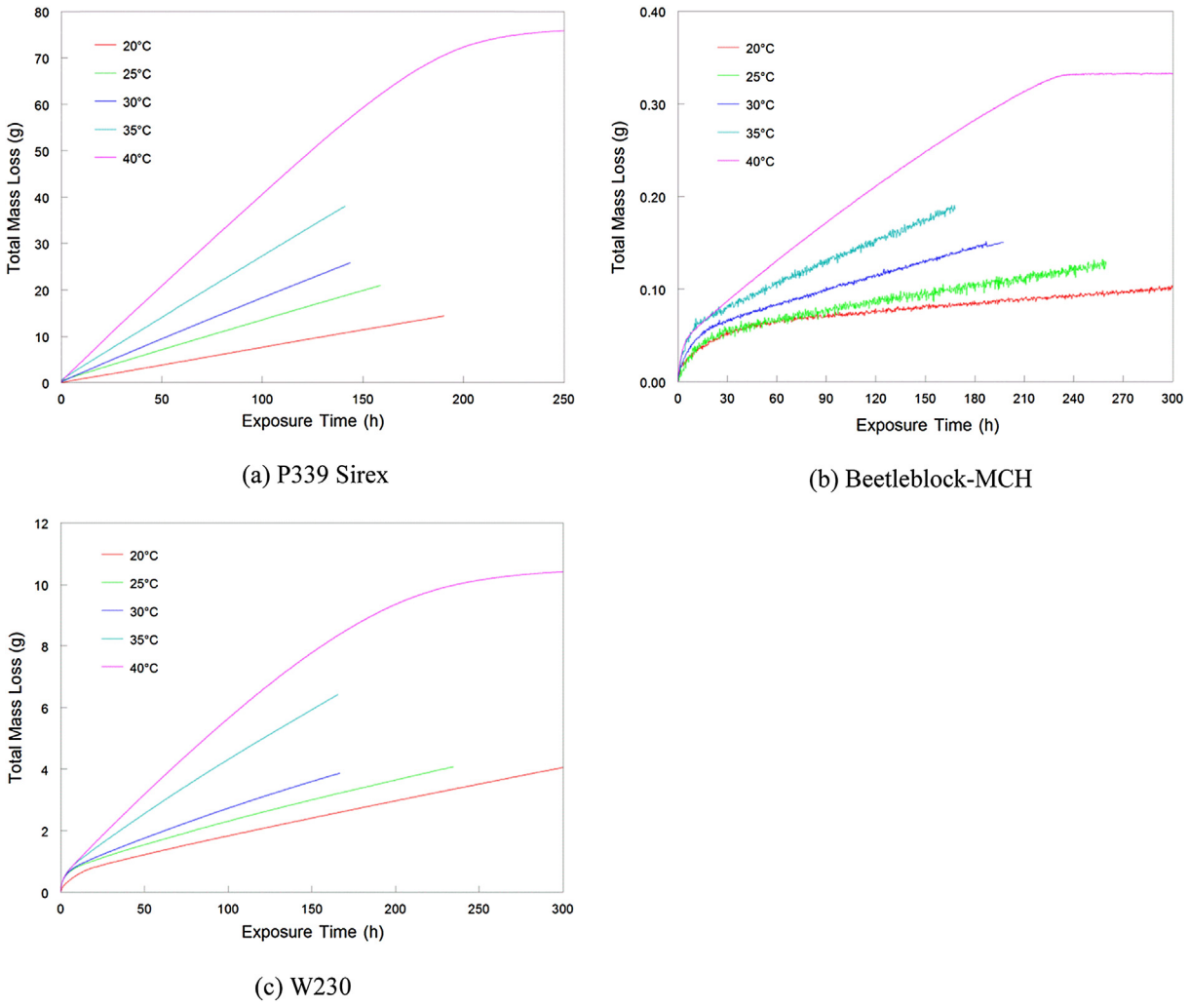


Fig. 6 – Total mass loss over exposure time at 20, 25, 30, 35, and 40 °C temperature and 50% relative humidity for three semiochemicals: (a) P339 Sirex, (b) Beetleblock-MCH, and (c) W230.

0.0369, 0.0425, and 0.0185 g for Beetleblock-MCH (Fig. 5b), and 0.2610, 0.8584, and 0.6276 g for W230 (Fig. 5c), respectively. At that time, the average sample mass was 87.7050 g for P339 Sirex, 1.4854 g for Beetleblock-MCH and 18.2477 g for W230. The maximum difference for the total mass loss among the three values of relative humidity was 0.1529 g for P339 Sirex, 0.0240 g for Beetleblock-MCH and 0.5974 g for W230. Similarly, after a 120 h exposure at 30%, 50% and 80% relative humidity and an ambient temperature of 30 °C, the actual sample mass was 68.1638 g for P339 Sirex, 1.4064 g for Beetleblock-MCH and 15.9169 g for W230, and the maximum differences for the total mass loss among the three values of relative humidity were 0.6459 g for P339 Sirex, 0.0092 g for Beetleblock-MCH and 0.2240 g for W230.

However, ambient temperature greatly influenced the semiochemical release rate. Figure 6 shows the total mass loss with exposure time at 20, 25, 30, 35, and 40 °C ambient temperature and 50% relative humidity for P339 Sirex, Beetleblock-MCH and W230. After a 10 h exposure to the air at 20, 25, 30, 35, and 40 °C, total mass losses were 0.7993, 1.8031, 2.0898, 3.3800 and 4.4840 g for P339 Sirex (Fig. 6a), 0.0323, 0.0386, 0.0425, 0.0559 and 0.0560 g for Beetleblock-MCH (Fig. 6b), and 0.5705, 0.8211, 0.8584, 0.9928 and 1.0213 g for W230 (Fig. 6c), respectively. As the temperature increased from 20 to 40 °C, the total mass loss increased 5.61 times for P339 Sirex, 1.73 times for Beetleblock-MCH and 1.79 times for W230. Similarly, after a 120 h exposure, as the temperature increased from 20 to 40 °C, the total mass loss increased 5.30,

Table 2 – Release rates of semiochemicals (P339 Sirex, Beetleblock-MCH and W230) at different set points of ambient temperature and relative humidity.

Ambient temperature (°C)	Relative humidity (%)	Release rate (g h^{-1})		
		P339 Sirex	Beetleblock-MCH	W230
20	50	0.0763	0.0002	0.0121
25	50	0.1290	0.0003	0.0148
30	30	0.1717	0.0006	0.0238
30	50	0.1774	0.0005	0.0187
30	80	0.1755	0.0007	0.0204
35	50	0.2645	0.0008	0.0342
40	50	0.3949	0.0013	0.0469

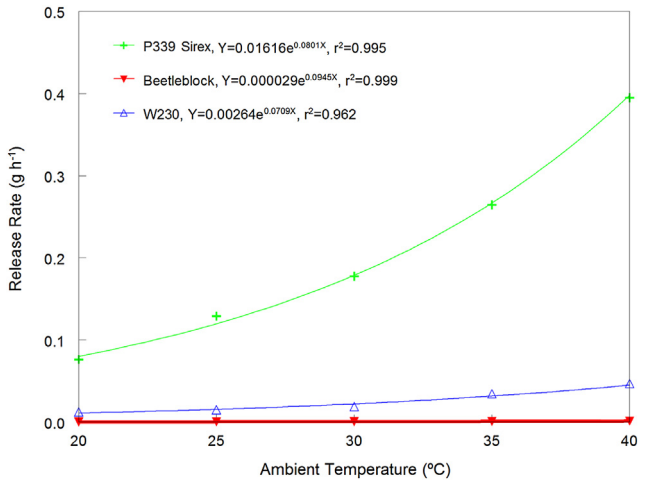


Fig. 7 – Exponential relationships between release rates of three semiochemicals (P339 Sirex, Beetleblock-MCH and W230) and the ambient temperature.

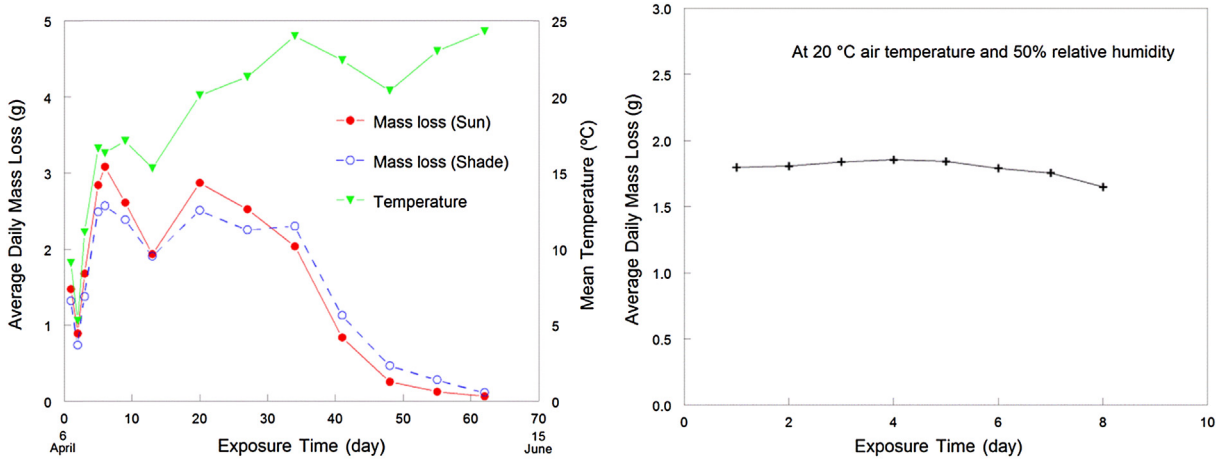
2.74 and 3.17 times for P339 Sirex, Beetleblock-MCH and W230, respectively.

The large-sized P339 Sirex samples lost mass linearly over the time period after they were exposed to the air (Fig. 6a), but the smaller Beetleblock-MCH and W230 samples lost their mass sharply during the first 10 h of exposure and then tended to lose their mass linearly with time (Fig. 6b and c). The passive semiochemicals Beetleblock-MCH and W230 samples released more chemical during the first day exposed. However, this linear relationship between the mass loss and time for all three semiochemicals ceased when the dispensers were nearly empty (Fig. 6 at 40 °C).

For the linear relationship ranges, the slopes of the curves that represented release rates of semiochemicals are illustrated in Table 2. Release rates for all three semiochemicals followed exponential functions with the ambient air temperature (Fig. 7) with coefficients of determination for the curve fitting of 0.995, 0.999 and 0.962 for P339 Sirex, Beetleblock-MCH and W230, respectively. When the ambient temperature increased from 20 to 40 °C, the release rate increased from 0.0763 to 0.3949 g h^{-1} (or 5.2 times) for P339 Sirex, 0.0002–0.0013 g h^{-1} (or 6.5 times) for Beetleblock-MCH, and 0.0121–0.0469 g h^{-1} (or 3.9 times) for W230.

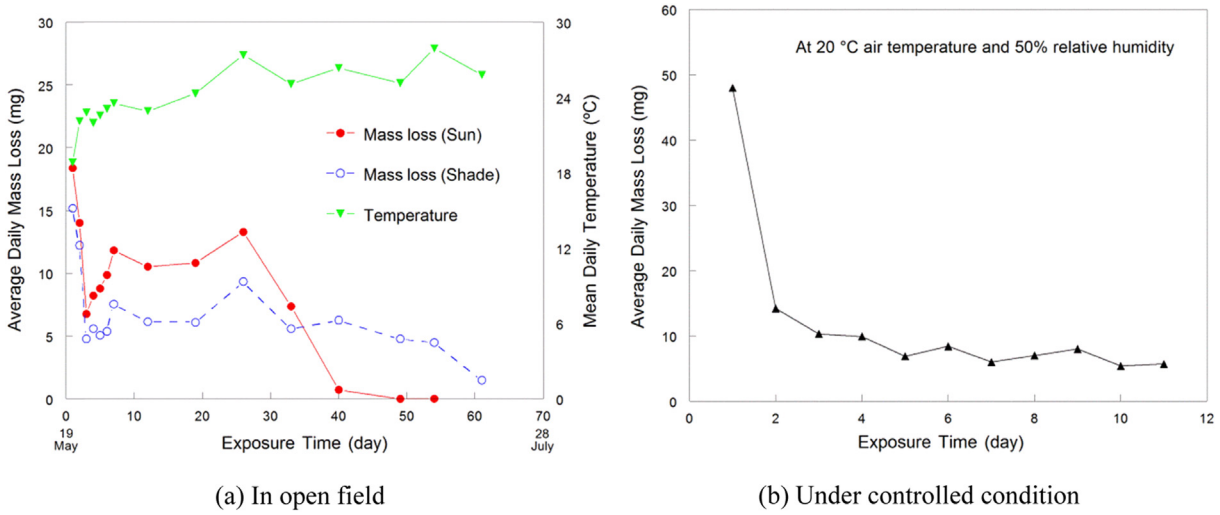
Semiochemical release from the three dispensers involves a phase change from liquid to vapour. More heat energy in the air can convert more sensible heat to latent heat to create more evaporation of the semiochemical. Thus, the release rates reflect the increased kinetic energy of the escaping molecules and the thermodynamics of vaporisation at high temperatures. Wind speed is another factor that can affect release rates of the semiochemicals. Air movement at the evaporating surface may increase evaporation by increasing the vapour concentration gradient away from the surface. In this way, gaseous diffusion may be increased and the near surface layer may not become saturated.

Daily mass losses of P339 Sirex, Beetleblock-MCH and W230, under full sun and full shade conditions, were gravimetrically evaluated by USDA Forest Service Southern Research Station at Pineville, LA, USA. Figure 8 shows the average daily mass losses of P339 Sirex exposed to the sun and in the shade (Fig. 8a) and measured with the controlled environmental system at 20 °C ambient temperature and 50% relative humidity (Fig. 8b). The average daily mass loss during 61 d of measurements was 1.9 g under the sun and 1.6 g in the shade while the average daily mass loss inside the environmental chamber was 1.79 g. Similar patterns under the sun, shade and controlled environmental conditions were also observed for Beetleblock-MCH (Fig. 9) and W230 (Fig. 10). The average daily mass loss of Beetleblock-MCH was 9.5 mg under the sun, 6.7 mg in the shade, and 8.18 mg inside the environmental chamber. For W230, its average daily mass loss was 0.22 g under the sun, 0.25 g in the shade, and 0.273 g inside the environmental chamber.



(a) In open field (b) Under controlled condition

Fig. 8 – Average daily mass loss of P339 Sirex over exposure time: (a) under the full sun and full shade in the open field evaluated by USDA Forest Service, and (b) under the controlled environmental condition with ambient temperature at 20 °C and relative humidity at 50%.



(a) In open field (b) Under controlled condition

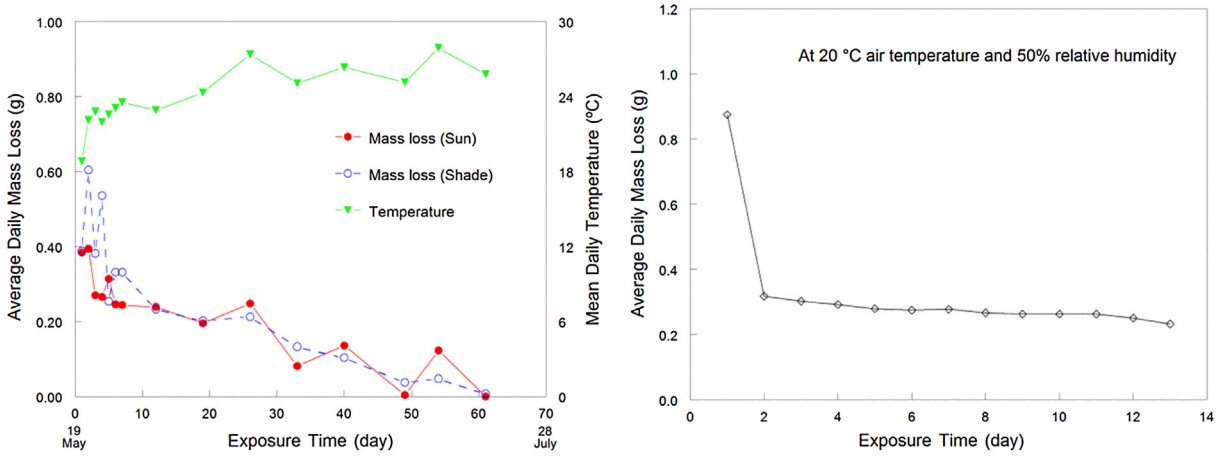
Fig. 9 – Average daily mass loss of Beetleblock-MCH over exposure time: (a) under the full sun and full shade in the open field evaluated by USDA Forest Service, and (b) under the controlled environmental condition with ambient temperature at 20 °C and relative humidity at 50%.

The average daily mass losses under the sun, the shade and the controlled environmental conditions were similar for all three semiochemicals, supporting the importance of ambient temperature as a determinant for release rate from passive semiochemical dispensers. However, under the sun and the shade, the daily mass losses for the three dispensers were much greater within the first 30 d of exposure than those later although the mean ambient temperatures in earlier days were lower than those later. Also, the patterns of the daily mass losses for the three dispensers under the sun and the shade fluctuated greatly on a daily basis (Figs. 8a, 9a, 10a). The mass loss variations might be the result of varied ambient temperature, rainfall, moisture, wind speed, and other unknown factors. In comparison, the measurements under the controlled environmental conditions avoided these confounding variables. Therefore, the controlled environmental system provided a more consistent approach to precisely evaluate and compare semiochemical release rates for potentially a better understanding of release dynamics.

4. Conclusions

A controlled environmental system was developed to evaluate semiochemical release rates. The system was able to independently control the air temperature and relative humidity within ±1.0 °C and ±2.0%, respectively and measure the semiochemical mass within 0.1 mg.

The system performance was evaluated with P339 Sirex, Beetleblock-MCH and W230 semiochemicals at ambient temperature of 20, 25, 30, 35 and 40 °C and relative humidity of 30%, 50% and 80%. Release rates of the three semiochemicals



(a) In open field (b) Under controlled condition

Fig. 10 – Average daily mass loss of W230 over exposure time: (a) under the full sun and full shade in the open field evaluated by USDA Forest Service, and (b) under the controlled environmental condition with ambient temperature at 20 °C and relative humidity at 50%.

increased exponentially as the ambient temperature increased but rates were not apparently affected by relative humidity. When the ambient temperature increased from 20 to 40 °C, the release rates increased from 0.0763 to 0.3949 g h^{-1} (5.2 times), 0.0002–0.0013 g h^{-1} (6.5 times), and 0.0121–0.0469 g h^{-1} (3.9 times) for P339 Sirex, Beetleblock-MCH, and W230, respectively.

Measurements of release rates of the three semiochemicals in the controlled environmental system were more precise, consistent and repeatable than measurements under field conditions. However, overall means for temperature and device mass loss from this controlled system were similar to those determined in the field. This general agreement with field results suggest that temperature can be used in a simple model, along with dispenser type, to predict performance and useful lifetime of semiochemical devices deployed for pest management in forests. Consequently, precise quantification of semiochemical release rates under different temperature and relative humidity conditions with the new system will provide baselines for modelling semiochemical longevity under field conditions, for deployment of semiochemicals, and for optimization of design of semiochemical release devices.

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REFERENCES

Alfaro-Cid, E., Esparcia-Alcázar, A. I., Moya, P., Femenia-Ferrer, B., Sharman, K., & Merelo, J. J. (2009). Modeling pheromone dispensers using genetic programming. In M. Giacobini, A. Brabazon, S. Cagnoni, G. A. Di Caro, A. Ekart, A. I. Esparcia-Alcázar, et al. (Eds.), *Evo Workshops 2009, LNCS 5484* (pp. 635–644). Heidelberg, Germany: Springer-Verlag.

Atterholt, C. A., Delwiche, M. J., Rice, R. E., & Krochta, J. M. (1999). Controlled release of insect sex pheromones from paraffin wax and emulsions. *Journal of Controlled Release, 57*, 233–247.

Baker, T. C. (2008). Use of pheromones in IPM. In T. Radcliffe, & B. Hutchinson (Eds.), *Integrated pest management* (pp. 73–285). Cambridge: Cambridge University Press.

Bradley, S. J., Suckling, D. M., McNaughton, K. G., Wearing, C. H., & Karg, G. (1995). A temperature-dependent model for predicting release rates of pheromone from a polyethylene tubing dispenser. *Journal of Chemical Ecology, 21*(6), 745–760.

Brunner, J. F., Welter, S., Calkins, C., Hilton, R., Beers, E. H., Dunley, J., et al. (2002). Mating disruption of codling moth: a perspective from the Western United States. In P. Witzgall, B. Mazomenos, & M. Konstantopoulou (Eds.), *25. IOBC-WPRS Bull* (pp. 11–19).

Clarke, S. R., Salom, S. M., Billings, R. F., Berisford, C. W., Upton, W. W., McClellan, Q. C., et al. (1999). A scentsible approach to controlling southern pine beetles. *Journal of Forestry, 97*, 26–31.

Cook, S. M., Khan, Z. R., & Pickett, J. A. (2007). The use of push-pull strategies in integrated pest management. *Annual Review of Entomology, 52*, 375–400.

Doane, C. C. (1999). *Controlled-release devices for pheromones: Controlled-release delivery systems for pesticides* (pp. 295–317). Marcel Dekker, Inc.

Golub, M., Weatherston, J., & Benn, M. H. (1983). Measurement of release rates of gossyplure from controlled release formulations by mini-airflow method. *Journal of Chemical Ecology, 9*(3), 323–333.

Hayes, J. L., Strom, B. L., Roton, L. M., & Ingram, L. L., Jr. (1994). Repellent properties of the host compound 4-allylanisole to the southern pine beetle. *Journal of Chemical Ecology, 20*, 1595–1615.

Heuskin, S., Verheggen, F. J., Haubruge, E., Wathelet, J. P., & Lognay, G. (2011). The use of semiochemical slow-release devices in integrated pest management strategies. *Biotechnology, Agronomy, Society and Environment, 15*(3), 459–470.

Hofmeyr, H., & Burger, B. V. (1995). Controlled-release pheromone dispenser for use in traps to monitor flight activity of false codling moth. *Journal of Chemical Ecology, 21*(3), 355–363.

Holsten, E. H., Shea, P. J., & Borys, R. R. (2003). MCH released in a novel pheromone dispenser prevents spruce beetle, *Dendroctonus rufipennis* (Coleoptera: Scolytidae), attacks in south-central Alaska. *Journal of Economic Entomology, 96*, 31–34.

Johansson, B. G., Anderbrant, O., Simandl, J., Avtzis, N. D., Salvadori, C., Hedenström, E., et al. (2001). Release rates for pine sawly pheromones from two types of dispensers and phenology of Neodiprion sertifer. *Journal of Chemical Ecology, 27*(4), 733–745.

Krüger, A. J., & Tolmay, A. T. (2002). Prediction of the release characteristics of alcohols from EVA using a model based on Fick's second law of diffusion. *Journal of Applied Polymer Science, 84*, 806–813.

Oehlschlager, A. C., Chinchilla, C., Castillo, G., & Gonzalez, L. (2002). Control of red ring disease by mass trapping of Rhynchophorus palmarum (Coleoptera: Curculionidae). *Florida Entomologist, 85*, 507–513.

Progar, R. A. (2005). Five-year operational trial of verbenone to deter mountain pine beetle (*Dendroctonus ponderosae*; Coleoptera: Scolytidae) attack of lodgepole pine (*Pinus contorta*). *Environmental Entomology, 34*, 1402–1407.

Ridgway, R. L., Inscoe, M. N., & Dickerson, W. A. (1990). Role of the boll weevil pheromone in pest management. In R. L. Ridgway, R. M. Silverstein, & M. N. Inscoe (Eds.), *Behavior-modifying chemicals for insect management* (pp. 437–472). New York: Marcel Dekker.

Ross, D. W., Daterman, G. E., & Gibson, K. E. (2002). Elution rate and spacing of antiaggregation pheromone dispensers for protecting live trees from *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). *Journal of Economic Entomology, 95*, 778–781.

Shem, P. M.., Shiundu, P. M., Gikonyo, N. K., Ali, A. H., & Saini, R.. K. (2009). Release kinetics of a synthetic tsetse allomone derived from waterbuck odour from a Tygon silicon dispenser under laboratory and semi field conditions. *American-Eurasian Journal of Agricultural & Environmental Sciences, 6*(6), 625–636.

Shorey, H. H., Sisk, C. B., & Gerber, R. G. (1996). Widely separated pheromone release sites for disruption of pheromone communication in two species of Lepidoptera. *Environental Entomology, 25*, 446–451.

Strom, B. L., & Clarke, S. R. (2011). Use of semiochemicals for southern pine beetle infestation management and resource protection. In R. N. Coulson, & K. D. Klepzig (Eds.), *Southern Pine*

Beetle II. GTR-SRS-140 (pp. 381–397). Asheville, NC: U.S. Department of Agriculture, Forest Service.

Thomson, D. (1997). Confusion amongst codling moth fellows continues: a commercial perspective on the implementation of codling moth mating disruption in North America. *IOBC wprs Bulletin, 20*(1), 57–63.

Van der Kraan, C., & Ebbers, A. (1990). Release rates of tetradecen-1-ol acetates from polymeric formulations in relation to temperature and air velocity. *Journal of Chemical Ecology, 16*(4), 1041–1058.

Wall, C. (1989). Monitoring and spray timing. In A. R. Justum, & R. F. S. Gordon (Eds.), *Insect pheromones and Plant Protection* (pp. 39–66). New York: John Willey & Sons.

Wall, C. (1990). Principles of monitoring. In R. L. Ridgway, R. M. Silverstein, & M. N. Inscoe (Eds.), *Behavior modifying chemicals for Insect Management: Applications of pheromones and other attractants* (pp. 9–24). New York: Marcel Dekker Inc.