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Optimizing postharvest methyl bromide treatments to control spotted wing drosophila, *Drosophila suzukii*, in sweet cherries from Western USA

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Abstract

Methyl bromide (MB) chamber fumigations were evaluated for postharvest control of spotted wing drosophila (SWD), *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae), in fresh sweet cherry exports from Western USA. Sweet cherries were infested with SWD, incubated to maximize numbers of the most MB-tolerant specimens (ca. 60 to 108-h old at fumigation, 88% 3rd & 2nd instars), buried amongst uninfested fruit in bins consistent with commercial practice, cooled to an average pulp temperature ≥ 8.3 °C, and then fumigated in a chamber. Treatment efficacy was diagnosed by the percentage of survivors emerging as adults from fumigated cherries relative to that from non-fumigated control cherries. A kinetic model of sorption was developed based on the measurement of MB and how calculated exposures varied across the fumigation trials. The model describes how to manipulate the applied MB dose, fumigation duration, and the load factor so that the resultant exposure is adequate for SWD control across various pulp temperatures when cherries are fumigated in wooden versus plastic bins. Results are discussed in the context of graduation toward optimized quarantine fumigation schedules for control of SWD, which will promote more strategic technical and economic Quarantine Pre-shipment (QPS) use of MB.

Keywords: Spotted wing drosophila, postharvest fumigation, methyl bromide, sweet cherries, quarantine treatments

Introduction

Spotted wing drosophila (SWD), *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae), is a pest of concern to certain countries that import fresh fruit from Western USA. The NAPPO host list for *Drosophila suzukii* (NAPPO, 2010) lists several types of fruit that are key international exports from Western USA, including: blueberry, blackberry, grape, raspberry, strawberry, and sweet cherry (Hamilton, 2004; NAPPO, 2010; Walsh et al., 2011). Unlike most drosophilids, which typically infest overripe or decaying fruit, SWD has been observed to also deposit eggs into skin of immature and/or ripening fruit through the use of a serrated ovipositor (Lee et al., 2011; Walsh et al., 2011).

Movement of host product to international markets often requires the certification of a phytosanitary treatment that satisfies the efficacy requirements of the importer. Several countries, including Australia, regulate SWD as a quarantine pest and require a preshipment treatment of fresh fruit hosts to mitigate the threat of introduction. Postharvest fumigation with methyl bromide (MB) is a treatment option and the use of MB in this capacity is regulated internationally via the Montreal Protocol on ozone-depleting substances under the Quarantine Pre-Shipment (QPS) Exemption (Ristiano and Thomas, 1997). The rapid, efficacious treatment afforded by postharvest MB fumigation is particularly important for those commodities, such as sweet cherries, which are highly perishable and have harvesting throughputs constrained by shipping and/or port logistics (Johnson et al., 2012). This study details experimental procedures,

predictive models, and toxicological results to support the use of postharvest MB chamber fumigation to control SWD in sweet cherry exports from Western USA.

Materials and Methods

Insects

D. suzukii pupae were obtained from three independent laboratory colonies. The respective colonies of Dr. Arytom Kopp (University of California at Davis) and Dr. Robert Van Steenwyk (University of California at Berkeley) both originated from wild specimens captured in cherry orchards of coastal California USA. *D. suzukii* pupae obtained from Dr. Jana Lee (USDA-ARS) originated from wild specimens captured in raspberry fields of Marion County, Oregon USA. Pupae from these three sources were integrated into a single colony maintained in several (6-8 ct.) nylon mesh enclosures (Bug Dorm-2[®], BioQuip Products, Rancho Dominguez, CA, US) housed in an 15.2-m³ rearing unit (24-27 °C, 80% RH, 16:8 [L:D] h) at the USDA-ARS-SJVASC (Parlier, California USA). Approximately twice a year, *D. suzukii* adults were captured in berry fields at various locations throughout the San Joaquin Valley of California, identified to species, and introduced into the SJVASC colony. Periodic shipments of pupae from each of the original sources were also received and integrated into the colony. Plastic vials (7.4 mL) containing saturated aqueous solutions of sucrose were capped and fitted with cotton wicks to serve as a food and water source for adults. Larvae were reared on standard cornmeal-(dextrose or sucrose)-agar-yeast medium, which also served as an ovipositional substrate, layered to 4.0 ± 0.6 mm ($\bar{x} \pm s$) on the bottom of 150-mm diameter Petri dishes. Petri dishes in each mesh enclosure were removed (and replaced) after 2-d ovipositional periods and relocated to a separate

nylon enclosure in the same incubation unit until adult emergence was complete. Enclosures were maintained at ~2000/cage.

Fruit infestation

Studies were conducted using fresh sweet cherries commensurate with postharvest commercial distribution from Western USA and/or Chile. Prior to use, fruit was refrigerated at 0.9 ± 0.7 °C ($\bar{x} \pm s$) in a 21.9 m³ cold-storage unit (Super Insulated Structures, Imperial Manufacturing, Portland, OR). Preceding infestation (*vida infra*), each fruit was quickly dipped in an ethanol bath, rinsed with DI water, and inspected for the presence of fungus, damage, rot, or bruising. Any commercially unacceptable fruits were discarded.

To simulate a naturally occurring infestation scenario, ovipositional/diet substrate was removed from an insect enclosure and replaced with stainless-steel trays (30 × 30 × 2 cm) that were filled with a monolayer of fresh sweet cherries. The stainless-steel trays containing infested sweet cherries were removed from the enclosures after ovipositional periods of durations that varied by test type and then infested cherries were transferred in pairs into a stainless-steel mesh ball cage (5.1-cm diameter). Mesh ball cages containing infested cherries were randomly selected, placed inside a pull-string cloth bag (~25 per bag), and used in laboratory-scale exploratory fumigations or buried throughout the load of commercial fruit bins in commodity fumigations. Alternatively, mesh ball cages were not fumigated and held as untreated controls to estimate the number of individuals treated during a respective fumigation. For the exploratory fumigations,

removal of cherries from a rearing enclosure and, subsequently, the rearing unit was synchronized to ensure discrete developmental groupings could be simultaneously treated. For the commodity fumigations, cherries were removed from an enclosure after a 48-h ovipositional period and maintained in the rearing unit for an additional 48 h so that only 48- to 96-h old larvae, the most MB-tolerant age of SWD (vide infra), underwent treatment.

Chemical analysis and calibration of standards

A 50-lb cylinder of compressed MB, Meth-o-gas 100, was obtained from Cardinal Professional Products (Woodland, CA, USA). MB concentration in headspace of fumigation chambers, [MB], was measured using gas chromatography (GC) with flame ionization detection (FID) (GC-FID); retention time (MB, $t_r = 3.2 \pm \text{min}$) was used for chemical verification and the integral of peak area, referenced relative to liner least-squares analysis concentration plotted versus detector response, was used to determine concentration. Detector response and retention indices were determined each day in calibration studies by diluting known volumes of gases into volumetric gas vessels. Analyses were with a Varian 3800 GC and splitless injection (150 °C) using a gas sampling port (110 °C) with a 1 mL-sample loop, a 2 mm id x 2 m Teflon® column packed with 10% OV-101 on Gas-Chrom Q® (100/120 mesh) held at 100 °C for 10 min, and 15 mLmin⁻¹ He carrier flow. The FID detector was at 275 °C with respective flows of 20 mLmin⁻¹ H₂, 250 mLmin⁻¹ air, and 5.0 mLmin⁻¹ N₂ make-up.

Commodity fumigations

Commercial fumigations were simulated using 241.9-L ($V_{chamber}$) steel chambers housed in a 22.7-m³ walk-in environmental room with programmable humidity (65% RH) and temperature (13.9, 12.2, 10.6, or 8.3 °C) set points (USDA, 2010). Cloth bags containing infested cherries were buried amongst uninfested cherries within wooden field bins (45.72l × 45.72w × 30.48h cm, surface area (SA) = 0.975 m², volume of the “packaged” load (V_{PL}) = 64 L), which were constructed out of 1.3-cm thick plywood as scaled-down replicates of those used in industry. Alternatively, scaled-down plastic field bins were used that had the same dimensions and values of SA and V_{PL} . To manipulate chamber load factors, as calculated by the method of Monro (9) ($V_{PL} V_{chamber}^{-1}$), chambers were first loaded with the appropriate number of 0.5-ft³ sand bags each wrapped in plastic packaging, which displaced ~14.2 L from $V_{chamber}$. Next, a bin was filled to ~75% capacity with either uninfested cherries or a combination of uninfested cherries and infested cherries in cloth bags. Importantly, the fumigation of sweet cherries in field bins (wooden or plastic) as described above reflects practices specific to Western USA and does not necessarily reflect practices used in other regions.

Loaded chambers, cherries infested with control specimens, source-gas cylinders, and gas-tight syringes (Hamilton ® 500-, 1000-, or 1500-mL) were acclimated to fumigation temperature, or tempered, for 12 h prior to treatment. Fruit pulp temperature (T) was confirmed prior to fumigation by each of three probes (YSI scanning tele-thermometer) that recorded the respective T of three uninfested cherries distributed at different locations within bins of the infested cherries undergoing treatment. Alternatively, a 5-inch HOBO U12 Probe was used (U12-015-02) in

concert with a Onset HOBO Data Logger to record T with a 30-min scanning/sampling rate. Temperature probes were then removed, circulation fans internal to the chamber were turned on, and chamber lids clamp-sealed in preparation for treatment. A vacuum of ca. 76 to 127 mmHg was established in each chamber. Gas-tight super-syringes were filled with a volume of MB to achieve the requisite applied dose as predetermined in preliminary studies. Filled syringes were fitted sequentially to a LuerLok® sampling valve, which was subsequently opened so that MB was steadily drawn into the chamber. After the addition of MB from the final syringe, the syringe was removed from the valve and normal atmospheric pressure (NAP) was reestablished in each chamber before the valve was closed; this marked the start of the fumigation and the beginning of the exposure period. Gas samples (40 mL) were taken from the chamber headspace through the sampling valve using a B-D® 100-mL gas-tight syringe and [MB] was quantified with GC-FID, as described above, at temporal intervals. Fumigant exposures were expressed as concentration (C) $\times$ time (t), Ct , cross products (mgL^{-1}h) and calculated by the method of Monro (Monro, 1969).

After the exposure period, chamber valves were opened to atmosphere and vacuum was pulled for 4 h to aerate the chamber. Chamber lids were opened; the treated as well as untreated control specimens were collected and transferred into respective 0.03-m^3 nylon-mesh rearing cubicles maintained in an incubator at 27.0 ± 1.0 °C and $80 \pm 2\%$ RH ($\bar{x} \pm s$).

Exploratory fumigations: most MB-tolerant specimens

Exposure-response data for egg and larval life stages of SWD was generated in an initial series of exploratory fumigations conducted in modified Labonco® 28.32-L vacuum chambers housed in a walk-in environmental room as described above. Three age groups of SWD, which spanned egg through 3rd instar larvae, were isolated (48- to 96-h old, 0- to 48-h old, and 0- to 24-h old) in sweet cherries (vide supra) and then fumigated concomitantly within a chamber for a particular fumigation trial. Test specimens as well as untreated control specimens were tempered to 8.3 or 15.6 ± 0.5 °C ($\bar{x} \pm s$) for 12 h prior to fumigation. MB was applied, [MB] quantified over the course of fumigation, and Ct exposures were calculated as above. After fumigation, lids and valves were opened to atmosphere and vacuum was pulled for 30 min to aerate the chambers. Post-treatment handling and incubation was as described above.

Mortality evaluation

Larval and egg mortality was assessed at 1-d intervals post-fumigation for 21 d; cages were removed from the cloth bags, opened, and live adult specimens were tallied and discarded. The cages were then resealed and placed back into the cloth bags for further incubation and evaluation. Quartered pieces of an uninfested cherry were added to the mesh ball cages approximately every other day to keep the test fruit and insects hydrated. Record was kept of the cumulative number of adults that emerged from each piece of fruit designated as an untreated control for a set of fumigation trials. An average ($\bar{x}$) emergence from each infested fruit left untreated was calculated along with a standard deviation ($\pm s$). The number of specimens ($n \pm s$) that were treated was estimated by multiplying the number of infested fruit treated in each trial by the average emergence from each fruit that was infested and untreated ($\bar{x} \pm s$). The total

number of specimens that were treated across a series of trials was estimated, via standard methods (Skoog and Leary, 1992), by summing the numbers from respective trials and propagating the respective standard deviations.

Rearing and incubation conditions of 27.0 ± 1.0 °C, $80 \pm 2\%$ RH ($\bar{x} \pm s$), and 16:8 [L:D] h photoperiod were fixed to maintain a consistent progression of development between trials and controls; resulting mortality in control specimens was assumed to be equal to that in fumigation trials. Insects were more likely to survive and there was greater certainty in diagnosing survivorship after the treatment if incubated under conditions described above rather than if refrigerated post-fumigation at 2 to 5 °C under simulated commercial transport conditions, which confound the effect of a fumigation event on mortality. To be detailed in a forthcoming publication on the effect of refrigeration on SWD, we generally observed increases in the mortality of all SWD life-stages, the length of the developmental periods of each life stage, and heterogeneity in the times required to complete development within each life stage.

Commercial fumigations

United States Department of Agriculture, Animal Plant and Health Inspection Service, Plant Protection and Quarantine (USDA-APHIS-PPQ) supervised (and certified) commercial postharvest fumigations of Western USA-grown sweet cherries for export to Japan (64 mg L^{-1} applied dose, 2-h duration, $12 > T \geq 6$ °C) were monitored. Key fumigation parameters, including: pulp temperature at treatment (T), field bin type (plastic or wooden), and chamber

load factor ($V_{PL} V_{chamber}^{-1}$) were recorded for respective fumigations. Gas samples were taken from the top-, middle-, and bottom of chamber headspace and quantitatively analyzed for [MB] using a fumiscope at temporal intervals (i.e., 15, 30, 60, and 120 min) following MB application. [MB] from each chamber level, at each sampling time, were averaged and Ct exposure expressed by the method of Monro (Monro, 1969) as described above. Data was obtained from eleven commercial fumigations conducted in Washington State in the 2008 and 2009 export seasons, which contained cherry loads in wooden bins, exclusively. Alternatively, data was obtained from eleven commercial fumigations conducted in California in the 2008 and 2009 export seasons, which exclusively contained cherry loads in plastic bins.

Modeling methyl bromide toxicology, exposure, and sorption

Haber's Rule ($Ct = \omega$) forms the basis for relating concentration (C), time (t), and ultimately exposures (Ct) to toxicological efficacy (ω), at least with respect to fumigation science. Its most familiar expression, $C^z t = \omega$, takes a form where ω is a response level specific to a Ct exposure and z is the response evoked by a specific toxicant in a particular organism. Efficacy data contributed by many investigators across a variety of targeted insect and mite pests, indicates that for MB, $z = 1$, at least when $t < 6$ h, which supports the above calculation of exposures as Ct , the product of $C \times t$.

A predictive kinetic model was developed in Walse et al. (Walse et al., 2013) to quantitatively estimate the relationship between exposure (Ct), load factor, and load geometry. The model

identifies how these parameters can be modulated (i.e., tuned) to ensure adequate toxicological efficacy is attained when fumigating loads that vary in the amount and type of produce and/or packaging.

Briefly, the relative distribution of a fumigant between the solid and gas phases is described as the ratio:

$$K_d = [\text{fum.}]_s / [\text{fum.}]_g \quad (1)$$

where K_d is termed the “solid to gas distribution coefficient”, $[\text{fum.}]_s$ is the concentration of fumigant sorbed into the solid substrate, and $[\text{fum.}]_g$ is the concentration of fumigant in the gas phase (e.g., chamber headspace). At equilibrium (K_{eq}), the sorption (and desorption) of a gaseous fumigant to a solid are equal in magnitude. Upon the application of a fumigant to a solid substrate, K_{eq} is approached as defined by the equilibrium:

$$d[\text{fum.}]_s/dt = d[\text{fum.}]_g/dt = 0 \text{ and } K_d = K_{eq} \quad (2)$$

K_d varies for each fumigant and changes as a function of many factors, including: total amount of fumigant applied, load of substrate, temperature, humidity, etc. However, over the range of conditions and concentrations that typify commercial fumigation scenarios involving fresh fruit, variation in K_d does not significantly affect modeling the kinetics of fumigant sorption and desorption.

K_{eq} is never, or at least very rarely, reached during a conventional MB fumigation of fresh fruit. Under these non-equilibrium conditions the sorption and/or desorption of MB is described as mass-transfer limited diffusion that is largely reversible (Darby, 2012). Fruit and packaging sorb and desorb (i.e., off-gas) fumigants to varying extents due to differences in the rate of diffusion across the surface area of the load, as given by Fick's first and second laws describing gradient-flux (Banks, 1985; Burg and Burg, 1965; Walse et al., 2013). Molecular diffusivity is generalized by the Stokes-Einstein equation

$$D = \frac{k_B T}{6\pi r \mu} \quad (3)$$

where k_B is the Boltzmann constant ($1.38 \times 10^{-23} \text{ kg m}^2 \text{ s}^{-2} \text{ K}^{-1}$), and r is the hydrodynamic radius of "spherical" MB ($\sim 4.47 \text{ \AA}$). Temperature (T) influences diffusivity via Brownian motion (numerator) and through changes to viscosity (μ) (denominator). However, the effect of temperature on diffusion (and sorption) is expected to be minimal as it pertains to sweet cherries where only $\sim 6^\circ\text{C}$ separates treatment temperatures (vide infra) (Walse et al., 2013).

Sorption during fumigation can be modeled as a non-steady state condition with variable surface concentration (Carslaw and Jaeger, 1959; Crank, 1975). In the case of sorption, the initial internal concentration is zero and the surface concentration at time, $\phi(t)$, varies linearly with a rate, k , such as:

$$\phi(t) = kt \quad (4)$$

The converse occurs for desorption; the internal concentration at time, $\phi(t)$, varies linearly with a constant rate, k , and the initial surface concentration is zero.

The temporal change in fumigant concentration, $-d[\text{fum.}]/dt$, is most easily measured by quantifying the loss in $[\text{fum.}]_g$, which typically follows first-order kinetics and is given by the equation:

$$\text{Sorption, } -d[\text{fum.}]/dt = k_{\text{OBS}} [\text{fum.}]_g \quad (5)$$

where k_{OBS} (h^{-1}) is the observable rate of fumigant sorption. Equations 5 and 6 can be further defined by,

$$k_{\text{OBS}} = a S k_{\text{SPT}} \quad (7)$$

where a (g m^{-3}) is the mass to volume ratio of the load, S ($\text{m}^2 \text{g}^{-1}$) is the SA to mass ratio of the load, and k_{SPT} (m h^{-1}) is the rate constant of fumigant sorption (or desorption) from the load.

Accordingly, the collective contribution of a fruit and its packaging (e.g., a bin or a box) toward the fumigant sorption can be quantified indirectly via measuring temporal change in [fum.]_g for each “packaged” load. Equation 7 was modified as in Walse (Walse et al., 2013) to conform with conventional measurements used in fumigation; mass is substituted with V_{PL} , such that

$$k_{OBS} = \left(\frac{V_{PL}}{V_{chamber}} \right) \left(\frac{SA}{V_{PL}} \right) k_{SPT} \quad (8)$$

where the fractional load factor is $V_{PL} V_{chamber}^{-1}$ (unitless) and the surface area (SA) to volume (V_{PL}) ratio of the packaged load is $SA V_{PL}^{-1}$ (m^{-1}).

Solving equations 7 or 8 for k_{SPT} yields the rate of fumigant sorption that is intrinsic to a load type, independent of how much load is fumigated ($V_{PL} V_{chamber}^{-1}$) as well as the geometry of the load ($SA V_{PL}^{-1}$).

Results and Discussion

Relative MB-tolerance of SWD specimens

Phytosanitary protocols to permit the international movement of a commodity typically specify that treatment efficacy be demonstrated on the most treatment-tolerant life stage of the offending pest (Jang and Moffitt, 1994; NAPPO, 2011). To identify the relative MB-tolerance of SWD egg

through larval life stages, age groups were isolated in cherries and fumigated concomitantly in exploratory fumigations conducted for 2 h at 8.3 ± 0.5 °C or 15.6 ± 0.5 °C ($\bar{x} \pm s$). Exposure-mortality regressions were modeled using Polo Plus (LeOra Software, 2002-2007) over the range, 7 to 128 mg L⁻¹ h. The estimated number of specimens treated, the regression heterogeneity (H), the projected exposures (*Ct*) to cause 50 and 95% mortality in the treated population (respectively LE₅₀ and LE₉₅), and the upper (UL) and lower limits (LL) of the 95% confidence limit (CL) are shown in Figure 1 (Finney, 1944, 1971). Likelihood ratio-based hypothesis testing of equality ($P < 0.05$, $\chi^2 = 486$, $df = 6$) and parallelism ($P < 0.05$, $\chi^2 = 16.98$, $df = 3$;) were rejected, indicating that the slopes and intercepts of the respective regression lines were not similar.

Lethal exposure ratios (LERs) were calculated with 95% confidence intervals (CI) and used to identify difference in MB-tolerance across ages and treatment temperature. At 8.3 ± 0.5 °C, LERs calculated for 48- to 96-h old specimens (pre-tempering age) relative to 0- to 48-h old specimens paralleled a ratio of 1 across exposures projected to cause 10 to 99% mortality, indicating that these age groups are of equivalent MB-tolerance (Figure 2). The greater MB-tolerance of 48- to 96-h old specimens fumigated at 8.3 ± 0.5 °C ($\bar{x} \pm s$) relative to 0- to 24-h old specimens fumigated at 8.3 ± 0.5 °C ($\bar{x} \pm s$) as well as 48- to 96-h old specimens fumigated at 15.6 ± 0.5 °C ($\bar{x} \pm s$) is also shown in Figure 2, as the LERs were >1 for all exposures projected to cause $> 10\%$ mortality in the treated populations. In general, an increase in treatment temperature (and *T*) is commensurate with an increase of insect metabolism and

increase in the efficacy of a fumigant (Monro, 1969). Results support this conclusion and indicate that, as treatment temperature (and T) of a 2-h MB chamber fumigation is lowered, greater exposures (Ct) are required to achieve 95% mortality in the treated population of 48- to 96-h old specimens in infested sweet cherries. .

When targeting internal feeders, such as SWD, the efficacy of MB is due, in large part, to its penetration into the fruit portion of the load. Over a 2-h fumigation time course, internal concentrations of fumigant within a cherry are relatively lower than on the surface of the fruit, where the concentrations are $\geq [MB]$ (Walse et al., 2012). We hypothesize that the relative MB-tolerance across SWD age groupings resulted from this gradient of MB concentrations. Relative to larger larvae ($3^{rd} \gg 2^{nd}$ instar) that were often observed to feed completely submerged within cherries, eggs and smaller larvae (1st instar $\gg 2^{nd}$ instar) were more frequently observed near the fruit periphery. The relative tolerance of SWD ages toward MB in infested cherries is consistent with earlier work concerning infested strawberries, which reported that adult and pupae were less tolerant toward MB than eggs of SWD (Walse et al., 2012).

Commodity fumigations: initial efficacy confirmation

To confirm the relative proportion of larger, mature larvae present in the 48- to 96-h old age grouping that entered commodity fumigation efficacy trials, cherries were removed from SWD-containing enclosures after a 48-h ovipositional period, maintained under rearing conditions (24-27 °C, 80% RH, 16:8 [L:D] h) for an additional 48 h, and transferred to 13.9 °C for 12 h (to include the effect of tempering). On five separate occasions, the probability of each SWD life

stage being present just before fumigation at 13.9 ± 0.5 °C was determined by dissecting samples of infested cherries until the life stage of ~ 1000 individual specimens was evaluated ($\bar{x} \pm s$; egg, 0.011 ± 0.006 ; 1st instar, 0.058 ± 0.018 ; 2nd instar, 0.226 ± 0.036 ; 3rd instar, 0.651 ± 0.035 ; pupa, 0.051 ± 0.015) (Figure 3). The probability of occurrence was calculated by normalizing the number recorded for each life stage to the total number recorded across all life stages (n). Immature SWD life stages were identified based on methods of Ashburner (Ashburner, 1989) and Kanzawa, (Kanzawa, 1936, 1939) as described in Bellamy et al. (Bellamy et al., 2013). In general, fumigation (and corresponding pre-treatment equilibration) of SWD-infested cherries conducted at $T < 13.9$ °C resulted in the occurrence of relatively fewer pupae at time of dissection.

A series of commodity fumigations were conducted in the context of verifying control (i.e., efficacy) of the most MB-tolerant SWD age (48- to 96-h old before tempering, 60- to 108-h old at fumigation), comprised principally of internal feeding large larvae (ca. 65% 3rd instar, 23% 2nd instar) , in sweet cherries fumigated with MB for 2 h in scaled-down replicates of wooden or plastic bins at a chamber load ($V_{PL} V_{chamber}^{-1}$) of 0.3 ± 0.007 ($\bar{x} \pm s$) (Table 1). Over $17.2 \geq T \geq 8.3 (\pm 0.5)$ °C, applied doses (mg L^{-1}) were increased incrementally with a decrease in T to yield exposures (Ct) that increased from 84.4 to 123.4 $\text{mg L}^{-1}\text{h}$. Fumigation at $T = 13.9 (\pm 0.5)$ °C with an applied dose of 48 mg L^{-1} resulted in exposures of 85.5 ± 2.5 ($\bar{x} \pm 2s$) $\text{mg L}^{-1}\text{h}$ and 0 survivors out of $43,642 \pm 1,851$ ($n \pm s$) treated, 99.9931% mortality (probit 8.81 at the 95% CL) as calculated by the method of Couey and Chew (1986) and Liquido and Griffin (2010) (Table 1). Fumigation at $T = 12.2 (\pm 0.5)$ °C with an applied dose of 56 mg L^{-1} resulted in exposures of 95.3

$\pm 4.3 (\bar{x} \pm 2s)$ mg L⁻¹h and 1 survivor out of $57,608 \pm 2,183 (n \pm s)$ treated, 99.9954% mortality (probit 8.91 at the 95% CL). Fumigation at $T = 10.6 (\pm 0.5)$ °C with an applied dose of 64 mg L⁻¹ resulted in exposures of $109.0 \pm 12.0 (\bar{x} \pm 2s)$ mg L⁻¹ h and 1 survivor out of $51,267 \pm 1,915 (n \pm s)$ treated, 99.9948% mortality (probit 8.88 at the 95% CL). Fumigation at $T = 8.3 (\pm 0.5)$ °C with an applied dose of 72 mg L⁻¹ resulted in exposures of $121.2 \pm 3.8 (\bar{x} \pm 2s)$ mg L⁻¹h and 0 survivors out of $70,492 \pm 3,094 (n \pm s)$ treated, 99.9957% mortality (probit 8.93 at the 95% CL). Commodity fumigation trials resulted in a grand sum of 2 survivors from $223,009 \pm 4,580 (n \pm s)$, 99.9981% mortality (probit 9.62 at 95% CL, probit 9 at 97% CL). Demonstrating 99.9968% (i.e., probit 9 at the 95% CL) mortality of quarantine insect pests is often requested to qualify phytosanitary treatment efficacy, particularly when commodity is moved internationally (Couey and Chew, 1986; Follett and Neven, 2006).

Commodity fumigations: sorption, modeling, and optimization

The variation in exposures (Ct) across commodity efficacy trials (Table 1), as verified by GC-FID quantification of [MB], was due to differential sorption of MB by the loads. Experimental data support the kinetic model described above, as plots of “ $\ln ([MB]_o/[MB]_t)$ ” versus time ($t-t_o$) were linear. The negative slope obtained from a least-squares analysis, k_{OBS} (h⁻¹), was determined for each fumigation trial along with respective correlation coefficients (all $r^2 > 0.93$). Corresponding to each trial, equation 7 was solved for k_{SPT} (m h⁻¹), the rate of MB sorption exhibited by the packaged load independent of load factor, $V_{PL} V_{chamber}^{-1}$ (unitless), and surface area to volume ratio, $SA V_{PL}^{-1}$ (m⁻¹).

A single factor-analysis of variance (ANOVA) at the 95% CL comparing the average k_{SPT} (m h^{-1}) value for wooden bins across all T with that for plastic bins (efficacy trial 8 & 11) at $10.6 (\pm 0.5) ^\circ\text{C}$ was significant ($F_{(21, 0.001)} = 7.12$; $p = 0.0014$), indicating the mean k_{SPT} value across all trials, $0.0454 \pm 0.0073 \text{ m h}^{-1}$ ($\bar{x} \pm s$) could not be used to estimate MB sorption irrespective of the trial. Tukey-Kramer HSD multiple means comparison ($\alpha = 0.05$) (SAS Institute, 2011) indicated significant difference between the mean k_{SPT} (m h^{-1}) for plastic bins, $0.0307 \pm 0.0027 \text{ m h}^{-1}$ ($\bar{x} \pm s$), and the mean k_{SPT} for wooden bins at each T (see Table 1), which were not significantly different across T . This finding supports the conclusion that suppression of metabolic and/or toxicological activity, and not decreased diffusion or sorption, is likely responsible for the fact that exposures (Ct) must be increased with decreasing treatment temperature (or T) to maintain a constant level of SWD mortality (e.g., LE₉₅).

Loads in the commodity fumigation efficacy trials contained uninfested sweet cherries as well as varying amounts of infested cherries, which were subject to rearing conditions (i.e., $27.0 \pm 1.0 ^\circ\text{C}$, $80 \pm 2\%$ RH) for 96 h prior to pre-fumigation tempering. Infested fruit was relatively softer than uninfested fruit, as the rearing temperature was warmer than the refrigeration temperature. To reduce variability in MB sorption (and k_{SPT} values) resulting from cherries of inconsistent quality (i.e., infested versus uninfested), an additional series of commodity fumigations were conducted with only uninfested cherries in wooden or plastic bins (Table 2). Again, experimental data supported the kinetic model, as plots of “ $\ln ([\text{MB}]_0/[\text{MB}]_t)$ ” versus time ($t-t_0$) were linear. The negative slope obtained from a least-squares analysis, k_{OBS} (h^{-1}), was determined for each

fumigation trial with respective correlation coefficients (all $r^2 > 0.91$). Load factors, applied doses, and treatment durations varied across the fumigations and influenced the observed exposures (Ct). The rate constants of fumigant sorption for a cherry load in a plastic bin, $k_{\text{SPT-plastic}}$ (m h^{-1}), and in a wooden bin, $k_{\text{SPT-wood}}$ (m h^{-1}), agreed with results from commodity efficacy trials above and were respectively 0.0235 ± 0.0017 and $0.0468 \pm 0.0043 \text{ mh}^{-1}$ ($\bar{x} \pm 2s$). A paired t -test yielded a two-tailed P value < 0.0001 ($t = 25.215$, $df = 7$, $SE = 0.01$), indicating the difference in the means were statistically significant at the 95% CL.

Commercial fumigation schedules usually specify key parameters, including: a minimum T , an applied dose, the duration, and a load factor maximum. Equation 8 was used to predict, given $k_{\text{SPT-plastic}}$ and $k_{\text{SPT-wood}}$ (m h^{-1}) for cherry loads in respectively plastic or wooden bins, values of the observable rate for MB loss, k'_{OBS} , based on a load factors ($V_{PL} V_{\text{chamber}}^{-1}$) from 0 (empty chamber) to 0.55, the range applicable to chamber fumigations of fresh fruit. Substitution of k'_{OBS} for a respective load factor into equation 5, given an applied (or initial) MB dose, and treatment duration allows one to predict headspace concentrations at any time, $[\text{MB}]_t$, as well as predict the corresponding exposure (Ct') with upper and lower 95% CI boundaries. The relation between load factor and predicted exposure (Ct') for sweet cherry loads in wooden and plastic bins is shown in Figure 4 across 8.3 to 12.2 (± 0.5) °C, the range of T frequently used by industry in commercial fumigations.

Note that observed exposures (Ct) during 2-h commodity efficacy trials (12.2 °C, 96.0 ± 4.3 ; 10.6 °C, 109.0 ± 12.0 ; 8.3°C, 121.2 ± 3.8) ($\bar{x} \pm 2s$) with a wooden bin load factor of 0.3 span

the upper and lower 95% CIs for the predicted exposures (Ct'). For each T , predicted exposures (Ct') increase if the applied dose is lowered by 8 mgL^{-1} and the fumigation duration is extended 0.5 h, suggesting that the observed exposures, as well as the associated efficacies, are expected with load factors ≤ 0.4 . If plastic bins are fumigated for 2 h, however, the observed exposures are superseded by the predicted lower 95% CI at load factors of 0.4 across the range in T . Predicted exposures (Ct') also increase commensurately for plastic bin loads if the applied dose is lowered by 8 mgL^{-1} and the fumigation duration is extended 0.5 h, suggesting that a load factor increase to ≤ 0.5 would yield efficacies consistent to that observed in the commodity efficacy trials.

Commodity fumigations: confirming efficacy of optimization

Results of initial commodity fumigation efficacy trials provide evidence to support the conclusion that SWD is controlled at mortality levels $\geq 99.9931\%$ following a 2-h MB fumigation of sweet cherries in wooden bins with load factors ≤ 0.3 given T -specific applied doses of: 48 mg L^{-1} , $T \geq 13.9^\circ\text{C}$; 56 mg L^{-1} , $13.9 > T \geq 12.2^\circ\text{C}$; 64 mg L^{-1} , $12.2 > T \geq 10.6^\circ\text{C}$; 72 mg L^{-1} , $10.6 > T \geq 8.3^\circ\text{C}$. However, the kinetic modeling described above was used to quantitatively predict, as a function of load type and amount, the amount of fumigant sorbed as well as the time it takes for this process to occur, thereby allowing for fumigation parameter optimization. Accordingly, a series of commodity fumigations were also conducted to verify control of the most MB-tolerant specimens in cherries fumigated across the range $12.2 \geq T \geq 8.3$

(± 0.5) °C for: 2 h in plastic bins with a chamber load of $40.0 \pm 0.7\%$, 2.5 h in wooden bins with a chamber load of $40.0 \pm 0.7\%$, and 2.5 h in plastic bins with a chamber load of $50.0 \pm 0.7\%$ ($\bar{x} \pm s$) (Table 3).

Fumigation for 2 h in plastic field bins with a chamber load of $40.0 \pm 0.7\%$ at $T = 12.2 (\pm 0.5)$ °C with an applied dose of 56 mg L^{-1} resulted in exposures of $106.6 \pm 4.2 (\bar{x} \pm 2s)$ mgL^{-1}h and 0 survivors out of $34,716 \pm 1,303 (n \pm s)$ treated, 99.9914% mortality (probit 8.76 at the 95% CL). Fumigation at $T = 10.6 (\pm 0.5)$ °C with an applied dose of 64 mg L^{-1} resulted in exposures of $116.2 \pm 4.7 (\bar{x} \pm 2s)$ $\text{mg L}^{-1}\text{h}$ and 0 survivors out of $32,378 \pm 1,447 (n \pm s)$ treated, 99.9907% mortality (probit 8.74 at the 95% CL). Fumigation at $T = 8.3 (\pm 0.5)$ °C with an applied dose of 72 mg L^{-1} resulted in exposures of $131.1 \pm 5.0 (\bar{x} \pm 2s)$ $\text{mg L}^{-1}\text{h}$ and 0 survivors out of $40,200 \pm 1,697 (n \pm s)$ treated, 99.9925% mortality (probit 8.79 at the 95% CL). Trials resulted in a grand sum of 0 survivors from $107,294 \pm 2,072 (n \pm s)$, 99.9972% mortality (probit 9.03 at 95% CL, probit 9 at 97% CL).

Fumigation for 2.5 h in wooden field bins with a chamber load of $40.0 \pm 0.7\%$ at $T = 12.2 (\pm 0.5)$ °C with an applied dose of 48 mg L^{-1} resulted in exposures of $94.1 \pm 2.7 (\bar{x} \pm 2s)$ mgL^{-1}h and 0 survivors out of $46,674 \pm 1,819 (n \pm s)$ treated, 99.9933% mortality (probit 8.82 at the 95% CL). Fumigation at $T = 10.6 (\pm 0.5)$ °C with an applied dose of 56 mg L^{-1} resulted in exposures of $106.4 \pm 3.1 (\bar{x} \pm 2s)$ $\text{mg L}^{-1}\text{h}$ and 0 survivors out of $31,590 \pm 990 (n \pm s)$ treated, 99.9905% mortality (probit 8.73 at the 95% CL). Fumigation at $T = 8.3 (\pm 0.5)$ °C with an applied dose of 64 mg L^{-1} resulted in exposures of $120.6 \pm 2.9 (\bar{x} \pm 2s)$ mgL^{-1}h and 1 survivor out of $43,084 \pm$

1,940 ($n \pm s$) treated, 99.9939% mortality (probit 8.84 at the 95% CL). Trials resulted in a grand sum of 1 survivor from $121,348 \pm 2,135$ ($n \pm s$), 99.9978% mortality (probit 9.09 at 95% CL, probit 9 at 96% CL).

Fumigation for 2.5 h in plastic field bins with a chamber load of $50.0 \pm 0.7\%$ at $T = 12.2 (\pm 0.5)$ °C with an applied dose of 48 mg L^{-1} resulted in exposures of $101.7 \pm 3.4 (\bar{x} \pm 2s)$ mgL^{-1}h and 0 survivors out of $47,396 \pm 1,959$ ($n \pm s$) treated, 99.9937% mortality (probit 8.83 at the 95% CL). Fumigation at $T = 10.6 (\pm 0.5)$ °C with an applied dose of 56 mg L^{-1} resulted in exposures of $117.5 \pm 2.9 (\bar{x} \pm 2s)$ $\text{mg L}^{-1}\text{h}$ and 1 survivor out of $37,662 \pm 1,562$ ($n \pm s$) treated, 99.9930% mortality (probit 8.81 at the 95% CL). Fumigation at $T = 8.3 (\pm 0.5)$ °C with an applied dose of 64 mg L^{-1} resulted in exposures of $134.4 \pm 5.3 (\bar{x} \pm 2s)$ $\text{mg L}^{-1}\text{h}$ and 0 survivors out of $33,774 \pm 1,326$ ($n \pm s$) treated, 99.9911% mortality (probit 8.75 at the 95% CL). Trials resulted in a grand sum of 1 survivor from $118,832 \pm 1,858$ ($n \pm s$), 99.9977% mortality (probit 9.08 at 95% CL, probit 9 at 96% CL).

Commercial versus commodity fumigations

Observed exposures (Ct) with upper and lower 95% CI boundaries corresponding to commercial fumigations with an applied dose of 64 mg L^{-1} applied dose at $12 > T \geq 6$ °C for 2 h, each conducted with exclusively plastic or exclusively wooden bins, were compared to predicted exposures (Ct') associated with the commodity fumigation of wooden or plastic bins with 64 mg

L^{-1} applied dose at $T = 10.6 (\pm 0.5) ^\circ\text{C}$ for 2 h (Figure 5). Respective to wooden as well as plastic bin loads, the slope of the linear least-squares regression (wooden, $m = 57.7$; plastic, $m = 43.8$) between the exposures (Ct) of commercial fumigations and the load factor ($V_{PL} V_{chamber}^{-1}$) was consistent with the slope of the analogous regressions (wooden, $m = 63.4$; plastic, $m = 39.9$) involving the predicted exposures (Ct') described above. For plastic bin loads, there was marked overlap between the upper and lower 95% CI boundaries associated with exposures (Ct) of commercial fumigations and the predicted exposures (Ct'). This result suggests that SWD control following commercial fumigation of plastic bins should equal that observed following a commodity fumigation conducted with identical parameters (i.e., applied dose, load factor, T , and duration). However, observed exposures (Ct) of commercial fumigations in wooden bins were slightly higher than those predicted in commodity fumigations (Ct') at load factors > 0.35 , suggesting that commodity fumigations described above may slightly over estimate sorption into wooden bins. We have interpreted this discrepancy to be a result of scaling and note that this error suggests SWD control following commercial fumigation of wooden bins should exceed, or at least equal, control following analogous commodity fumigation (i.e., identical parameters: applied dose, load factor, T , and duration) conducted procedurally as above.

Conclusion

Postharvest MB chamber fumigation was evaluated for control of SWD in sweet cherry exports from Western USA. A kinetic model of sorption was developed and can be used to as a tool to modulate the applied MB dose, fumigation duration, and the load factor so that the resultant

exposure is adequate for > 99.99 % control of SWD when sweet cherries at various pulp temperatures are fumigated in wooden versus plastic bins, as is the commercial practice in the Western USA. Results are presented in the context of graduation toward optimized quarantine fumigation schedules for control of SWD, which will promote more strategic technical and economic QPS use of MB.

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Trial #	# treated specimens (n ± s)	Applied (mg L ⁻¹) (± 0.5 °C)	T (± 0.5 °F)	Load (%)	Bin type	0.5 h [MB] _t	1 h [MB] _t	2 h [MB] _t	[MB] % loss	C _T (mg L ⁻¹ h)	survivors	k obs (h ⁻¹)	r ²	k SPT (m h ⁻¹)	
1	12,548 ± 1,387	72.0	8.3	47.0	30.0	wood	69.3	62.1	46.3	39.1	123.4	0	0.2383	0.97	0.0518
2	12,548 ± 1,388	72.0	8.3	47.0	30.0	wood	66.5	61.8	44.9	40.9	121.1	0	0.247	0.97	0.0537
3	14,321 ± 1,002	72.0	8.3	47.0	30.0	wood	68.0	60.2	49.1	35.4	122.7	0	0.2045	1.00	0.0445
4	14,321 ± 1,002	72.0	8.3	47.0	30.0	wood	67.1	59.2	46.1	39.3	120.0	0	0.2368	1.00	0.0515
5	16,754 ± 1,847	72.0	8.3	47.0	30.0	wood	70.1	57.2	43.5	42.8	118.7	0	0.2783	0.97	0.0605
Σ 70,492 ± 3,094											Σ 0 (99.9957 % mort.)				0.0524 ± 0.0057 ^A (x ± s)
6	8,734 ± 892	64.0	10.6	51.0	30.0	wood	57.6	49.1	40.0	41.2	102.6	0	0.2466	0.99	0.0536
7	8,734 ± 892	64.0	10.6	51.0	30.0	wood	59.7	57.5	42.7	37.2	101.3	0	0.2103	0.95	0.0457
12	11,007 ± 470	64.0	10.6	51.0	30.0	wood	60.2	55.3	43.4	34.2	109.8	0	0.1952	0.99	0.0424
9	4,686 ± 549	64.0	10.6	51.0	30.0	wood	60.5	52.3	44.5	34.6	108.7	1	0.1954	0.98	0.0425
10	4,686 ± 549	64.0	10.6	51.0	30.0	wood	60.3	53.0	44.4	34.7	109.1	0	0.1953	0.99	0.0425
11	4,686 ± 549	64.0	10.6	51.0	30.0	plastic	64.9	59.1	50.7	25.4	119.1	0	0.1497	0.96	0.0326
8	8,734 ± 892	64.0	10.6	51.0	30.0	plastic	63.1	55.5	48.9	34.0	112.6	0	0.1324	0.93	0.0288
Σ 51,267 ± 1,915											Σ 1 (99.9948 % mort.)				0.0307 ± 0.0027 ^B (x ± s)
13	9,722 ± 1,102	56.0	12.2	54.0	30.0	wood	51.1	43.9	37.0	38.3	92.0	0	0.2182	0.98	0.0474
14	9,722 ± 1,102	56.0	12.2	54.0	30.0	wood	51.8	44.9	38.0	36.7	93.6	0	0.2053	0.99	0.0446
15	8,548 ± 652	56.0	12.2	54.0	30.0	wood	52.6	46.5	39.3	34.5	95.8	1	0.1884	0.99	0.0410
16	9,872 ± 799	56.0	12.2	54.0	30.0	wood	55.4	46.7	36.2	39.7	95.8	0	0.2425	0.97	0.0527
17	9,872 ± 799	56.0	12.2	54.0	30.0	wood	55.8	47.5	38.1	36.5	97.6	0	0.2154	0.96	0.0468
18	9,872 ± 799	56.0	12.2	54.0	30.0	wood	54.6	47.0	39.1	34.8	97.1	0	0.1978	0.98	0.0430
Σ 57,608 ± 2,183											Σ 1 (99.9954 % mort.)				0.0459 ± 0.0041 ^A (x ± s)
19	9,965 ± 768	48.0	13.9	57.0	30.0	wood	48.0	41.5	32.5	37.5	84.4	0	0.2177	0.96	0.0473
20	9,965 ± 768	48.0	13.9	57.0	30.0	wood	47.9	42.3	31.9	38.7	84.6	0	0.2264	0.95	0.0492
21	8,436 ± 884	48.0	13.9	57.0	30.0	wood	49.0	42.4	35.5	31.7	87.1	0	0.173	0.93	0.0376
22	15,276 ± 1,210	48.0	13.9	57.0	30.0	wood	47.8	41.8	34.8	33.1	85.7	0	0.1797	0.96	0.0391
Σ 43,642 ± 1,851											Σ 0 (99.9931 % mort.)				0.0433 ± 0.0058 ^A (x ± s)

Table 1. Efficacy data related to 2-h methyl bromide fumigations at pulp temperatures (T) of 8.3 to 17.2 (± 0.5) °C and exposures (Ct) ranging from 84.4 to 123.4 mgL⁻¹h resulted in a grand sum of 2 survivors from 223,009 $\pm$ 4,580 treated ($n \pm s$) (probit 9.62). Mean values of k_{SPT} (m h⁻¹) at each, or across, treatment temperature not connected by the same letter are significantly different (Tukey-Kramer HSD).

Trial #	T ($\pm 0.5^{\circ}\text{C}$)	T ($\pm 0.8^{\circ}\text{F}$)	Bin type	Load (%)	Applied (mg L^{-1})	[MB] ₀	0.25 h [MB] _t	0.5 h [MB] _t	1 h [MB] _t	1.5 h [MB] _t	2 h [MB] _t	2.5 h [MB] _t	3 h [MB] _t	3.5 h [MB] _t	k_{obs} (h^{-1})	r^2	k_{SPT} (m h^{-1})
1	8.3	47.0	wood	30.0	80	76.1	69.9	61.4	55.2	49.1	44.6	42.1	-	-	0.2186	0.97	0.0475
2	10.6	51.0	wood	25.0	64	64.6	58.8	52.2	46.2	41.7	39.6	37.4	36.3	-	0.1687	0.93	0.0440
3	8.3	47.0	wood	15.0	64	63.7	58.9	56.1	52.7	49.9	47.8	46.1	-	-	0.107	0.98	0.0465
4	12.2	54.0	wood	20.0	72	69.5	64.3	61.5	55.1	52.0	49.5	47.8	-	-	0.1333	0.96	0.0435
5	8.3	47.0	wood	20.0	72	69.3	64.0	60.3	55.4	50.5	48.8	47.0	-	-	0.1379	0.96	0.0450
6	13.9	57.0	wood	20.0	64	65.4	61.0	57.3	51.9	48.4	47.0	-	-	-	0.1508	0.95	0.0492
7	10.6	51.0	wood	30.0	80	78.5	68.5	62.0	54.3	49.8	47.1	-	-	-	0.2116	0.96	0.0460
8	10.6	51.0	wood	30.0	64	67.7	55.5	51.5	44.4	40.3	37.5	-	-	-	0.2253	0.98	0.0490
9	8.3	47.0	wood	25.0	72	70.5	61.7	56.9	50.2	46.2	43.9	40.0	-	-	0.1843	0.97	0.0481
10	12.2	54.0	wood	40.0	56	60.2	50.2	41.9	35.2	32.5	29.5	24.2	20.1	-	0.301	0.98	0.0491
$k_{\text{SPT-wood}} = 0.0468 \pm 0.0043$ ($\bar{x} \pm 2s$)																	
11	8.3	47.0	plastic	40.0	88	87.5	79.6	75.0	64.7	59.7	54.8	53.0	51.5	50.3	0.1419	0.95	0.0231
12	12.2	54.0	plastic	15.0	72	76.1	72.5	68.1	64.6	62.1	61.0	59.9	59.6	59.4	0.056	0.94	0.0244
13	10.6	51.0	plastic	10.0	80	79.8	77.5	76.8	73.8	72.1	70.6	69.7	69.4	69.2	0.0369	0.91	0.0241
14	10.6	51.0	plastic	30.0	88	94.0	86.4	83.0	73.9	69.7	65.2	63.6	62.2	61.2	0.1074	0.91	0.0234
15	13.9	57.0	plastic	15.0	72	78.1	76.4	74.7	70.8	68.6	68.0	66.3	64.9	64.4	0.0517	0.94	0.0225
16	8.3	47.0	plastic	35.0	88	96.5	89.9	85.0	74.8	70.1	67.1	64.6	61.7	60.3	0.1198	0.93	0.0223
17	12.2	54.0	plastic	15.0	64	61.4	59.2	58.7	56.8	55.0	53.9	-	-	-	0.0569	0.99	0.0247
18	8.3	47.0	plastic	25.0	64	60.7	58.7	56.7	53.6	51.8	50.1	-	-	-	0.0899	0.98	0.0235
$k_{\text{SPT-plastic}} = 0.0235 \pm 0.0017$ ($\bar{x} \pm 2s$)																	

Table 2. Loads (% , $100 \times V_{PL} V_{chamber}^{-1}$), applied doses, headspace concentrations of methyl bromide ([MB]) at specified time (t), and treatment durations were varied across a series of commodity fumigations conducted with only uninfested cherries in wooden or plastic bins. The rate constants of fumigant sorption for a cherry load in a plastic bin, $k_{\text{SPT-plastic}}$ (m h^{-1}), and in a wooden bin, $k_{\text{SPT-wood}}$ (m h^{-1}), 0.0235 ± 0.0017 and 0.0468 ± 0.0043 ($\bar{x} \pm 2s$) respectively, were significantly different at the 95% CL (paired t -test, $P < 0.0001$) and agreed with results from the commodity efficacy trials (Tables 1 & 3).

Trial #	# treated specimens (<i>n</i> ± <i>s</i>)		Applied (mg L ⁻¹)	<i>T</i> (± 0.5 °C) (± 0.8 °F)		Load (%)	Bin type	Duration (h)	Ct (mgL ⁻¹ h)	survivors
1	10,528	± 936	72.0	8.3	47.0	40.0	plastic	2.0	132.5	0
2	10,528	± 936	72.0	8.3	47.0	40.0	plastic	2.0	129.7	0
3	9,572	± 751	72.0	8.3	47.0	40.0	plastic	2.0	128.4	0
4	9,572	± 751	72.0	8.3	47.0	40.0	plastic	2.0	133.9	0
Σ 40,200 ± 1,697									131.1 ± 5.0 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9925 % mort.)
5	7,548	± 605	64.0	10.6	51.0	40.0	plastic	2.0	115.4	0
6	7,548	± 605	64.0	10.6	51.0	40.0	plastic	2.0	118.6	0
7	8,641	± 825	64.0	10.6	51.0	40.0	plastic	2.0	113.3	0
8	8,641	± 825	64.0	10.6	51.0	40.0	plastic	2.0	117.6	0
Σ 32,378 ± 1,447									116.2 ± 4.7 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9907 % mort.)
9	9,720	± 744	56.0	12.2	54.0	40.0	plastic	2.0	108.6	0
10	9,720	± 744	56.0	12.2	54.0	40.0	plastic	2.0	105.7	0
11	7,638	± 543	56.0	12.2	54.0	40.0	plastic	2.0	104.0	0
12	7,638	± 543	56.0	12.2	54.0	40.0	plastic	2.0	107.9	0
Σ 34,716 ± 1,303									106.6 ± 4.2 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9914 % mort.)
13	11,245	± 1,002	64.0	8.3	47.0	40.0	wood	2.5	120.3	0
14	11,245	± 1,002	64.0	8.3	47.0	40.0	wood	2.5	120.9	1
15	10,297	± 937	64.0	8.3	47.0	40.0	wood	2.5	118.9	0
16	10,297	± 937	64.0	8.3	47.0	40.0	wood	2.5	122.4	0
Σ 43,084 ± 1,940									120.6 ± 2.9 (<i>X</i> ± 2 <i>s</i>)	Σ 1 (99.9939 % mort.)
17	9,248	± 552	56.0	10.6	51.0	40.0	wood	2.5	105.6	0
18	9,248	± 552	56.0	10.6	51.0	40.0	wood	2.5	104.7	0
19	6,547	± 430	56.0	10.6	51.0	40.0	wood	2.5	107.2	0
20	6,547	± 430	56.0	10.6	51.0	40.0	wood	2.5	108.1	0
Σ 31,590 ± 990									106.4 ± 3.1 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9905 % mort.)
21	12,494	± 1025	48.0	12.2	54.0	40.0	wood	2.5	94.6	0
22	12,494	± 1025	48.0	12.2	54.0	40.0	wood	2.5	92.1	0
23	10,843	± 777	48.0	12.2	54.0	40.0	wood	2.5	95.1	0
24	10,843	± 777	48.0	12.2	54.0	40.0	wood	2.5	94.6	0
Σ 46,674 ± 1,819									94.1 ± 2.7 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9933 % mort.)
25	10,006	± 871	64.0	8.3	47.0	50.0	plastic	2.5	137.4	0
26	10,006	± 871	64.0	8.3	47.0	50.0	plastic	2.5	131.2	0
27	6,881	± 347	64.0	8.3	47.0	50.0	plastic	2.5	135.4	0
28	6,881	± 347	64.0	8.3	47.0	50.0	plastic	2.5	133.5	0
Σ 33,774 ± 1,326									134.4 ± 5.3 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9911 % mort.)
29	9,826	± 689	56.0	10.6	51.0	50.0	plastic	2.5	117.5	0
30	9,826	± 689	56.0	10.6	51.0	50.0	plastic	2.5	117.0	0
31	9,005	± 863	56.0	10.6	51.0	50.0	plastic	2.5	119.4	0
32	9,005	± 863	56.0	10.6	51.0	50.0	plastic	2.5	115.9	1
Σ 37,662 ± 1,562									117.5 ± 2.9 (<i>X</i> ± 2 <i>s</i>)	Σ 1 (99.9930 % mort.)
33	13,450	± 1,105	48.0	12.2	54.0	50.0	plastic	2.5	99.7	0
34	13,450	± 1,105	48.0	12.2	54.0	50.0	plastic	2.5	103.6	0
35	10,248	± 835	48.0	12.2	54.0	50.0	plastic	2.5	101.1	0
36	10,248	± 835	48.0	12.2	54.0	50.0	plastic	2.5	102.5	0
Σ 47,396 ± 1,959									101.7 ± 3.4 (<i>X</i> ± 2 <i>s</i>)	Σ 0 (99.9937 % mort.)

Table 3. Efficacy and exposure (*Ct*) data related to a series of commodity fumigations conducted to verify control of SWD in sweet cherries fumigated at pulp temperatures (*T*) of 8.3 to 12.2 (± 0.5) °C for: 2 h in plastic bins with a chamber load of 40.0 ± 0.7%, 2.5 h in wooden bins with a chamber load of 40.0 ± 0.7%, and 2.5 h in plastic bins with a chamber load of 50.0 ± 0.7% ($\bar{x} \pm s$).

Figure 1. Probit analysis of the *Ct* exposure-mortality response for spotted wing drosophila (SWD) age groups infesting sweet cherries following exploratory fumigations with methyl bromide (MB) for 2 h at treatment temperature of 8.3 or 15.6 (± 0.5) °C ($\bar{x} \pm s$).

Suseptability of 48- to 96-h old SWD toward fumigation at 8.3 °C relative to:

□ 0- to 48-h old at 8.3 °C

— 0- to 24-h old at 8.3 °C

▲ 48- to 96-h old at 15.6 °C

Mortality (%) of SWD following MB fumigation in exploratory trials

Figure 2. Lethal exposure ratios (LERs) were calculated with 95% confidence intervals (CI) and used to identify difference in MB-tolerance across ages. LERs calculated for 48- to 96-h old SWD relative to 0- to 48-h and 0- to 24-h old specimens across exposures at pulp temperature of 8.3 ± 0.5 °C paralleled a ratio of 1 and superseded 1, respectively. Results suggest that larger larvae, which were often observed to feed completely submerged within cherries containing 48- to 96-h old specimens, are more MB-tolerant than the younger larvae and eggs more frequently observed near the fruit periphery and chamber headspace.

Figure 3. On five separate occasions, the probability of each SWD life stage being present just before a commodity fumigation at $T = 13.9 \pm 0.5$ °C was determined by dissecting samples of infested sweet cherry until the life stage of ~ 1000 individual specimens was evaluated ($\bar{x} \pm s$; egg, 0.011 ± 0.006 ; 1st, 0.058 ± 0.018 ; 2nd, 0.226 ± 0.036 ; 3rd, 0.651 ± 0.035 ; pupa, 0.051 ± 0.015).

Figure 4. The relation between load factor and predicted exposures (Cr') (wooden —, plastic —) with upper and lower 95% CI boundaries (wooden —, plastic —) across 8.3 to 12.2 (± 0.5) °C, the range of pulp temperature (T) frequently used by industry in commercial fumigations. Note that (Cr) exposures ($\bar{x} \pm 2s$) (—) observed during 2-h commodity efficacy trials (12.2 °C, 96.0 ± 4.3 mgL⁻¹h; 10.6 °C, 109.0 ± 12.0 mgL⁻¹h; 8.3°C, 121.2 ± 3.8 mgL⁻¹h) with a wooden bin load factor of 0.3 span the upper and lower 95% CIs of the respective predicted exposures (Cr'). Results suggest that similar efficacy toward SWD would be expected if the applied dose was lowered by 8 mgL⁻¹, the duration was extended 0.5 h, and load factors were increased to ≤ 0.4 . For plastic bins, similar efficacy toward SWD is expected for a 2-h or a 2.5-h fumigation at load factors of $\leq 0.4 \leq 0.5$, respectively.

Figure 5. Observed exposures (Ct) (wooden —, plastic —) with upper and lower 95% CI boundaries (wooden —, plastic —) corresponding to commercial fumigations with an applied dose of 64 mg L^{-1} applied dose at pulp temperature $12 > T \geq 6^\circ\text{C}$ for 2 h, each conducted with exclusively plastic or exclusively wooden bins, were compared to predicted exposures (Ct') (wooden —, plastic —) with upper and lower 95% CI boundaries (wooden —, plastic —) with associated with the commodity fumigation of wooden or plastic bins with 64 mg L^{-1} applied dose at $T = 10.6 (\pm 0.5)^\circ\text{C}$ for 2 h. Result indicate that exposures (Ct) following commercial fumigation are consistent with those observed in commodity fumigation trails and suggest that SWD control following commercial fumigations should be equivalent to that observed following a commodity fumigation conducted with identical parameters (i.e., applied dose, load factor, T , and duration).

Female spotted wing drosophila, *Drosophila suzukii*, use a serrated ovipositor (top panel) to deposit an egg through the surface of a sweet cherry (bottom panel).