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Probabilities for survival of glassy-winged sharpshooter and olive fruit fly pests in urban yard waste piles

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Abstract

Glassy-winged sharpshooter (*Homolodisca coagulate*) and olive fruit fly (*Bactrocera oleae*) were introduced into unturned, chipped yard waste piles to evaluate their survival with time and depth within the piles. In all three trials, no pests lasted more than 14 d, and in no trial did pests survive more than 4 d at the 30 and 100 cm depths. No survivors were found after 14 d in any of the treatments at any depth. Neither of the pests survived 100 cm after 2 d. A mathematical model for describing pest survival probabilities is described. The model modifies time according to the Arrhenius equation in order to include heat effects on pest survival and can be used to determine exposure times necessary to eliminate these pests with a determined statistical probability. Model projections suggest that for conditions similar to this study, there is 99% confidence that all glassy-winged sharpshooter eggs would be eliminated from 1000 infected leaves in 6.1 d at 15 cm depth and in 4.8 d at 30 cm or below. Olive fruit fly larvae at these depths would require 4.8 and 4.1 d, respectively, for 1000 infected olive fruits. Projected elimination times at the surface were longer, 6.5 d for sharpshooter eggs and 14.3 d for fruit fly larvae.

Keywords: Glassy-winged sharpshooter; Olive fruit fly; Compost; Model; Survival

1. Introduction

Urban yard waste is being used in considerable quantities in California agriculture as a mulch for tree crops, most notably avocado. Organic mulches have a multitude of effects on this crop as well as other tree crops, such as citrus. Appropriately used, mulch can reduce some disease incidence, control weeds, reduce water requirements, improve infiltration and soil structure, and alter soil fertility (Faber et al., 2003). Introduction of organic mulches has had a beneficial effect on the control of avocado root rot, a major world-wide disease (Downer et al., 2002).

The ready availability of large amounts of urban yard waste is a recent phenomenon. Since 2000, California law has required counties to divert half of historically landfilled wastes to beneficial uses (CIWMB, 2001). To meet this demand, many counties require households to separate their lawn trimmings. This material is collected by haulers, taken to a processing facility where it is chipped, cleaned, and stockpiled until it can be delivered to a grower. Since a certain volume is needed to justify spreading logistics and economics, growers will often stockpile materials further until the necessary volume is present. Growers are spreading various amounts, but a standard practice is to spread 200 Mg ha^{-1}.

Plant materials entering the waste stream vary depending on season and point of collection, thus, conjuring up possibilities for just about anything to be in the stream. Because of this high variability of materials in newly chipped piles, it is conceivable that pests can be transported

Abbreviations: OFF, olive fruit fly; GWSS, glassy-winged sharpshooter; PI, pre-insertion; pdf, probability density function; pgf, probability generating function; TAT, temperature-adjusted time.

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Nomenclature

d°	temperature-adjusted days (d)
E_A	Arrhenius activation energy (kJ mol^{-1})
$G(z)$	generic pgf
$G_B(z)$	Bernoulli distribution pgf
$G_b(z)$	binomial distribution pgf
$G_P(z)$	Poisson distribution pgf
$G_s(z)$	distribution pgf for the survival of a pests on or within an infected plant part
i	number of bags found to be positive for a pest of interest
j	possible value for a discrete random variable described by a pgf
k	pest inactivation rate (d^{-1} or d°$^{-1}$)
k_r	Arrhenius equation reference inactivation rate (d^{-1})
k_T	temperature-adjusted inactivation rate (d^{-1})
n	number of pest in the fixed fraction of the initial pest distribution
p_t	probability that a pest survives until time t
Q_{10}	Fractional change in the inactivation rate after a 10 °C increase in temperature from the reference temperature
r	number of inserted bag replications
R	universal gas constant (kJ mol^{-1} K^{-1})
t	time (d)
$t°$	temperature-adjusted time or TAT (d°)
$T(t)$	temperature at time t (K)
T_r	Arrhenius equation reference temperature (K)
w	probability that no pests survive at a given TAT
x	for a specific pest, the number of infected plant parts either placed in a bag or contained within a pile
Y	random variable associated with the number of pests of a particular type surviving with a bag
z	dummy variable used to formulate a pgf
β	binomial probability density function
λ_t	probability that a bag is positive for a pest of interest at time t
π_j	probability that a rv described by a pgf equals exactly j
θ	Poisson distribution mean value

undetected, spreading them to uninfected areas. In Ventura County, California, materials are currently moved from urban to rural areas as far as 100 km away. To help reduce costs, these materials are generally not actively composted, although the decomposition process begins as soon as the homeowner collects the plant materials. Weeds, plant pathogens and other pests can therefore be introduced with whatever plant materials occur in the waste stream. Active composting has generally been seen as a method of reducing pests and pathogens in organic materials (Elorriota et al., 2003; Noble and Roberts, 2004; Termorshuizen et al., 2005; Yuen and Raabe, 1984), but little is known about the behavior of pests in stockpiled wastes (Noble and Roberts, 2004). This freshly chipped material may have more potential to spread a problem from one area to another, affecting not only the farm receiving the material, but an entire agricultural region.

This paper considers the potential for two pests, *Homolodisca coagulate* (glassy-winged sharpshooter, GWSS) and *Bactrocera oleae* (olive fruit fly, OFF), to survive within stockpiled yard trimmings. These GWSS and OFF were selected because of the ease of finding them throughout the year in coastal Southern California and because they have caused serious problems for the California grape and olive industries. To assess potential of these pests for surviving stockpiling, samples of infested plant residues were introduced into three piles constructed at different times of the year and then sampled over time. Infested samples were noted.

A model was then developed and parameterized using probability procedures in order to evaluate the survival rates of the organisms. The probabilistic approach taken here was developed after the experiment was concluded. Although designed to represent the particular conditions and measurements used in this particular experiment, similar approaches should be useful for quantifying the survival of a variety pests over time in many different circumstances. The approach requires four activities: (1) deciding upon a distribution to represent the presence of the pests in the environment of interest, (2) reformulating the distribution in terms of the survival model, (3) modeling survival kinetics over time, (4) adjusting the distribution, as necessary, to represent how the pests are sampled during the experiment, (5) fitting all model parameters so that they best represent experimental observations, and (6) determining a function describing the expected number of pests over time from the fitted distribution.

2. Methods

2.1. Experimental design

Five 8 m^3 piles were created at three different times of the year from the materials available at that time. To assess the survival of the GWSS and OFF pests, living specimens at four depths in the piles were harvested in a time sequence over a 2 month period. The piles remained unturned in an

attempt to create the optimum conditions for pest survival in stockpiled yard waste.

Piles were built using chipped yard waste collected within 2 h of grinding. The materials were chipped with a horizontal hog grinder (Morbark Inc. Winn, MI) with no screen and had a coarse constancy (1–30 cm in length and 1–5 cm in width). The piles were built in two stages. First, 4 m^3 of chipped yard waste was deposited on the ground and then leveled to a 1 m height and approximately 3 m diameter. Permeable 2 L bags manufactured from oriented polypropylene film (Delnet® brand, Applied Extrusion Technologies (AET), Inc., Middltown, Delaware) were filled with the pest specimens and laid out in a radial fashion from the center of the pile. To insure contact with the pests in the bags and surrounding material, the bags were partially filled with the same material that they were being buried into. The pests had been collected the day prior to bag assembly. The bags were tied with colored polypropylene cord to aid future recovery. Individual bags were placed, at a 0.5 m height, into or on the piles in a line at distances of 0, 0.15, 0.3, and 1 m from the edge of the pile. Nine lines were laid out radially on each pile, each line representing a different sampling date. Once the bags were in place, an additional 4 m^3 was added to the top of the pile. The experiment was repeated three times, with trials beginning on October 16, 2001; April 19, 2001; and July 18, 2002. Each experiment included 5 pile replicates arranged in a randomized complete block design.

This first sampling event was between 8 and 14 h after pile creation, then on a regular schedule 1, 2, 4, 7, 14, 21, 28, and 56 d after pile creation. Temperature data loggers (Watch Dog Model 100, Spectrum Technologies, IL.) were included in the last radial line of each pile, representing the last harvest date. At each sampling date a manual temperature reading was taken with a type J thermocouple-based digital thermometer (Digi-Sense, 8528-20, ColeParmer, Niles, IL, accuracy $\pm$ 0.5 °C) at all studied locations and piles.

Sample bags from the piles were removed and returned to the lab within 2 h from excavation. At the lab, the bags were opened and the leaves and olives were removed. Olives containing OFF larvae and citrus leaves carrying GWSS eggs were evaluated for viability under a dissecting microscope. Because there was significant variability in the numbers of insects on infested fruit and leaves, two leaves containing GWSS eggs and two fruit containing OFF larvae were placed in each bag to ensure that there were a number of viable individuals in the bags. Viability was determined as either alive or dead at the time of sampling on either the leaf or fruit samples from the bags. Fruit and leaves were tested for insect viability prior to building the bags and were found to be 90% viable based on visual inspection of either the eggs or the larvae.

2.2. Modeling approach and parameterization

Because the occurrence and survival of pests on plants are discrete phenomena, the probabilistic strategy taken here is most conveniently conveyed using probability generating functions (pgf). Probability generating functions can be used to calculate event probabilities, moments such as the distribution mean and variance, sums of independent random variables (rv's), known as *convolutions*, as well as *stopped-sum* distributions which arise when results from a random number of identically distributed discrete rv's are lumped together and the number of those rv's has its own discrete distribution. Individual event probabilities, π_j, from any pgf, $G(z)$, can be quickly determined using symbolic or numeric mathematical processing software, such as MathCAD® (Parametric Technology Corporation (PTC), Needham, Massachusetts), the application used for this study. The probability, π_j, that j individuals will be observed from a process with a distribution described by some pgf, $G(z)$, is

$$\pi_j = \left[\frac{1}{j!}\frac{\mathrm{d}^j G(z)}{\mathrm{d}z^j}\right]_{z=0}. \quad (1)$$

This equation can be solved quickly using a mathematical processing application (Johnson et al., 2005).

2.2.1. Initial distribution

The presence of viable pests prior to insertion was assessed and used to formulate an initial distribution. Separate samples consisting of 20 contaminated leaves and 20 olives were gathered and evaluated on October 10, 2001 and on April 10, 2002. A Kolmogorov–Smirnov Z test (Norušis, 2002) did not establish the independence of the two samples ($\alpha \geqslant 0.05$) so the data for each pest were lumped together into two pre-insertion (PI) samples ($n = 40$).

Because all samples were required to have at least one viable egg or larvae, the underlying distribution was defined as a *fixed value*, n, plus a *random number* of additional eggs or larvae. For both pests, the numbers of additional egg or larvae were assumed to be Poisson distributed with mean θ.

2.2.2. Survival distribution

Survival (or inactivation) was assumed to be independent and identically distributed at pest-specific rates. The survival of each individual pest was modeled as a Bernoulli rv, with pgf $G_B(z)$, and describes the event of that pest surviving to a particular point in time with probability, p_t:

$$G_B(z) = 1 - p_t + p_t z. \quad (2)$$

To model the survival potential for all of the pests deposited on a leaf or within an olive fruit, it is necessary to consider both the fixed and variable terms in the initial distribution. The survival distributions of the fixed PI pests are described using a binomial distribution with pgf $G_b(z)$ where $n = 1$ for OFF, $n = 5$ for GWSS:

$$G_b(z) = (1 - p_t + p_t z)^n. \quad (3)$$

For OFF this is also a Bernoulli rv, as $n = 1$. The pgf for the Poisson distribution, $G_P(z)$, representing the random number of additional eggs or larvae is

$$G_P(z) = e^{\theta(z-1)}. \quad (4)$$

Survival distributions from the stochastic PI pests after some period of time may be determined as a Poisson stopped-sum of a Bernoulli rv, that is, a Poisson number of pests, each surviving (or not) as a Bernoulli event with survival probability, p_t. This stopped-sum distribution can be determined as (Johnson et al., 2005)

$$G_P(G_B(z)) = e^{\theta p_t(z-1)}. \quad (5)$$

Survival can now be represented as a convolution of the distributions representing both fixed and stochastic PI survivors. The resulting pgf, $G_s(z)$, can be determined as

$$G_s(z) = G_b(z)G_P(G_B(z)). \quad (6)$$

Recall, however that two infected leaves and two infected olives were placed in each bag so that a further convolution of $G_s(z)$ with itself describes the total distribution of pests in each bag. For two pests per bag, $x = 2$,

$$G_s^x(z) = (1 - p_t + p_t z)^{xn} e^{x\theta p_t(z-1)}. \quad (7)$$

2.2.3. Survival kinetics

The proportion of pests expected to be inactivated over time, p_t, can be represented as a first-order process (Wang et al., 2002). Standard first-order survival is expressed as

$$p_t = e^{-kt}, \quad (8)$$

where t is time (d), and k is an inactivation rate constant (d^{-1}). Survival kinetics strongly depend on temperature, however. To apply this equation under varying temperature conditions the following integrals must be solved:

$$p_t = e^{-\int_0^t k(T(\hat{t}))d\hat{t}}, \quad (9)$$

where survival constant k is a function of temperature, T (K), which is in turn a function of time, $\hat{t}$ (d). While insect development is typically modeled as a function of degree-days (Al-Wahaibi and Morse, 2003; Wilson and Barnett, 1983), survival has historically been addressed using probit analysis, an approach limited to constant temperature conditions (Finney, 1971; Wang et al., 2002). To overcome this problem, engineers and scientists studying the survival of insects using heat have been applying the Arrhenius relationship to survival kinetics to a variety of pests including GWSS, and several fruit fly species (Gazit et al., 2004; Johnson et al., 2004; Hallman et al., 2005; Wang et al., 2002). For convenience, this equation can be written in terms of the popular and intuitive Q_{10} parameter,

$$k_T = k_r Q_{10}^{(1+T_r/10)(1-T_r/T)}, \quad (10)$$

where k_T (d^{-1}) is the decay rate at temperature T (K), k_r (d^{-1}) is the decay rate at reference temperature T_r (K), and Q_{10} is the relative proportion by which k_r increases after a 10 K temperature increase from the reference temperature ($Q_{10} = k_{T_r+10}/k_{T_r}$) (Crohn and Valenzuela-Solano, 2003). TAT has also been used recently to incorporate dynamic temperature effects into mulch decomposition and N mineralization models (Valenzuela-Solano and Crohn, 2006) and to optimize manure application schedules (Crohn, 2006). When the Arrhenius equation is substituted into (9), the survival rates can be brought outside of the integrals. A numerical solution to (9) can then be constructed in terms of temperature-adjusted time (TAT) which has units represented as d° to indicate temperature-adjusted days:

$$p_t = e^{-kt^\circ} \quad (11)$$

and

$$t^\circ = \sum_{\forall i \ni \hat{t}_i < t} Q_{10}^{\left(1+\frac{T_r}{10}\right)\left(1-\frac{T_r}{T(\hat{t}_i)}\right)} (\hat{t}_{i+1} - \hat{t}_i), \quad (12)$$

where $\hat{t}_i$ are ordered points in time and an exact solution to (12) is found as $i \to \infty$. Rate k here has units of $d^{\circ -1}$ and is constant across all temperatures.

2.2.4. Sampled distribution

Because the protocol for this experiment considered only the presence or absence of pests in the collected samples, the data collected at each sampling event can be regarded as Bernoulli (presence/absence) events, each with a probability λ_t of containing one or more pests. Of the $r = 5$ replications, the number of survivors, $i \in \{1, \ldots, 5\}$. The number of positive bags collected in a particular event can be represented as a further binomial event, with a probability density function (pdf) of

$$\beta(i|\lambda_t, r) = \binom{r}{i} \lambda_t^i (1 - \lambda_t)^{r-i}. \quad (13)$$

The probability that a particular bag is positive at time t can be determined as the complement of the bag being negative, that is $\lambda_t = \Pr(Y \geqslant 1) = 1 - \Pr(Y = 0)$. This is easily determined from (7) and (1) where $j = 0$,

$$\lambda_t = 1 - (1 - p_t)^{xn} e^{-x\theta p_t}. \quad (14)$$

As before, $x = 2$ since two infested plants parts were added to each bag for each pest. The pdf describing the occurrence of one or more pests in a particular bag at a given time can now be expressed in TAT by combining Eqs. (9), (11) and (14):

$$\beta(i|\theta, r, k, t^\circ) = \binom{r}{i} [1 - (1 - e^{-kt^\circ})^{2n} e^{-2\theta e^{-kt^\circ}}]^i \times [(1 - e^{-kt^\circ})^{2n} e^{-2\theta e^{-kt^\circ}}]^{r-i}, \quad (15)$$

where t° (d°) represents TAT.

2.2.5. Parameterization

Parameters r and t° are directly measurable and n and θ were determined directly from the PI sample, but parame-

ters k and Q_{10} must be estimated from observations made during the experiment. This was done using maximum log-likelihood estimation (Johnson et al., 2005) using the numerical solver built into Microsoft Excel. If i_j represents the number of bags in sample j that contain one or more viable pests ($0 \leqslant i_j \leqslant r = 5$), then since r and t_j (the sample collection time) are known and θ was previously estimated, estimation is only necessary for k and Q_{10}:

$$\text{Max} \sum_{\forall j} \ln[\beta(i_j|k, Q_{10})]. \tag{16}$$

The reasonableness of the approach was checked with a Kolmogorov–Smirnov goodness-of-fit test (Conover, 1999). The cumulative distribution function (cdf) used for this test was determined by using Monte Carlo simulation (*Crystal Ball* software) to generate 100,000 sets of binomially-distributed data derived from (15) where each set contained one rv for each of the 96 bag collection events.

The expected number of survivors per bag can be determined directly from (7) for $x = 2$, by reconfiguring it as a moment generating function. The rth moment, μ_r, of a distribution with pdf $G(z)$ is (Johnson et al., 2005)

$$\mu'_r = \left[\frac{\mathrm{d}^r G(\mathrm{e}^\tau)}{\mathrm{d}\tau^r}\right]_{\tau=0}. \tag{17}$$

Since $E(Y) = \mu'_1$, substituting (11) gives

$$E(Y) = 2(n+\theta)\mathrm{e}^{-kt^\circ}. \tag{18}$$

Since the associated variance is $\mathrm{Var}(Y) = \mu'_2 - (\mu'_1)^2$,

$$\mathrm{Var}(Y) = 2(n+\theta)\mathrm{e}^{-kt^\circ} - 2n\mathrm{e}^{-2kt^\circ}. \tag{19}$$

3. Results

Pre-insertion data consisting of viable OFF per olive fruit had a mean of 1.78 and a variance of 0.64. Corresponding statistics for viable GWSS larvae were 6.88 and 2.73, respectively. These statistics suggest that the data have underlying probability distributions that are underdispersed. OFF PI data ranged from 1 to 3 per fruit, while GWSS PI data fell between 5 and 10 viable eggs per leaf. For OFF, therefore, $n = 1$ with an additional number of larvae per fruit having a Poisson mean of $\theta = 0.775$. Because 10 of the GWSS leaves carried 5 eggs (and 11 carried 6), but none were less than 5, it was decided that 5 would be considered a biologically determined minimum for GWSS ($n = 5$), with an associated number of random additional larvae described with a Poisson mean, $\theta = 1.88$ eggs per leaf for GWSS.

Table 1 shows temperatures at different depths over the 56 d period during which the trials were run using representative data from trial 2. Within 2 d, even the 15 cm depth had exceeded 55 °C while at deeper depths temperatures exceeded 65 °C. Surface temperatures were more similar to air temperatures but were moderated by the presence of the compost so that mean surface temperatures did not vary more than a few degrees from season to season.

Table 1
Mean pile temperatures over time at four depths (mean ± 1 standard deviation)

Time (d)	Measurement depth			
	0 cm	15 cm	30 cm	100 cm
0.5	25.8 ± 10.5	50.1 ± 11.9	62.9 ± 9.0	57.5 ± 6.0
1	30.5 ± 2.6	60.8 ± 3.5	68.4 ± 4.0	63.0 ± 4.1
2	33.3 ± 3.0	57.6 ± 3.1	66.5 ± 2.5	66.9 ± 3.7
4	31.9 ± 4.7	49.3 ± 1.7	63.0 ± 0.9	67.2 ± 2.3
7	26.7 ± 8.1	44.1 ± 5.7	62.2 ± 5.2	66.6 ± 3.1
14	26.0 ± 8.2	31.9 ± 5.6	46.9 ± 9.4	63.5 ± 2.9
21	26.4 ± 2.1	31.3 ± 13.8	40.8 ± 16.2	55.5 ± 13.5
28	24.7 ± 6.8	31.5 ± 6.3	42.3 ± 10.0	57.2 ± 0.5
56	27.4 ± 6.8	24.5 ± 2.4	25.2 ± 4.8	42.8 ± 8.8

Statistics describe temperatures during three trials commencing on October 16, 2001; April 19, 2001; and July 18, 2002, respectively ($n = 3$).

At the 30 and 100 cm depths the olive fruit soon appeared to be softened from the heat, while at the surface the fruit were quickly covered with fungi. By the time the GWSS egg masses had lost their color, they began to have a dried out appearance.

No pests in any trial lasted more than 14 d, and in no trial did pests survive more than 4 d at 30 cm (Table 2)

Table 2
Mean survival of pests at different depths over time

Time (d)	Depth (cm)	Trial 1		Trial 2		Trial 3	
		GWSS	OFF	GWSS	OFF	GWSS	OFF
0.5	0	0.6	1	0.8	1	0.4	0.8
	15	0.6	0.4	0.2	0.8	0.2	0.6
	30	0.8	0.2	0.2	0.6	0	0
	100	0.6	0	0	0	0	0
1	0	0.6	0.6	0.6	0.6	0.6	0.6
	15	0.6	0	0.2	0.6	0	0.2
	30	0.6	0	0.2	0.2	0	0
	100	0.8	0	0	0	0	0
2	0	0.4	0.2	0.2	0.4	0.2	0.6
	15	0.2	0	0.2	0.6	0	0
	30	0	0	0.4	0	0	0
	100	0	0	0	0	0	0
4	0	0	0	0.2	0.2	0.2	0.2
	15	0	0	0.2	0	0	0
	30	0	0	0	0	0	0
	100	0	0	0	0	0	0
7	0	0	0	0	0	0	0.2
	15	0	0	0	0	0	0
	30	0	0	0	0	0	0
	100	0	0	0	0	0	0
14	0	0	0	0	0	0	0
	15	0	0	0	0	0	0
	30	0	0	0	0	0	0
	100	0	0	0	0	0	0

Survival value is mean of any surviving pests from five piles at different sampling dates. A bag that had any surviving pests received a score of "1", no surviving pests received a score of "0".

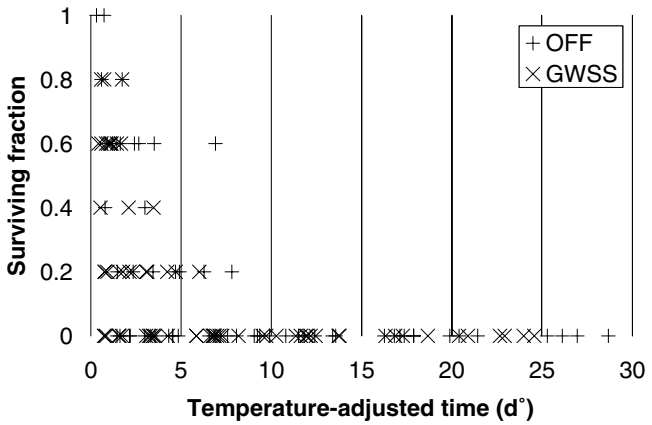

Fig. 1. Fraction of the initial five replicates surviving in temperature-adjusted time (TAT) for all trials and depths.

or longer than 2 d at 100 cm. No survival was found after 14 d in any of the piles or trials. Distribution (15) parameters for OFF were $n = 1$, $\theta = 0.775$, $r = 5$, $Q_{10} = 1.502$ ($T_r = 298.15$ K), and $k = 0.733\ \mathrm{d}^{-1}$. For GWSS they were $n = 5$, $\theta = 1.875$, $r = 5$, $Q_{10} = 1.158$ ($T_r = 298.15$ K), and $k = 1.942\ \mathrm{d}^{-1}$. Fig. 1 illustrates survival in TAT for all trials and depths. Recall that n and θ were estimated from analyses of infected plant parts prior to the experiments, that r was determined from the number of bag replicates associated with each sampling event, and that k and Q_{10} were maximum log-likelihood estimates. Neither parameterization of (15) was rejected by the Kolmogorov–Smirnov goodness-of-fit test ($\alpha \geqslant 0.05$).

4. Discussion

The techniques are particularly useful for estimating pest survival potential where temperatures vary. From (18) and (19), the mean and variance of the surviving OFF in the inserted bags as a function of TAT are $3.55\mathrm{e}^{-0.733t^\circ}$ and $3.55\mathrm{e}^{-0.733t^\circ}$–$2\mathrm{e}^{-1.47t^\circ}$, respectively ($Q_{10} = 1.551$). Corresponding statistics for the surviving GWSS in the inserted bags are $13.75\mathrm{e}^{-1.94t^\circ}$ and $13.75\mathrm{e}^{-1.94t^\circ}$–$10\mathrm{e}^{-3.88t^\circ}$ where ($Q_{10} = 1.158$). These statistics represent survival on two infected leaves or olive fruit. They can also be expressed in terms of any number, x, of infected parts.

$$E(Y_{\mathrm{OFF}}) = x1.78\mathrm{e}^{-0.733t^\circ}, \tag{20}$$

$$Var(Y_{\mathrm{OFF}}) = x1.78\mathrm{e}^{-0.733t^\circ} - x\mathrm{e}^{-1.47t^\circ}; \quad Q_{10} = 1.551, \tag{21}$$

$$E(Y_{\mathrm{GWSS}}) = x6.88\mathrm{e}^{-1.94t^\circ}, \tag{22}$$

and

$$Var(Y_{\mathrm{GWSS}}) = x6.88\mathrm{e}^{-1.94t^\circ} - 5x\mathrm{e}^{-3.88t^\circ}; \quad Q_{10} = 1.158. \tag{23}$$

These equations could be used to estimate the overall survival of pests in a pile by dividing a pile into approximately isothermal zones, estimating the number of infected leaves or olives fruits within each zone, and applying (20) and (22) to each.

It is also possible to estimate the TAT required to eliminate a pest to a pre-determined confidence level. If w is the desired confidence level such that $w = \Pr(Y = 0|t^\circ)$, from (1), (7) and (11),

$$w = (1 - \mathrm{e}^{-kt^\circ})^{xn}\mathrm{e}^{-x\theta\mathrm{e}^{-kt^\circ}}. \tag{24}$$

To find the TAT, t_w°, required to eliminate all pests with probability w, the following equation can be solved efficiently through iteration:

$$t_w^\circ = -\frac{1}{k}\ln\left(1 - w^{\frac{1}{xn}}\mathrm{e}^{\frac{\theta}{n}\mathrm{e}^{-kt^\circ}}\right). \tag{25}$$

For OFF, to have probability, $w = 0.95$ that no pests survive within 1000 initial infected olives, a TAT period of at least 14.3 d° must elapse. To reach a $w = 0.99$ confidence level, 16.5 d° must pass. Corresponding values for GWSS are 6.1 and 7.0 d°. Note that the TAT values for these two organisms are not comparable since their Q_{10} values differ. Exposure times at the 30 and 100 cm depths were effectively the same. Based on the mean pile temperatures recorded during this experiment, complete elimination at the $w = 0.95$ probability level would take 12.3 d (not TAT) at the surface, 5.1 d at 15 cm, and 3.2 d at both 30 and 100 cm. At the $w = 0.99$ probability level exposure times would require 14.3, 6.1, and 4.8 d, respectively. For GWSS and $w = 0.95$, corresponding values are 5.7, 4.2, and 3.6 d. If $w = 0.99$, 6.5, 4.8, and 4.1 d would be required.

Like any model, this one includes a number of simplifying assumptions, particularly with respect to survival processes. These include the assumption that, because adult OFF and GWSS nymphs are expected to perish within the compost heap, heat-accelerated development due and life-cycle transitions can be lumped together with mortality. It seems unlikely that development occurred anywhere except the surface, however, since internal temperatures were elevated above survivable conditions (Table 1). For OFF, mortality rates have been shown to increase above 25 °C (Hong and Rosa, 2003), though significant survival rates for fruit flies have been observed at 35 °C temperatures (Duyck et al., 2004). Development rates for GWSS eggs peak at approximately 32 °C after which mortality rates rapidly increase (Al-Wahaibi and Morse, 2003). Mean ± 1 standard deviation data for the temperatures at the 100, 30, 15, and 0 cm depths were 66.2 ± 6.4, 64.9 ± 4.4, 52.0 ± 7.8, 29.5 ± 5.7 °C, respectively. Because rapid development of both OFF and GWSS can occur at temperatures consistent with surface measurements, it is possible that organisms in some of the surface samples continued with their development, emerging as adults (OFF) or nymphs (GWSS). Only a small percentage of the compost material is located at the surface of even modest compost piles. The pile environment generally is not conducive to pest survival, even if temperatures were not elevated. GWSS nymphs are xylem feeders and would not be able to survive without leaving the pile. To develop within the olive fruit, OFF must contend with bacteria and fungi that attack the fruit throughout the pile, making their emer-

gence unlikely. Because this experiment was initially conceived as a simple check on pest survival, forensic analysis was not included to determine the extent of emergence by the pests. Future experiments should include such an effort, particularly at the surface of the piles.

Another assumption is that temperature is the dominant factor controlling survival and that survival rates follow Arrhenius kinetics. Reality is likely to be more complicated. First, it is possible that pests in the compost piles able to make metabolic adjustments that increase their resistance to heat (Wang et al., 2004; Yin et al., 2006), although the extent of such adjustments is largely unknown and will vary according to species and development stage. By contrast, inactivation in the passive compost piles was likely increased by a number of factors in addition to heat with synergistic effects that would be difficult to quantify separately. Passively managed compost environments are relatively high in ammonia, carbon dioxide, decomposer organisms, and organic acids (Haug, 1993) all of which may increase inactivation rates. These factors are very likely to inactivate pests at rates above those associated with temperature increases alone. Because these additional factors also contribute to inactivation at even modest temperatures, the relative effect of temperature increases on inactivation, while strong, would be expected to be substantially less than in phytosanitation in which heat is the sole factor involved in mortality. This is consistent with the activation energy values reported in the literature. In (12), the Q_{10} parameter substitutes for the activation energy concept, E_A, used by Wang et al. (2002) and others. Values for E_A (kJ mol^{-1}) can be determined directly from Q_{10}, as

$$E_A = RT_r\left(1+\frac{T_r}{10}\right)\ln(Q_{10}), \tag{26}$$

where R is the universal gas constant and $R = 8.314 \times 10^{-3}$ kJ mol^{-1} K^{-1}. Corresponding E_A for the OFF and GWSS in this study are 30.1 and 10.8 kJ mol^{-1}, respectively. These values are substantially less than those reported in carefully controlled studies conducted at higher temperatures (on the order of 44–52 °C) to determine the exposure times needed to sanitize quarantined plant commodities. Values reported by Gazit et al. (2004), Johnson et al. (2004), Hallman et al. (2005) and Wang et al. (2002) range from approximately 200 to 1000 kJ mol^{-1}, generally falling toward the middle of this range.

The approach taken here uses first-order kinetics to model survival. Recent high temperature phytosanitation work has also shown that half-order process models can correlate with some data sets more closely than first-order models (Gazit et al., 2004; Johnson et al., 2004; Hallman et al., 2005; Wang et al., 2002). Unfortunately, use of half-order kinetics does not allow for varying temperature conditions, and leads to inherently contradictory time series even when temperatures are constant. Consider first-order survival as described by, Eq. (8), $p_t = e^{-kt}$, where p_t is the fraction of initial pests remaining at time, t (d), and k (d^{-1}) is the survival rate. The corresponding half-order function is $p_t = (1 - kt)^2$. For first-order processes, two time periods, t_1 and t_2, can be added without losing information, $e^{-kt_1}e^{-kt_2} = e^{-k(t_1+t_2)}$. This is not true of half-order kinetics, for which, $(1 - kt_1)^2(1 - kt_2)^2 \neq [1 - k(t_1 + t_2)]^2$. First-order kinetics are therefore preferred for dynamic environments, such as occur in compost. A mechanistic explanation as to why half-order kinetics best describe a variety of highly controlled survival experiments would be a significant contribution to our understanding of the process.

5. Conclusions

Neither OFF nor GWSS appeared to survive the compost piles, despite the fact that the piles were not actively managed. No pests survived beyond 7 d at any depth. Although it is possible some pests located at the surface may have migrated out of the bags, their survival on the compost is unlikely. This was a worst case scenario for pest transmission. The piles were unturned and no water or nitrogen was added to accelerate decomposition and consequent heating of the piles. The evaluation of pest survival was based on whether any individual pests survived on retrieval of the bags. These were two different pests, and although they do not represent the full range of pest survival techniques, they have different life stages and pose a year long potential for being spread by poorly composted yard waste. In these circumstances, it would appear that just leaving a pile for two weeks prior to spreading the material on a farm should be sufficient for killing these pests. If the piles were more actively managed, however, destruction would be more rapid and complete. Exposure periods required to eliminate pests at 30 and 100 cm depths were similar. The Arrhenius approach taken here offers a conservative estimate as to the effectiveness of compost systems in eliminating OFF and GWSS. The first-order approach accommodates the fluctuations in temperature as would be expected in a static or turned pile. Neither GWSS nor OFF pose a threat from these piles unless the pests are able to migrate from the surface of the pile to an environment in which they can develop. Although this is unlikely, a 14 d stockpile of the chipped material in pile prior to transport to the application site should be adequate to control these pests. The probabilistic approach developed here is a useful screening model for survival in compost heaps or similar environments. Although it requires several steps and an elementary understanding of probability theory, the procedures can be quickly mastered and are flexible enough to be applied to situations where survival probabilities and heat treatment are considered.

References

Al-Wahaibi, A.K., Morse, J.G., 2003. Homalodisca coagulata (Hemiptera: Cicadellidae) embryonic development at constant temperatures. Florida Entomologist 86, 477–478.

CIWMB, 2001. Comprehensive analysis of the integrated waste management act diversion rate measurement system: final report to the legislature, Publication # 340-01-017. Integrated Waste Management Board Public Affairs Office, Sacramento, 61p.

Conover, W.J., 1999. Practical Nonparametric Statistics, third ed. John Wiley & Sons Inc., New York.

Crohn, D.M., 2006. Optimizing organic fertilizer applications under steady-state conditions. Journal of Environmental Quality 35, 658–669.

Crohn, D.M., Valenzuela-Solano, C., 2003. Modeling temperature effects on decomposition. Journal of Environmental Engineering—ASCE 129, 1149–1156.

Downer, J., Faber, B., Menge, J., 2002. Factors affecting root rot control in mulched avocado orchards. Hort Technology 12, 601–605.

Duyck, P.F., Sterlin, J.F., Quilici, S., 2004. Survival and development of different life stages of Bactrocera zonata (Diptera: Tephritidae) reared at five constant temperatures compared to other fruit fly species. Bulletin of Entomological Research 94, 89–93.

Elorriota, M.A., Suarez-Estrella, F., Lopez, M.J., Vargas-Garcia, MC., Moreno, J., 2003. Survival of phytopathogenic bacteria during waste composting. Agriculture Ecosystems & Environment 96, 141–146.

Faber, B.A. Downer, A.J., Menge, J., 2003. Effects of mulch on avocado and citrus. In: Proceedings of the World Avocado Congress V, October 19–24, 2003, Granda-Málaga, Spain. Junta de Andalucía, Consejería de Agricultura y Pesca, pp. 719–724.

Finney, D.J., 1971. Probit Analysis, third ed. Cambridge University Press, Cambridge.

Gazit, Y., Rossler, Y., Wang, S., Tang, J., Lurie, S., 2004. Thermal death kinetics of egg and third instar Mediterranean fruit fly (Diptera: Tephritidae). Journal of Economic Entomology 97, 1540–1546.

Hallman, G.J., Wang, S.J., Tang, J.M., 2005. Reaction orders for thermal mortality of third instars of Mexican fruit fly (Diptera: Tephritidae). Journal of Economic Entomology 98, 1905–1910.

Haug, R.T., 1993. Practical Handbook of Compost Engineering. Lewis Publishers, Boca Raton, Florida.

Hong, G., Rosa, A., 2003. Simulation of olive fly development using artificial life technique. In: Mohammadian, M., Sarker, R.A., Yao, X. (Eds.), Computational Intelligence in Control. Idea Group Pub., Hershey, Pennsylvania, pp. 183–196.

Johnson, J.A., Valero, K.A., Wang, S., Tang, J., 2004. Thermal death kinetics of red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae). Journal of Economic Entomology 97, 1868–1873.

Johnson, N.L., Kemp, A.W., Kotz, S., 2005. Univariate Discrete Distributions, third ed. John Wiley & Sons Inc., Hoboken, New Jersey.

Noble, R., Roberts, S.J., 2004. Eradication of plant pathogens and nematodes during composting: a review. Plant Pathology 53, 548–568.

Norušis, M.J., 2002. GWSS Base 11.0 Guide to Data Analysis. Prentice Hall, Upper Saddle River, New Jersey.

Termorshuizen, A.J., van Rijn, E., Blok, W.J., 2005. Phytosanitary risk assessment of composts. Compost Science & Utilization 13, 108–115.

Valenzuela-Solano, C., Crohn, D.M., 2006. Is the release of N from decomposing organic mulches determined mainly by their chemical composition? Soil Biology and Biochemistry 38, 377–384.

Wang, S., Tang, J., Johnson, J.A., Hansen, J.D., 2002. Thermal-death kinetics of fifth-instar *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae). Journal of Stored Products Research 38, 427–440.

Wang, S., Yin, X., Tang, J., Hansen, J.D., 2004. Thermal resistance of different life stages of the codling moth (Lepidoptera: Tortricidae). Journal of Stored Products Research 40, 565–574.

Wilson, L.T., Barnett, W.W., 1983. Degree-days: an aid in crop and pest management. California Agriculture 37, 4–7.

Yin, X., Wang, S., Tang, J., Hansen, J.D., 2006. Thermal resistance of fifth-instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) as affected by pretreatment conditioning. Journal of Stored Products Research 42, 75–85.

Yuen, G., Raabe, R.D., 1984. Effects of small-scale aerobic composting on survival of some fungal plant pathogens. Plant Disease 68, 134–136.