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Rainfastness and Residual Activity of Insecticides to Control Japanese Beetle (Coleoptera: Scarabaeidae) in Grapes

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ABSTRACT Field-based bioassays and residue profile analysis were used to determine the relative toxicity, rainfastness, and field degradation over time of five insecticides from five insecticide classes on adult Japanese beetles, Popillia japonica Newman (Coleoptera: Scarabaeidae), in grapes, Vitis labrusca L. Bioassays assessed Japanese beetle condition as alive, knockdown, or immobile when exposed for 24 h or 7-d field-aged residues of phosmet, carbaryl, bifenthrin, thiamethoxam, or indoxacarb after 0, 12.7, or 25.4 mm of rain had been simulated. We found that the two most toxic insecticides to Japanese beetle were phosmet and carbaryl, followed by bifenthrin, thiamethoxam, and then indoxacarb. The efficacy of phosmet decreased because of rainfall, but not because of field aging. The efficacy of carbaryl decreased because of rainfall and field aging. The efficacies of bifenthrin and thiamethoxam were not affected by rainfall but decreased because of field aging. The efficacy of indoxacarb was not affected by rainfall or field aging. This study will help vineyard managers make informed decisions on when reapplications of insecticides are needed with the aim of improving integrated pest management programs.

KEY WORDS rainfastness, residual activity, Japanese beetle, grapes, residue profile

In eastern and central North America, the Japanese beetle, Popillia japonica Newman (Coleoptera: Scarabaeidae), is an invasive pest of ornamentals, turfgrass, fruits, and vegetables. Japanese beetles were first discovered in the United States 1916 in New Jersey and are now a major pest, causing US$450 million in damage to ornamental plants and turf in the eastern United States (Fleming 1972, Potter and Held 2002). The Japanese beetle is univoltine; the adults emerge in midsummer (depending on climate) and feed on plant foliage. During this time, females dig into the ground to lay eggs. The eggs hatch, and the larvae feed on plant roots for the remainder of the summer and then overwinter in the soil. During the spring, the larvae complete their development, and by early summer they emerge as adults. During the periods of adult emergence, late June to September in Michigan, Japanese beetles feed in aggregations on the foliage of their host plants. Japanese beetle adults feed on >300 plant species, including grapes (Vitis spp.) (Fleming 1972, Potter and Held 2002). The phenology and behavior of Japanese beetles make them difficult to control in the crops they favor.

On grape foliage, Japanese beetle feeding damage is evident as clusters of small holes in the leaf tissue. Grape vines are able to withstand some feeding damage, but too much defoliation can decrease and delay fruit set as well as reduce fruit quality (Boucher and Pfeiffer 1989). Defoliation also may decrease the cold hardiness of the buds and canes (Mansfield and Howell 1981). The grape industry is economically important to Michigan, with the value of the 2008 grape crop worth >US$26 million (USDA–NASS 2010). Currently, broad-spectrum insecticides such as organophosphates, carbamates, and pyrethroids are the most commonly used insecticides for Japanese beetle control in Michigan grapes (Agriculture Across Michigan 2009).

The rate and pattern of insecticide degradation in the environment varies for different compounds and is influenced by several key drivers such as temperature, UV light, plant metabolism, and microorganisms (Bertrand and Barceló 1991, Baskaran et al. 1999, Burrows et al. 2002, Sinderhauf and Schwack 2003, de Urzedo et al. 2007). Recent studies in fruit crops have shown that applications of organophosphate insecticides result in primarily surface residues on the fruit and foliage, whereas for neonicotinoid insecticides the portions of residues that penetrate plant tissues provide extended residual activity (Wise et al. 2006). The decline in insecticide active residues due to field aging is a concern to farmers, and the ultimate impact on plant protection varies by the specific pesticide, insect, and crop involved (Wise and Whalon 2009).

Michigan receives an average of 24.5–38.1 millimeters of rainfall during the grape growing season (Michigan Automated Weather Network 2011). This has important implications for the fate of insecticides sprayed. Overestimation of wash-off can cause unwar-
ranted reapplications of insecticides, and underestima-
tion may result in vine damage and crop loss. In-
secticide wash-off also has important environmental
Research to date on the impact of precipitation on
insecticides has primarily targeted older chemistries,
such as organophosphates and carbamates, or is in
the context of cotton and field crops (McDowell et al.
Thus, the information available for grape farmers
about reaplication of insecticides after rainfall comes
from either this limited research or “conventional wis-
dom.”

Many of the newer reduced risk (USEPA 1997)
insecticides have chemical properties different from
the conventional organophosphate, carbamate, and
pyrethroid compounds and have not been studied
under rainfall conditions. Understanding the perfor-

cance characteristics of old and newer insecticides
under rainfall conditions could prevent unnecessary
insecticide reaplication and the associated costs.

The objectives of this study were to 1) determine
the effect of rainfall on the effectiveness against Japa-
nese beetles of five different insecticides represent-
ing five major classes of insecticides, 2) determine the
relative effect of aging in the field for these insecti-
cides, and 3) compare the relative performance of
these insecticides against each other as they age and
receive rainfall.

**Materials and Methods**

**Insects.** Japanese beetle adults were collected from
grow field plots at the Michigan State University Trevor
Nichols Research Center (TNRC) in Fennville, MI
(42.5951° N, –86.1561° W), during July 2008 and Au-

gerst 2009. Beetles were captured using yellow and

green canister traps with a floral lure (Great Lakes

IPM, Vestaburg, MI) during the 24-h period preceding

the collection of beetles from the traps. For each study.
After collection, beetles were held in cages

as bioassay arenas were prepared, five randomly se-

lected Japanese beetle adults were placed in the bot-

tom of each arena and the containers were held in the

laratory at 21° C and a photoperiod of 16:8 (L:D) h.

**Field Plots and Treatment Applications.** In 2008, each field plot consisted of one row of seven mature

*V. labrusca* ‘Concord’ grape vines, with five replicate

plots for each of the five insecticide treatments and

one control (Table 1). We avoided the addition of any

spray adjuvants so as to attain baseline data that rep-

resent the rainfastness characteristics of representa-
tive insecticides alone. A minimum of two buffer rows

separated each treatment row. Insecticide treatments

were applied at labeled rates by using an FMC 1029

airblasting sprayer calibrated to deliver 467.5 liters wa-
ter/ha (50 gal/acre) (Table 1). Insecticide applica-
tions were made on 22 July 2008 and 5 August 2009 at
timings that are representative offspring sprays for

Japanese beetles in Michigan vineyards (Wise et al.
2010b). These plots served as the source of foliage for
use in bioassays and residue analysis. Untreated con-

control (UTC) plots were not sprayed. Daily high and low

temperatures, and precipitation volumes were re-
corded with an automated weather station (Michigan
Automated Weather Network 2011) located within 1
km of the field plots.

**Bioassays.** In 2008 bioassays were used to compare
the toxicity of the five insecticides and to determine the
temporal progression of these effects as the resi-
dues aged in the field and received rainfall. Grape

shoots of four to five leaves were collected from the
field plot 24 h and 7 d after application.

Shoots were then randomly selected for exposure to
different simulated rainfall regimes. Shoots were

placed in water-soaked floral foam bricks (Smithers-

Oasis Co., Kent, OH) that were placed in the rain

booth, a Generation three Research Track Sprayer

(DeVries Manufacturing, Hollandale, MN). Shoots re-

ceived either 0, 12.7, or 25.4 mm of simulated rain.

Three rain gauges were placed around the inside of the

rain booth to accurately assess the amount and uni-

formity of simulated rain treatments. Shoots not as-

signed to receive rainfall were not placed in the rain

booth.

From each shoot the most recent fully expanded

leaf from the distal end was removed and placed in

water-soaked floral foam in a clear polypropylene

950-ml container (Fabri-Kal, Kalamazoo, MI), with a

lid added to complete the bioassay chamber. The foam

was covered with sealing wax (Gulf Wax, distributed

by Royal Oak Sales, Inc., Roswell, GA) to preserve the

integrity of the foliage by reducing evaporation. Holes

were punched in the lid to reduce condensation of

water vapor inside the container and minimize risk of

fumigation effects. Each of these containers was con-

sidered an experimental unit in the bioassays. As soon

as bioassay arenas were prepared, five randomly se-

lected Japanese beetle adults were placed in the bot-

tom of each arena and the containers were held in the

laboratory at 21°C and a photoperiod of 16:8 (L:D) h.

There were five replicates for each treatment at each

post application time interval and rainfall amount


<table>
<thead>
<tr>
<th>Formulated name</th>
<th>Chemical class</th>
<th>AI</th>
<th>Rate/acre</th>
<th>g (AI)/a</th>
<th>ppm</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidan 70 WP</td>
<td>Organophosphate</td>
<td>Phosmet</td>
<td>2 lb</td>
<td>1,569</td>
<td>3,355</td>
<td>Gowan Company Yuma, AZ</td>
</tr>
<tr>
<td>Sevin XLR 4L</td>
<td>Carbamate</td>
<td>Carbaryl</td>
<td>2 qt</td>
<td>4,811</td>
<td>9,586</td>
<td>Bayer CropScience, Pittsburgh, PA</td>
</tr>
<tr>
<td>Capture 2EC</td>
<td>Pyrethroid</td>
<td>Bifenthrin</td>
<td>6.4 fl oz</td>
<td>112</td>
<td>240</td>
<td>FMC Corp., Princeton, NJ</td>
</tr>
<tr>
<td>Actara 25 WG</td>
<td>Neonicotinoid</td>
<td>Thiamethoxam</td>
<td>3.3 oz</td>
<td>61</td>
<td>131</td>
<td>Syngenta Crop Protection, Greensboro, NC</td>
</tr>
<tr>
<td>Avantra 30WG</td>
<td>Oxadiazine</td>
<td>Indoxacarb</td>
<td>6 oz</td>
<td>128</td>
<td>269</td>
<td>DuPont Crop Protection, Wilmington, DE</td>
</tr>
</tbody>
</table>

All preparations were based on 468 liter/ha spray volume (50 gal/acre).
combination. The number of beetles that were alive, immobile, or in a knockdown condition was recorded after 0, 4, 24, and 48 h of exposure. The knockdown condition was defined as beetles that were twitching in a nonupright position at the bottom of the container. Beetles were counted as alive if they seemed to behave normally.

The proportion of the leaf defoliated by Japanese beetles was determined for each leaf used in the bioassay. This was done by using Photoshop Elements, version 8.0 (Adobe Systems, San Jose, CA). Images of the leaves were scanned into a computer using a Canon Image Runner c2880/c3380. Different layers of the image were created for damaged and undamaged areas of leaf tissue using the Magic Wand Tool in Photoshop (Adobe Systems). The numbers of pixels comprising the two layers of the image were determined using the Histogram window in Photoshop, and the proportion of the leaves defoliated was calculated. These data were arcsine square-root transformed before being analyzed by a two-way analysis of variance (ANOVA) in which there were two levels of the field aging factor (24 h and 7d) and three levels in the rainfall simulation factor (0, 12.7, or 25.4 mm).

The mean proportions of beetles in a particular condition were compared across insecticide treatment by an ANOVA on arcsine square-root–transformed values. Mean separation was done using Tukey’s honestly significant difference (HSD) test. These data also were analyzed by logistic regression to determine the time at which half of the organisms were in the immobile condition (LT50) (Robertson et al. 2007). Logistic regressions analyses were performed at every insecticide, rainfall, and aging combination. These analyses were conducted in R, version 2.12.1 (R Development Core Team 2010) using the MASS library (Venables and Ripley 2002), the Intest library (Zeileis and Hothorn 2002), and the doBy library (Højsgaard et al. 2011).

In 2009, a similar spray and rainfall regimen was repeated during the summer, but with a focus on fruit cluster residues. After 24-h aging time in the field, clusters of grapes were collected from field plots of Concord grapes. These clusters were subjected to the same rainfall regimen as the shoots were in 2008. The clusters were pruned to 10 berries and placed in bioassay chambers constructed as they were in 2008. Beetles were evaluated in the same manner as in 2008, and data were analyzed the same as in 2008. A 7-d harvest, rainfall simulation, and bioassay setup were planned for the 2009 experiment, but a natural rainfall event occurred on 10 August 2009, so the 7-d part of the experiment was eliminated.

Insecticide Residue Analysis. In 2008, a parallel series of foliage samples were taken from field plots after 24 h postapplication time and received the same rainfall regimen as the shoots used in the bioassays (0, 12.7, or 25.4 mm). There were three replicates for each treatment at both of the postapplication time intervals.

To determine the amount of residue on the leaf surfaces, 10-g samples of grape leaves were placed in 150 ml of high-performance liquid chromatography (HPLC)-grade acetonitrile (EMD Chemicals, Inc., Gibbstown, NJ) and sonicated for 10–15 s. The acetonitrile was decanted through 5 g of reagent-grade anhydrous sodium sulfate (EMD Chemicals, Inc.) to remove water. The sample was dried via rotary evaporation and brought up in acetonitrile for HPLC analysis. The remaining leaf samples were ground in 50 ml of HPLC-grade dichloromethane (Burkard & Jackson, Muskegon, MI). The extracts were passed through 5 g of anhydrous sodium sulfate. The samples were dried via rotary evaporation and brought up in acetonitrile. Any remaining particulates were removed by passing the sample through a 0.45-μm Acrodisc 13-mm syringe filter (Pall, East Hills, NY).

Samples were analyzed for insecticide residue with a 2690 Separator Module HPLC equipped with a 2487 Dual Wavelength Absorbance Detector (Waters, Milford, MA) set at 270 nm, and a C18 reversed phase column (150 by 4.6 mm bore, 5-μm particle size, Restek, Bellefonte, PA) (Bayer AG 1998). The mobile phase was water/acetonitrile (80:20) at 55°C. The HPLC level of quantification was 0.457 μg/g (ppm) active ingredient, and level of detection was 0.138 ppm.

In 2009, the fruit residues were analyzed using the same methods as in 2008, except that 10 g of grape fruit were used for insecticide analysis.

Results

Inherent Toxicity. In 2008, Japanese beetles exposed to grape leaves with 24-h field-aged insecticide residues exhibited significantly higher numbers in the immobile condition after 48 h than those exposed to untreated grape leaves ($F = 90.55; df = 5, 24; P < 0.001$) (Fig. 1). Japanese beetles exposed to grape leaves with 24-h field-aged insecticide residues exhibited significantly lower numbers of beetles in the alive condition after 48 h than when exposed to untreated grape leaves after 48 h ($F = 33.93; df = 5, 24; P < 0.001$) (Fig. 1). Beetles exposed to grape leaves with 24-h field-aged residues of thiamethoxam, indoxacarb, and bifenthrin exhibited significantly higher numbers in the knockdown condition after 48 h than those exposed to residues of phosmet, carbaryl, and untreated grape leaves ($F = 11.75; df = 5, 24; P < 0.001$) (Fig. 1). In 2009, Japanese beetles exposed to grape berries with carbaryl and bifenthrin 24-h field-aged residues exhibited significantly higher numbers in the immobile condition after 48 h than those exposed to untreated grape clusters ($F = 6.09; df = 5, 24; P < 0.001$) (Fig. 2). Japanese beetles exposed to grape berries with thiamethoxam 24-h field-aged residues exhibited significantly higher numbers in the knockdown condition than those exposed to untreated grape fruit ($F = 3.53; df = 5, 24; P = 0.016$) (Fig. 2). Japanese beetles exposed to grape fruit with phosmet, carbaryl, bifenthrin, or thiamethoxam 24-h field-aged residues exhibited significantly lower numbers of beetles displaying the alive condition than those exposed to untreated grape fruit ($F = 17.73; df = 5, 24; P < 0.001$) (Fig. 2).
Effect of Rainfall and Field Aging. Using the 2008 data, the time at which half of the Japanese beetles were killed (LT$_{50}$) by insecticides was calculated as a measure of toxicity for each insecticide on grape leaves at different rainfall and aging combinations. The LT$_{50}$ values for phosmet were higher on leaves receiving rainfall, but no increase in LT$_{50}$ values was seen after 7-d field aging of leaves treated with phosmet (Table 2). The LT$_{50}$ values for carbaryl increased as rainfall increased but did not increase with field aging time (Table 2). The LT$_{50}$ values for bifenthrin on grape leaves did not increase with rainfall, but they did increase after 7-d field aging (Table 2). The LT$_{50}$ values for thiamethoxam did not increase on leaves after rainfall occurred and did not increase after the residues had been aged for 7 d in the field (Table 2). The LT$_{50}$ values for indoxacarb did not increase on leaves after rainfall occurred and did not increase after the residues had been aged for 7 d in the field (Table 2).

Rainfall amount and field aging time affected defoliation by depending on which insecticide was sprayed. Defoliation of leaves sprayed with phosmet was significantly affected by rainfall on the leaves ($F = 8.45; df = 1, 26; P = 0.007$) but not aging ($F = 1.58; df =$

Fig. 1. Mean proportion of beetles observed in different conditions after 48 h of exposure to grape foliage with 24-h field-aged residues from 2008. Letters above the bars within a row show significant differences among insecticides within each condition, and bars with the same letter are not significantly different ($P < 0.05$). Data were arcsine square-root transformed before ANOVA. Mean separation calculated using the Tukey’s HSD test. Data shown are nontransformed means.

Fig. 2. Mean proportion of beetles observed in different conditions after 48 h of exposure to grape fruit with 24-h field-aged residues from 2009. Letters above the bars within a row show significant differences among insecticides within each condition, and bars with the same letter are not significantly different ($P < 0.05$). Data were arcsine square-root transformed before ANOVA. Mean separation calculated using the Tukey’s HSD test. Data shown are nontransformed means.
In 2009, the residue analysis of grape fruit treated with insecticides showed evidence of wash off because of rain for some compounds and differences between patterns of wash-off between surface and subsurface residues. Phosmet readily washed off the surface of the fruit, but subsurface residues were less affected (Table 5). Carbaryl, bifenthrin, and thiamethoxam residues remained relatively stable under rainfall conditions, but declining subsurface values suggest cuticle partitioning as surface residues are exposed to water. For indoxacarb, the limited surface residues were susceptible to washed off, but subsurface residues were stable under rainfall conditions.

**Discussion**

This study provides new insights into the rainfastness of grape insecticides as well as the influence of inherent toxicity and field residual on the overall performance of a compound after precipitation. We found that the two most toxic insecticides to Japanese beetle were phosmet and carbaryl, followed by bifenthrin, thiamethoxam, and then indoxacarb. For the more toxic compounds, especially phosmet and bifenthrin, their inherent toxicity in effect masks their weakness in terms of wash-off susceptibility. This was most evident when comparing the high proportion of residue loss at 12.7 mm of simulated rainfall, but the minimal impact on performance in terms of Japanese residue loss at 12.7 mm of simulated rain, whereas thiamethoxam residues remained stable.

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beetle survival in the 24-h field-aged bioassays. Differing patterns were also found between insecticide toxicity on grape leaves versus fruit. A compound’s field residual also influences the observed performance under rainfall conditions. As with inherent toxicity, the negative effects of residue wash-off for phosmet is minimized by its relatively high environmental persistence. Conversely for carbaryl and bifenthrin, the negative effects of residue wash-off are compounded by their weaker residual activity. Even though thiamethoxam and indoxacarb were the weakest in terms of inherent toxicity, based on both residue and bioassay results, they were shown to be the most resistant to wash-off from precipitation.

Fig. 3. Mean ± SE proportion of grape leaves defoliated alive after 48 h of beetle exposure to leaves treated with insecticides. Insecticide treated leaves were aged in the field for 24 h or 7 d before bioassay setup. A significant effect of rainfall is represented with an asterisk (*). A significant effect of field aging is represented with a diamond (○). Data were arcsine square-root transformed before two-way ANOVA (α = 0.05). Nontransformed means are shown.

Table 3. LT50 values for insecticides sprayed on grape berries after 0, 12.7, or 24.5 mm of rainfall, for Japanese beetle adults from the 2009 experiment

<table>
<thead>
<tr>
<th>Insecticide</th>
<th>Rainfall (mm)</th>
<th>n</th>
<th>Slope (+SE)</th>
<th>LT50 (h)</th>
<th>95% CI</th>
<th>χ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosmet</td>
<td>0</td>
<td>20</td>
<td>0.06 (+0.06)</td>
<td>49.80 (36.59, 63.01)</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>20</td>
<td>-0.06 (+0.02)</td>
<td>55.84 (40.39, 71.29)</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.4</td>
<td>20</td>
<td>-0.02 (+0.016)</td>
<td>153.41 (−90.31, 397.13)</td>
<td>0.2948</td>
<td></td>
</tr>
<tr>
<td>Carbaryl</td>
<td>0</td>
<td>20</td>
<td>-0.07 (+0.01)</td>
<td>23.40 (16.50, 30.30)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>20</td>
<td>-0.03 (+0.01)</td>
<td>57.53 (25.71, 89.35)</td>
<td>0.0161</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.4</td>
<td>20</td>
<td>-0.07 (+0.01)</td>
<td>33.63 (25.46, 41.81)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Bifenthrin</td>
<td>0</td>
<td>20</td>
<td>-0.06 (+0.01)</td>
<td>34.71 (25.57, 43.86)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>20</td>
<td>-0.06 (+0.01)</td>
<td>19.05 (11.14, 26.95)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.4</td>
<td>20</td>
<td>-0.02 (+0.01)</td>
<td>103.08 (−1.23, 207.39)</td>
<td>0.1300</td>
<td></td>
</tr>
<tr>
<td>Thiamethoxam</td>
<td>0</td>
<td>20</td>
<td>-0.05 (+0.04)</td>
<td>109.62 (−20.79, 240.02)</td>
<td>0.2536</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>20</td>
<td>-0.06 (+0.01)</td>
<td>44.09 (32.44, 55.74)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.4</td>
<td>20</td>
<td>-0.02 (+0.02)</td>
<td>177.63 (−186.99, 542.24)</td>
<td>0.4077</td>
<td></td>
</tr>
<tr>
<td>Indoxacarb</td>
<td>0</td>
<td>20</td>
<td>-0.03 (+0.02)</td>
<td>58.07 (21.51, 154.64)</td>
<td>0.0599</td>
<td></td>
</tr>
</tbody>
</table>
The contact toxicity of thiamethoxam on beetles is known to be short lived, but as residues move into plant tissue antifeedant effects become more prominent (Hoffmann et al. 2010). The antifeedant effects of thiamethoxam on Japanese beetle protect grape leaves from defoliation (Fig. 3E), but as measured in this study would not be credited as direct toxicity. One possible reason indoxacarb was shown to be the least toxic to Japanese beetles in this experiment is that ingestion is an important mode of entry for the bio-activation of formulated DPX-JW062 to its decarboxylated metabolite (Wing et al. 1998, Tillman et al. 2002). If the time duration used in our bioassays was longer, higher levels of mortality may have been observed.

Insecticides were less toxic to Japanese beetles when applied to grape fruit than to grape leaves, and the toxicity of the insecticides on grape fruit was not affected by rainfall. There are a couple of reasons why this may have occurred. In the bioassay experiments, Japanese beetles consumed more leaf material than fruit material. It is expected that ingestion of the insecticides causes higher toxicity than physical contact. Indoxacarb, for example, must be ingested for the insecticide to become activated (Wing et al. 1998, Tillman et al. 2002). The decreased exposure to insecticide residues from ingestion of fruit would mask the effects of rainfall on toxicity to Japanese beetles. There are probably cuticular and wax composition differences between the grape leaves and fruit that also could account for differences in an insecticide’s performance.

One physical property of insecticides which affects its behavior in the environment, including rainfastness, is the octanol-water partition coefficient, $K_{ow}$, defined as the ratio of a chemical’s concentration in an octanol solution ($[C_i]_{octanol}$) over its concentration in aqueous solution ($[C_i]_{water}$) (Leo et al. 1971):

$$K_{ow} = \frac{[C_i]_{octanol}}{[C_i]_{water}}$$

$K_{ow}$ varies from $10^{-3}$ to $10^2$ and is usually expressed as log($K_{ow}$) = $P_{ow}$. Chemicals with lower $P_{ow}$ are polar and have high solubility in water. Chemicals with higher $P_{ow}$ are nonpolar and have low water solubility (Ragnarsdottir 2000). Phosmet has a $P_{ow}$ of 2.83 (Chiu et al. 1977), an indication that phosmet has a lower water solubility and is more lipophilic. This would allow phosmet molecules to bind to the waxy cuticle, but have very limited penetrative capacity further into plant tissues. Although resistant to aging, phosmet was susceptible to wash-off. Carbaryl has a log($P_{ow}$) of 2.34 (Noble 1993), indicating some resistance to wash-off by rainfall. The residue data in our study showed carbaryl to be relatively rainfast at 12.7 mm of rain, but at 25.4 mm dramatic loss of residues was observed. It is well documented that carbaryl degrades in aqueous environments when exposed to sun and sun-like light (Zepp and Cline 1977, Wolfe et al. 1978, Bertrand and Barceló 1991). In addition, carbaryl has been found to become more unstable at higher temperatures (Lartiges and Garrigues 1995) and have its shortest half-life, $t_{1/2}$, during June and July compared with the rest of the year (Wolfe et al. 1978). The $P_{ow}$ of bifenthrin is $<6$ (Baskaran et al. 1999), indicating that bifenthrin is highly lipophilic. It is likely the lipophilic tendency of bifenthrin that made it highly rainfast in this study. Although pyrethroids are considered to be more stable than pyrethrins, this study demonstrated a dramatic loss of efficacy for bifenthrin after 7 d of field aging. Thiamethoxam has a $P_{ow}$ of $<0.13$ and is a systemic insecticide. It is known that thiamethoxam degrades readily when exposed to UV light (de Urzedo et al. 2007); thus, the systemic nature of thiamethoxam is probably the reason for its rainfastness. The systemic property of this insecticide is noticeable by its relatively low toxicity to Japanese beetles (Table 2) but its relatively high level of protection of the foliage (Fig. 3). Thiamethoxam is also known to be converted to clothianidin in plants (Nauen et al. 2003), which may provide extended protection to plants sprayed with thiamethoxam in the field. Indoxacarb has a $P_{ow}$ of 4.6, indicating that indoxacarb is highly lipophilic. Indoxacarb’s rainfastness is probably a result of penetration.

<table>
<thead>
<tr>
<th>Insecticide</th>
<th>0 mm</th>
<th>12.7 mm</th>
<th>25.4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosmet</td>
<td>220.7</td>
<td>146</td>
<td>157.6</td>
</tr>
<tr>
<td>Carbaryl</td>
<td>40.9</td>
<td>39.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Bifenthrin</td>
<td>558.9</td>
<td>249.5</td>
<td>130.4</td>
</tr>
<tr>
<td>Thiamethoxam</td>
<td>2.9</td>
<td>2.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Indoxacarb</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Residue values are presented as in micrograms per gram (ppm) of active ingredient per 10 g of leaves.

<table>
<thead>
<tr>
<th>Insecticide</th>
<th>Simulated rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
</tr>
<tr>
<td>Phosmet</td>
<td>0.08</td>
</tr>
<tr>
<td>Carbaryl</td>
<td>0.05</td>
</tr>
<tr>
<td>Bifenthrin</td>
<td>0.24</td>
</tr>
<tr>
<td>Thiamethoxam</td>
<td>0.02</td>
</tr>
<tr>
<td>Indoxacarb</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Residue values are presented in micrograms per gram (pppm) of active ingredient per 10 g of fruit.
into the plant cuticle by means of the lipophilic pathway, compared with the polar pathway preferentially used by systemic insecticides such as the neonicotinoids (Buchholz 2006, Schönherr 2006).

As a result of this research we emphasize that vineyard managers should consider the compound’s rainfastness characteristics as well as the relative toxicity and field residual of the insecticide as a part of their integrated pest management (IPM) decision-making process. The decision of whether or not to reapply an insecticide after a rainfall event will depend on these parameters as well as the nature of the target insect, whether it is a direct or indirect pest, and the quality standards of the market for which the crop will be sold. We have developed a “rainfastness decision chart” as a practical research-based guide for grape growers to use in their IPM program, with the purpose of reducing unnecessary pesticide sprays, and to enhance the sustainability of domestic fruit production (Wise et al. 2010a).

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