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# The Effectiveness of Riparian Hedgerows at Intercepting Drift from Aerial Pesticide Application

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## Abstract

The primary tool used currently for preventing pesticide drift from entering streams is a no-spray buffer zone. Riparian hedgerows may provide an additional option; however, quantitative information on their effectiveness is limited. To quantify the potential benefit of riparian hedgerows for drift reduction, aerial malathion {diethyl 2-[(dimethoxyphosphorothioyl) sulfanyl]butanedioate} applications on blueberry (*Vaccinium corymbosum* L.) farms with fields adjacent to streams or ditches were monitored. Drift from fields with extensive dense woody riparian vegetation was compared with drift from fields with no dense woody riparian vegetation. Overall, total instream malathion deposition was 96.1% lower at vegetated sites compared with nonvegetated sites. Univariable models identified six variables that were significantly related to decreasing instream total malathion deposition: increasing bank canopy cover, increasing average site canopy cover, increasing canopy angle, increasing the distance between the field edge and vegetation edge, increasing the distance between the field edge and center of stream, and decreasing bank slope. For the variables most feasible for landowners to alter, the following increases could result, on average, in a 26% decrease in the total instream malathion deposition: bank canopy cover (7%), distance between field and vegetation (0.3 m), and distance between field and center of stream (0.9 m). No-spray buffer sizes needed for significant deposition reductions may be large, but for nonvegetated or minimally vegetated streams similar to those studied here, increasing bank canopy cover may give comparable advantages while allowing the use of the entire field area and conferring additional ecosystem benefits such as shading streams and improving habitat.

## Core Ideas

- Instream pesticide deposition was significantly higher at nonvegetated sites.
- Riparian vegetation can be used as a tool to mitigate pesticide loading to streams.
- Increasing riparian canopy cover and angle may reduce pesticide drift into streams.
- Future studies on drift reduction should reduce collinearity of variables.

Spotted wing *Drosophila* (*Drosophila suzukii* Matsumura) has been observed in the Pacific Northwest since about 2009 (Beers et al., 2010) and is now established in northwest Washington, representing a new and significant pest challenge for Washington blueberry (*Vaccinium corymbosum* L.) and red raspberry (*Rubus idaeus* L.) growers (Beers et al., 2010). Growers in the region have been making regular applications of insecticides, including malathion products, by ground airblast sprayer or aerially by helicopter to control this introduced pest. Although the use of coarse droplet sizes reduces the amount of deposition moving offsite (Segawa et al., 1991), monitoring conducted by the California Department of Food and Agriculture in the 1990s confirmed through runoff sampling that after aerial applications, malathion was detected outside of the treatment area (Segawa et al., 1991; Turner et al., 1991; Bradley et al., 1997).

Both ground and aerial pesticide applications result in some migration of the active ingredient away from the target (Maybank et al., 1978), although aerial applications have been found to result in more drift than ground applications (Maccollom et al., 1986). In general, pesticide applications during unsuitable meteorological conditions or with inappropriate application methods can result in spray drift (Yarpuz-Bozdogan, 2016). Pesticides can drift from agricultural areas to nearby water bodies (Wolf et al., 2005; Thistle et al., 2009), resulting in damage or injury to humans, plants, animals, the environment, or property (Maybank et al., 1978; Craig et al., 1998), contaminated air, soil, and water (Antuniassi et al., 2014), and impairment to aquatic ecosystems.

Detailed information on how to quantify pesticide drift resulting from aerial applications is relatively limited (Antuniassi et al., 2014). Fritz (2006) found that wind speed was the primary factor affecting transport of aerially applied products. Maybank et al. (1978) advises spraying under little or no wind, especially when near plants, animals, or crops that could be harmed. Other drift mitigation tools include mandatory no-spray buffer zones, low-drift sprays, and riparian vegetation (Wolf et al., 2005).

Baudry et al. (2000) state that a hedgerow can be either planted or naturally occurring vegetation that is managed to control size or for other purposes. The function of hedgerows varies,



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**Abbreviations**: eBLUE, estimated best linear unbiased estimate; eBLUP, estimated best linear unbiased predictor; F, edge of the field; $LC_{50}$, lethal concentration; PAL, Pacific Agricultural Laboratory; V, outer edge of the riparian vegetation; W, center of the stream.

from delineating boundaries, retaining livestock, preventing erosion due to wind or water, providing useful or salable products, forming snow- and windbreaks, and providing wildlife habitat or corridors (Baudry et al., 2000). For clarity, dense woody riparian vegetation, whether naturally occurring or intentionally planted, will be referred to here as riparian hedgerows.

Effective pesticide drift reduction tools such as riparian hedgerows have the potential to reduce the impact of pesticides on aquatic ecosystems. In recent years, several studies have addressed the relationship between hedgerows and drift interception (Ucar and Hall, 2001; Lazzaro et al., 2008; Thistle et al., 2009; Kjær et al., 2014). A vegetative barrier as small as a single row of trees can greatly reduce spray drift, even more so when used in combination with drift-reducing nozzles or adjuvants (Ucar and Hall, 2001). Lazzaro et al. (2008) found that off-target spray reduction without a hedgerow ranged from 50.5 to 60.5%, whereas off-target spray reduction at sites with at least one hedgerow ranged from 82.6 to 97%. Results from Thistle et al. (2009) also provide evidence that riparian hedgerows reduce pesticide drift deposition into streams by an average of 92%. Characteristics such as height, width, and optical porosity of hedgerows influence the drift reduction achieved (Lazzaro et al., 2008; Ohliger and Schulz, 2010; Kjær et al., 2014). Peterson (2008) studied the influence of trees planted in single or multiple rows on drift and found that the drift cloud split into two portions, one flowing over the vegetation and one passing through. A literature review by Hewitt (2001) concluded that drift can be reduced by 45 to 90% by using natural or artificial barriers.

This study investigated the effects of riparian hedgerows on aerial malathion drift to streams. A secondary goal was to determine which vegetative characteristics have the greatest influence on drift reduction. It was predicted that the presence of dense woody riparian vegetation would reduce instream malathion deposition from aerial applications. Vegetation characteristics and site characteristics were documented to allow the identification of the most important characteristics that reduced malathion drift. To the knowledge of the authors, there has been no research on malathion drift mitigation by riparian hedgerows.

# Materials and Methods

## Malathion Applications

Malathion applications were monitored at five sites, two nonvegetated sites (Nonveg1 and Nonveg2) that lacked dense woody riparian vegetation and three vegetated sites (Veg1, Veg2, and Veg3) with dense woody riparian vegetation. All five sites were in Whatcom County, located within the Nooksack River basin in northwestern Washington State. A total of eight aerial malathion application events on blueberry fields were monitored, four at nonvegetated sites and four at vegetated sites. Application time and duration were recorded but were not significant in the analysis. All application events took place in summer 2015.

The product used was Gowan Malathion 8 Flowable (Gowan Company), which was applied to all fields used for this study. The tank mix application rate was 94 L ha$^{-1}$ (10 gal acre$^{-1}$) for every site. The malathion application rate was either 1.2 or 1.5 L ha$^{-1}$ (16 or 20 oz acre$^{-1}$). Several different additives were used, either Sb-56 (Genesis Agri-Products), Epoleon (Epoleon Corporation), Grip (J.R. Simplot Company), or Interlock (WinField Solutions). Additive concentration in the tank mix was either 0.1 or 0.2 L ha$^{-1}$ (4 or 8 oz 100 gal$^{-1}$). Based on nozzles, nozzle settings, and flow rate, the droplet size distribution met the American Society of Agricultural and Biological Engineers (ASABE) Standard S572.1 droplet size classification of coarse/very coarse. Applications were conducted using an N3829 Hiller UH-12E helicopter with a rotor diameter of 10.8 m, equipped with 29 CPO3 nozzles and a boom length of 8.1 m. Helicopter flight path data were reviewed and there were no consistent trends between flight direction and sampler placement.

## Site Layout and Depositional Sampling

At each site, the total field length was measured and divided by seven to determine the spacing between each of six transects (Fig. 1). The furthest downstream and upstream transects were Transects 1 and 6, respectively. Deposition was sampled in the center of the stream (W), at the outer edge of the riparian vegetation (V), and at the edge of the field (F). When blueberries were present on both sides of the stream, which occurred at Veg3 and Nonveg1, depositional samplers were placed at the V and F locations on both sides. Distances between W and V (center of the stream and vegetation edge) and V and F (vegetation edge and edge of field) along each transect were measured. For nonvegetated sites, samplers at the V location were placed at the mowed edge of the field closest to the stream. Depositional sampler stands at F were placed at the average crop height, which ranged from 1.3 to 1.7 m at different sites. Depositional samplers at the V and W locations were placed at a height of 0.5 m above the ground and water surface, respectively.

Depositional sampling methods were adapted from methods described in Bargar (2012). Depositional sampler stands were constructed in two parts: a removable horizontal platform and a T-post or a section of 1.27-cm-diam. rebar. A T-post or rebar section was installed at each location on each transect (W, V, and F). The removable section consisted of a 30.48-cm square plywood platform with an extruded polystyrene rigid foam block fastened on top, attached to a polyvinyl chloride (PVC) pipe large enough in diameter to slide over the T-post or piece of rebar. Prior to malathion applications, removable components were cleaned with methanol, wrapped in aluminum foil, and placed on preinstalled T-posts or rebar at each sampling position. No more than 1 h prior to application, one piece of filter paper (270-mm diam., Grade 4 qualitative cellulose filter paper, circular, Whatman) was placed on each stand and secured to the foam using T-pins.

## Sample Collection and Analysis

Samples were collected 1 h after the malathion applications; filter paper was folded, placed into prelabeled amber glass jars, and sealed with a polytetrafluoroethylene (PTFE)-lined lid. Samples were immediately placed in a cooler and kept below 4°C. Samples were shipped to the Pacific Agricultural Laboratory (PAL) in Portland, OR, for analysis. Sample extraction and analysis were completed by PAL following USEPA Method 3572 (USEPA, 2014). Nearly all depositional samples were extracted within the method-specified 14-d hold time; 30 samples were extracted 16 d after collection. In addition, samples from five of eight events exceeded temperature storage requirements by between 6 and 7°C, arriving at PAL with temperatures of 10 to 11°C. After consulting with laboratory staff about temperature

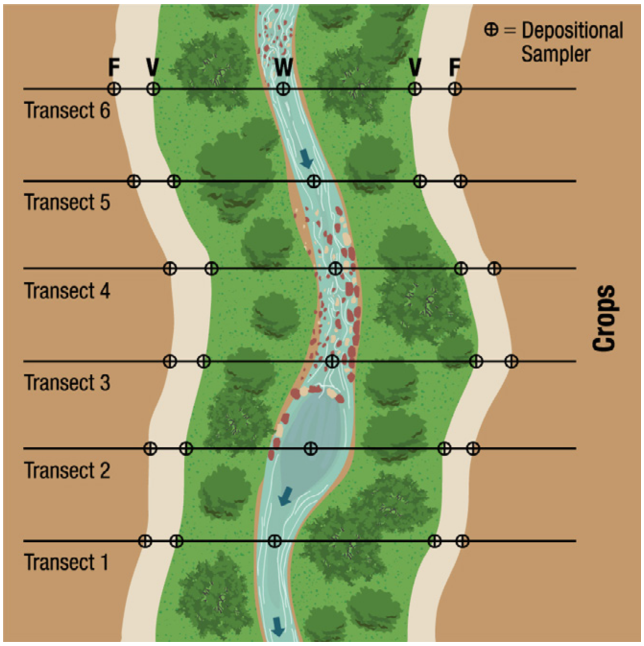



**Fig. 1. Layout of transects and depositional samplers at a two-sided vegetated site. F, edge of the field; V, outer edge of the riparian vegetation; W, center of the stream.**

storage requirements and hold times, the decision was made to include all of the samples in the analysis.

Both malathion and malaoxon recoveries were reported by PAL for each filter paper. Malathion and malaoxon recoveries for each filter paper were combined to account for malathion degradation into malaoxon between application time and sample collection. Malathion and malaoxon were combined based on reaction stoichiometery, with one molecule of malathion degrading into one molecule of malaoxon. Combined concentrations were rounded to two significant digits to be consistent with laboratory reporting and are referred to as total malathion.

## Stream Characteristics and Vegetation Assessment

At each transect, wetted width, bankfull width, and thalweg depth were measured. Vegetation plots were established extending 5 m upstream, 5 m downstream, and encompassing the width of the streamside vegetation at each transect. Vegetation width was measured as the distance between the bankfull edge of the stream and the outer edge of the vegetation, facing the field. Convex densiometers (Model A, Forestry Suppliers) were used to assess instream canopy cover measured from the stream center at each transect and again in the center of the streamside vegetation (halfway between bankfull edge and outer edge of vegetation facing the field) in the four cardinal directions following the methods of Mulvey et al. (1992). In addition to instream and bank canopy densiometer readings, an average was calculated between the two (average site canopy cover) for comparison with deposition and use as an alternative to the individual stream and bank canopy measurements. Instream canopy angle was also measured from the center of the stream channel using a clinometer (PM-5, SUUNTO). Average vegetation height was calculated from three height measurements taken at each transect using a hypsometer (Truepulse 360 B, Laser Technology). Average site geometry characteristics were calculated using measurements from all six transects at each site. Vegetation assessments were completed within 1 mo of monitored application events to ensure habitat characteristics were consistent.

## Weather Station Deployment

HOBO (U30-NRC, Onset) weather stations were deployed at least 1 h prior to all application events. Weather stations were placed at a maximum distance of 5 km from the center of the stream channel in a location that would not be affected by helicopter turbulence, tall structures, power lines, paved areas, or other factors. Weather stations were leveled, oriented north, and programmed to collect temperature, relative humidity, wind direction, wind speed, solar radiation, and dew point every 30 s for the entire application period.

## Data and Statistical Analysis

Results from depositional samplers, vegetation and stream assessments, and weather station data were stored in a Microsoft Access database. Statistical analysis was completed using SAS 9.4 (SAS Institute, 2014), and linear mixed models were analyzed using the MIXED procedure. Figures were prepared in R (Chang, 2014; Wickham, 2016; Auguie, 2017; Kassambara, 2018; R Core Team, 2018).

A linear mixed model was used to model the $\log_{10}$ of total malathion deposition. This model had a fixed effect for site type (nonvegetated vs. vegetated) and random effects for individual site and transect. Although the vegetated sites were not homogeneous with regard to dense woody riparian vegetation, the use of a fixed effect discriminating nonvegetated from vegetated sites was useful for estimating potential differences in malathion deposition. The random effects were included to properly model variation introduced by the experimental design. Variability from multiple applications at the same site was not estimable, likely due to an inconsistent pattern in the mean total malathion deposition for Events 1 and 2 across the transects, and was dropped from the model. Due to different variances at certain locations, the model was created separately for left field, left vegetation, center, right vegetation, and right field locations. A $\text{logarithmic}_{10}$ transformation was necessary to ensure homogeneity of variance and normality of the residuals at each location.

In an effort to determine what site characteristics (including distances and vegetation characteristics) most influenced the amount of instream deposition, univariable and multivariable linear mixed models were created. These models used site characteristics as fixed effects and also included random effects for individual site and transect. When a curvilinear pattern was present in the univariable model, a quadratic fixed effect was added to the linear effect as long as its $p$ value was <0.05. As with the previous linear mixed model at each location, variability from multiple applications at the same site was not estimable and thus not included in the model. Multivariable models were created by including two, three, or four covariates in a single model. Each potential two-, three-, and four-covariate model was analyzed. Due to concerns about collinearity, models were presented in which all covariates had $p$ values <0.05, and the slope estimate for each variable had the same sign as the estimate for the univariable model.

Mean estimates of site types (nonvegetated vs. vegetated) were made using estimated best linear unbiased estimates (eBLUEs). Predicted means of individual sites were made using estimated best linear unbiased predictors (eBLUPs).

# Results and Discussion

## Study Site Physical Characteristics

The two nonvegetated sites (Nonveg1 and Nonveg2) were located on unnamed artificial agricultural drainage ditches that were 290 and 371 m in length, respectively. The three vegetated sites (Veg1, Veg2, and Veg3) were on naturally occurring streams in the Fishtrap Creek and Fourmile Creek subbasins. Site Veg2 had the shortest stream reach length at 177 m, Veg1 had a reach length of 225 m, and Veg3 had the longest reach length at 451 m.

The riparian vegetation communities at the two nonvegetated sites were very similar to each other and were dominated by reed canary grass (*Phalaris arundinacea* L.) interspersed with non-native Himalayan blackberry (*Rubus armeniacus* Focke). The vegetated sites contained more diverse riparian vegetation communities than the nonvegetated sites and were dominated by dense woody vegetation, such as willows (*Salix* spp.), spiraea (*Spiraea douglasii* Hook.), red-osier dogwood [*Swida sericea* (L.) Holub], and alder [*Alnus sinuate* (Regel) Rydb.]. Pacific ninebark [*Physocarpus capitatus* (Pursh) Kuntze], salmonberry (*Rubus parviflorus* Nutt.) and reed canary grass were also present at vegetated sites but were not among the dominant species. Non-native species present at vegetated sites included Himalayan blackberry and evergreen blackberry (*Rubus lacinatus* Willd.). Sites Veg1 and Veg2 contained riparian hedgerows that were planted in 2002, 13 yr prior to this study. The riparian vegetation community at the Veg3 site differed from those at sites Veg1 and Veg2 due to it being naturally established, mature, and intermixed with large cottonwood trees (*Populus trichocarpa* Torr. & A. Gray ex Hook.) and western red cedar (*Thuja plicata* Donn ex D. Don.). Riparian hedgerows at all three vegetated sites were consistent with riparian hedgerows found in northwest Washington State, which are typically 3 to 4.5 m wide.

Site physical characteristics were summarized for all transects at nonvegetated and vegetated sites (Table 1). In general, site distances (center water to vegetation edge to field edge) were much lower at nonvegetated than at vegetated sites. Mean distances between vegetation edge (V) and center water (W) and between field edge (F) and vegetation edge (V) were three and two times larger, respectively, at vegetated sites than at nonvegetated sites. The vegetation at site Veg3 was naturally occurring and was the oldest, widest, and tallest of the vegetated sites. Bankfull width was the largest at Veg3, whereas Veg1, Veg2, and the nonvegetated sites had similar bankfull width.

Instream canopy cover at vegetated sites was nearly double the instream canopy cover at nonvegetated sites. At Veg1 and Veg2, instream canopy angles were close to 90°, with instream and vegetation canopy cover close to 90%. At Veg3, which was wider, canopy angle and instream canopy cover were lower. Canopy angles at nonvegetated sites were zero. Reed canary grass was the dominant species at nonvegetated sites, reaching heights of roughly 1 to 1.5 m and providing some instream canopy cover. At Nonveg2, the coverage of reed canary grass was dense enough that instream canopy cover (during Event 1) was similar to that at vegetated sites. Canopy angle was still zero, due to the relatively low height of the vegetation and the difference in measurement location between canopy cover and canopy angle. Between the first and second application events, the site was mowed, and all instream canopy cover was eliminated before the second application event.

## Weather Conditions during Applications

Application events took place either early in the morning or late in the evening when temperatures were lower than at midday. Weather conditions were fairly consistent, with the exception of Nonveg1 Event 1 on 26 June, which was hotter and drier than the rest of the application events. Across all events, temperatures were between 15.5 and 26.7°C and humidity was 67 to 86%. Solar radiation was low, with lower values observed for evening application times and very early morning application times. The two highest values occurred at the two application events taking place latest in the morning, Veg2 Event 2 and Nonveg2 Event 1, which both took place around 8:00 AM (weather data not shown).

Because of the early morning and late evening application times, winds during applications were generally low (often below the accuracy of 1.1 m $s^{-1}$ for the instrument, with a maximum of 2.52 m $s^{-1}$ at Nonveg2 Event 2). Wind speed and direction were used to calculate wind speed perpendicular to the stream during each application event. This perpendicular wind speed was still lower, with wind at only one application event exceeding 1 m $s^{-1}$ perpendicular to the stream (1.8 m $s^{-1}$, at Nonveg2 Event 2) (wind data not shown). None of these weather conditions had a statistically significant influence on instream total malathion deposition.

## Depositional Results and Statistical Analysis

Total malathion deposition varied dramatically, between application events at the same site, between different depositional samplers in similar positions (e.g., water depositional samplers), and between replicates in the same field position (data not shown) (Table 2). The cause of this variability is not known but may have resulted from issues with spray equipment or the influence of helicopter flight path (e.g., the helicopter flying directly over some samplers and not others).

Deposition reduction between field edge and water depositional samplers was much higher at vegetated sites than at nonvegetated sites. Mean estimates of total malathion deposition from the mixed model (eBLUEs) are compared in Fig. 2. Results from this analysis account only for sample location and not effects of vegetation characteristics. Although eBLUEs for total malathion deposition were higher for most locations at nonvegetated sites than at vegetated sites, the difference was statistically significant only for instream deposition. Mean instream deposition was reduced by 96.1% at vegetated sites compared with nonvegetated sites ($p = 0.001$). Individual site percentage reductions between field edge and water were also calculated from the mixed model (eBLUPs) at all locations. These percentage reductions were 61 and 69% at Nonveg1 and Nonveg2, respectively, and 97, 96, and 97% at Veg1, Veg2, and Veg3, respectively.

In an effort to determine what site characteristics (including distances and vegetation characteristics) most influenced the amount of instream deposition, univariable and multivariable linear mixed models were created. Characteristics included in the analysis were the site distances and vegetation characteristics presented in Table 1, and weather observations (data not shown). Through this analysis, six variables were identified as having a significant relationship with instream total malathion

**Table 1. Comparison of mean vegetation characteristics between vegetated and nonvegetated sites (means ± 1 SD are shown).**

| Parameter | Vegetated sites | | | Nonvegetated sites | | |
|---|---|---|---|---|---|---|
| | *N* | Mean | SD | *N* | Mean | SD |
| Bankfull width (m) | 18 | 6.25 | 1.62 | 12 | 5.18 | 1.05 |
| Bank slope (%) | 24 | 22.79 | 11.34 | 18 | 66.89 | 22.23 |
| W–V† distance (m) | 24 | 9.51 | 2.87 | 18 | 3.23 | 0.83 |
| V–F† distance (m) | 24 | 6.83 | 1.02 | 18 | 3.20 | 0.89 |
| W–F† distance (m) | 24 | 16.49 | 3.21 | 18 | 6.59 | 1.13 |
| Canopy angle (°) | 24 | 71.79 | 21.61 | 18 | 0.00 | 0.00 |
| Stream canopy cover (%) | 18 | 89.79 | 16.24 | 18 | 46.32 | 47.79 |
| Bank canopy cover (%) | 24 | 95.77 | 11.78 | 24 | 0.00 | 0.00 |
| Average site canopy cover (%) | 24 | 91.05 | 12.74 | 24 | 22.86 | 23.40 |
| Vegetation width (m) | 24 | 6.62 | 2.03 | n/a‡ | n/a | n/a |
| Vegetation height (m) | 24 | 6.60 | 4.26 | n/a | n/a | n/a |
| Tree count (DBH§ = 3–90 cm) | 24 | 20.29 | 10.20 | 18 | 0.00 | 0.00 |

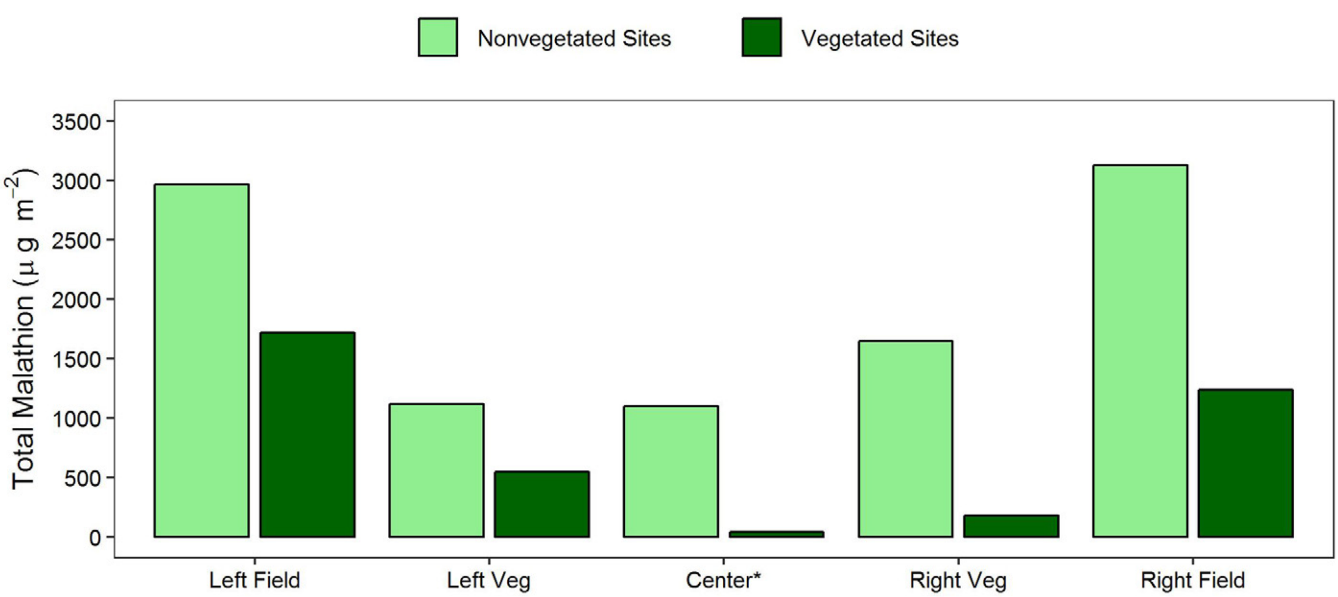
† F, edge of the field; V, outer edge of the riparian vegetation; W, center of the stream.

‡ n/a, not applicable.

§ DBH, diameter at breast height.

**Table 2. Instream total malathion deposition at all sites and events (vegetation and field deposition not shown).**

| Transect | Veg1 Event 1 | Veg2 Event 1 | Veg2 Event 2 | Veg3 Event 1 | Nonveg1 Event 1 | Nonveg1 Event 2 | Nonveg2 Event 1 | Nonveg2 Event 2 |
|---|---|---|---|---|---|---|---|---|
| | $\mu g\ m^{-2}$ | | | | | | | |
| 1 | 14 | 5.5 | 12 | 1200 | 6500 | 440 | 330 | 470 |
| 2 | 120 | 4.6 | 18 | 230 | 1100 | 1000 | 1000 | 880 |
| 3 | 64 | 7.0 | 17 | 51 | 2300 | 1400 | 1700 | 600 |
| 4 | 8.2 | 78 | 31 | 50 | 2400 | 650 | 1300 | 660 |
| 5 | 4000 | 69 | 31 | 78 | 4000 | 320 | 1000 | 670 |
| 6 | 22 | 110 | 17 | 55 | 4000 | 750 | 1500 | 1700 |




| | Nonveg Left F | Veg Left F | Nonveg Left V | Veg Left V | Nonveg W | Veg W | Nonveg Right V | Veg Right V | Nonveg Right F | Veg Right F |
|---|---|---|---|---|---|---|---|---|---|---|
| Upper 95% C.Inter. | 40831.94 | 23768.40 | 12402.24 | 6064.57 | 2871.44 | 111.33 | 8410.08 | 1171.39 | 33174.16 | 18932.15 |
| Lower 95% C.Inter. | 214.88 | 124.74 | 101.20 | 49.75 | 421.11 | 16.33 | 323.82 | 27.21 | 294.44 | 80.91 |

**Fig. 2. Mean estimates of instream total malathion deposition at nonvegetated and vegetated sites (eBLUEs), with 95% confidence intervals (95% C. Inter.). * Statistically significant difference. F, edge of the field; V, outer edge of the riparian vegetation; W, center of the stream.**

deposition: bank canopy cover, average site canopy cover, canopy angle, bank slope, distance between field and edge of vegetation (F–V distance), and distance between field and center of the stream (F–W distance). All variables had significant inverse relationships with instream total malathion deposition except bank slope, which was positively correlated.

The relationships involving canopy characteristics (canopy cover and canopy angle) and distances from the stream were consistent with the anticipated results of this study. Canopy cover and canopy angle relate to canopy density, tree height, and the degree to which canopy is closed over the stream; increases in all of these intercept more total malathion deposition, resulting in decreased instream deposition. Increasing distance between the application area and the stream allows more opportunity for total malathion to deposit before it reaches the stream, resulting in decreased instream deposition. The last relationship, increasing bank slope correlated to an increase in instream total malathion concentration, was unexpected and is attributed to the striking difference in channel geometry between a natural stream (vegetated sites, with a shallower slope) and a manmade ditch (nonvegetated sites, with steeper banks). It is not expected that intentionally altering bank slope would have an effect on total malathion deposition in the way that increasing canopy cover or distance between the application area and the stream would be expected to reduce total malathion deposition. Differences in site characteristics and methods used to measure canopy cover can help explain why instream canopy cover did not significantly affect instream deposition, whereas average site canopy cover and bank canopy cover did. Instream canopy cover was measured 30 cm above the water surface, which allowed low-lying vegetation, including tall grasses, to influence the reading. These measurements were also taken in the center of the channel, meaning that a wide stream channel with a mature riparian area (Veg3) could have lower instream canopy cover readings than a narrower site with similar vegetation characteristics. Figure 3 shows the relationships between all significant parameters and the instream total malathion deposition.

Additional parameters considered in this analysis but not found to have a significant relationship with total malathion deposition were instream canopy cover, bankfull width, vegetation width, vegetation height, tree count, wind characteristics such as average perpendicular speed and gust, maximum speed and gust, and wind direction, temperature, relative humidity, and solar radiation. The significance of some shading variables and nonsignificance of others (like vegetation height) was unexpected and is as yet unexplained. Future analyses using fewer canopy variables may reduce collinearity.

As discussed above, the univariable analysis identified bank canopy cover, average site canopy cover, canopy angle, bank slope, distance from field edge to vegetation edge, and distance from field edge to center of water as being significantly related to instream $\log_{10}$ total malathion deposition. For each, an estimate of the expected change in instream $\log_{10}$ total malathion deposition due to an increase in the parameter was calculated (Table 3).

Given these model results, to reduce the $\log_{10}$ total malathion deposition by an average of 0.1 (or ∼26%) at nonvegetated or minimally vegetated sites, it would be necessary to make the following changes:

- increase bank canopy cover by 7% (range = 0–100%),
- increase the average site canopy cover by 3% (range = 50–100%),
- increase the canopy angle by 6° (range, 0–90°),
- decrease the bank slope by 3% (range, 10–60%),
- increase the distance between the field edge and the vegetation edge by 0.3 m (range = 2.2–8.3 m), or
- increase the distance between the field edge and the center of the stream by 0.9 m (range = 4.8–20.6 m).

Note that the values in parentheses indicate the studied ranges over which the relationships are valid.

As described in the Materials and Methods, these parameters were then explored through two-, three-, and four-covariate linear mixed models comparing distances, slope, and canopy-specific parameters. All three- and four-covariate models showed signs of multicollinearity; as a result, only univariable and two-covariate models are discussed here. A single model was identified in which both covariates had $p$ values <0.10, and the slope of their regression line was in the same direction as that for the univariable model (Table 3). Based on log likelihood statistics, the univariable models with either distance between field edge and vegetation edge, canopy angle, or canopy cover were preferred to the two-covariate model. The observation that some single-covariate models were better than models with combinations of covariates likely reflects factors such as (i) many of the covariates are highly correlated, so adding another highly correlated covariate to a one-covariate model does not provide new information that improves the statistical explanation of the variability; and (ii) although the study was large in labor hours and experimental effort, the number of sites was relatively small.

For the parameters most feasible for landowners to alter (i.e., application distance from the stream and bank canopy cover), relative effects were estimated from the univariable models. Increasing the distance from field edge to vegetation or from field edge to water was about 23 and 13% more powerful, respectively, than bank canopy cover at reducing malathion deposition across the studied range.

Given the results of the two-covariate model in Table 3, to reduce the $\log_{10}$ of instream total malathion deposition by 0.1 (or ∼26%), it would be necessary to increase the distance between the application area and the edge of the riparian vegetation by 0.6 m or increase the canopy cover by 10%.

## Estimated Ecotoxicological Effects

To address potential ecotoxicological impacts, instream depositional sampler results were used to estimate instream total malathion concentrations by assuming instantaneous mixing and a water body depth of 50 cm (adopting calculation methodology from Donald et. al., 2001). Instream total malathion concentration was estimated for each transect at each vegetated and nonvegetated site and application event. The resultant range of individual transect estimates at vegetated sites was 0 to 8 μg L$^{-1}$. Averaged across all transects for each site and application event, mean concentrations were 1.4 μg L$^{-1}$ at Veg1, 0.1 and 0.4 μg L$^{-1}$ at Veg2, and 0.6 μg L$^{-1}$ at Veg 3. In contrast, individual transect estimates at nonvegetated sites ranged from 0.6 to 13 μg L$^{-1}$, with

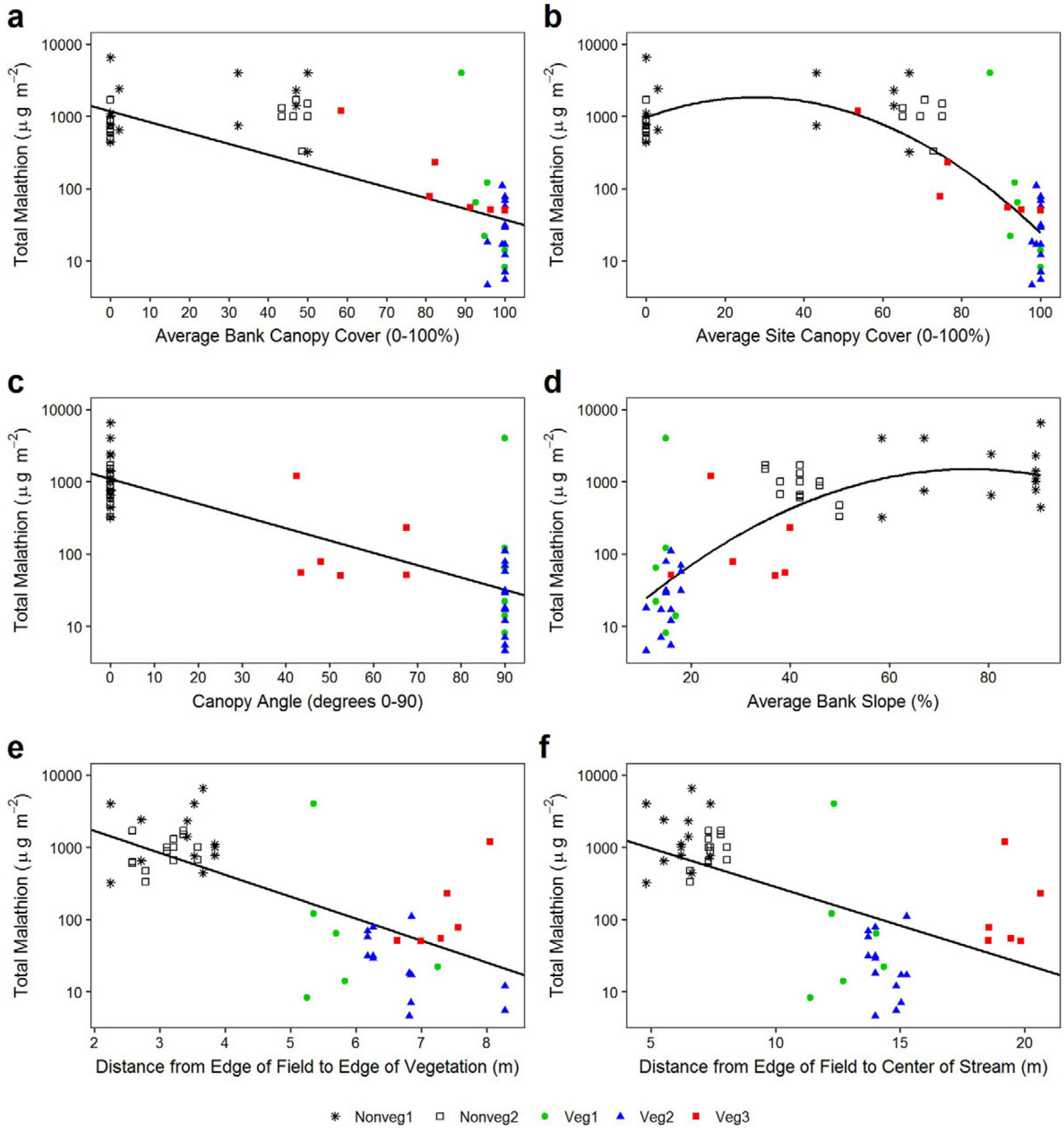



**Fig. 3. Significantly correlated variables and respective relationships to total malathion deposition (a) average bank canopy cover,(b) average site canopy cover, (c) canopy angle, (d) average bank slope, (e) distance from edge of field to edge of vegetation, and (f) distance from edge of field to center of stream.**

**Table 3. Results of univariable and two-covariate models (expected changes in total malathion deposition due to increases in vegetation and distance parameters).**

| Model | Parameter modeled | Expected change in $\log_{10}$ of instream total malathion deposition† | *p* value |
|---|---|---|---|
| Univariable model | | | |
| 1 | Bank canopy cover (%) | −0.015 | 0.0006 |
| 2 | Avg. site canopy cover (linear) (%) | 0.020 | 0.0015 |
| | Avg. site canopy cover (quadratic) (%) | −0.00036 | <0.0001 |
| 3 | Canopy angle (°) | −0.017 | 0.0002 |
| 4 | Bank slope (linear) (%) | 0.064 | 0.003 |
| | Bank slope (quadratic) (%) | −0.00042 | 0.028 |
| 5 | Distance from field edge to vegetation edge (m) | −0.303 | 0.002 |
| 6 | Distance from field edge to center of water (m) | −0.107 | 0.031 |
| Two-covariate model | | | |
| 1 | Avg. site canopy cover | −0.010 | 0.016 |
| 1 | Distance between field edge and vegetation edge | −0.188 | 0.025 |

† This estimate represents the expected change in $\log_{10}$ of instream total malathion deposition resulting from a one-unit increase in the corresponding parameter.

site and event averages of 6.8 and 1.5 μg $L^{-1}$ at Nonveg1 and 2.3 and 1.7 μg $L^{-1}$ at Nonveg2. Estimated instream total malathion concentrations were compared with published ecotoxicological endpoints for malathion because total measured malathion deposition was predominately malathion (not malaoxon). The endpoints used were fish and invertebrate $LC_{50}$ (lethal concentration), which is the concentration at which mortality of study organisms is 50%. Estimated site average total malathion concentrations for all events exceeded the invertebrate $LC_{50}$ (0.098 μg $L^{-1}$), whereas the estimated site average total malathion concentration from only one event (Nonveg1 Event 1) exceeded the fish $LC_{50}$ (4.1 μg $L^{-1}$) (Mastrota and Wente, 2009). However, there were two events where estimated instream total malathion concentrations at individual transects exceeded the fish $LC_{50}$ (i.e., Veg1 Event 1 and Nonveg1 Event 1). Although instream total malathion concentrations were not determined, these estimates imply that even with the reductions in deposition observed due to riparian hedgerows, instream total malathion concentrations could still exceed concentrations of ecotoxicological consequence.

## Conclusions

A total of eight aerial malathion applications were monitored, four at nonvegetated sites and four at vegetated sites. Instream malathion deposition at the vegetated sites was reduced by an average of 96% compared with nonvegetated sites. Six variables had a significant relationship with instream total malathion deposition: bank canopy cover, average site canopy cover, canopy angle, bank slope, distance between field and edge of vegetation, and distance between field and center of stream. Results from the univariable models indicate that repeated increases in either bank canopy cover (by 7%), distance between the field edge and the vegetation (by 0.3 m), or distance between the field edge and the center of the stream (by 0.9 m) would result in a 0.1 decrease (∼26%) in the $\log_{10}$ total instream malathion deposition for each iteration at nonvegetated or minimally vegetated sites. Currently, pesticide loading to streams is mitigated mainly by increasing distance; however, vegetation characteristics such as canopy cover should also be considered.

## Conflict of Interest

The authors declare no conflict of interest.

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