Effect of insecticide formulation and adjuvant combination on agricultural spray drift

Colliln J Preftakes [Corresp., 1] , **Jerome J.J. Schleier III** [2] , **Greg Kruger** [3] , **David K Weaver** [1] , **Robert K.D. Peterson** [1]

[1] Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, United States

[2] Corteva agroscience, Indianapolis, Indiana, USA

[3] West Central Research & Extension Center, University of Nebraska, North Platte, Nebraska, United States

Corresponding Author: Colliln J Preftakes
Email address: collin.preftakes@student.montana.edu

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EFFECT OF INSECTICIDE FORMULATION AND ADJUVANT COMBINATION ON AGRICULTURAL SPRAY DRIFT

Collin J. Preftakes[a], Jerome J. Schleier III[b], Greg Kruger[c], David K. Weaver[a], Robert K. D. Peterson[a]

a. Department of Land Resources and Environmental Sciences, Montana State Univ., Bozeman, Montana 59717

b. Dow AgroSciences, 9330 Zionsville Road, Indianapolis, Indiana 46268

c. University of Nebraska, West Central Research & Extension Center, 402 West State Farm Rd., North Platte, Nebraska 69101

Corresponding Author:
Collin J. Preftakes[a]
7750 Kingsbury Blvd 2S Clayton MO 63105, USA
Email address: collin.preftakes@msu.montana.edu

ABSTRACT

Losses of crop protection products when agricultural spray applications drift has economic and ecological consequences. Modification of the spray solution through tank additives and product formulation is an important drift reduction strategy that could mitigate these effects, but has been studied less than most other strategies. Therefore, an experimental field study was conducted to evaluate spray drift resulting from agricultural ground applications of an insecticide formulated as a suspension concentrate and as a wettable powder, with and without two adjuvants. Droplet sizes were also measured in a wind tunnel to determine if indirect methods could be substituted for field experimentation to quantify spray drift from these technologies. Results suggest that drift was reduced by as much as 37% by formulation type alone and reached 63% by incorporating certain spray adjuvants, but the outcome depended on the formulation/adjuvant combination. The wind tunnel data for droplet spectra showed strong agreement with field deposition trends, suggesting that droplet statistics could be used to estimate drift reduction of spray solutions. These findings can be used to develop a classification scheme for formulated products and tank additives based on their potential for reducing spray drift.

INTRODUCTION

Spray drift from agricultural applications of pesticides is an expected outcome, regardless of measures to minimize its occurrence [1-4]. The U.S. Environmental Protection Agency (EPA) defines drift as the "movement of pesticide dust or droplets through the air at the time of application or soon after, to any site other than the area intended" [5]. Loss of crop protection products via drift can result in potentially harmful human and environmental health effects, inefficient pest control, and economic losses to the product user. Pesticide drift is axiomatically

40   problematic because it compromises the objectives of integrated pest management, which are to
41   reduce pest status through means that are effective, economically sound, and ecologically
42   compatible [6]. Developments in drift reduction technologies (DRTs) and environmental policy
43   for pesticides have progressed through increased knowledge of drift phenomena, but important
44   research gaps remain.
45   Environmental conditions can affect pesticide spray drift and must be considered when making
46   an application, but these cannot be controlled. The only option when facing unfavorable
47   environmental conditions is to decide to postpone or cancel the application. Operating
48   conditions, on the other hand, can be manipulated to mitigate spray drift by the person making
49   the application decision. Environmental conditions such as wind speed and direction,
50   temperature, relative humidity, atmospheric stability, and crop characteristics interact with
51   airborne droplets and influence their deposition. Operational parameters such as boom height,
52   driving speed, spray pressure, nozzle orientation, and application rate can reduce drift and are
53   among the variables that can be readily manipulated by the equipment operator. Nozzle type,
54   nozzle size, formulation type, and tank additives are commercially available DRTs designed to
55   decrease drift through modification of the droplet size distribution upon atomization. Other
56   DRTs such as shielded- and air-assisted sprayers function by interrupting the interaction between
57   airborne droplets and the surrounding air movement.
58   There are a number of commercially available DRTs and the EPA has recently developed a
59   protocol for verifying and rating their drift reduction potential [7]. The protocol provides a
60   standard method for the application technology industry to voluntarily test DRTs. Pesticide drift
61   considerations are included in all registration processes and registrants are encouraged by EPA to
62   include verified DRT options on product labels. However, there are limitations to this protocol
63   because it has only been evaluated for spray nozzles in low- and high-speed wind tunnels, and
64   does not include the effect of tank mixes.
65   In this paper, the combination of a formulated pesticide active ingredient, with or without an
66   adjuvant, is referred to as the spray solution. A pesticide formulation is a mixture of chemicals
67   designed to maximize intended biological efficacy. Physical properties of certain formulation
68   types have been shown to influence how droplets are formed upon atomization at the spray
69   nozzle. Adjuvants are tank additives that are marketed for their enhancement benefits according
70   to the function they are designed to perform. Some adjuvants are designed to enhance the
71   performance of the pesticide, usually through better absorption, whereas others are designed to
72   enhance qualities of the spray by modifying the physical properties of the spray solution [9, 10].
73   Manipulating components in the spray solution as a drift reduction strategy has been reported in
74   the scientific literature less than other technologies such as nozzle type, and results are variable
75   [11-15]. Quantification of drift reduction due to formulation and adjuvant type is an important
76   objective because these components can have effects that are equivalent to those due to nozzle
77   type on downwind deposition [13]. Furthermore, selecting the formulation with optimal drift
78   reduction potential could reduce the need to include drift reduction adjuvants, which may not
79   perform consistently when employed in different combinations. Therefore, this research

80   characterizes downwind deposition of two common formulation types and adjuvants from a
81   ground sprayer in a three-year field study.
82
MATERIALS & METHODS
84   Field experiments were conducted over three consecutive summers from 2014 to 2016 at the
85   Dow AgroSciences Western U.S. Research Center near Fresno, California. The topography at the
86   field site was flat, and there was no vegetation because it had been fallow the previous season,
87   and disked before the start of the experiment. The spray swath was 145-m long by 15-m wide,
88   and oriented with driving direction perpendicular to the wind direction. The off-target area was
89   110 m by 145 m and downwind from the spray source. Two sample lines 2.5 m to the left and
90   right of the center of the off-target plot consisted of both horizontal (ground) and vertical (1 and
91   2 m above ground) sample locations. The sample lines were perpendicular to the spray line and
92   approximately parallel to the wind direction. The orientation and relative lengths of the spray
93   swath and sample lines (Figure 1) were designed so that spray droplets could travel toward the
94   farthest downwind sample locations if no more than a 30° deviation angle in wind direction was
95   allowed [16].
96   Downwind insecticide ground deposition was collected with 14-cm diameter plastic Petri dishes
97   (Fisher Scientific Cat. No. FB0875714). Petri dishes were horizontally placed on plywood at 8
98   distances of 1, 2, 4, 8, 16, 32, 64, and 110 m from the field edge, along each of the two sample
99   lines. The downwind samplers along the two lines were subsamples, so for statistical analysis the
100   deposition data were averaged for each distance. Plywood was placed on the ground to provide a
101   level surface for the dishes. Also, along the two sample lines (averaged for statistical analysis) at
102   2, 8, 32, 64, and 110 m, vertical samplers were positioned 1 and 2 m above the ground to sample
103   the size distribution of the spray droplets at different heights and distances. Each vertical sampler
104   (spinner) consisted of two rotating microscope slides with a spin rate of 600 rpm, designed to
105   impinge airborne droplets (Leading Edge Associates, Inc.). The microscope slides were coated
106   with a magnesium oxide (MgO) powder so that analysis could be done at a later date. This is
107   made possible by the MgO–coating because measurements are made on the droplet imprints
108   instead of the droplets themselves, which are prone to evaporation [17].
109   An untreated area located 15-m upwind from the spray swath contained negative controls for
110   both horizontal and vertical samplers, and a weather station to monitor environmental conditions.
111   The weather station consisted of a Hobo Micro Station Data Logger (Onset Computer
112   Corporation) attached to 12-bit temperature and relative humidity sensors with a solar radiation
113   shield and a wind speed and direction smart sensor positioned 2.5 m above the ground. The Hobo
114   wind speed smart sensor (S-WSA-M003) had a starting threshold of ≤ 1 m/sec and the logger
115   was set to measure wind speed every 20 seconds. The average wind speed was calculated over
116   the first 10 minutes of each treatment replication to characterize wind speeds before, during, and
117   after each application.

118 Hobo temperature and relative humidity data loggers were also used at different heights (2.5 and
119 9.2 m) to monitor atmospheric stability. Atmospheric stability was categorized by first
120 calculating the stability ratio with the following equation from Fritz [18]:
121
122 SR = [(TZ2 – Tz1/μw2] · 10^5 (1)
123
124 where SR is the stability ratio, TZ2 and Tz1 is the air temperature (°C) at 9.2 m and 2.5 m
125 respectively, μw is the mean wind velocity (cm/s) at 2.5 m, and 10^5 gives the ratio acceptable
126 units. The SR for each treatment application was calculated from the average wind speed and
127 temperatures and were assigned to 4 categorical variables, "unstable", "neutral", "stable", and
128 "very stable" [18].
129 Treatments consisted of two formulation types, two adjuvants, and water only. Each formulation
130 type and adjuvant was applied individually (4 treatments), and each formulation type was also
131 combined with each of the adjuvants (4 treatments). This results in 9 treatments, when including
132 water only, from a 3x3 factorial design. We used the active ingredient spinosad (a mixture of
133 spinosyn A and spinosyn D) formulated as a wettable powder (WP) and a suspension concentrate
134 (SC) under the product names Entrust® insecticide and Entrust® SC insecticide containing 80 and
135 22.5% active ingredient, respectively (Dow AgroSciences, LLC). The two adjuvant products
136 were Maximizer (Loveland Products, Inc.) and Powerlock (Winfield Solutions, LLC).
137 Maximizer is composed of paraffin based petroleum oil (83%) and nonionic surfactant (16.3%),
138 whereas Powerlock contains modified vegetable oil (63%) and nonionic surfactant (32%). The
139 water-soluble fluorescent dye Rhodamine-WT (CAS No: 37299-86-8) was mixed with the spray
140 solution of each treatment (0.2% v/v) to allow for the quantification of spray deposition [19].
141 Petri dishes and spinners were placed within the control area at the beginning of each replication
142 and the treatment solution was sampled immediately before application to measure the actual
143 fluorescent dye concentration in the tank. From the tank sample, two control dishes were loaded
144 with 0.1 mL to quantify potential tracer degradation and recovery for each replication. Eight
145 Petri dishes were also placed within the spray swath before application to estimate deposition
146 within the targeted area. These samplers were evenly spaced 29.3 m apart along the middle of
147 each of the two spray lines.
148 Treatments were selected in random order and applications were made with a ground rig boom
149 sprayer (Avenger high clearance tractor by Lee). The boom length was 7.62 m and all
150 applications were made with a boom height above the ground of 58 cm. For this study, 15 TeeJet
151 XR11002 flat fan broadcast nozzles with a 110° spray angle, and a size 50 mesh, were evenly
152 spaced 50.8 cm apart, along the length of the boom. Spray pressure was measured at the end of
153 the spray boom and driving speed was monitored by an onboard GPS system; these were held at
154 2.07 bar and 6.8 km/h (4.2 mph), respectively. Two spray passes per application were made so as
155 to simulate a single pass with a 15 m spray boom.
156 Following each treatment replication (spray application) horizontal and vertical samples were
157 collected from all locations (off-target, on-target, and untreated). Sample collection began three

158   minutes after the sprayer had been turned off at the end of the spray swath to allow for deposition
159   to occur at the farthest samplers. Exposed Petri dishes and microscope slides were placed in dark
160   containers to minimize photo-degradation of any insecticide or fluorescent material, and control
161   samples were the last to be collected. Replications were performed over time within the same
162   day or over multiple days with 9 replications of each of the 9 treatments, totaling 81 spray events
163   in the months of July (2014), and May (2015, 2016).
164   Insecticide deposition on Petri dishes was extracted with 15 ml of D.I. H2O and decanted into
165   20-ml scintillation vials (Thermo Fisher Scientific). Analysis vials were wiped with Kimwipes
166   (Kimberly-Clark, LLC) to remove exterior moisture, and were inspected for clarity before being
167   analyzed. Light absorption at a specific wavelength, representing the amount of dye present in
168   each sample, was quantified and recorded using a GFL-1A fluorometer (Opti-Sciences, Inc). The
169   source and detection filters that were used for the excitation and detection of Rhodamine-WT
170   were 530 and 590 nm, respectively (manufacturer recommendation). Standard curves were
171   prepared using serial dilutions prepared in D.I. water. The detection limit (DL) of Rhodamine-
172   WT, given the sensitivity of the fluorometer, was estimated by adding three standard deviations
173   of a known low concentration measured 20 times to the mean of a blank sample [20]. After
174   extraction and analysis, Petri dishes were discarded and scintillation vials were triple rinsed with
175   D.I. H2O before reuse. Less than 10% of the ground samples consisted of concentrations below
176   the DL so one half of the DL was substituted for non-detectable concentrations [21-23].
177   Statistical analysis for ground deposition was conducted using the amount of Rhodamine-WT
178   deposited per unit area ($\mu g/cm2$) for each distance, averaged over the two sample lines. Tank
179   mixes for each treatment were analyzed for actual dye mixing rates following the procedure
180   above. Based on the actual amount of dye in the tank, the estimated volume on the spiked control
181   plates was compared to the actual volume of the spike (0.1 mL) to estimate recovery rates for
182   each treatment. To represent deposition as a percentage of the total material applied, first the area
183   for each sample location was calculated, as one-half the distance between two sample locations
184   multiplied by the diameter of the Petri dish (Table 1). The application rate of the dye for each
185   treatment was then estimated by multiplying the actual dye mixing rates by the application rate
186   (Table 2). Multiplying the application rate of the dye by the total area of the sample locations
187   returned the total mass of dye applied. The area for each sample location was then multiplied by
188   the deposition data, averaged over the two sample lines, for each distance, to return mass of dye
189   per sample location. Finally, the mass of dye per sample location was divided by the total dye
190   applied to express deposition as a percentage of applied material. Deposition data for both in
191   swath and downwind samples were calculated in this way.
192   Due to minimal ground deposition beyond 32 m, only 6 downwind distances were included in
193   the statistical analysis. This resulted in a total of 486 data points (9 treatments, 6 distances, 9
194   reps) for ground deposition which were analyzed using multiple linear regression in the
195   statistical software package R, version 3.3.2 [24]. Exploratory data analysis was done to identify
196   outliers, potential interactions, linearity, and normality, among dependent and independent
197   variables. Table 3 lists summary statistics for numerical variables considered in this data set.

198   Log transformations on the deposition of Rhodamine-WT (µg/cm2) and the independent
199   variable, distance (m), were required before parametric statistics could be used. Correlation
200   coefficients between independent variables was used to eliminate those with a correlation greater
201   than 0.5 to avoid collinearity. This resulted in the exclusion of temperature and relative humidity
202   (RH) at the upper height (9.2 m), as well as temperature measured at the lower height (2.5 m).
203   Temperature, instead of RH, at 2.5 m was removed because RH resulted in a better fit for the
204   regression model, and because 2.5 m is a more practical measurement height. Model selection
205   with Akaike's information criterion (A.I.C.) was used to select between candidate models, which
206   were based on specific hypotheses about pesticide drift. Full and reduced models were compared
207   using an extra sums of squares (ESS) F-test to determine the contribution of certain independent
208   variables in explaining variability in the response variable. The model with the lowest AIC was
209   selected and diagnostic plots were used to check that the requirements for linear regression were
210   met regarding statistical assumptions. The data were centered by subtracting the average RH so
211   that the main term coefficients for treatment could be interpreted as the estimates at average RH,
212   rather than zero.
213   Droplet spectra resulting from deposition on vertically positioned microscope slides were
214   recorded with a DropVision measurement system (trademark of Leading Edge Associates, Inc).
215   The DropVision system integrates a compound microscope and image processing software to
216   recognize, count, and measure droplets while eliminating background objects. A calibration slide
217   containing circles of known diameters was used to calibrate the system at 10X magnification.
218   This is achieved by relating the number of pixels contained in the calibration circle to its
219   diameter. Microscope slides for all three years (4,221 slides) were scanned by a single person
220   following a specific protocol to minimize user error. A specific viewing pattern was designed to
221   sample a representative number of droplet impressions from an evenly distributed area of the
222   slide surface. A minimum of 100 droplets or 200 pictures were required before moving to the
223   second slide from a given field location (each spinner contains two slides). Once 200 droplets
224   were counted, or the entire surface area of both slides was viewed, the droplet statistics were
225   compiled into a report produced by the software. The diameter at which half of the volume was
226   contained in droplets smaller than the median (VMD) was recorded for all slide sets containing
227   30 or more droplets, which limited the farthest downwind distance from the spray source to 32
228   m, resulting in 273 data points for statistical analysis.
229   The same statistical approach for ground deposition was used to analyze the droplet data.
230   Correlated independent variables that were excluded above were also excluded here. Exploratory
231   analysis suggested a log transformation of the response (VMD) was required to meet
232   assumptions of normality and AIC model selection was used to choose the final model. The
233   predictor variable for height was analyzed as a categorical variable at 1 and 2 m above the
234   ground. Linear model assumptions were assessed using residual plots and the global validation
235   package, gvlma, in R [25]. These data were centered by subtracting the average wind speed so
236   that the main term coefficients for treatment could be interpreted as estimates at average wind
237   speed.

238 The droplet spectra of all treatments were also measured in a wind tunnel so that general trends
239 in droplet size could be compared to differences in ground deposition from the field study. Using
240 the same application system as in the field study (i.e. nozzle set up, application rate, and spray
241 pressure) three replications of each treatment were sprayed in a wind tunnel at the University of
242 Nebraska West Central Research & Extension Center in North Platte, Nebraska. A Sympatec
243 laser diffraction particle size analyzer (Sympatec Inc.) positioned near the spray nozzle was used
244 to measure droplet spectra for each of the treatments in the wind tunnel. Droplet sizing data
245 measured for each treatment included VMD, the 10% and 90% diameters, the relative span, and
246 the percent spray volume contained in droplets less than 141 μm. This percentage represents the
247 fraction of spray droplets within the "fine" classification (100-175 μm) for droplet sizes [26], and
248 was used as an indicator for spray drift. The treatments were ranked according to the percentage
249 of droplets within this size range and compared to the ranks for ground deposition (Table 6).
250 An insecticide efficacy experiment was also conducted to test differences in insect control
251 between the treatments used in the drift study. The study was conducted August 2016 at the same
252 experimental station in Fresno, California. The experimental setup was a randomized complete
253 block design with 7 treatments (treatments consisting of only adjuvant were excluded) and 4
254 replications (blocks) of each treatment. Each plot was 3.05 m long and 2.03 m wide, and
255 contained two rows of newly planted broccoli (Green Magic variety of Brassicaceae sp., 16
256 plants per plot). Plots were 1.5 m apart, and two empty rows (2.03 m) were left between blocks
257 so as to avoid contamination from adjacent plots. Before spraying on application day a pre-count
258 was conducted to record cabbage looper larvae (*Trichoplusia ni*) on broccoli plants in the study
259 area which had been infested by endemic populations. Applications were made with a handheld
260 boom sprayer at the same rate, and with the same nozzle type, as in the drift study. All treatments
261 were applied in random order and *Trichoplusia ni* larvae on the broccoli plants were counted to
262 estimate percentage mortality at 1, 3, and 7 days after application.
263 Efficacy data were represented and analyzed as count data, and as a fraction of the untreated
264 control plots at each time-step after application. Count data and percent mortality data were
265 analyzed using ANOVA fit to a linear model for a randomized block design in R, version 3.3.2
266 [24]. The hypothesis that was tested with the count data was that there would be no differences in
267 the number of *Trichoplusia ni* larvae between treated and untreated plots. For the percent
268 morality data the tested hypothesis was that there would be at least one difference in percent
269 mortality between treatments.
270

271 **RESULTS**
272 *Ground deposition*
273 The recovery rates of Rhodamine-WT for each treatment were within the recommended range of
274 80 to 120% [7, 16]. The high recovery rate of the dye from the control plates suggests that
275 degradation of the fluorescent dye in samples was negligible due to the short exposure time to
276 sunlight. In some cases, more material was deposited on the swath plates than was expected
277 given the application rate of the dye. Potential sources of error that may have contributed to an

278   inaccurate estimation of recovery include fluctuations in the actual driving speed, spray pressure,
279   flow rate, or errors in the analysis on the fluorometer [27].
280   Coefficient estimates and standard errors for the selected model for ground deposition, centered
281   on average relative humidity, are listed in Table 4. Treatment, log of distance (m), wind speed
282   (m/s), relative humidity (%), and a term for the interaction between treatment and relative
283   humidity were included in the final model. Year, stability ratio, and stability category were
284   excluded because they had no effect on deposition, and did not significantly change the error
285   sums of squares when compared to the final model (ESS F-test, F=1.46, p=0.2004, on 461 and
286   466 degrees of freedom). Diagnostic plots of the model residuals suggested that the assumptions
287   of normality, linearity, and homoscedasticity were reasonably met. The selected regression
288   model for the ground deposition data was shown to explain 89.3% of the variability in the
289   response variable (adjusted R-squared of 0.8934 for overall model). The regression equation
290   centered on relative humidity with water as the reference level for treatment is:
291
292   LT= -5.43+0.305*WP+0.162*SC-0.660*WPMax-0.683*WPPL-0.491*SCMax
293   -0.894*SCPL -0. 543*Max-1.058 *PL -1.662*LD+0.456*Wind-0.019*RH
294   +0.006(WP*RH)-0.038(Max*RH)+0.034(PL*RH)+0.0176(SCMax*RH)
295   +0.003(SCPL*RH)-0.033(SC*RH)+0.034(WPMax*RH)-0.001(WPPL*RH)   (2)
296
297   where LT is the log of the Rhodamine-WT deposition (μg/cm2), WP= Entrust (WP) insecticide,
298   Max=Maximizer, SCPL=Entrust SC insecticide with PowerLock, WPMax=Entrust (WP) with
299   Maximimzer, WPPL=Entrust (WP) with PowerLock, LD is the log of the distance (m),Wind is
300   wind speed (m/s), and RH is the relative humidity (%) at 2.5m above the ground. Full
301   coefficients for equation 2 are listed in Table 4.
302   Deposition of Rhodamine-WT (μg/cm^2) for all treatments decreased with increasing distance
303   from the field edge as indicated by the negative coefficient for logged distance in the overall
304   regression model (p<0.0001, Table 4). After controlling for wind speed and RH, this decrease in
305   deposition was estimated to be 68.40% with an associated 95% confidence interval from 67.19 to
306   69.57% for every doubling of distance (e.g. going from one ground sample to the next in this
307   study, Figure 2). The treatments with the highest and lowest amounts of active ingredient
308   observed at the farthest downwind distance were Entrust SC insecticide with Maximizer and
309   Entrust (WP) insecticide with PowerLock, respectively.
310   All treatments also exhibited more deposition in higher wind conditions as indicated by the
311   negative coefficient for wind speed in the overall regression (p<0.0001, Table 4), with every
312   additional unit increase in wind speed (m/s) resulting in an estimated 36.59% increase in
313   deposition after controlling for distance and RH (95% CI from 28.13 to 44.06%) (Figure 3).
314   The interaction between RH and treatment suggests that the effect of RH on deposition depends
315   on treatment type. Neither Entrust SC nor Entrust (WP) were affected by RH, but water alone, as
316   well as all treatments which included adjuvant, exhibited higher deposition with increasing RH
317   over the range of RH measured in this study.

318   Relative humidity had a larger positive effect on deposition of Entrust SC with Maximizer
319   compared to the Entrust SC treatment alone (p=0.041). However, the effect of RH on deposition
320   of the Entrust SC with PowerLock combination was not significantly different than for Entrust
321   SC alone (p=0.10). The same trend was observed when comparing the effect of RH on
322   deposition between the WP formulation and WP plus the two adjuvants. Deposition of Entrust
323   WP with Maximizer was more affected by RH than Entrust WP alone (p=0.010), but Entrust WP
324   with PowerLock was not affected differently than Entrust WP alone (p=0.623).
325   At the average RH (58.55%) recorded in this study, deposition of the SC formulation was lower
326   than for the WP formulation after controlling for distance and wind speed (p=0.0045). The
327   estimated difference in deposition between Entrust SC and Entrust WP was 32.27% with an
328   associated 95% confidence interval from 13.54 to 54.48%. With the exception of the Entrust WP
329   and Entrust SC insecticide treatments, deposition of the water only treatment was greater than for
330   all other treatments at the average RH, and fixed distance and wind speed (α=0.05).
331   The difference in deposition between the formulated product with and without the adjuvant is
332   interpreted as the effect on drift caused by the adjuvant. When comparing deposition of the
333   Entrust SC treatment to deposition of this formulation with each of the two adjuvants,
334   PowerLock reduced deposition, but Maximizer did not (p<0.001 & p=0.0594, respectively). The
335   estimated reduction in deposition caused by the addition of PowerLock to the SC formulation
336   was 51.94% at average RH, and after controlling for distance and wind (95% CI from 33.33 to
337   65.35%).
338   Deposition of the WP formulation was reduced with the addition of both the PowerLock and the
339   Maximizer adjuvants by roughly the same amount, at average RH (p<0.0001). After controlling
340   for distance and wind speed, this reduction was an estimated 62.75% (95% CI from 50.34 to
341   72.06%) and 61.88% (95% CI from 48.46 to 71.80%) for PowerLock and Maximizer,
342   respectively.
343

344   *Vertical deposition*
345   Coefficient estimates and standard errors for the selected model for VMD, centered on average
346   wind speed, are listed in Table 5. Treatment, log of VMD (μm), wind speed (m/s), and relative
347   humidity (%), were included in the final model for vertical deposition. Year, stability ratio, and
348   stability category were excluded because they had no effect on deposition, and did not
349   significantly change the error sums of squares when compared to the final model (ESS F-test,
350   F=1.204, p=0.3079, on 247 and 252 d.f.). Diagnostic plots of the model residuals suggested that
351   the assumptions of normality, linearity, and homoscedasticity were reasonably met. The selected
352   regression model for the VMD data was shown to explain 41.9% of the variability in the
353   response variable (Adjusted R-squared of 0.4187 for overall model). The estimated regression
354   equation for logVMD from the selected model centered on wind speed and with water as the
355   reference level for treatment is:
356

357   lVMD= 3.941+0.133*WP+0.119*SC+0.109*WPMax+0.093*WPPL+0.089*SCMax

358   +0.149*SCPL+0.073*Max+0.135*PL-6.9E-4 *D-0.005*RH-0.070*Height

359   + 0.101*Wind+0.125(WP*Wind)+0.094(SC* Wind) +0.018(WPMax* Wind)

360   -0.030(WPPL* Wind)+0.081(SCMax* Wind) +0.085(SCPL* Wind)

361   -0.044(Max* Wind)+0.072(PL* Wind)   (3)

362

363   Where lVMD is the log of the VMD (μm), D is the distance from the field edge (m), and Height

364   is the vertical distance above the ground from 1 to 2 m, at which the rotating microscope slides

365   were positioned. All other variables are defined the same as in equation (2). Full coefficients for

366   equation 3 are listed in Table 5.

367   The VMD was not significantly affected by distance after controlling for height, wind speed, and

368   RH ($p=0.3087$). Elevated RH led to smaller VMD values for all treatments at fixed height and

369   wind speed as indicated by a negative coefficient from the overall regression model ($p<0.0001$).

370   The estimated rate at which VMD decreased was 0.544% for every 1-unit increase in RH (%)

371   with an associated 95% CI from 0.411 to 0.677%. The results also suggest that larger droplets

372   were collected on spinners at the lower height (1 m) compared with the upper heights (2 m) for

373   all treatments and distances ($p<0.0001$). Droplets collected at 1m were an estimated 6.7% larger

374   than droplets collected at 2 m with an associated 95% CI from 4.35 to 9.15%.

375   The interaction between treatment and wind speed suggests that the effect of wind speed on

376   droplet size differs between treatments. Of the treatments that were affected by wind speed, the

377   effect was such that higher wind speed resulted in larger VMD values (positive slope). The effect

378   of wind speed on VMD was not different between Entrust SC insecticide and Entrust (WP)

379   insecticide ($p=0.568$). When the SC formulation was combined with either of the adjuvants the

380   degree to which wind affected VMD was not changed ($p=0.861$ and $p=0.714$ for Entrust SC with

381   PowerLock and Entrust SC with Maximizer, respectively). When the two adjuvants were added

382   to the WP formulation the addition of PowerLock resulted in a lesser influence of wind speed on

383   VMD ($p=0.011$), but the effect on VMD was not different between Entrust WP with Maximizer

384   and Entrust (WP) alone ($p=0.058$). The effect of wind speed on VMD for water was significantly

385   lower than for either formulations alone ($p=0.024$ and $p=0.044$, for Entrust SC and Entrust WP,

386   respectively).

387   At the average wind speed (2.38 m/s), and after controlling for RH, distance, and height, there

388   was not difference in VMD between the two formulations ($p=0.666$), or between either

389   formulation in combination with either of the adjuvants ($p=0.283; 0.272; 0.606; 0.175$ for

390   PowerLock and Maximizer combined with Entrust SC and Entrust WP, respectively). The VMD

391   of water was significantly lower than all other treatment combinations at average wind speed and

392   fixed values for RH, height, and distance. The VMD of water was an estimated 8.43% smaller

393   than the treatment with the next largest VMD (Entrust SC with Maximizer), with an associated

394   95% CI from 2.74 to 13.79%. At the average wind speed there was no difference in VMD

395   between either formulation with PowerLock or either formulation with Maximizer ($p=0.110$ and

396   0.451, respectively).

397   The fraction of spray volume containing droplets less than 141 μm, measured in the wind tunnel,
398   can be viewed in Table 6. The order in which treatments had the highest to lowest fraction of
399   fine droplets (<141 μm), measured in a wind tunnel, was the same for treatments ordered by
400   ground deposition.
401
402   *Biological efficacy experiment*
403   There were statistically fewer *Trichoplusia ni* larvae in the treated plots than in the untreated
404   plots at 3 and 7 days after application, suggesting that all treatments were effective at reducing
405   the pest population ($p<0.05$, ANOVA on 18 d.f.). Furthermore, no difference in percentage
406   mortality was observed between treatments at either 3 or 7 days after application, suggesting that
407   all treatments were similarly effective ($p>0.05$, ANOVA on 15 d.f.).
408

409 **DISCUSSION**
410   Our findings support previous studies in that formulation type can affect spray drift, and should
411   be considered when evaluating a given spray system for its drift potential. Specifically, our
412   results differentiate between two formulations that are typically categorized together with regard
413   to their drift potential. Both wettable powders and suspension concentrates are formulations of
414   solid crystalline active ingredients which form non-deformable dispersions throughout the spray
415   solution [8]. These formulations likely share a common mechanism for affecting spray
416   atomization on the basis of this physical property [28]. However, current scientific literature is
417   inconclusive regarding the effect of solid dispersions on droplet size, and therefore drift [12, 14,
418   29-31]. This study provides evidence that spray solutions of formulations with solid particles do
419   influence drift, and that drift of the WP formulation was greater than for sprays of water alone.
420   Differentiating the drift potential of these closely related formulations could help inform DRT
421   manufacturing decisions, although generalizations are premature.
422   The greater drift reduction of PowerLock compared to Maximizer in this study is consistent with
423   results from Western et al. [32], who found that adjuvants of vegetable oil, rather than mineral
424   oils, were more effective at reducing drift, but others have found the effect of these adjuvant
425   types on VMD to be small [33]. Given the many interactions between certain properties of the
426   spray solution and other components of the system, it could be advantageous if no additional
427   tank additives were required to improve drift reduction. Both of the adjuvants tested in this study
428   were shown to effectively reduce deposition without any apparent tradeoffs with biological
429   efficacy, but their effect depended on the formulation type with which they were combined. This
430   demonstrates the additional level of uncertainty introduced by incorporating adjuvants marketed
431   for drift reduction into spray solutions.
432   Deposition on the vertical samplers was used to characterize the size distribution of spray
433   droplets throughout the off-target area. Over the distances that were sampled in this study, there
434   was more of a vertical, rather than horizontal, stratification of droplet sizes, with larger droplets
435   collected below 2 m heights. The discrepancy between droplet size and ground deposition with
436   increasing distance could be explained by the fact that the total number of droplets at each

437   distance was not quantified. It is likely that at the greater distances fewer droplets were
438   contributing to both ground deposition and droplet size on the spinners. At average RH and wind
439   speed, the treatment containing only water and Rhodamine-WT had the second highest ground
440   deposition, and the smallest VMD. This suggests that smaller droplets resulted in greater drift,
441   but this cannot be conclusively stated. To test the well supported assumption that smaller droplet
442   sizes lead to greater drift [3, 13, 15, 28, 34-36], we analyzed the droplet spectra of our treatments
443   in a wind tunnel. As expected, we found that treatments with smaller droplets correlated with
444   greater off-target deposition in the field.
445   Meteorological factors that affected deposition were wind speed and relative humidity. The
446   observed effect of wind speed on drift is consistent with previous studies [3, 18, 37-39], and is
447   further supported by the presence of larger droplets on the vertical samplers during higher wind
448   conditions. The positive correlation between relative humidity and deposition for some
449   treatments in this study is also reasonable given the relatively short sampling distance from the
450   field edge. Conditions with higher relative humidity are less conducive to evaporation of spray
451   droplets, which may have led to larger droplets and greater deposition over the distances
452   sampled. This may still be true even though the relationship between RH and VMD observed in
453   this study would suggest otherwise. The effect of RH was small relative to the effect of wind
454   speed on VMD, with < 0.1% decrease in droplet size for every 10% increase in RH, whereas a
455   10% increase in wind speed led to an estimated 1.3% increase in VMD.
456   Our results provide information on deposition and environmental factors related to agricultural
457   spray drift of two of the most commonly used formulation types [8] under realistic application
458   scenarios, including the use of enhancement additives. Overall, ground deposition values were
459   within the range of EPA assumptions for drift (1-5%) for estimating pesticide exposure to
460   adjacent areas when models are not used [3]. The fraction of applied material, and the estimated
461   68% decrease in ground deposition for every doubling of distance from the field edge, are
462   comparable to findings from other drift experiments [40]. Quantification of exposure and risk to
463   non-target organisms using actual environmental concentrations from this, and similar studies, is
464   needed to fully characterize the benefits of drift reduction technologies.
465   This research demonstrates that droplet size is an effective indicator of agricultural spray drift
466   resulting from different formulation types and adjuvants. The EPA verification protocol currently
467   stipulates that when the combined effect of nozzle design and formulated product is evaluated,
468   the drift reduction rating is only valid for that specific combination [7]. Our results suggest that
469   droplet size data could be used to demonstrate drift reduction regardless of the formulated
470   product being sprayed, but more spray mixtures need to be tested before reference sprays can be
471   efined for comparing and rating spray mixtures as DRTs.
472   ®™ Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow.
473
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475   **ACKNOWLEDGEMENTS**

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Conflict of Interest Statement

C.J. Preftakes was an employee/student at Montana State University during the conduct of the study and is currently an employee of Bayer, Crop Sciences. J. Schleier was an employee of Dow AgroSciences, which is the primary registrant of spinosad, during the conduct of the study.

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581

Table 1. Sample areas for in-swath and downwind ground deposition samplers

3 Table 1. Sample areas for in-swath and downwind ground deposition samplers

Swath			Downwind		
Sample Location (m)	Range (m)	Sample Area (given a sampler diameter of 14 cm) (cm^2)	Sample Location (m)	Range (m)	Sample Area (given a sampler diameter of 14 cm) (cm^2)
18.13	0 to 36.25	50750	1	0 to 1.5	2100
54.38	36.25 to 72.5	50750	2	1.5 to 3	2100
90.63	72.5 to 108.75	50750	4	3 to 6	4200
126.88	108.75 to 145	50750	8	6 to 12	8400
			16	12 to 24	16800
			32	24 to 32	11200

Table 2. Application rates of Rhodamine-WT (RWT) for each treatment

[a] Suspension concentrate formulation of the insecticide spinosad [b] Wettable powder formulation of the insecticide spinosad [c] Spray enhancement additives

2   Table 2. Application rates of Rhodamine-WT (RWT) for each treatment

Treatment	Dye Mixing Rate (μg/mL)	Flow Rate (L/ha)	RWT Application Rate (μg/cm^2)
Entrust SC insecticide [a]	80.06	123.47	0.0988
Entrust insecticide [b]	96.46	127.21	0.1227
Entrust SC & PowerLock	103.15	127.21	0.1312
Entrust SC & Maximizer	72.35	128.15	0.0927
Entrust & PowerLock	93.26	130.02	0.1213
Entrust & Maximizer	83.38	127.21	0.1061
PowerLock [c]	93.69	124.41	0.1165
Maximizer [c]	80.41	124.41	0.1000
Water	82.07	127.21	0.1044

4   [a] Suspension concentrate formulation of the insecticide spinosad
5   [b] Wettable powder formulation of the insecticide spinosad
6   [c] Spray enhancement additives

Table 3. Summary statistics for numerical variables

VMD = volume median diameter; Temp = temperature; RH = relative humidity

2   Table 3. Summary statistics for numerical variables

Variable	Units	Mean	SD	Range	
				Minimum	Maximum
Rhodamine-WT	$\mu g/cm^2$	2.88×10^{-3}	6.27×10^{-3}	2.60×10^{-7}	5.08×10^{-2}
Active Ingredient	$\mu g/cm^2$	0.0236	0.0619	6.05×10^{-7}	0.6938
Tank Solution	$\mu L/plate$	5.025	0.0109	4.50×10^{-4}	88.52
VMD	μm	36.7	5.08	26.08	52.54
Wind Speed	m/s	2.27	0.6865	0.3	3.82
Temp @2.5 m	°C	20.39	4.14	13.38	30.14
Temp @9.5 m	°C	21.2	4.56	12.96	31.08
RH @2.5 m	%	58.55	12.23	26.94	82.08
RH @9.5 m	%	55.03	13.68	22.67	86.16
Stability Ratio		2.11	5.83	-27.22	32.56
Distance	m			1	32

4   VMD = volume median diameter; Temp = temperature; RH = relative humidity

Table 4. Coefficient estimates and SEs for selected ground deposition model [a]

[a] Data centered on mean RH so that the estimates of the main term effects can be interpreted at average RH instead of zero. Overall model had an adjusted R^2 of 0.8934. [b] Spray enhancement additives * Statistically significant at α=0.05 WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension concentrate formulation of insecticide spinosad); RH = Relative humidity

2 Table 4. Coefficient estimates and SEs for selected ground deposition model [a]

Ref. = Water	Estimate	Std.Error	t value	Pr(>|t|)
(Intercept)	-5.42587	0.20664	-26.258	< 0.0001*
WP	0.304542	0.146499	2.079	0.038*
SC	-0.16177	0.166646	-0.971	0.332
Maximizer [b]	-0.54323	0.150797	-3.602	0.0003*
PowerLock[b]	-1.05842	0.148866	-7.11	< 0.0001*
SC Maximizer	-0.49139	0.153832	-3.194	0.001*
SC PowerLock	-0.89444	0.146654	-6.099	< 0.0001*
WP Maximizer	-0.65979	0.160134	-4.12	< 0.0001*
WP PowerLock	-0.68294	0.159084	-4.293	< 0.0001*
log Distance (m)	-1.66215	0.02758	-60.267	< 0.0001*
Wind Speed (m/s)	0.455592	0.063746	7.147	< 0.0001*
RH (%)	0.019221	0.006816	2.82	0.005*
WP × RH (%)	-0.00602	0.01066	-0.565	0.572
SC × RH (%)	-0.03335	0.021728	-1.535	0.125
Maximizer × RH (%)	-0.03756	0.014681	-2.558	0.010*
PowerLock × RH (%)	0.034091	0.010877	3.134	0.001*
SC Maximizer × RH (%)	0.017643	0.016531	1.067	0.286
SC PowerLock × RH (%)	0.002819	0.009565	0.295	0.768
WP Maximizer × RH (%)	0.03434	0.014663	2.342	0.019*
WP PowerLock × RH (%)	-0.00109	0.009062	-0.121	0.904*

3 [a] Data centered on mean RH so that the estimates of the main term effects can be interpreted at
4 average RH instead of zero. Overall model had an adjusted R^2 of 0.8934.
5 [b] Spray enhancement additives
6 * Statistically significant at α=0.05
7 WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension
8 concentrate formulation of insecticide spinosad); RH = Relative humidity

Table 5. Coefficient estimates and SEs for selected volume median diameter (VMD) [a]

[a] Data centered on mean wind speed so that the estimates of the main term effects can be interpreted at average wind speed instead of zero. Overall model had an adjusted R^2 of 0.4187. * Statistically significant at α=0.05 WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension concentrate formulation of insecticide spinosad); RH = Relative humidity

2 Table 5. Coefficient estimates and SEs for selected volume median diameter (VMD) [a]

Ref. = Water	Estimate	Std. Error	t-value	Pr(>|t|)
(Intercept)	3.94112	0.049635	79.402	< 0.0001*
WP	0.13277	0.03384	3.923	0.0001*
SC	0.118991	0.029544	4.028	< 0.0001*
Maximizer	0.073092	0.031878	2.293	0.023*
PowerLock	0.134597	0.031834	4.228	< 0.0001*
SC Maximizer	0.088095	0.030629	2.876	0.004*
SC PowerLock	0.149319	0.030304	4.927	< 0.0001*
WP Maximizer	0.108916	0.029193	3.731	0.0002*
WP PowerLock	0.093255	0.037198	2.507	0.013*
Distance (m)	-0.00069	0.00068	-1.02	0.309
RH (%)	-0.00546	0.000679	-8.042	< 0.0001*
Height (m)	-0.07025	0.013066	-5.377	< 0.0001*
Wind Speed (m/s)	0.007064	0.035475	0.199	0.842
WP* Wind Speed (m/s)	0.124947	0.061732	2.024	0.044*
SC* Wind Speed (m/s)	0.093626	0.041187	2.273	0.024*
Maximizer × Wind Speed (m/s)	-0.04367	0.053981	-0.809	0.419
PowerLock × Wind Speed (m/s)	0.071954	0.050305	1.43	0.154
SC Maximizer × Wind Speed (m/s)	0.081286	0.04373	1.859	0.064
SC PowerLock × Wind Speed (m/s)	0.084699	0.058615	1.445	0.149
WP Maximizer × Wind Speed (m/s)	0.01789	0.042898	0.417	0.677
WP PowerLock × Wind Speed (m/s)	-0.03036	0.050863	-0.597	0.551

4 [a] Data centered on mean wind speed so that the estimates of the main term effects can be
5 interpreted at average wind speed instead of zero. Overall model had an adjusted R^2 of 0.4187.
6 * Statistically significant at α=0.05
7 WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension
8 concentrate formulation of insecticide spinosad); RH = Relative humidity

Table 6. Treatments ordered by droplet size and ground deposition [a]

[a] The treatments with the largest fraction of "fine" droplets (100-175 μm) measured in the wind tunnel had the highest downwind ground deposition in the field study at any downwind distance. WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension concentrate formulation of insecticide spinosad)

2   Table 6. Treatments ordered by droplet size and ground deposition [a]

Treatments Containing Active Ingredient Sprayed in Wind Tunnel	% Spray Volume Containing Droplets ≤ 141 µm (SD)	Treatments Ordered by Ground Deposition (Highest to Lowest)	Droplet Size is Indication of Spray Drift
WP	19.98 (0.61)	WP	Yes
SC	15.30 (0.28)	SC	Yes
SC & Maximizer	13.62 (0.03)	SC & Maximizer	Yes
WP & Maximizer	13.33 (0.08)	WP & Maximizer	Yes
WP & PowerLock	12.18 (0.23)	WP & PowerLock	Yes
SC and PowerLock	11.69 (0.08)	SC and PowerLock	Yes

4   [a]   The treatments with the largest fraction of "fine" droplets (100-175 µm) measured in the wind
5   tunnel had the highest downwind ground deposition in the field study at any downwind
6   distance.
7   WP = Entrust (wettable powder formulation of insecticide spinosad); SC = Entrust SC (Suspension
8   concentrate formulation of insecticide spinosad)

Figure 1. Field layout for drift experiment in Fresno, California.

Blue circles represent locations where only horizontal ground samplers (14-cm diameter Petri dishes) were placed. Blue triangles represent locations where ground samplers and 2-m vertical samplers (rotating impingers) were placed. Blue rectangles represent locations were ground samplers and 1- and 2-m vertical samplers were placed. Black rectangles (located at farthest downwind distance from spray source) represent locations were only 1- and 2-m vertical samplers were placed, no ground samplers were placed there in 2015 and 2016. The control area was located 15 m from the farthest upwind edge of spray line 2. Collector locations in diagram are not representative of actual distances in the field.
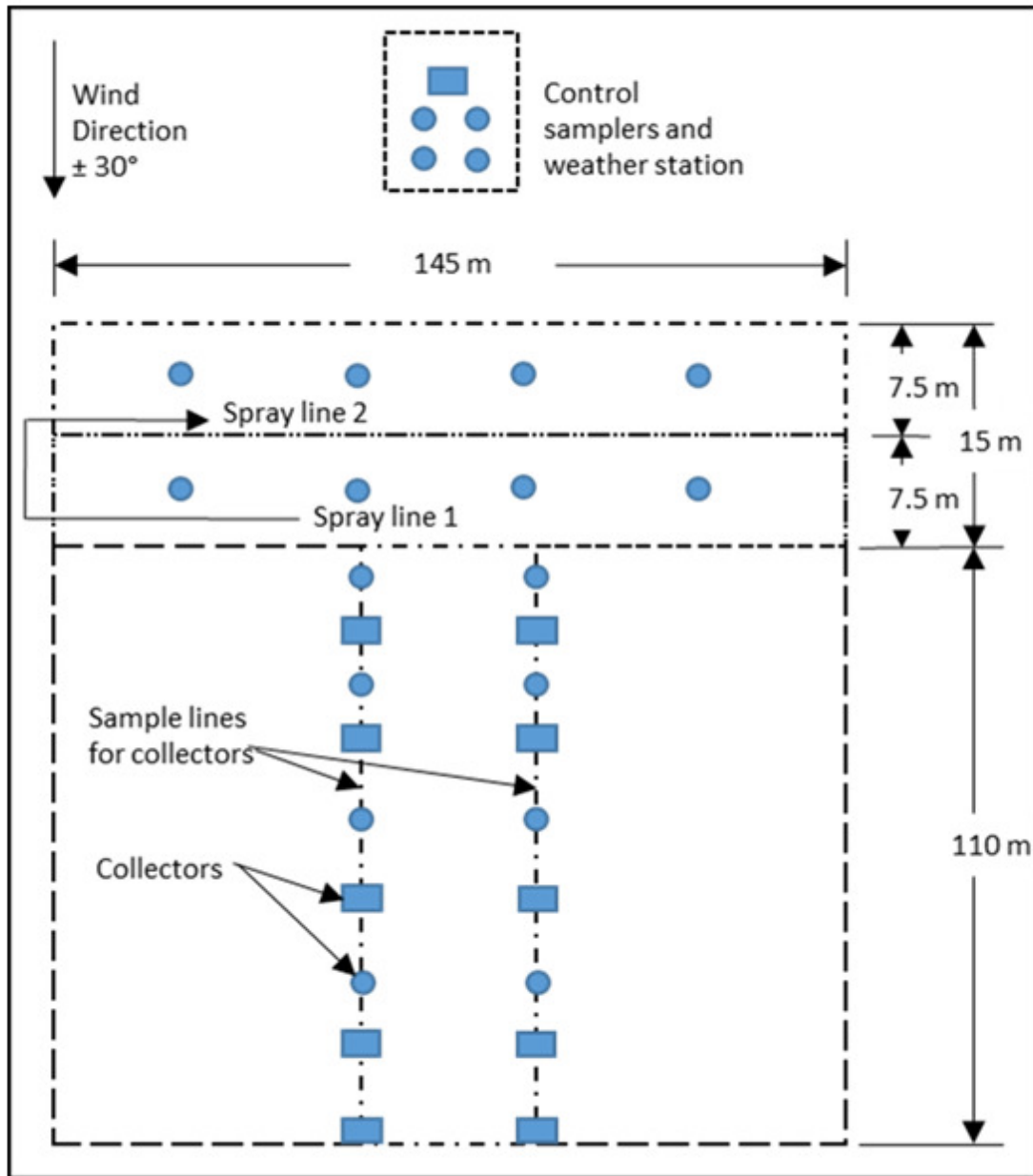
Figure 2. Predicted deposition of Rhodamine-WT as a function of distance at average RH and wind speed.

After controlling for wind speed and RH, this decrease in deposition was estimated to be 68.4% with an associated 95% confidence interval from 67.19 to 69.57% for every doubling of distance (i.e. going from one ground sample to the next in this study). Adjusted R^2 of 0.8934 from overall model and gray bands represent the 95% C.I.
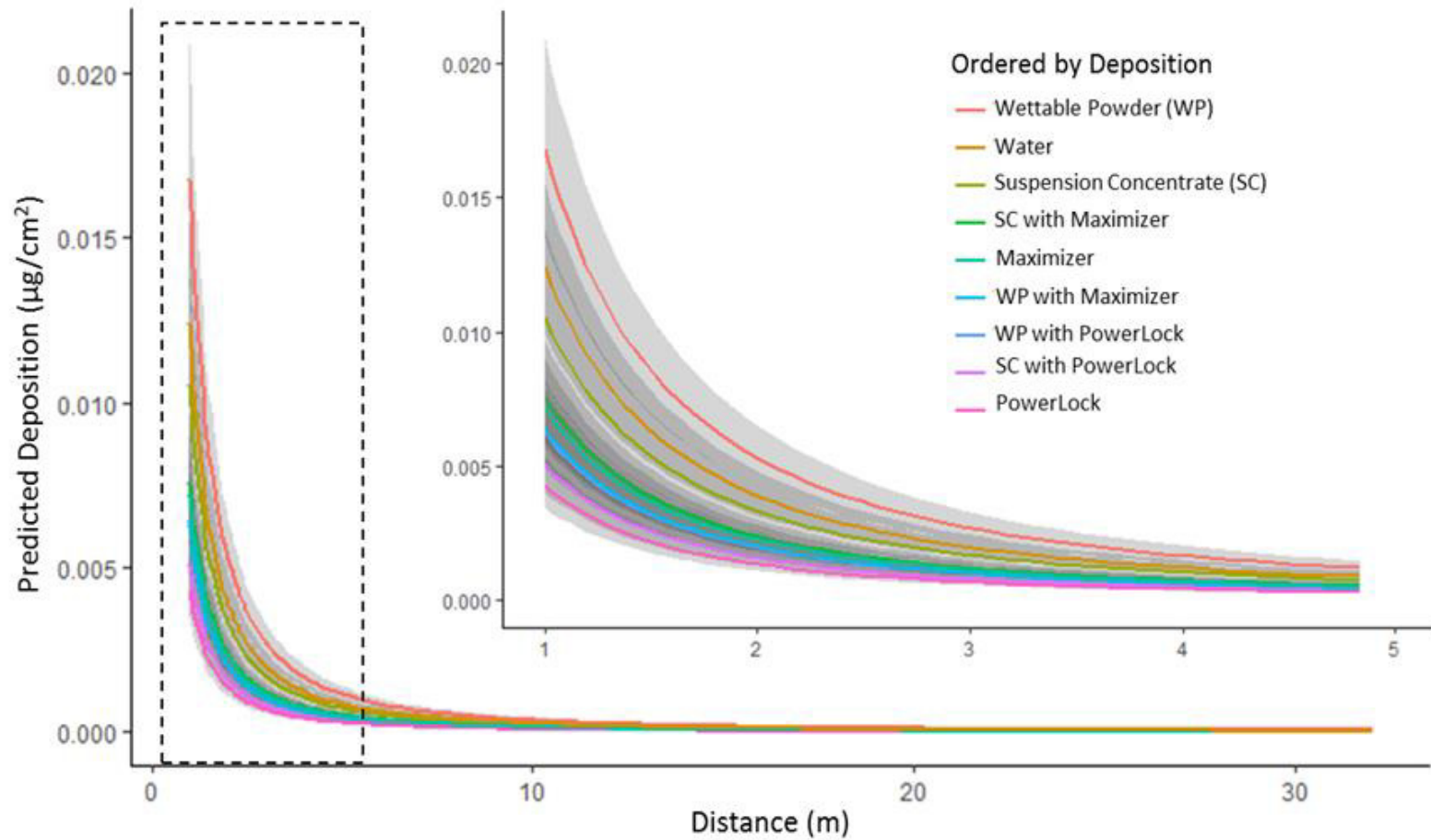
Figure 3. Predicted deposition of Rhodamine-WT as a function of wind speed at average RH and a distance of 1 m.

All treatments exhibited more deposition in higher wind conditions with every additional 1-unit increase in wind speed (m/s) resulting in an estimated 36.59% increase in deposition after controlling for distance and RH (95%CI from 28.13 to 44.06%). Adjusted R^2 of 0.8934 from overall model and gray bands represent the 95% C.I.