Effect of insecticide formulation and adjuvant combination on agricultural spray drift

Collin J Preftakes [Corresp., 1], Jerome J Schleier [2], Greg Kruger [3], David 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: Collin J Preftakes
Email address: collin.preftakes@student.montana.edu

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 spray drift was reduced by 37% when comparing the suspension concentrate to the wettable powder formulation. As much as 63% drift reduction was achieved by incorporating certain spray adjuvants, but this 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.

EFFECT OF INSECTICIDE FORMULATION AND ADJUVANT COMBINATION ON AGRICULTURAL SPRAY DRIFT

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

a. Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, United States

b. Corteva AgroSciences, Indianapolis, Indiana, USA

c. University of Nebraska, West Central Research & Extension Center, North Platte, Nebraska, USA

Corresponding Author:
Collin J Preftakes[a]
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 spray drift was reduced by 37% when comparing the suspension concentrate to the wettable powder formulation. As much as 63% drift reduction was achieved by incorporating certain spray adjuvants, but this 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
46 Environmental conditions can affect pesticide spray drift and must be considered when making
47 an application, but these cannot be controlled. The only option when facing unfavorable
48 environmental conditions is to decide to postpone or cancel the application. Operating
49 conditions, on the other hand, can be manipulated to mitigate spray drift by the person making
50 the application decision. Environmental conditions such as wind speed and direction,
51 temperature, relative humidity, atmospheric stability, and crop characteristics interact with
52 airborne droplets and influence their deposition. Operational parameters such as boom height,
53 driving speed, spray pressure, nozzle orientation, and application rate can reduce drift and are
54 among the variables that can be readily manipulated by the equipment operator. Nozzle type,
55 nozzle size, formulation type, and tank additives are commercially available DRTs designed to
56 decrease drift through modification of the droplet size distribution upon atomization. Other
57 DRTs such as shielded- and air-assisted sprayers function by interrupting the interaction between
58 airborne droplets and the surrounding air movement.
59
60 There are a number of commercially available DRTs and the EPA has recently developed a
61 protocol for verifying and rating their drift reduction potential [7]. The protocol provides a
62 standard method for the application technology industry to voluntarily test DRTs. Pesticide drift
63 considerations are included in all registration processes and registrants are encouraged by EPA to
64 include verified DRT options on product labels. However, there are limitations to this protocol
65 because it has only been evaluated for spray nozzles in low- and high-speed wind tunnels, and
66 does not include the effect of tank mixes.
67
68 In this paper, the combination of a formulated pesticide active ingredient, with or without an
69 adjuvant, is referred to as the spray solution. A pesticide formulation is a mixture of chemicals
70 designed to maximize intended biological efficacy. Physical properties of certain formulation
71 types have been shown to influence how droplets are formed upon atomization at the spray
72 nozzle. Adjuvants are tank additives that are marketed for their enhancement benefits according
73 to the function they are designed to perform. Some adjuvants are designed to enhance the
74 performance of the pesticide, usually through better absorption, whereas others are designed to
75 enhance qualities of the spray by modifying the physical properties of the spray solution [9, 10].
76
77 Manipulating components in the spray solution as a drift reduction strategy has been reported in
78 the scientific literature less than other technologies such as nozzle type, and results are variable
79 [11-15]. Quantification of drift reduction due to formulation and adjuvant type is an important

80 objective because these components can have effects that are equivalent to those due to nozzle
81 type on downwind deposition [13]. Furthermore, selecting the formulation with optimal drift
82 reduction potential could reduce the need to include drift reduction adjuvants, which may not
83 perform consistently when employed in different combinations. Therefore, this research
84 characterizes downwind deposition of two common formulation types and adjuvants from a
85 ground sprayer in a three-year field study.
86
MATERIALS & METHODS
88 **Field Trial Design.**
89 Field experiments were conducted over three consecutive summers from 2014 to 2016 at the
90 Dow AgroSciences Western U.S. Research Center near Fresno, California. The topography at the
91 field site was flat, and there was no vegetation because it had been fallow the previous season,
92 and disked before the start of the experiment. The spray swath was 145-m long by 15-m wide,
93 and oriented with driving direction perpendicular to the wind direction. The off-target area was
94 110 m by 145 m and downwind from the spray source. Two sample lines 2.5 m to the left and
95 right of the center of the off-target plot consisted of both horizontal (ground) and vertical (1 and
96 2 m above ground) sample locations. The sample lines were perpendicular to the spray line and
97 approximately parallel to the wind direction. The orientation and relative lengths of the spray
98 swath and sample lines (Figure 1) were designed so that spray droplets could travel toward the
99 farthest downwind sample locations if no more than a 30° deviation angle in wind direction was
100 allowed [16].
101
102 Downwind insecticide ground deposition was collected with 14-cm diameter plastic Petri dishes
103 (Fisher Scientific Cat. No. FB0875714). Petri dishes were horizontally placed on plywood at 8
104 distances of 1, 2, 4, 8, 16, 32, 64, and 110 m from the field edge, along each of the two sample
105 lines. The downwind samplers along the two lines were subsamples, so for statistical analysis the
106 deposition data were averaged for each distance. Plywood was placed on the ground to provide a
107 level surface for the dishes. Also, along the two sample lines (averaged for statistical analysis) at
108 2, 8, 32, 64, and 110 m, vertical samplers were positioned 1 and 2 m above the ground to sample
109 the size distribution of the spray droplets at different heights and distances. Each vertical sampler
110 (spinner) consisted of two rotating microscope slides with a spin rate of 600 rpm, designed to
111 impinge airborne droplets (Leading Edge Associates, Inc.). The microscope slides were coated
112 with a magnesium oxide (MgO) powder so that analysis could be done at a later date. This is
113 made possible by the MgO–coating because measurements are made on the droplet imprints
114 instead of the droplets themselves, which are prone to evaporation [17].
115
116 An untreated area located 15-m upwind from the spray swath contained negative controls for
117 both horizontal and vertical samplers, and a weather station to monitor environmental conditions.
118 The weather station consisted of a Hobo Micro Station Data Logger (Onset Computer
119 Corporation) attached to 12-bit temperature and relative humidity sensors with a solar radiation

120 shield and a wind speed and direction smart sensor positioned 2.5 m above the ground. The Hobo
121 wind speed smart sensor (S-WSA-M003) had a starting threshold of ≤ 1 m/sec and the logger
122 was set to measure wind speed every 20 seconds. The average wind speed was calculated over
123 the first 10 minutes of each treatment replication to characterize wind speeds before, during, and
124 after each application.

125

126 Hobo temperature and relative humidity data loggers were also used at different heights (2.5 and
127 9.2 m) to monitor atmospheric stability. Atmospheric stability was categorized by first
128 calculating the stability ratio with the following equation from Fritz [18]:

129

130 $SR = [(TZ_2 - Tz_1/\mu w^2] \cdot 10^5$ (1)

131

132 where SR is the stability ratio, TZ_2 and Tz_1 is the air temperature (°C) at 9.2 m and 2.5 m
133 respectively, μw is the mean wind velocity (cm/s) at 2.5 m, and 10^5 gives the ratio acceptable
134 units. The SR for each treatment application was calculated from the average wind speed and
135 temperatures and were assigned to 4 categorical variables, "unstable", "neutral", "stable", and
136 "very stable" [18].

137

138 Treatments consisted of two formulation types, two adjuvants, and water only. Each formulation
139 type and adjuvant was applied individually (4 treatments), and each formulation type was also
140 combined with each of the adjuvants (4 treatments). This results in 9 treatments, when including
141 water only, from a 3x3 factorial design. We used the active ingredient spinosad (a mixture of
142 spinosyn A and spinosyn D) formulated as a wettable powder (WP) and a suspension concentrate
143 (SC) under the product names Entrust® insecticide and Entrust® SC insecticide containing 80 and
144 22.5% active ingredient, respectively (Dow AgroSciences, LLC). The two adjuvant products
145 were Maximizer (Loveland Products, Inc.) and Powerlock (Winfield Solutions, LLC).
146 Maximizer is composed of paraffin based petroleum oil (83%) and nonionic surfactant (16.3%),
147 whereas Powerlock contains modified vegetable oil (63%) and nonionic surfactant (32%). The
148 water-soluble fluorescent dye Rhodamine-WT (CAS No: 37299-86-8) was mixed with the spray
149 solution of each treatment (0.2% v/v) to allow for the quantification of spray deposition [19].

150

151 Petri dishes and spinners were placed within the control area at the beginning of each replication
152 and the treatment solution was sampled immediately before application to measure the actual
153 fluorescent dye concentration in the tank. From the tank sample, two control dishes were loaded
154 with 0.1 mL to quantify potential tracer degradation and recovery for each replication. Eight
155 Petri dishes were also placed within the spray swath before application to estimate deposition
156 within the targeted area. These samplers were evenly spaced 29.3 m apart along the middle of
157 each of the two spray lines.

158

159   Treatments were selected in random order and applications were made with a ground rig boom
160   sprayer (Avenger high clearance tractor by Lee). The boom length was 7.62 m and all
161   applications were made with a boom height above the ground of 58 cm. For this study, 15 TeeJet
162   XR11002 flat fan broadcast nozzles with a 110° spray angle, and a size 50 mesh (TeeJet 8079-
163   PP-50), were evenly spaced 50.8 cm apart, along the length of the boom. Spray pressure was
164   measured at the end of the spray boom and driving speed was monitored by an onboard GPS
165   system; these were held at 2.07 bar and 6.8 km/h (4.2 mph), respectively. Two spray passes per
166   application were made to simulate a single pass with a 15 m spray boom.
167
168   Following each treatment replication (spray application) horizontal and vertical samples were
169   collected from all locations (off-target, on-target, and untreated). Sample collection began three
170   minutes after the sprayer had been turned off at the end of the spray swath to allow for deposition
171   to occur at the farthest samplers. Exposed Petri dishes and microscope slides were placed in dark
172   containers to minimize photo-degradation of any insecticide or fluorescent material, and control
173   samples were the last to be collected. Replications were performed over time within the same
174   day or over multiple days with 9 replications of each of the 9 treatments, totaling 81 spray events
175   in the months of July (2014), and May (2015, 2016).
176

177   **Field Trial Analysis.**
178   Insecticide deposition on Petri dishes was extracted with 15 ml of deionized (D.I.) water and
179   decanted into 20-ml scintillation vials (Thermo Fisher Scientific). Analysis vials were wiped
180   with Kimwipes (Kimberly-Clark, LLC) to remove exterior moisture, and were inspected for
181   clarity before being analyzed. Light absorption at a specific wavelength, representing the amount
182   of dye present in each sample, was quantified and recorded using a GFL-1A fluorometer (Opti-
183   Sciences, Inc). The source and detection filters that were used for the excitation and detection of
184   Rhodamine-WT were 530 and 590 nm, respectively (manufacturer recommendation). Standard
185   curves were prepared using serial dilutions prepared in D.I. water. The detection limit (DL) of
186   Rhodamine-WT, given the sensitivity of the fluorometer, was estimated by adding three standard
187   deviations of a known low concentration measured 20 times to the mean of a blank sample [20].
188   After extraction and analysis, Petri dishes were discarded and scintillation vials were triple rinsed
189   with D.I. water before reuse. Less than 10% of the ground samples consisted of concentrations
190   below the DL so one half of the DL was substituted for non-detectable concentrations [21-23].
191

192   Statistical analysis for ground deposition was conducted using the amount of Rhodamine-WT
193   deposited per unit area ($\mu g/cm^2$) for each distance, averaged over the two sample lines. Tank
194   mixes for each treatment were analyzed for actual dye mixing rates following the procedure
195   above. Based on the actual amount of dye in the tank, the estimated volume on the spiked control
196   plates was compared to the actual volume of the spike (0.1 mL) to estimate recovery rates for
197   each treatment. The following steps were followed to represent deposition as a percentage of the
198   total material applied [24]. First the area for each sample location was calculated, as one-half the

199 distance between two sample locations multiplied by the diameter of the Petri dish (Table 1). The
200 application rate of the dye for each treatment was then estimated by multiplying the actual dye
201 mixing rates by the application rate (Table 2). Multiplying the application rate of the dye by the
202 total area of the sample locations returned the total mass of dye applied. The area for each
203 sample location was then multiplied by the deposition data, averaged over the two sample lines,
204 for each distance, to return mass of dye per sample location. Finally, the mass of dye per sample
205 location was divided by the total dye applied to express deposition as a percentage of applied
206 material. Deposition data for both in swath and downwind samples were calculated in this way.
207
208 Due to minimal ground deposition beyond 32 m, only 6 downwind distances were included in
209 the statistical analysis. This resulted in a total of 486 data points (9 treatments, 6 distances, 9
210 reps) for ground deposition which were analyzed using multiple linear regression in the
211 statistical software package R, version 3.3.2 [25]. Exploratory data analysis was done to identify
212 outliers, potential interactions, linearity, and normality, among dependent and independent
213 variables. Table 3 lists summary statistics for numerical variables considered in this data set.
214
215 Log transformations on the deposition of Rhodamine-WT (μg/cm^2) and the independent variable,
216 distance (m), were required before parametric statistics could be used. Correlation coefficients
217 between independent variables was used to eliminate those with a correlation greater than 0.5 to
218 avoid collinearity. This resulted in the exclusion of temperature and relative humidity (RH) at the
219 upper height (9.2 m), as well as temperature measured at the lower height (2.5 m). Temperature,
220 instead of RH, at 2.5 m was removed because RH resulted in a better fit for the regression model,
221 and because 2.5 m is a more practical measurement height. Model selection with Akaike's
222 information criterion (A.I.C.) was used to select between candidate models, which were based on
223 specific hypotheses about pesticide drift. Full and reduced models were compared using an extra
224 sums of squares (ESS) F-test to determine the contribution of certain independent variables in
225 explaining variability in the response variable. The model with the lowest AIC was selected and
226 diagnostic plots were used to check that the requirements for linear regression were met
227 regarding statistical assumptions. The data were centered by subtracting the average RH so that
228 the main term coefficients for treatment could be interpreted as the estimates at average RH,
229 rather than zero.
230
231 Droplet spectra resulting from deposition on vertically positioned microscope slides were
232 recorded with a DropVision measurement system (trademark of Leading Edge Associates, Inc).
233 The DropVision system integrates a compound microscope and image processing software to
234 recognize, count, and measure droplets while eliminating background objects. A calibration slide
235 containing circles of known diameters was used to calibrate the system at 10X magnification.
236 This is achieved by relating the number of pixels contained in the calibration circle to its
237 diameter. Microscope slides for all three years (4,221 slides) were scanned by a single person
238 following a specific protocol to minimize user error. A specific viewing pattern was designed to

239   sample a representative number of droplet impressions from an evenly distributed area of the
240   slide surface. A minimum of 100 droplets or 200 pictures were required before moving to the
241   second slide from a given field location (each spinner contains two slides). Once 200 droplets
242   were counted, or the entire surface area of both slides was viewed, the droplet statistics were
243   compiled into a report produced by the software. The diameter at which half of the volume was
244   contained in droplets smaller than the median (VMD) was recorded for all slide sets containing
245   30 or more droplets, which limited the farthest downwind distance from the spray source to 32
246   m, resulting in 273 data points for statistical analysis.
247
248   The same statistical approach for ground deposition was used to analyze the droplet data.
249   Correlated independent variables that were excluded above were also excluded here. Exploratory
250   analysis suggested a log transformation of the response (VMD) was required to meet
251   assumptions of normality and AIC model selection was used to choose the final model. The
252   predictor variable for height was analyzed as a categorical variable at 1 and 2 m above the
253   ground. Linear model assumptions were assessed using residual plots and the global validation
254   package, gvlma, in R [26]. These data were centered by subtracting the average wind speed so
255   that the main term coefficients for treatment could be interpreted as estimates at average wind
256   speed.
257
258   **Wind Tunnel.**
259   The droplet spectra of all treatments were also measured in a wind tunnel so that general trends
260   in droplet size could be compared to differences in ground deposition from the field study. Using
261   the same application system as in the field study (i.e. nozzle set up, application rate, and spray
262   pressure) three replications of each treatment were sprayed in a wind tunnel at the University of
263   Nebraska West Central Research & Extension Center in North Platte, Nebraska. A Sympatec
264   laser diffraction particle size analyzer (Sympatec Inc.) positioned near the spray nozzle was used
265   to measure droplet spectra for each of the treatments in the wind tunnel. Droplet sizing data
266   measured for each treatment included VMD, the 10% and 90% diameters, the relative span, and
267   the percent spray volume contained in droplets less than 141 μm. This percentage represents the
268   fraction of spray droplets within the "fine" classification (100-175 μm) for droplet sizes [27], and
269   was used as an indicator for spray drift. The treatments were ranked according to the percentage
270   of droplets within this size range and compared to the ranks for ground deposition (Table 4).
271
272   **Efficacy.**
273   An insecticide efficacy experiment was also conducted to test differences in insect control
274   between the treatments used in the drift study. The study was conducted August 2016 at the same
275   experimental station in Fresno, California. The experimental setup was a randomized complete
276   block design with 7 treatments (treatments consisting of only adjuvant were excluded) and 4
277   replications (blocks) of each treatment. Each plot was 3.05 m long and 2.03 m wide, and
278   contained two rows of newly planted broccoli (Green Magic variety of Brassicaceae sp., 16

279   plants per plot). Plots were 1.5 m apart, and two empty rows (2.03 m) were left between blocks
280   to avoid contamination from adjacent plots. Before spraying on application day a pre-count was
281   conducted to record cabbage looper larvae (*Trichoplusia ni*) on broccoli plants in the study area
282   which had been infested by endemic populations. Applications were made with a handheld boom
283   sprayer at the same rate, and with the same nozzle type, as in the drift study. All treatments were
284   applied in random order and *Trichoplusia ni* larvae on the broccoli plants were counted to
285   estimate percentage mortality at 1, 3, and 7 days after application.
286
287   Efficacy data were represented and analyzed as count data, and as a fraction of the untreated
288   control plots at each time-step after application. Count data and percent mortality data were
289   analyzed using ANOVA fit to a linear model for a randomized block design in R, version 3.3.2
290   [25]. The hypothesis that was tested with the count data was that there would be no differences in
291   the number of *Trichoplusia ni* larvae between treated and untreated plots. For the percent
292   morality data the tested hypothesis was that there would be at least one difference in percent
293   mortality between treatments.
294

295   **RESULTS**
296   **Ground deposition.**
297   The recovery rates of Rhodamine-WT for each treatment were within the recommended range of
298   80 to 120% [7, 16]. The high recovery rate of the dye from the control plates suggests that
299   degradation of the fluorescent dye in samples was negligible due to the short exposure time to
300   sunlight. In some cases, more material was deposited on the swath plates than was expected
301   given the application rate of the dye. Potential sources of error that may have contributed to an
302   inaccurate estimation of recovery include fluctuations in the actual driving speed, spray pressure,
303   flow rate, or errors in the analysis on the fluorometer [28].
304
305   Coefficient estimates and standard errors for the selected model for ground deposition, centered
306   on average relative humidity, are listed in Table 5. Treatment, log of distance (m), wind speed
307   (m/s), relative humidity (%), and a term for the interaction between treatment and relative
308   humidity were included in the final model. Year, stability ratio, and stability category were
309   excluded because they had no effect on deposition, and did not significantly change the error
310   sums of squares when compared to the final model (ESS F-test, F=1.46, *p*=0.2004, on 461 and
311   466 degrees of freedom). Diagnostic plots of the model residuals suggested that the assumptions
312   of normality, linearity, and homoscedasticity were reasonably met. The selected regression
313   model for the ground deposition data was shown to explain 89.3% of the variability in the
314   response variable (adjusted R-squared of 0.8934 for overall model). The regression equation
315   centered on relative humidity with water as the reference level for treatment is:
316
317   LT= -5.43+0.305*WP+0.162*SC-0.660*WPMax-0.683*WPPL-0.491*SCMax
318   -0.894*SCPL -0. 543*Max-1.058 *PL -1.662*LD+0.456*Wind-0.019*RH

319   +0.006(WP*RH)-0.038(Max*RH)+0.034(PL*RH)+0.0176(SCMax*RH)

320   +0.003(SCPL*RH)-0.033(SC*RH)+0.034(WPMax*RH)-0.001(WPPL*RH)   (2)

321

322   where LT is the log of the Rhodamine-WT deposition ($\mu g/cm^2$), WP= Entrust (WP) insecticide,

323   Max=Maximizer, SCPL=Entrust SC insecticide with PowerLock, WPMax=Entrust (WP) with

324   Maximimzer, WPPL=Entrust (WP) with PowerLock, LD is the log of the distance (m),Wind is

325   wind speed (m/s), and RH is the relative humidity (%) at 2.5m above the ground. Full

326   coefficients for equation 2 are listed in Table 5.

327

328   Deposition of Rhodamine-WT ($\mu g/cm^2$) for all treatments decreased with increasing distance

329   from the field edge as indicated by the negative coefficient for logged distance in the overall

330   regression model ($p<0.0001$, Table 5). After controlling for wind speed and RH, this decrease in

331   deposition was estimated to be 68.40% with an associated 95% confidence interval (CI) from

332   67.19 to 69.57% for every doubling of distance (e.g. going from one ground sample to the next

333   in this study, Figure 2). The treatments with the highest and lowest amounts of active ingredient

334   observed at the farthest downwind distance were Entrust SC insecticide with Maximizer and

335   Entrust (WP) insecticide with PowerLock, respectively.

336

337   All treatments also exhibited more deposition in higher wind conditions as indicated by the

338   negative coefficient for wind speed in the overall regression ($p<0.0001$, Table 5), with every

339   additional unit increase in wind speed (m/s) resulting in an estimated 36.59% increase in

340   deposition after controlling for distance and RH (95% CI from 28.13 to 44.06%) (Figure 3).

341   The interaction between RH and treatment suggests that the effect of RH on deposition depends

342   on treatment type. Neither Entrust SC nor Entrust (WP) were affected by RH, but water alone, as

343   well as all treatments which included adjuvant, exhibited higher deposition with increasing RH

344   over the range of RH measured in this study.

345

346   Relative humidity had a larger positive effect on deposition of Entrust SC with Maximizer

347   compared to the Entrust SC treatment alone ($p=0.041$). However, the effect of RH on deposition

348   of the Entrust SC with PowerLock combination was not significantly different than for Entrust

349   SC alone (p=0.10). The same trend was observed when comparing the effect of RH on

350   deposition between the WP formulation and WP plus the two adjuvants. Deposition of Entrust

351   WP with Maximizer was more affected by RH than Entrust WP alone ($p=0.010$), but Entrust WP

352   with PowerLock was not affected differently than Entrust WP alone ($p=0.623$).

353

354   At the average RH (58.55%) recorded in this study, deposition of the SC formulation was lower

355   than for the WP formulation after controlling for distance and wind speed (p=0.0045). The

356   estimated difference in deposition between Entrust SC and Entrust WP was 37.27% with an

357   associated 95% confidence interval from 13.54 to 54.48%. With the exception of the Entrust WP

358 and Entrust SC insecticide treatments, deposition of the water only treatment was greater than for
359 all other treatments at the average RH, and fixed distance and wind speed (α=0.05).
360
361 The difference in deposition between the formulated product with and without the adjuvant is
362 interpreted as the effect on drift caused by the adjuvant. When comparing deposition of the
363 Entrust SC treatment to deposition of this formulation with each of the two adjuvants,
364 PowerLock reduced deposition, but Maximizer did not (p<0.001 & p=0.0594, respectively). The
365 estimated reduction in deposition caused by the addition of PowerLock to the SC formulation
366 was 51.94% at average RH, and after controlling for distance and wind (95% CI from 33.33 to
367 65.35%).
368
369 Deposition of the WP formulation was reduced with the addition of both the PowerLock and the
370 Maximizer adjuvants by roughly the same amount, at average RH (p<0.0001). After controlling
371 for distance and wind speed, this reduction was an estimated 62.75% (95% CI from 50.34 to
372 72.06%) and 61.88% (95% CI from 48.46 to 71.80%) for PowerLock and Maximizer,
373 respectively.
374
375 **Vertical deposition.**
376 Coefficient estimates and standard errors for the selected model for VMD, centered on average
377 wind speed, are listed in Table 6. Treatment, log of VMD (μm), wind speed (m/s), and relative
378 humidity (%), were included in the final model for vertical deposition. Year, stability ratio, and
379 stability category were excluded because they had no effect on deposition, and did not
380 significantly change the error sums of squares when compared to the final model (ESS F-test,
381 F=1.204, p=0.3079, on 247 and 252 d.f.). Diagnostic plots of the model residuals suggested that
382 the assumptions of normality, linearity, and homoscedasticity were reasonably met. The selected
383 regression model for the VMD data was shown to explain 41.9% of the variability in the
384 response variable (Adjusted R-squared of 0.4187 for overall model). The estimated regression
385 equation for logVMD from the selected model centered on wind speed and with water as the
386 reference level for treatment is:
387
388 lVMD= 3.941+0.133*WP+0.119*SC+0.109*WPMax+0.093*WPPL+0.089*SCMax
389 +0.149*SCPL+0.073*Max+0.135*PL-6.9E-4 *D-0.005*RH-0.070*Height
390 + 0.101*Wind+0.125(WP*Wind)+0.094(SC* Wind) +0.018(WPMax* Wind)
391 -0.030(WPPL* Wind)+0.081(SCMax* Wind) +0.085(SCPL* Wind)
392 -0.044(Max* Wind)+0.072(PL* Wind)   (3)
393
394 Where lVMD is the log of the VMD (μm), D is the distance from the field edge (m), and Height
395 is the vertical distance above the ground from 1 to 2 m, at which the rotating microscope slides
396 were positioned. All other variables are defined the same as in equation (2). Full coefficients for
397 equation 3 are listed in Table 6.

398

399   The VMD was not significantly affected by distance after controlling for height, wind speed, and
400   RH (p=0.3087). Elevated RH led to smaller VMD values for all treatments at fixed height and
401   wind speed as indicated by a negative coefficient from the overall regression model (p<0.0001).
402   The estimated rate at which VMD decreased was 0.544% for every 1-unit increase in RH (%)
403   with an associated 95% CI from 0.411 to 0.677%. The results also suggest that larger droplets
404   were collected on spinners at the lower height (1 m) compared with the upper heights (2 m) for
405   all treatments and distances (p<0.0001). Droplets collected at 1m were an estimated 6.7% larger
406   than droplets collected at 2 m with an associated 95% CI from 4.35 to 9.15%.

407

408   The interaction between treatment and wind speed suggests that the effect of wind speed on
409   droplet size differs between treatments. Of the treatments that were affected by wind speed, the
410   effect was such that higher wind speed resulted in larger VMD values (positive slope). The effect
411   of wind speed on VMD was not different between Entrust SC insecticide and Entrust (WP)
412   insecticide (p=0.568). When the SC formulation was combined with either of the adjuvants the
413   degree to which wind affected VMD was not changed (p=0.861 and p=0.714 for Entrust SC with
414   PowerLock and Entrust SC with Maximizer, respectively). When the two adjuvants were added
415   to the WP formulation the addition of PowerLock resulted in a lesser influence of wind speed on
416   VMD (p=0.011), but the effect on VMD was not different between Entrust WP with Maximizer
417   and Entrust (WP) alone (p=0.058). The effect of wind speed on VMD for water was significantly
418   lower than for either formulations alone (p=0.024 and p=0.044, for Entrust SC and Entrust WP,
419   respectively).

420

421   At the average wind speed (2.38 m/s), and after controlling for RH, distance, and height, there
422   was no difference in VMD between the two formulations (p=0.666), or between either
423   formulation in combination with either of the adjuvants (p=0.283; 0.272; 0.606; 0.175 for
424   PowerLock and Maximizer combined with Entrust SC and Entrust WP, respectively). The VMD
425   of water was significantly lower than all other treatment combinations at average wind speed and
426   fixed values for RH, height, and distance. The VMD of water was an estimated 8.43% smaller
427   than the treatment with the next largest VMD (Entrust SC with Maximizer), with an associated
428   95% CI from 2.74 to 13.79%. At the average wind speed there was no difference in VMD
429   between either formulation with PowerLock or either formulation with Maximizer (p=0.110 and
430   0.451, respectively).

431

432   The fraction of spray volume containing droplets less than 141 μm, measured in the wind tunnel,
433   can be viewed in Table 4. The order in which treatments had the highest to lowest fraction of
434   fine droplets (<141 μm), measured in a wind tunnel, was the same for treatments ordered by
435   decreasing ground deposition.

436

437

438 **Biological efficacy experiment.**
439 There were statistically fewer *Trichoplusia ni* larvae in the treated plots than in the untreated
440 plots at 3 and 7 days after application, suggesting that all treatments were effective at reducing
441 the pest population ($p<0.05$, ANOVA on 18 d.f.). Furthermore, no difference in percentage
442 mortality was observed between treatments at either 3 or 7 days after application, suggesting that
443 all treatments were similarly effective ($p>0.05$, ANOVA on 15 d.f.).

444

445 **DISCUSSION**
446 Our results provide information on deposition and environmental factors related to agricultural
447 spray drift of two of the most commonly used formulation types [8] under realistic application
448 scenarios, including the use of enhancement additives. Overall, ground deposition values were
449 within the range of EPA assumptions for drift (1-5%) for estimating pesticide exposure to
450 adjacent areas when models are not used [3]. The fraction of applied material, and the estimated
451 68% decrease in ground deposition for every doubling of distance from the field edge, are
452 comparable to findings from other drift experiments [41]. Quantification of exposure and risk to
453 non-target organisms using actual environmental concentrations from this, and similar studies, is
454 needed to fully characterize the benefits of drift reduction technologies.

455

456 Our findings support previous studies in that formulation type can affect spray drift, and should
457 be considered when evaluating a given spray system for its drift potential. Specifically, our
458 results differentiate between two formulations that are typically categorized together with regard
459 to their drift potential. Both wettable powders and suspension concentrates are formulations of
460 solid crystalline active ingredients which form non-deformable dispersions throughout the spray
461 solution [8]. These formulations likely share a common mechanism for affecting spray
462 atomization on the basis of this physical property [29]. However, current scientific literature is
463 inconclusive regarding the effect of solid dispersions on droplet size, and therefore drift [12, 14,
464 29-31]. This study provides evidence that spray solutions of formulations with solid particles do
465 influence drift, and that drift of the WP formulation was greater than for sprays of water alone.
466 Differentiating the drift potential of these closely related formulations could help inform DRT
467 manufacturing decisions, although generalizations are premature.

468

469 The greater drift reduction of PowerLock compared to Maximizer in this study is consistent with
470 results from Western et al. [33], who found that adjuvants of vegetable oil, rather than mineral
471 oils, were more effective at reducing drift, but others have found the effect of these adjuvant
472 types on VMD to be small [34]. Given the many interactions between certain properties of the
473 spray solution and other components of the system, it could be advantageous if no additional
474 tank additives were required to improve drift reduction. Both of the adjuvants tested in this study
475 were shown to effectively reduce deposition without any apparent tradeoffs with biological
476 efficacy, but their effect depended on the formulation type with which they were combined. This

477 demonstrates the additional level of uncertainty introduced by incorporating adjuvants marketed
478 for drift reduction into spray solutions.
479
480 Deposition on the vertical samplers was used to characterize the size distribution of spray
481 droplets throughout the off-target area. Over the distances that were sampled in this study, there
482 was more of a vertical, rather than horizontal, stratification of droplet sizes, with larger droplets
483 collected below 2 m heights. The discrepancy between droplet size and ground deposition with
484 increasing distance could be explained by the fact that the total number of droplets at each
485 distance was not quantified. It is likely that at the greater distances fewer droplets were
486 contributing to both ground deposition and droplet size on the spinners. At average RH and wind
487 speed, the treatment containing only water and Rhodamine-WT had the second highest ground
488 deposition, and the smallest VMD. This suggests that smaller droplets resulted in greater drift,
489 but this cannot be conclusively stated. To test the well supported assumption that smaller droplet
490 sizes lead to greater drift [3, 13, 15, 28, 35-37], we analyzed the droplet spectra of our treatments
491 in a wind tunnel. As expected, we found that treatments with smaller droplets correlated with
492 greater off-target deposition in the field.
493
494 Meteorological factors that affected deposition were wind speed and relative humidity. The
495 observed effect of wind speed on drift is consistent with previous studies [3, 18, 38-40], and is
496 further supported by the presence of larger droplets on the vertical samplers during higher wind
497 conditions. The positive correlation between relative humidity and deposition for some
498 treatments in this study is also reasonable given the relatively short sampling distance from the
499 field edge. Conditions with higher relative humidity are less conducive to evaporation of spray
500 droplets, which may have led to larger droplets and greater deposition over the distances
501 sampled. This may still be true even though the relationship between RH and VMD observed in
502 this study would suggest otherwise. The effect of RH was small relative to the effect of wind
503 speed on VMD, with < 0.1% decrease in droplet size for every 10% increase in RH, whereas a
504 10% increase in wind speed led to an estimated 1.3% increase in VMD.
505
506 **CONCLUSION**
507 This research demonstrates that droplet size is an effective indicator of agricultural spray drift
508 resulting from different formulation types and adjuvants. The EPA verification protocol currently
509 stipulates that when the combined effect of nozzle design and formulated product is evaluated,
510 the drift reduction rating is only valid for that specific combination [7]. Our results suggest that
511 droplet size data could be used to demonstrate drift reduction regardless of the formulated
512 product being sprayed, but more spray mixtures need to be tested before reference sprays can be
513 defined for comparing and rating spray mixtures as DRTs.
514
515
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524

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620

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/cm²)
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. 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)
1
2 Table 4. 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)

1["

2 Table 5. 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 6. 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 6. 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

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.
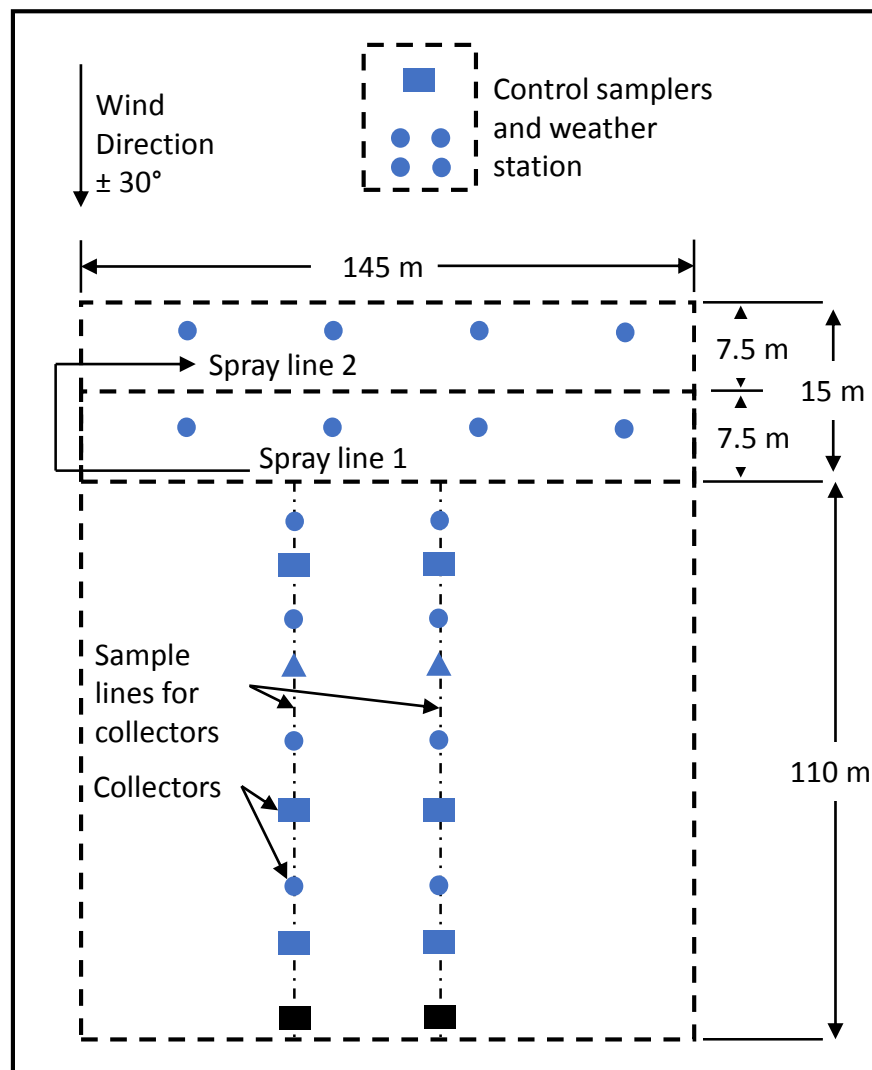
Figure 2. Predicted deposition of Rhodamine-WT as a function of distance at average RH and wind speed.

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 dotted lines represent the 95% C.I.
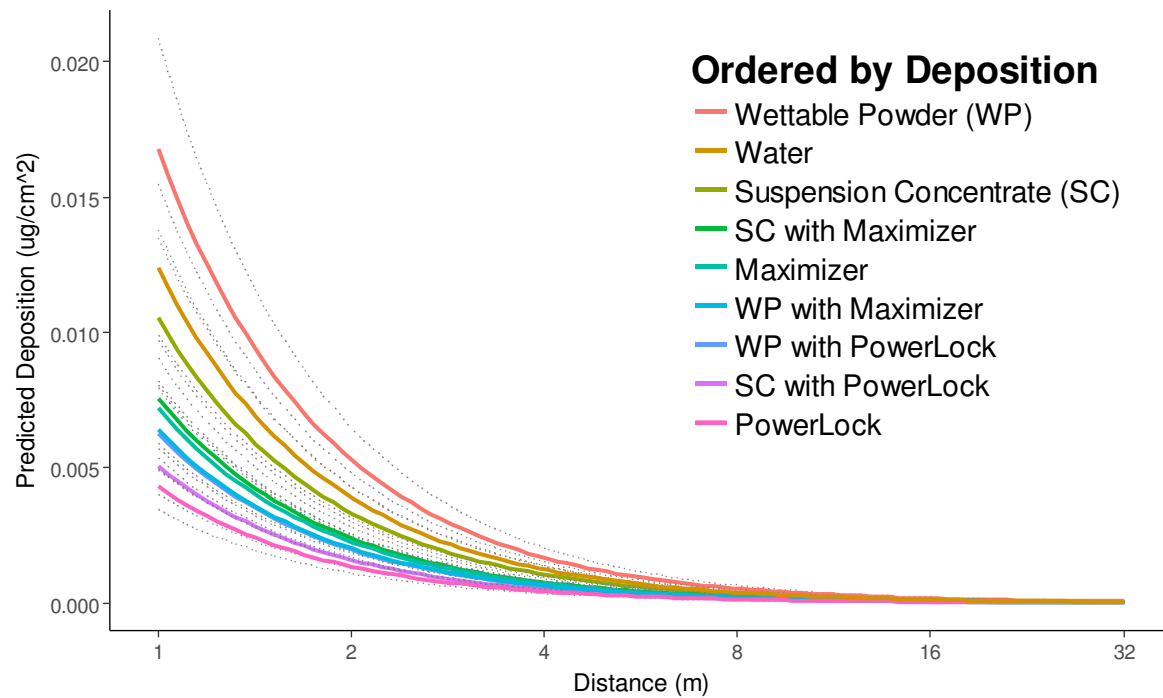
Figure 3. Predicted deposition of Rhodamine-WT as a function of wind speed at average RH and a distance of 1 m.

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 dotted lines represent the 95% C.I.