A Tracer Investigation of Pheromone Dispersion in Lodgepole and Ponderosa Pine Forest Canopies

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Abstract

Tracer experiments were conducted in 2000 and 2001 to study spread of insect pheromone plumes in forest canopies. The field sites consisted of lodgepole pine (*Pinus contorta*) and ponderosa pine (*P. ponderosa*) canopies in 2000 and 2001, respectively. Ranges of temperature, wind speed, and turbulence conditions were similar in the two campaigns, and field data showed comparable variability on near-instantaneous time scales of wind speed, wind direction, and plume behavior. We developed simple empirical equations to estimate average horizontal and vertical plume spread as functions of standard turbulence statistics, downwind distance from the source, and wind speed. For horizontal plume spread, predicted dispersion coefficients were within a factor of 3, or better, for 97 percent of the observed values in the combined dataset from 2000 and 2001. Likewise, 99 percent of the predicted vertical dispersion coefficients were within a factor of 3 of the observed data.

Key words: average plume spread, bark beetles, *Dendroctonus*, dispersion coefficients, forest canopy, mountain pine beetle, pheromones, tracer experiments

Introduction

Bark beetle populations are currently distressing forests throughout the Rocky Mountain region and elsewhere. Tree mortality attributed to bark beetles in the western United States increased from ~ 1.4 million ac in 1997 to 10.7 million ac in 2003 (USDA Forest Service 2004). In Montana forests alone, beetle-caused mortality was estimated at 820,400 ac in 2005 (USDA Forest Service 2006) and at 1.9 million ac in 2008 (USDA Forest Service 2009a).

Lodgepole pine (*Pinus contorta*) and ponderosa pine (*P. ponderosa*) serve as hosts for bark beetles (Hicke et al. 2006), and mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has been linked to major infestations in the United States (USDA Forest Service 2000, 2004, 2006, 2009b). Mountain pine beetles are considered as "aggressive" species because they attack and kill living trees (Byers 1996).

Bark beetles and other insects communicate using gaseous semiochemicals known as "pheromones." The USDA Forest Service and others have developed techniques of pest control using natural and synthetic pheromones as alternatives to traditional insecticides (Suckling 2000, Bentz et al. 2005). Proper application and effectiveness of pheromones for pest control, however, require a fundamental understanding of the transport and diffusion of gases through forest canopies (Aylor 1976, Farrell et al. 2002). In addition, quantifying absolute concentrations of pheromones in the field is difficult (Van der Pers and Minks 1993, Thorpe and Tcheslavkaia 2001); hence, we have been using tracers to study short-term diffusion and time-averaged dispersion of gaseous plumes in a variety of forest types (Peterson et al. 2004, Smith et al. 2004, Strand et al. 2009, Thistle et al. 2002a, 2002b, and 2004).

This is the second in a series of Intermountain Journal of Sciences papers regarding recent research efforts to understand and model behavior of insect pheromones in forest canopies. Previously, Peterson et al. (2004) described tracer experiments conducted during July 2000 at the Potomac site, a lodgepole pine forest located in western Montana. Winds in the canopy were erratic, and diffusion patterns were intermittent and complex on instantaneous time scales. Time-averaged plume profiles were approximately Gaussian in shape, and a simple empirical equation was developed to relate average horizontal plume spread to 3-dimensional wind data measured at the source.

In particular, the horizontal dispersion coefficient (σ_y) was estimated as:

$$\sigma_y = 2.06(\sigma_u^{\ 2} + \sigma_v^{\ 2})^{0.5} \frac{X}{U} \quad (1)$$

Where σ_y represented the standard deviation of a Gaussian plume profile in the horizontal direction; σ_u and σ_v were standard deviations of wind speed in the horizontal u and v directions; X was downwind distance from the tracer or pheromone source; and U was average wind speed. In this equation, we measured wind speed and turbulence statistics at source height, and the 2.06 factor was empirically determined from a subset of six experiments. Predicted σ_y values were then compared to observed data for 158 plume profiles. Approximately 96 percent of the predicted dispersion coefficients were within a factor of 2 of the observed values, and 99 percent were within a factor of 3.

The remainder of this paper addresses two important research needs. First, microclimates in canopies are complex and influenced by factors such as tree density and vertical forest structure (Thistle et al. 2004, Strand et al. 2009). As illustrated by our tracer data, wind speed and turbulence at the source play an important role in affecting dispersion on scales studied here; however, Equation 1 was developed and tested in a lodgepole pine forest; thus, it is necessary to evaluate performance for additional canopy types. Second, for modeling purposes, vertical spread of pheromone plumes must also be characterized.

Study Areas

As described in Peterson et al. (2004), we conducted field experiments in July 2000 amid a lodgepole pine forest located ~ 16 km east of Missoula, Montana. Elevation of the Potomac site was 1200 m above sea level. The stand was uniform with an average height of 30 m and a density of 1521 stems/ha with little or no underbrush. Based on data from a plant canopy analyzer (PCA), the average leaf area index (LAI) for the Potomac site ranged 0.8-3.3 with an average of 2.18; based on the hemispheric photographic technique (HPT), LAI ranged 1.0-6.1 with an average of 2.50.

During June 2001, the experimental site was a forested area ~ 50 km south of Bend, Oregon. Elevation at LaPine was 1450 m. The canopy consisted of ponderosa pine with an average height of 35 m and a density of 389 stems/ha. The vertical structure of the site included large gaps in the canopy with underbrush as high as 1.5 m (Strand et al. 2009). During the LaPine campaign, ranges of LAI measurements were 1.1-3.2 and 2.1-6.4 from the PCA and HPT, respectively; and the corresponding average LAI values were 1.8 and 3.3.

Methods And Materials

Equipment and experimental layouts were similar for the Potomac and LaPine campaigns. Sulfur hexafluoride (SF_6) was the tracer gas used to simulate a generic insect pheromone in both studies. At a height of 1.2 m above the ground, SF_6 emitted from the center of an array of air sampling units arranged in three concentric circles with radii of 5, 10, and 30 m. We designed these source and sampling locations with the goal of reproducing pheromone diffusion in the trunk space of the canopy on scales similar to bark beetle attacks, and both experimental sites included buffer zones to minimize microclimate responses due to edge effects (Gehlhausen et al. 2000).

Most of the samplers were deployed at a height of 1.2 m above the ground to characterize the horizontal spread of the plume; however, some were elevated to capture vertical concentration profiles. During the Potomac campaign, for example, samplers were elevated at heights of 2.4 and 4.1 m along the 10-m arc at azimuths of 0 and 180°. In LaPine, additional sampling units were allocated for capturing vertical plume profiles at a height of 4.1 m on the 5-m arc at azimuths of 90 and 270°, and at heights of 4.1 and 7.5 m along the 10-m arc at azimuths of 0, 90, 180, and 270°.

Air samplers used in this research were based on the design of Krasnec et al. (1984) with 30-cc hypodermic syringes to collect air samples. Over a period of 4.5 hr/day, the sampling units simultaneously deployed nine sequential syringes at a rate of 30 min/syringe. After the ninth test each day, we quantified tracer concentrations in the syringes using a calibrated, fast-response SF_6 analyzer with an electron capture detector (Benner and Lamb 1985).

In addition to 30-min average concentrations in the syringe samples, a fast-response SF_6 analyzer measured near-instantaneous concentrations in the field at a rate of 1 Hz. We placed this analyzer within the sampling array along the 5- or 10-m arcs with an inlet height of 1.2 m.

For characterizing winds during the tests, a 3-dimensional sonic anemometer operated in the center of the sampling array at a height of 1.2 m, and three anemometers were installed on a tower at heights of 1.5, 14.5, and 24.9 m above the ground. In all cases, anemometer sampling rate was 10 Hz.

Results

Regarding meteorological conditions throughout the two studies, ranges of ambient temperature at the source locations were similar (280-300 K and 281-303 K for the Potomac and LaPine sites, respectively); ranges of average wind speed at the 1.2-m height were 0.17-1.11 m s^{-1} and 0.25-1.63 m s^{-1}. General trends for both campaigns followed the insolation cycle with cooler temperatures and lower wind speeds occurring during morning hours with maxima in afternoon (Fig. 1); however, LaPine data exhibited more variability than the Potomac data.

Standard deviation of wind speed is a measure of atmospheric turbulence. In particular, σ_u and σ_v are indicators of horizontal eddying motions in the airflow passing over a sensor, and σ_w is an indicator of vertical air movements. Again, variability at LaPine was greater than at Potomac, but features were quite similar with lowest levels of turbulence in early morning (Fig. 2). Following onset of convection, turbulence statistics increased 2-5 times by mid afternoon. In terms of magnitudes, horizontal wind fluctuations were about twice the levels of vertical turbulence in the canopy.

Table 1 describes test conditions for one day (21 Jun 2001) during the LaPine study. The lowest average wind speed was 0.77 m s^{-1} at 1030 PDT, and the highest was 1.24 m s^{-1} at 1300 PDT. In terms of turbulence statistics, the smallest σ_u, σ_v, and σ_w values were observed during the first tests of the day, and the largest were observed during the last tests.

Figure 3 illustrates example data for Period 6 on 21 June 2001 (Test L621P6). Wind speed varied between 0 and 4 m s^{-1} during the 30-min test (Fig. 3a), and wind direction fluctuated with several dramatic changes of $\geq 360°$ over short time scales (Fig. 3b). Based on the fast-response SF_6 analyzer located along the 10-m arc at a receptor angle of 90°, instantaneous exposure was intermittent as the narrow plume passed back-and-forth across the receptor, primarily during the first 10 min of the test (Fig. 3c). In agreement with most experiments in the LaPine and Potomac campaigns, average plume profiles along the 5- and 10-m arcs were nearly Gaussian in shape (Fig. 3d).

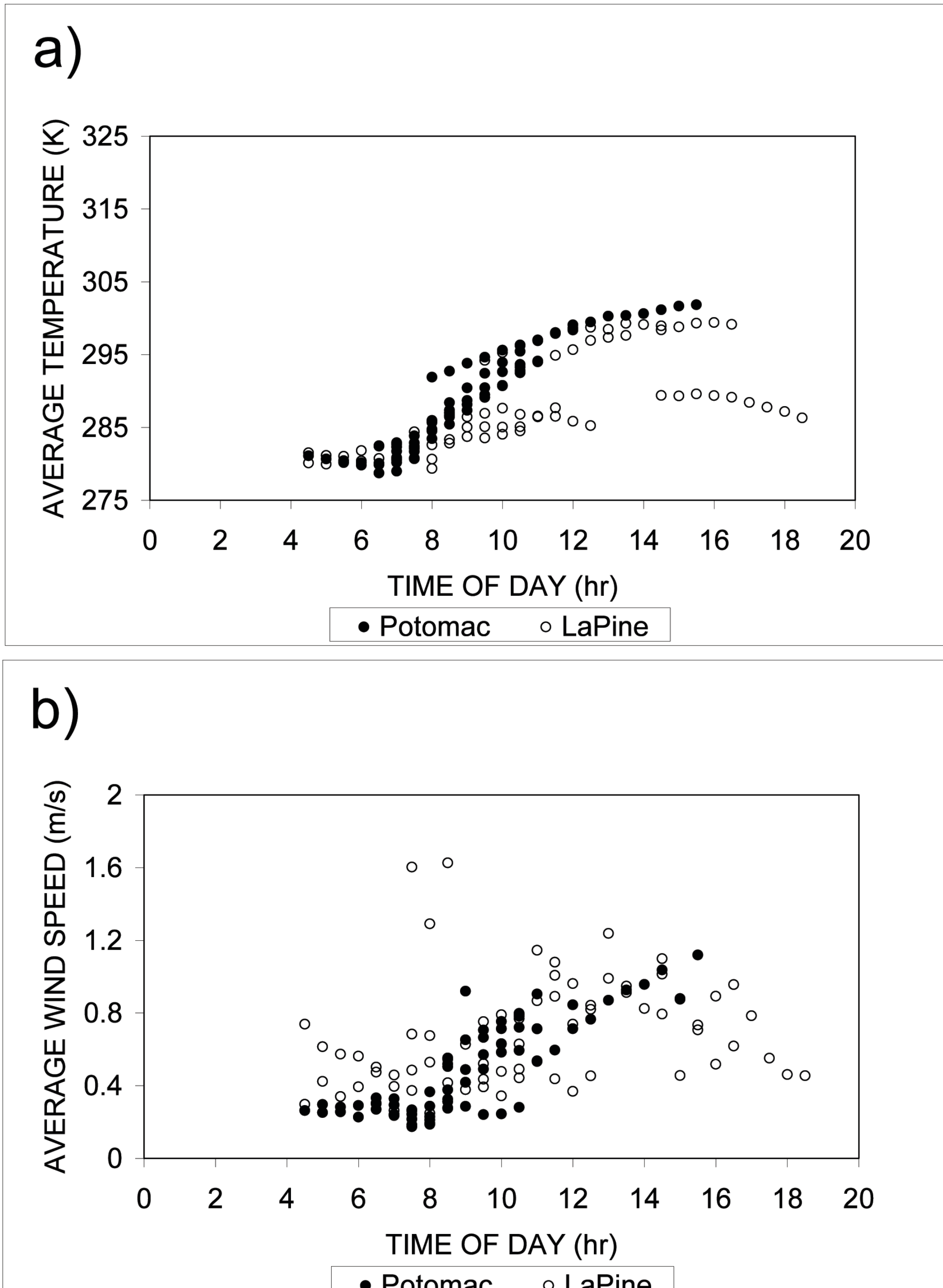


Figure 1. Meteorological conditions of a) average temperature and b) wind speed versus time of day during the Potomac and LaPine campaigns of 2000 and 2001, respectively.

We tested the ability of Equation (1) to predict average plume spread in the LaPine study, and compared results to the Potomac study. Equation 1 tended to overestimate σ_y in the LaPine study more frequently compared to the Potomac study (Fig. 4) probably because of higher levels of turbulence in the canopy, but most of the data fell within the 3:1 and 1:3 lines of correspondence. More specifically, the

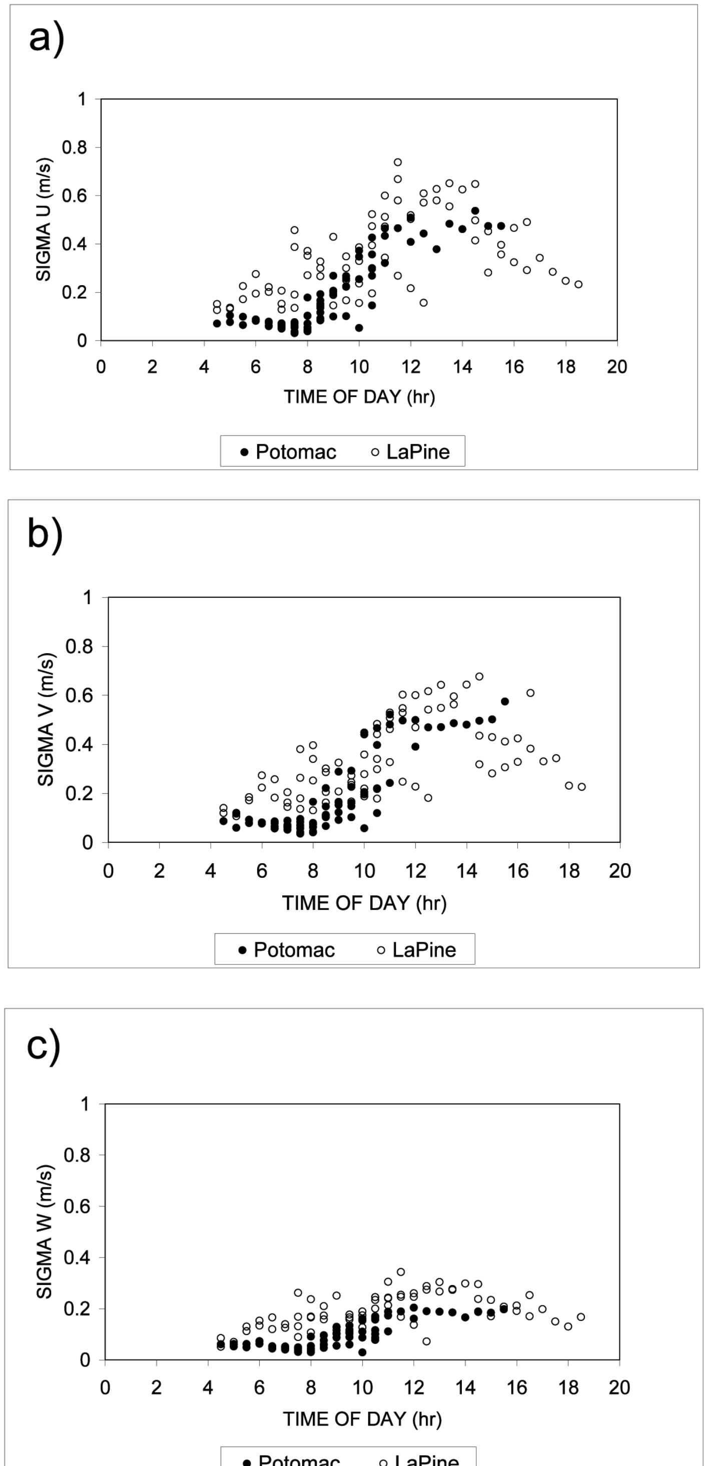


Figure 2. Standard deviation of wind speed versus time of day for the a) horizontal u component, b) horizontal v component, and c) vertical w component for the Potomac and LaPine campaigns of 2000 and 2001.

Table 1. Test Conditions on 21 June 2001 of the LaPine Field Experiments

Test	Dat e	Start Time	U	σ_u	σ_v	σ_w	T	Q_{SF6}
	(D/M/YR)	(PDT)	(m s^{-1})	(m s^{-1})	(m s^{-1})	(m s^{-1})	(K)	(μg s^{-1})
L621P1	21/06/2001	1030	0.77	0.39	0.34	0.17	297.2	84
L621P2	21/06/2001	1100	1.15	0.47	0.46	0.24	297.7	84
L621P3	21/06/2001	1130	1.08	0.58	0.53	0.25	298.4	147
L621P4	21/06/2001	1200	0.74	0.52	0.60	0.26	299.1	146
L621P5	21/06/2001	1230	0.84	0.61	0.62	0.29	299.5	146
L621P6	21/06/2001	1300	1.24	0.58	0.55	0.27	299.2	146
L621P7	21/06/2001	1330	0.91	0.56	0.60	0.27	299.4	146
L621P8	21/06/2001	1400	0.82	0.63	0.64	0.30	299.7	146
L621P9	21/06/2001	1430	1.10	0.65	0.68	0.30	299.8	146

Test duration - 30 min
U - average wind speed
σ_u - standard deviation of horizontal wind speed in the u direction
σ_v - standard deviation of horizontal wind speed in the v direction
σ_w - standard deviation of vertical wind speed in the w direction
T - ambient temperature
Q_{SF6} - release rate of tracer gas

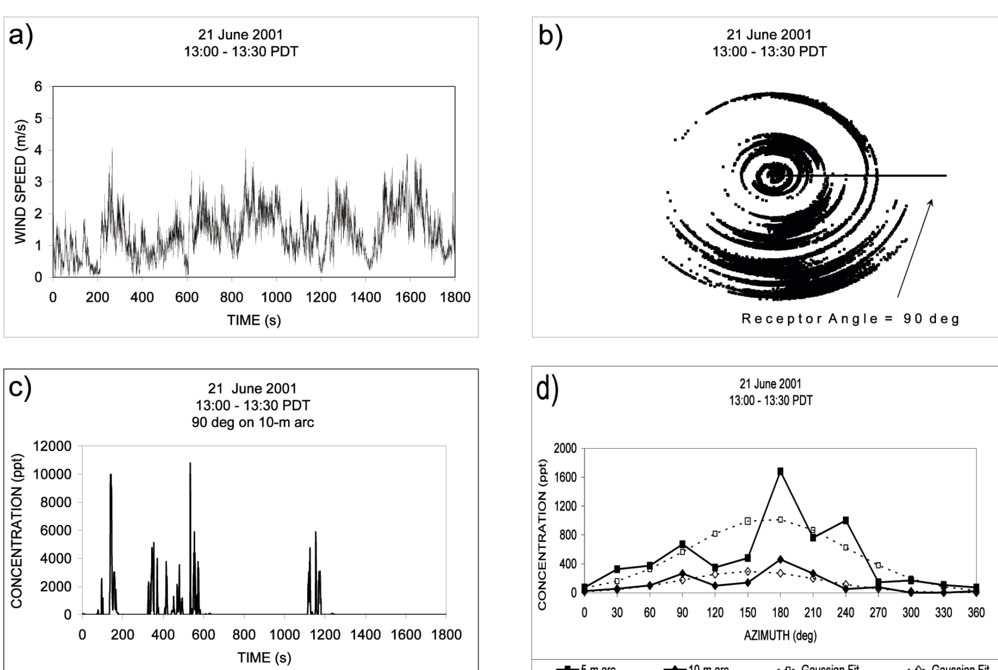


Figure 3. Measurements of a) wind speed and b) wind direction, c) instantaneous concentration, and d) average concentration profiles during Test L621P6 of the LaPine study.

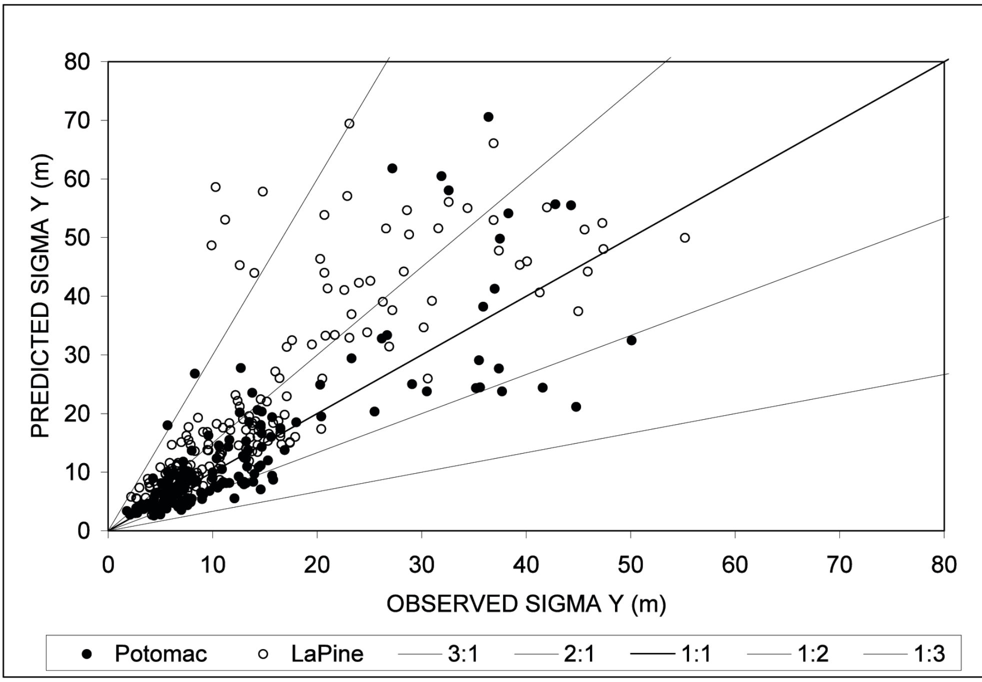


Figure 4. Predicted horizontal dispersion coefficients from Equation (1) versus observed values for the datasets from the Potomac and LaPine field campaigns. Also shown are the 3:1, 2:1, 1:1, 1:2, and 1:3 lines-of-correspondence.

average predicted-to-observed ratio (P:O) was 1.46 for LaPine data, and 88.6 and 96.5 percent of the predicted values were within a factor of 2 and 3, respectively, of the observed values. The combined dataset of 361 profiles resulted in an average P:O of 1.29 with a standard deviation of 0.61. In addition, 93.1 percent of the predicted values were within a factor of 2 of the observed data, and with 97.5 percent within a factor of 3.

Based on these results, our simple approach provided realistic estimates of average horizontal dispersion rates for the range of conditions tested at the Potomac and LaPine sites. Vertical dispersion of pheromone plumes, however, is also important for modeling purposes. Applying a technique similar to the method developed for horizontal dispersion (Peterson et al. 2004), we examined vertical dispersion for a subset of tests from the LaPine dataset.

Figure 5 depicts vertical concentration profiles along the 10-m arc for Test L621P6. Most of the sampler data inferred concentrations decreasing with height in a Gaussian manner; thus, vertical dispersion coefficients (σ_z) were calculated as follows:

$$\sigma_z = \frac{(Z_2 - Z_1)}{\left(-2.0 \ln \frac{C_2}{C_1}\right)^{0.5}} \qquad (2)$$

where C_1 and C_2 were concentrations measured at heights Z_1 and Z_2, respectively. Individual σ_z values ranged 2.34-4.88 m (Table 2). Because airflow in a forest canopy is not homogeneous, we expect some variation in σ_z, and the average coefficient for data collected during Test L621P6 was 3.15 m with a standard deviation of 0.92 m.

Similar to horizontal dispersion data in Peterson et al. (2004), our tracer plumes spread vertically with increasing downwind distance, and a regression of the data resulted in the following empirical equation to predict an average vertical dispersion coefficient as a function of the vertical

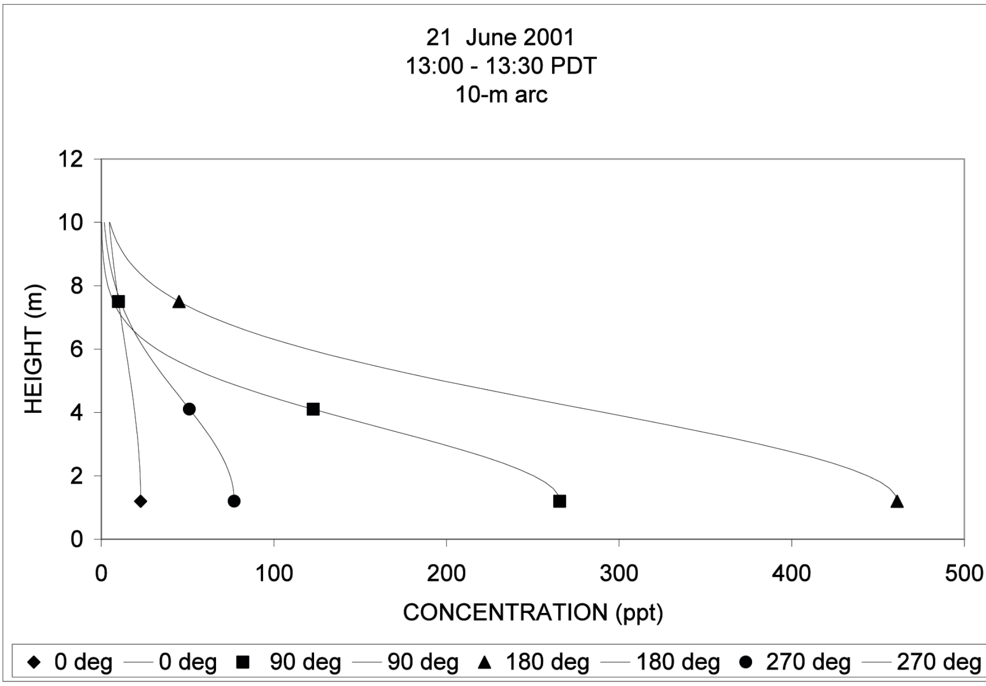


Figure 5. Vertical concentrations along the 10-m arc at azimuths of 0, 90, 180, and 270 deg for Test L621P6 of the LaPine study. Shown are sampler data and Gaussian profiles generated with calculated σz values.

Table 2. Vertical Dispersion Data on 10-m Arc for LaPine Test L621P6

Azimuth (deg)	Height Z (m)	Concentration (ppt)	Profile σ_z (m)	Average σ_z ± std dev (m)
0	1.2	23		
0	7.5	10	4.88	
90	1.2	266		
90	4.1	123	2.34	
90	7.5	10	2.46	
180	1.2	461		
180	7.5	45	2.92	
270	1.2	77		
270	4.1	51	3.20	
270	7.5	10	3.12	
				3.15 ±0.92

Profile σ_z – Vertical dispersion coefficient as calculated using Eq. (2)

turbulence statistic (σ_w), downwind distance (X), average wind speed (U):

$$\sigma_z = 1.21\sigma_w \frac{X}{U} \quad (3)$$

where R^2 was 0.56 for the nine tests on 21 June 2001. In this case, predicted and observed dispersion coefficients were within 0.08 m at best, and within 1.12 m at worst, for the 5-m and 10-m arcs (Table 3). In addition, Equation (3) predicted similar temporal changes of σ_z during the nine, sequential, half-hour periods on 21 June 2001.

To test the method against other dispersion measurements, we compared predicted σ_z values from Equation (3) to data from 131 profiles within the LaPine dataset and 56 profiles within the Potomac dataset (Fig. 6). On average, this method tended to overestimate σ_z for the 10-m arc with average P:O values of 1.24 and 1.42 for LaPine and Potomac, respectively, as compared to an average P:O of 1.05 for the 5-m arc. However, 82.1-89.4 percent of the predicted data were within a factor of 2 of the observed values, and 98.5-100 percent were within a factor of 3. The combined dataset of 187 profiles resulted in an average predicted-to-observed ratio of 1.17 with a standard deviation of 0.50. In addition, approximately 87 and 99 percent of the predicted coefficients were within a factor of 2 and 3, respectively.

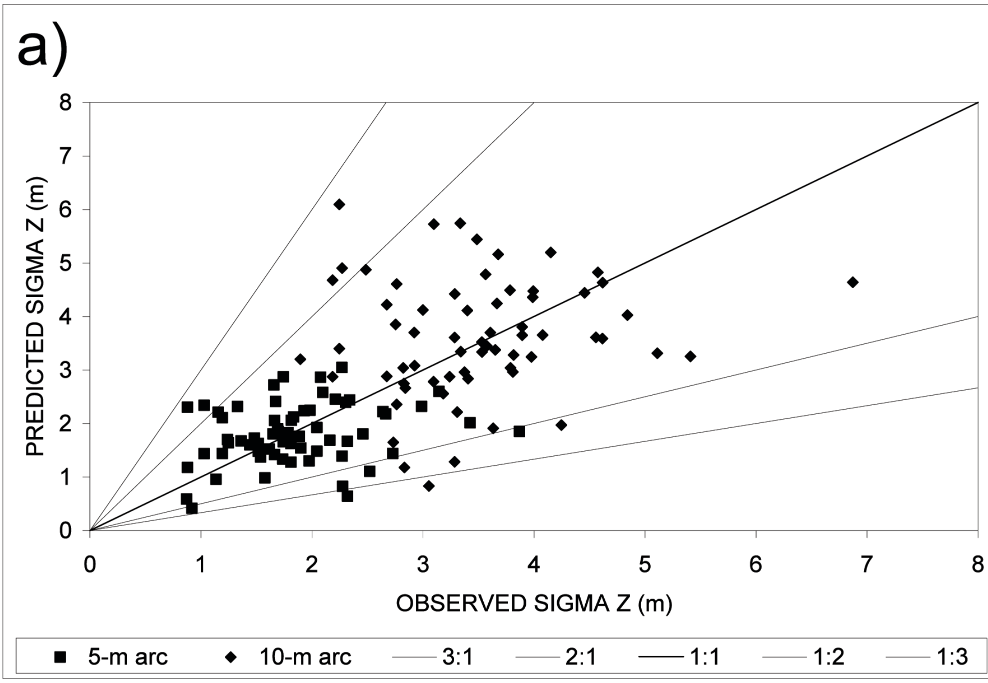
Conclusions

In this paper, we examined dispersion in bark beetle habitats for two canopy types with different conditions of stand density and vertical forest structure. Dispersion coefficients in the horizontal and vertical directions were modeled as functions of wind speed and turbulence statistics measured at the source. When tested against field data, Equation (1) predicted within a factor of 2 for 93 percent of the observed profiles for horizontal dispersion, and within a factor of 3 for 97 percent of the cases. Likewise, for vertical dispersion, Equation (3) predicted values within a factor of 2 in 87 percent of the observed profiles, and within a factor of 3 in 99 percent of

Table 3. Vertical Dispersion Data on 21 June 2001 of the LaPine Field Experiments

Test	σ_z–5m (m)	σ_z–5mp (m)	σ_z–10m (m)	σ_z–10mp (m)
L621P1	1.74	1.33	2.84	2.66
L621P2	1.81	1.28	3.18	2.56
L621P3	1.54	1.37	2.83	2.75
L621P4	1.83	2.12	3.67	4.25
L621P5	1.82	2.06	3.00	4.12
L621P6	1.97	1.30	3.16	2.60
L621P7	2.46	1.80	3.28	3.61
L621P8	2.66	2.18	3.99	4.36
L621P9	1.81	1.62	3.98	3.25

σ_z–5m - Observed vertical dispersion coefficient along the 5-m arc
σ_z–5mp - Predicted vertical dispersion coefficient along the 5-m arc using Eq. (3)
σ_z–10m - Observed vertical dispersion coefficient along the 10-m arc
σ_z–10mp - Predicted vertical dispersion coefficient along the 10-m arc using Eq. (3)



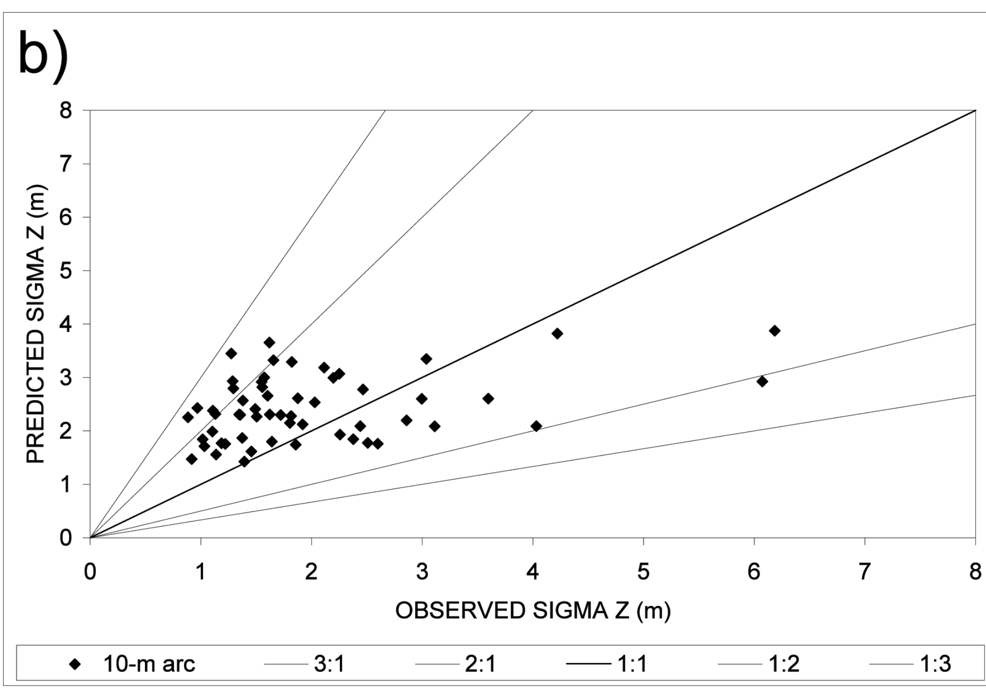


Figure 6. Predicted vertical dispersion coefficients from Equation (3) versus observed values for the datasets from the a) LaPine and b) Potomac field campaigns. Also shown are the 3:1, 2:1, 1:1, 1:2, and 1:3 lines-of-correspondence.

the cases. Even though canopy conditions were dissimilar at the two sites, we were able to model plume spread using the same empirical equations. This conclusion led directly to the question addressed in our next paper in this series: how do changes in stand density at a particular site affect microclimate and dispersion of insect pheromones?

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