Plume Dispersion in Four Pine Thinning Scenarios: Development of a Simple Pheromone Dispersion Model

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Abstract

A unique field campaign was conducted in 2004 to examine how changes in stand density may affect dispersion of insect pheromones in forest canopies. Over a 14-day period, 126 tracer tests were performed, and conditions ranged from an unthinned loblolly pine (*Pinus taeda*) canopy through a series of thinning scenarios with basal areas of 32.1, 23.0, and 16.1 m2ha-1. In this paper, one case study was used to visualize the nature of winds and plume diffusion. Also, a simple empirical model was developed to estimate maximum average concentration as a function of downwind distance, travel time, wind speed, and turbulence statistics at the source location. Predicted concentrations from the model were within a factor of 3 for 82.1 percent and 88.1 percent of the observed concentrations at downwind distances of 5 and 10 m, respectively. In addition, the model was used to generate a field chart to predict optimum spacing in arrays of anti-aggregation pheromone dispensers.

Key words: Pheromones, tracer experiments, forest canopy, stand density

Introduction

Recent outbreaks of bark beetles in North America have focused interest on forest management to prevent large-scale infestations by improving forest health. Twenty-five years ago, Nebecker and Hodges (1985) discussed thinning as a technique to reduce tree mortality caused by southern pine beetle (*Dendroctonus frontalis* Zimmermann). Today, however, mechanisms by which this occurs are still not understood, but they probably consist of multiple, perhaps even synergistic, factors.

Tools for managing bark beetles and their habitats continue to be developed, especially those that use a group of semiochemicals known as "pheromones" to manipulate beetle behavior (Werner and Holsten 1995). There have been many successful applications of semiochemicals to manage beetles and many failures (Shea et al. 1992, Amman 1993, Borden 1995). Causes of failures remain largely unexplored, but bark beetle communication systems are complex, involving insect and host physiology, pheromone chemistry, and microclimate processes in the forest stand. An increased understanding of how meteorological variables behave in a forest canopy, and in turn, how they are affected by changes in stand density, will undoubtedly improve the ability of forest managers to mitigate forest damage from these important pests.

Background

In lieu of research initiated in the late 1970s and early 1980s, mitigation efforts that emphasize thinning of pine stands have recently been renewed. In fact, guidelines to reduce residual stand densities now exist and are a cornerstone of current prevention programs (Nowak and Kleipzig 2007). Although mechanisms through which thinning reduces tree mortality are not completely clear, changes in the dispersion of pheromone plumes possibly play an important role.

All tree-killing bark beetles must attack a host *en masse* to reproduce. This requires "aggregation" of beetles to a source tree, a process directed by a suite of attractive semiochemicals (Geiszler et al. 1980). One type of management strategy to reduce tree attack is to use anti-aggregation pheromones. Holsten et al. (2003), for example, released 3-methyl-2-cyclohexen-1-one (MCH), a synthetic anti-aggregation pheromone of the spruce beetle (*Dendroctonus rufipennis* Kirby), in a forest canopy in south-central Alaska. The experimental design consisted of 25 MCH-dispensing devices deployed in a 5 by 5 array with 9-m spacing. The MCH release rate of each dispenser was 2.6 mg day^{-1} (0.03 μg s^{-1}), and results at the end of the summer showed 87 percent decrease in tree attacks by the spruce beetle. Because airflow and turbulence conditions may be dramatically different elsewhere, the experimental design of Holsten et al. (2003) might not have been as effective if they had conducted the experiment in a different forest canopy. In other words, for widespread application of this type of management strategy, a better understanding of plume dispersal patterns is necessary for optimizing pheromone release rates and/or for deciding on spacing and required number of pheromone dispensers for a field site.

Fares et al. (1980) used Gaussian modeling to describe pheromone dispersion in a forest, and Elkinton et al. (1987) evaluated the utility of time averaged models to this end. More recently, Farrell et al. (2002) created a model including high frequency dispersion of pheromone plumes, and Strand et al. (2009) developed a puff model to describe in-canopy pheromone movement on near-instantaneous time frames. Dispersion in a realistic plant canopy is complicated on many levels, however, and modeling efforts remain to be a challenge (Edburg 2005).

While modeling has helped, most of what we understand about plume dispersion in forest canopies has been determined experimentally. In addition to our previous campaigns (Thistle et al. 2004, Peterson et al. 2004), others have studied in-canopy plumes in a variety of forest types (Aylor 1976, Aylor et al. 1976, Murlis and Jones 1981). This paper addresses one important question that has not been studied extensively in the field: how do changes in stand density affect dispersion of semiochemicals on near-source scales? Another related question is: can we take stand density and/or plume dispersion into consideration and develop tools for improving the success of field applications involving anti-aggregation pheromones?

Experimental Design

Similar to the campaigns described by Thistle et al. (1995, 2004) and Peterson et al. (2004), we conducted field experiments for this project using sulfur hexafluoride (SF_6) as a tracer to simulate a generic insect pheromone. The configuration was to surround a point source of SF_6 with a dense array of air samplers and to monitor meteorological conditions.

Sulfur hexafluoride gas was chosen as the tracer gas because SF_6 is non-toxic, non-radioactive, with low detection limits in the parts-per-trillion (ppt) range. Also, a large body of scientific literature exists including examples of SF_6 as a gaseous tracer in the field of air pollution (i.e., Peterson and Lamb 1992, 1995, Peterson et al. 1990, 1999, 2003). Sulfur hexafluoride is conservative (non-reactive) in the atmosphere over the short distances studied here.

Throughout the experiments, we released a continuous stream of SF_6 from a gas cylinder through a mass flow controller. Release height in the trunk space was 1.2 m above the ground, and to investigate dispersion of SF_6 in our experiments, we deployed 50-60 sampling units based on the design of Krasnec et al. (1984). Each sampler collected nine sequential samples of air in 30-cc syringes with an averaging time of 30 min/syringe; thus, each trial day lasted 270 min (4.5 hr). By conducting experiments on 14 trial days in May of 2004, we acquired data for 126 individual (30-min) tests.

For the receptor array, we positioned samplers in concentric circles around the SF_6 source at radial distances of 5, 10, and 30 m. We located samplers every 30˚ of the compass along the 5-m arc, and every 15-30˚ along the 10-m and 30-m arcs. Most of the samplers operated at a height of 1.2 m above the ground, but we also positioned elevated samplers at 4.0- and 7.6-m heights every 90˚ along the 5- and 10-m arcs, respectively.

In addition, we operated a calibrated, fast-response SF_6 analyzer based on the design of Benner and Lamb (1985) at one location along the sampling array, usually along the 10-m arc. At a height of 1.2 m above the ground, real-time concentration data were collected at a frequency of 1 Hz. Following each trial day, another calibrated SF_6 analyzer measured time-averaged concentrations in the syringe samples.

In terms of meteorological equipment, 3-dimensional sonic anemometers (ATI, Longmont, Colorado) collected wind vector and turbulence data at a rate of 10 Hz throughout the study. The anemometers were deployed in a vertical profile on a meteorological tower with one instrument in the trunk space at a height of 2.6 m above the forest floor, one near the vertical canopy density maximum at a height of 16.6 m, and one near the average canopy top (22.9 m). A fourth sonic anemometer was co-located with the SF_6 source at a height of 1.2 m in the center of the sampling array. Net radiation (R.E.B.S, Seattle, WA) was also measured.

Regarding forest characteristics in a canopy, leaf area index (LAI) is a unitless term defined as "the total one-sided area of leaf tissue/unit ground surface area" (Breda 2003). For this campaign we made leaf area measurements using two methods. The plant canopy analyzer (PCA) method estimates foliage amounts based on the attenuation of diffuse sky radiation as it passes through the canopy. The LI-COR 2000 Plant Canopy Analyzer (LI-COR, Inc. Lincoln, Nebraska) measures light attenuation at five zenith angles. Due to concerns about the accuracy of the PCA, especially in coniferous canopies, we also employed the hemispherical photographic technique (HPT) of Evans and Coombe (1959). Stem maps were created and basal area (with units of m^2 ha^{-1}) was measured for each stand condition.

Experimental Site

The forested site for the field campaign (31˚ 53' 23.3" N, 92˚50' 39.9" W) was located in the Winn District, Kisatchie National Forest, outside of Winnfield, LA. Local terrain was level with a dirt road adjacent to the site to the northeast. The canopy consisted of an overgrown loblolly pine (*Pinus taeda*) plantation with canopy top between 15 and 25 m in height with an average of 20 m.

The tracer campaign consisted of 14 trial days reflecting four canopy scenarios (Table 1). We conducted Trials 1-4 in the original (unthinned) forest conditions. After the deciduous understory was removed from the site over an area of about 1.13 ha, Trials 5-7 were run in the canopy with a basal area of 32.1 m^2 ha^{-1}. The canopy was then thinned again, this time to a basal area of 23.0 m^2 ha^{-1}, and three more tests were performed (Trials 8-10). After the final thinning, the last four trials (11-14) corresponded to a basal area of 16.1 m^2 ha^{-1}.

Results

Canopy Metrics

The plant canopy analyzer estimated average leaf area index values ranging from 3.71 in the unthinned canopy to 1.47 after the third thinning, and the hemispheric photographic technique produced average LAI values between 3.18 and 1.08 (Table 1). The resulting thinning ratios for our three successive stages in the campaign were similar for both methods (0.71, 0.53,

Table 1. Canopy Data

	Trail Days			
Canopy Description	**1-4 Lobloby Pine (unthinned)**	**5-7 Lobloby Pine with understory removed (1st thinning)**	**8-10 Lobloby Pine (2nd thinning)**	**11-14 Lobloby Pine (3rd thinning)**
Basal Area (m^2 ha^{-1})	--	32.1	23.0	16.1
Density (stems ha^{-1})*	1219	975	569	325
		LAI Measurements from PCA		
Range	3.2-4.7	2.0-3.3	1.6-2.5	1.0-2.0
Average	3.71	2.63	1.98	1.47
Standard Deviation	0.34	0.31	0.19	0.26
Thin Ratio	1.00	0.71	0.53	0.40
		LAI Measurements from HPT		
Range	2.2-5.3	1.4-3.0	1.1-2.0	0.8-1.4
Average	3.18	2.11	1.57	1.08
Standard Deviation	0.73	0.30	0.18	0.13
Thin Ratio	1.00	0.66	0.49	0.34

* Stems greater than 7.6 cm
LAI - Leaf Area Index
PCA – Plant Canopy Analyzer
HPT – Hemispheric Photographic Technique

and 0.40 from the PCA, and 0.66, 0.49, and 0.34 from the HPT). Generally, both of these approaches to measuring LAI are most accurate when canopy light is not directional. As the canopy was thinned and larger gaps appeared, accuracy of these measurements probably fell. However, these LAI estimates were comparable to values found elsewhere (Teske and Thistle 2004).

Example Field Data

Figures 1 and 2 illustrate the types of field data collected during one 30-min test of the campaign. The start time for this period was 1230 EDT on Trial Day 2 (15 May 2004), and conditions included a net radiation of 96 W m^{-2} and an ambient temperature of ~ 25 ºC. Average wind speeds were 0.30, 0.46, and 1.68 m s^{-1} at the 2.6-, 16.6-, and 22.9-m heights, respectively, on the meteorological tower.

Figures 1a and 1b depict the fluctuating nature of winds in the canopy during the test. Corresponding to anemometer data in Figure 1a, average wind speed at the source was 0.38 m s^{-1} with standard deviations of 0.18 and 0.06 m s^{-1} in the horizontal and vertical directions, respectively. According to the radial time series (Fig. 1b), wind direction at the source was primarily toward the south, southwest, and southeast throughout this 30-min period.

In terms of dispersion characteristics, plume profiles were nearly Gaussian in shape in the horizontal (Fig. 2a) and vertical (Fig. 2b) directions. Maximum average concentrations (normalized by SF_6 release rate) along the 5-m arc were 0.16 s m^{-3} based on the sampler data and 0.13 s m^{-3} based on the Gaussian best-fit curve. Along the 10-m arc, the maximum concentration was 0.04 s m^{-3}. Horizontal

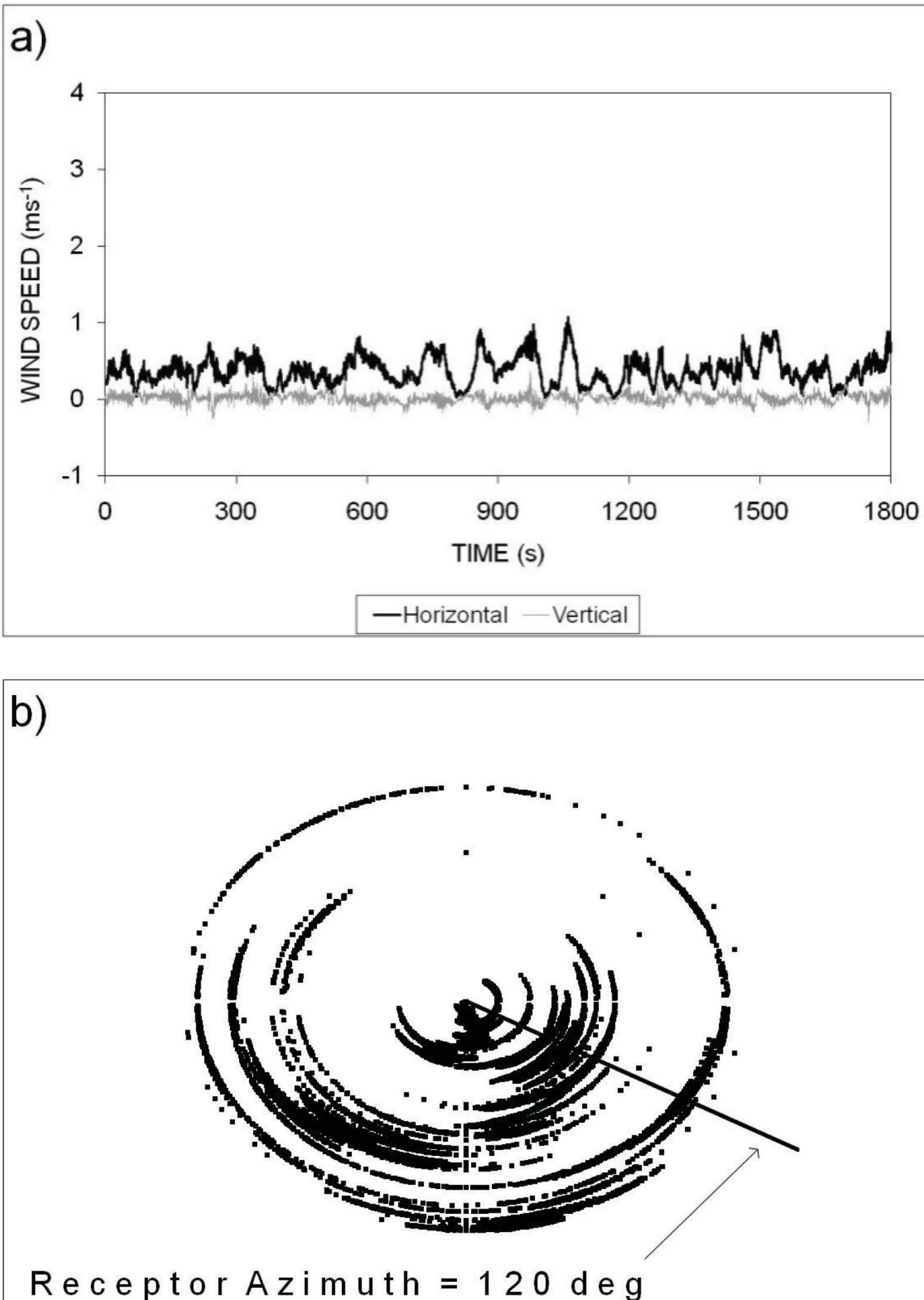

Figure 1. Measurements during 1230-1300 EDT on Trial Day 2 for: a) wind speed at the source, and b) radial wind direction at the source.

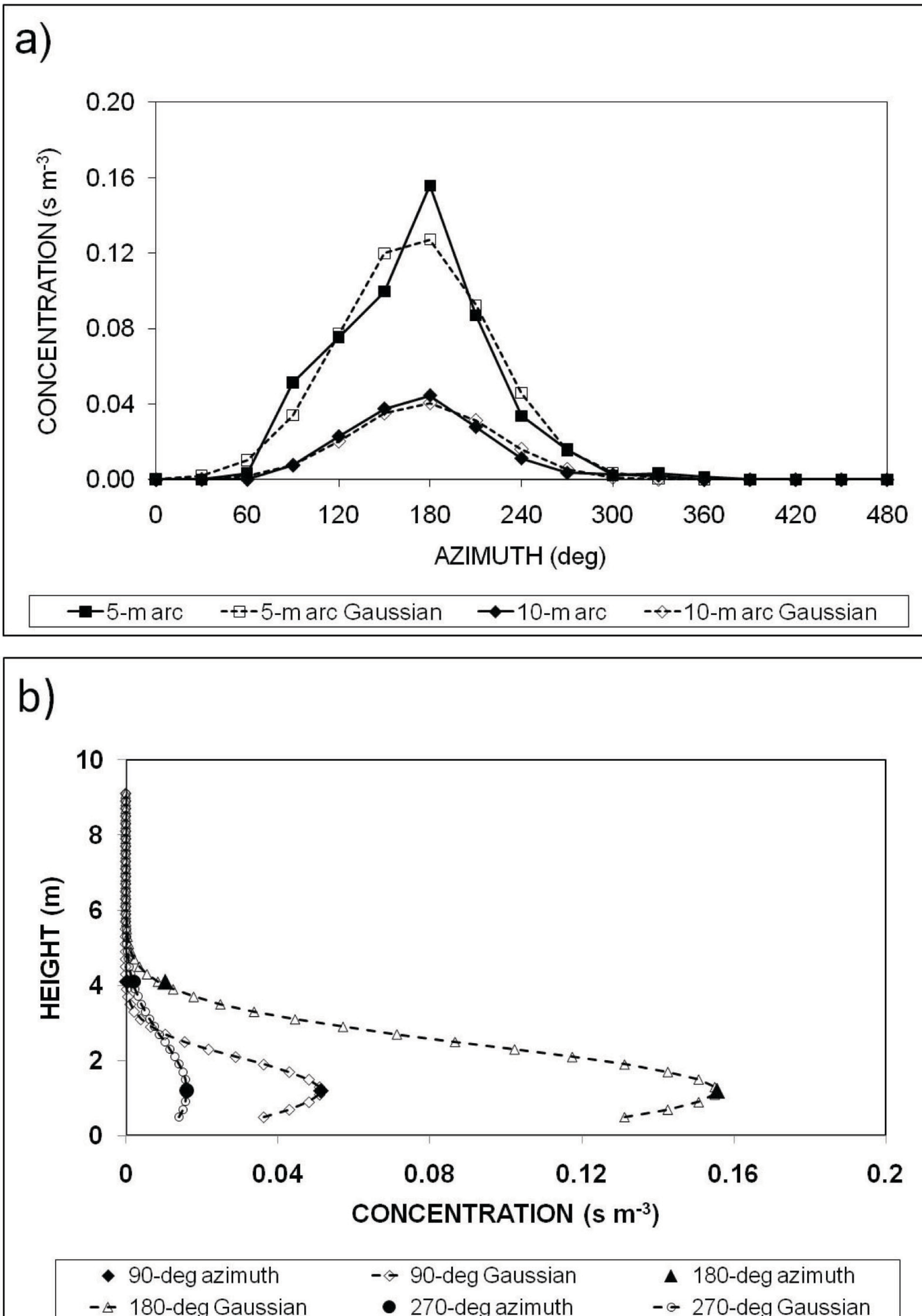

Figure 2. Measurements during 1230-1300 EDT on Trial Day 2 for: a) horizontal plume profiles along the 5- and 10-m arcs, and b) vertical plume profiles on the 5-m arc.

dispersion coefficients (σ_y values) for the 5- and 10-m arc profiles in Figure 2a were 4.2 and 8.2 m, respectively. Vertical dispersion coefficients (σ_z values) for the 5-m arc in Figure 2b were 0.84, 1.20, and 1.38 m from the samplers at the 90-, 180-, and 270-deg azimuth locations.

Winds Statistics at the Source

Wind speed and turbulence statistics from the sonic anemometer at the source varied as a function of time of day throughout the 14 trial days (Figure 3). In general, we observed higher wind speeds and more turbulence with each successive stage of thinning. As depicted in Figure 3a, average wind speed ranged 0.19-0.48 m s^{-1} in the unthinned canopy (Trials 1-4), 0.27-0.63 m s^{-1} during Trials 5-7, 0.20-0.66 m s^{-1} during Trials 8-10, and 0.26-0.73 m s^{-1} during Trials 11-14.

Standard deviations of wind speed, σ_u and σ_w, are measures of turbulence in the horizontal and vertical directions, respectively. Corresponding to data in Figures 3b and 3c, ranges of σ_u and σ_w were 0.09-0.24 m s^{-1} and 0.03-0.08 m s^{-1} during Trials 1-4, 0.11-0.39 m s^{-1} and 0.07-0.19 m s^{-1} during Trials 5-7, 0.09-0.38 m s^{-1} and 0.04-0.20 m s^{-1} during Trials 8-10, and 0.14-0.40 m s^{-1} and 0.06-0.25 m s^{-1} during Trials 11-14.

Model Development and Application

Pheromone concentrations in a canopy should decrease with increasing distance from the source in response to two processes: 1) dilution from the wind speed, and 2) dispersion from the turbulence. In the field of air pollution, a Gaussian approach is often utilized for modeling concentrations downwind of an industrial smokestack using the Gaussian plume equation (Turner and Schultz 2007):

where C_{xyz} is average concentration at a receptor with coordinates x,y,z; Q is mass release rate of the pollutant; σ_y and σ_z are horizontal and vertical dispersion coefficients, respectively; U is mean wind speed, usually at stack height; and H_e is effective source height (physical stack height plus plume rise). Versions of Equation (1) are incorporated into air pollution models used by the United States Environmental Protection Agency (USEPA) and others to predict average concentrations downwind of industrial sources with averaging times as small as 1 hour, and as large as 1 year (USEPA 1995).

Dispersion coefficients (σ_y and σ_z) in air pollution models reflect the horizontal and vertical spread of the plume. As described by Turner and Schultz (2009), they are normally estimated using empirical equations that are functions of downwind distance and atmospheric stability class, i.e., Pasquill classes A-F/G, or they can be estimated using equations that are functions of turbulence statistics and travel time (t = x/U). Dispersion coefficients in the models for air pollution purposes represent downwind distances much longer than distances applicable for near-source pheromone processes; the Gaussian approach, however, was a logical starting point for development of a simple pheromone dispersion model.

Similar to tracer data in Figures 2a and 2b, all of the horizontal and vertical concentration profiles in our dataset were approximately Gaussian in shape. We assumed σ_y and σ_z for our profiles should be functions of turbulence statistics at the source and travel time [i.e., $\sigma_y = f(\sigma_u t)$ and $\sigma_z = f(\sigma_w t)$]. Following the general framework of the Gaussian plume equation, we assumed maximum normalized concentration (C/Q) at each downwind distance should therefore be a function of $\pi\sigma_u t\sigma_w tU$.

$$(1)\quad C_{xyz} = \frac{Q}{2\pi\sigma_y\sigma_z U}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{H_e - z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H_e + z}{\sigma_z}\right)^2\right]\right\}$$

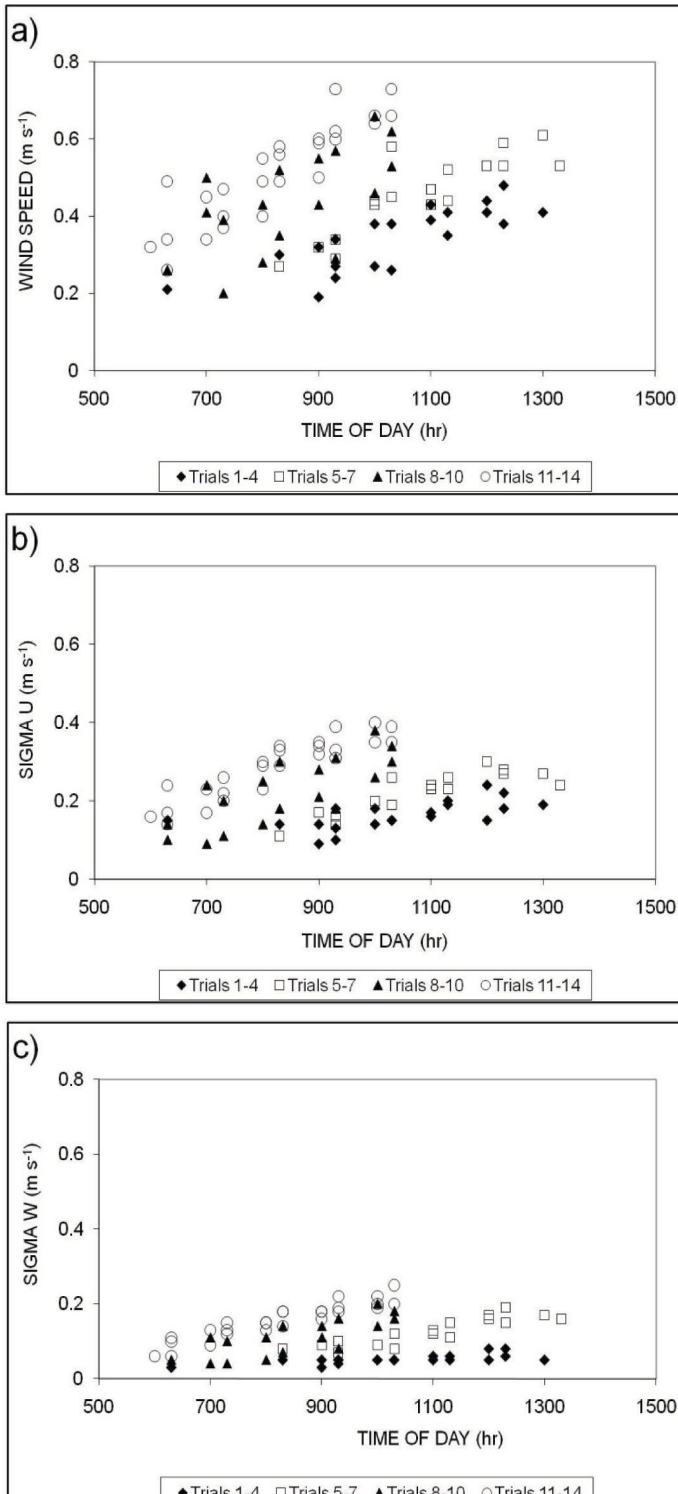

Figure 3. Graphs of: a) average wind speed, b) standard deviation of the horizontal wind speed, and c) standard deviation of vertical wind speed at the source versus time of day for all tests.

Figure 4 shows graphs of "concentration versus $\pi\sigma_u t\sigma_w tU$" for the 5-m and 10-m arcs with trials segregated, including the lines for best-fit regressions. Based on curve-fitting, equations for the 5-m and 10-m arc, respectively, were:

$$\frac{C}{Q} = \frac{0.4184}{(\pi\sigma_u t\sigma_w tU)^{1.630}} \quad (2)$$

and

$$\frac{C}{Q} = \frac{1.6406}{(\pi\sigma_u t\sigma_w tU)^{1.627}} \quad (3)$$

with R^2 correlation coefficients of ~ 0.6 on the 5-m arc, and ~0.7 on the 10-m arc.

We also analyzed the relationship between the numerators (0.4184 and 1.6406)

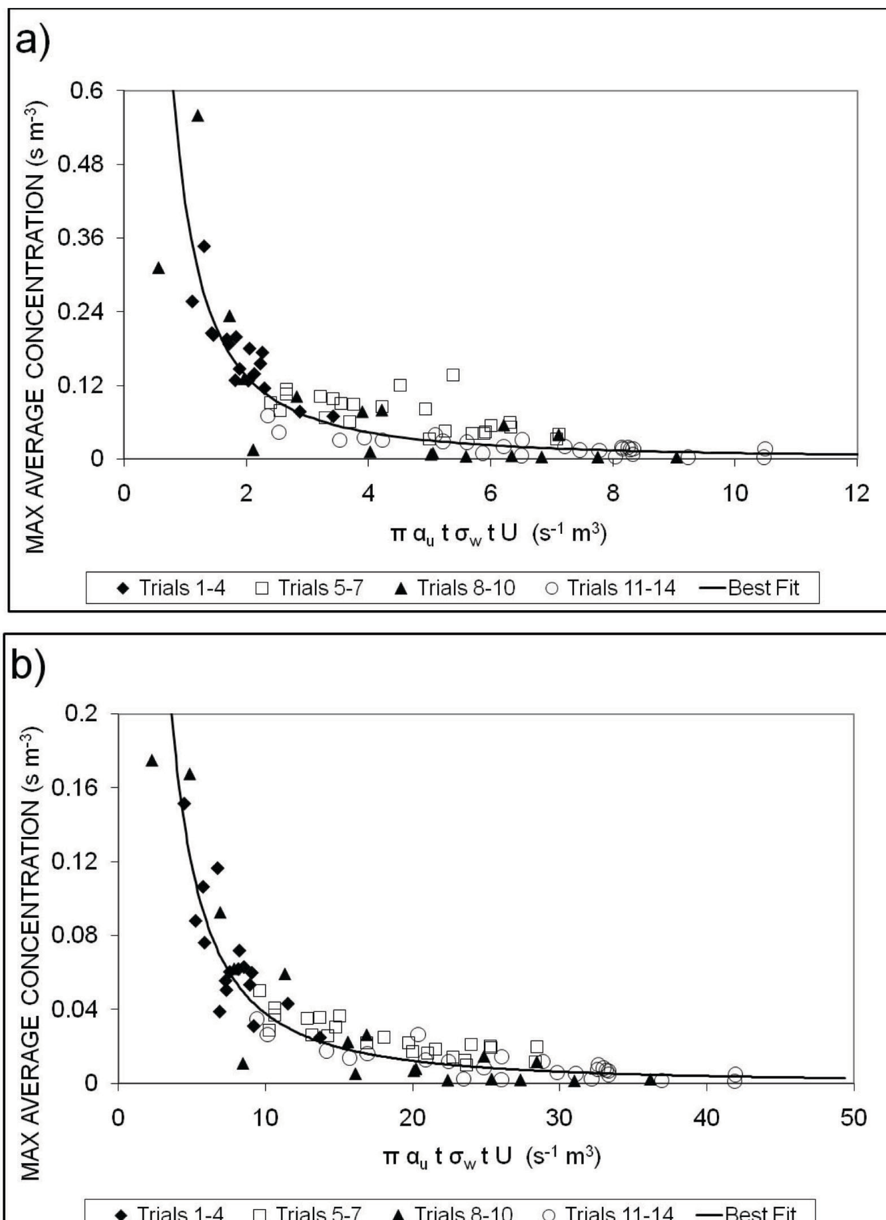

Figure 4. Maximum average concentration versus $\pi\sigma_u t\sigma_w tU$ for the: a) 5-m arc, and b) 10-m arc for all tests.

in Equations (2) and (3) as a function of downwind distance (x), and the resulting equation to predict maximum average concentration at any distance was

$$\frac{C}{Q} = \frac{0.0175x^{1.97}}{(\pi\sigma_u t\sigma_w tU)^{1.63}} \tag{4}$$

where U, σ_u, and σ_u correspond to meteorological conditions at the source location.

Figure 5 shows modeled concentrations from Equation (4) as a function of downwind distance from the tracer source for the 30-min test beginning at 1230 EDT on Trial Day 2. Concentration decreased quickly within the first 2 m. At distances of 5 and 10 m, predicted concentrations of 0.11 and 0.05 s m^{-3}, respectively, were similar to the observed concentrations of 0.16 and 0.04 s m^{-3}.

Concentrations from Equation (4) were compared to observed values from all of the tracer experiments. On the 5-m arc, predicted and observed concentrations were within a factor of 2, or better, for 67.8 percent of the profiles, and within a factor of 3 for 82.1 percent of the distributions. On the 10-m arc, predicted and observed values were within a factor of 2 in 78.1 percent and within a factor of 3 in 88.1 percent of the cases.

As an investigation of how our model could be used by forest managers or others, Equation (4) was rearranged to solve for downwind distance x:

$$x = \left[0.002708 \frac{Q}{C}\left(\frac{U}{\sigma_u \sigma_w}\right)^{1.63}\right]^{0.775} \tag{5}$$

and the field chart of "x versus C/Q" in Figure 6 was developed for $U(\sigma_u \sigma_w)^{-1}$ values ranging 10-60 s m^{-1}. With this chart and with minimal on-site data, the method was designed to be a simple way to incorporate plume diffusion into decisions about how closely to space pheromone dispensers in anti-aggregation applications.

For example, assume average wind conditions at a site are described by 0.30, 0.15, and 0.05 m s^{-1}, for U, σ_u, and σ_w, respectively; and assume each dispensing unit will have a pheromone release rate

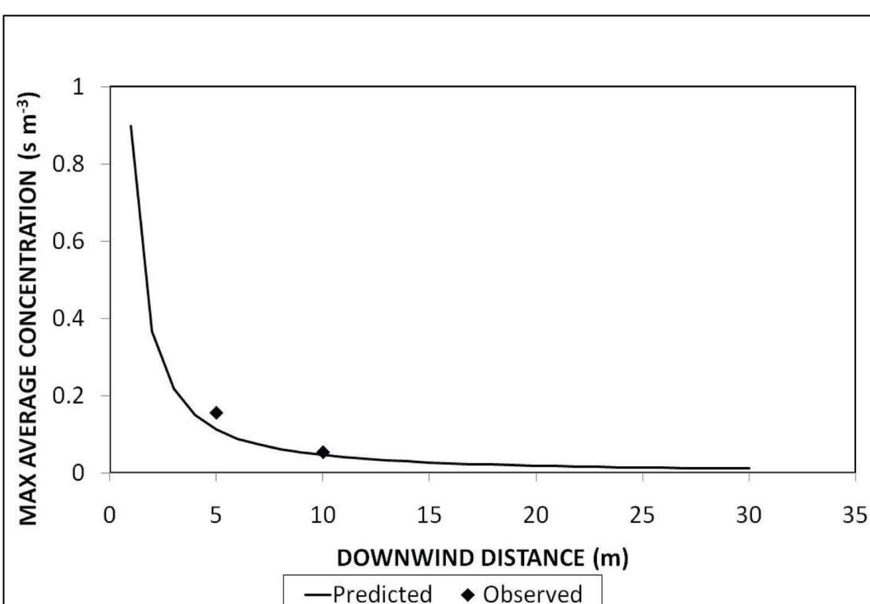

Figure 5. Predicted concentrations from Equation (4) and observed data versus downwind distance for the test conducted at 1230-1300 EDT on Trial Day 2.

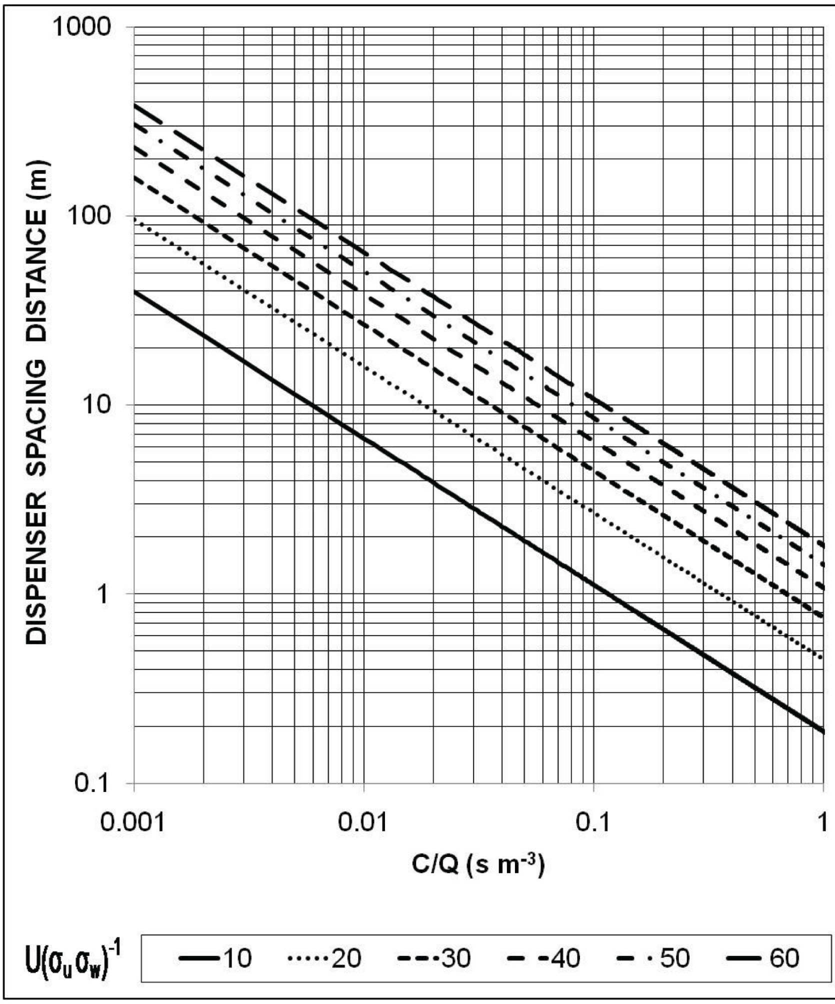

Figure 6. Example field chart of dispenser spacing distance versus maximum average concentration for $U(\sigma_u\ \sigma_w)^{-1}$ ranging between 10 and 60. [Units on $U(\sigma_u\ \sigma_w)^{-1}$ are s m^{-1}.]

of 0.03 µg s^{-1}. To design an array for concentrations greater than or equal to 0.0017 µg m^{-3}, these data correspond to

$$\frac{U}{\sigma_u \sigma_w} = \frac{0.30ms^{-1}}{(0.15ms^{-1})(0.05ms^{-1})} = 40sm^{-1}$$

$$\frac{C}{Q} = \frac{0.0017\mu gm^{-3}}{0.03\mu gs^{-1}} = 0.06sm^{-3}$$

and

$$x = \left[0.002708\left(\frac{1}{0.06sm^{-3}}\right)\left(40sm^{-1}\right)^{.63}\right]^{0.775} = 9.6m$$

using Equation (5) directly; or, if estimating a value from Figure 6, we would choose a pheromone dispenser spacing of about 10 m.

Regarding limitations of the method at this time, conditions in our tracer campaign corresponded to a release height of 1.2 m above the ground, and $U(\sigma_u\ \sigma_w)^{-1}$ values at this height were between 6.72 and 70.37 s m^{-1}.

Therefore, until we can research this further, we caution against using Equation (5) or Figure 6 in canopies with turbulence data outside of this range.

Summary

In this paper, we described a unique field project in which tracer technologies were applied to study pheromone dispersion in a forest canopy. While we have conducted similar experiments in other forest types, this is the first campaign designed specifically to examine effects of stand density.

During our campaign, 126 tracer experiments were conducted over a 14-day period in which the forest stand ranged from an unthinned loblolly pine canopy (with dense understory) through a series of thinning scenarios reflecting basal areas of 32.1, 23.0, and 16.1 m^2ha^{-1}. Each successive thinning resulted in higher wind speeds and more turbulence in the trunk space near the ground, and these conditions translated to increased dispersion and lower concentrations in the tracer plumes.

Our field data were used to develop a simple pheromone dispersion model describing how plume concentrations decreased as a function of downwind distance based on wind speed and turbulence data measured at the source. Predicted concentrations from the model were within a factor of 3 for 82.1 and 88.1 percent of the observed concentrations at downwind distances of 5 and 10 m, respectively.

Lastly, our model equation was rearranged to predict downwind distance as a function of release rate, concentration, and wind statistics. From this equation, a field chart was developed to predict optimum spacing for dispenser arrays in applications of anti-aggregation pheromones.

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