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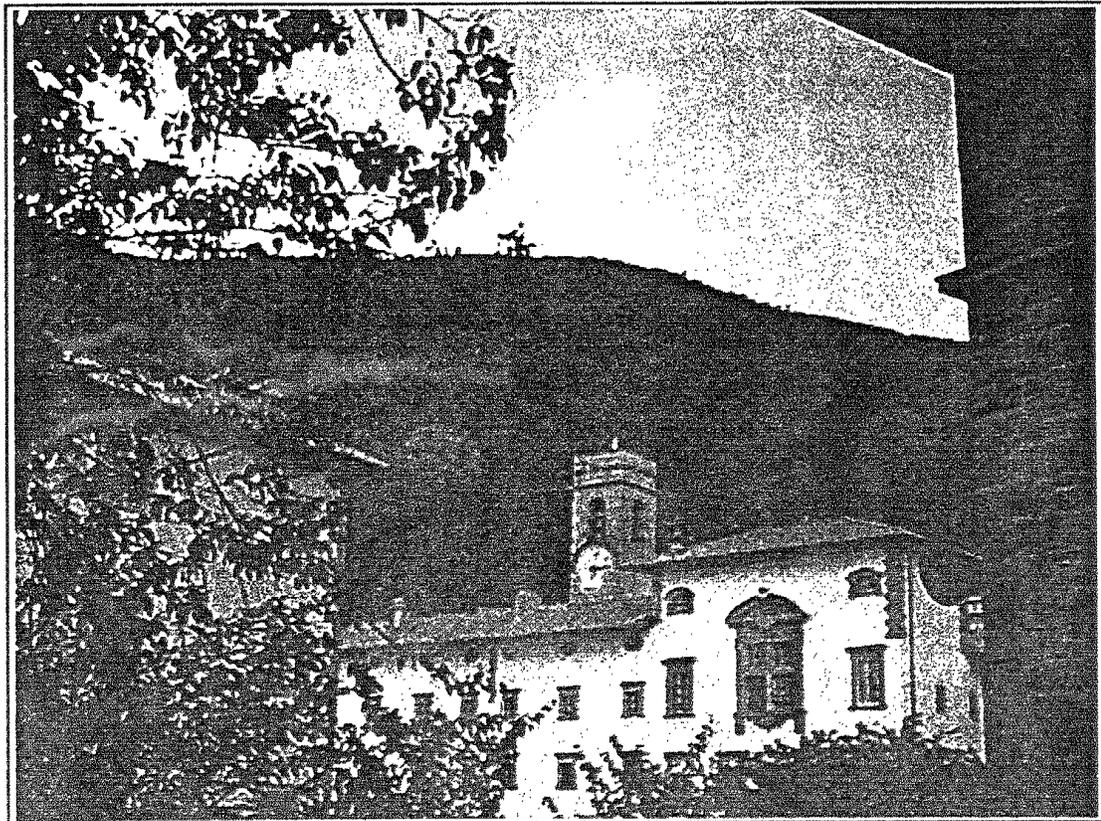
## Proceedings

# Integrating Cultural Tactics into the Management of Bark Beetle and Reforestation Pests

Edited by:

J.C. Grégoire  
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F.M. Stephen  
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Vallombrosa, Italy  
September 1-3, 1996



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#### Cover

The photograph on the cover is of the Monastery of Vallombrosa, Vallombrosa, Italy (Photo by A. Liebhold).

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# Proceedings

## Integrating Cultural Tactics into the Management of Bark Beetle and Reforestation Pests<sup>1</sup>

Vallombrosa, Italy  
September 1-3, 1996

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<sup>1</sup> A meeting sponsored by the International Union of Forestry Research Organizations (IUFRO) working parties S7.03.03 "Insects affecting reforestation", S7.03.05 "Integrated control of scolytid bark beetles", S7.03.07 "Population dynamics of forest insects".

## PREFACE

This proceedings results from a conference held at the Monastery of Vallombrosa, near Florence, Italy, on September 1st - 3rd 1996. The meeting, held under the guidelines of the International Union of Forestry Research Organizations, gathered three IUFRO Working Parties: S7.03.03 (Insects Affecting Reforestation), S7.03.05 (Integrated Control of Scolytid Bark Beetles) and S7.03.07 (Population Dynamics of Forest Insects). Forty-nine participants, from 15 countries, presented 33 papers and 8 posters. These figures understate the contributors' input; considerable sharing of expertise and enthusiasm also occurred between the sessions, and links for present or future co-operation were renewed or established.

The organizers wish to express their gratitude to the Italian colleagues who helped to organize locally the meeting: Prof. Riziero Tiberi and Dr. Franco Cerchiarini (Istituto di Patologia e Zoologia Forestale e Agraria, Universita degli Studi, Firenze), Dr. Andrea Battisti and Mr. Massimo Faccoli (Istituto di Entomologia Agraria, Universita' degli Studi, Padova).

We also thank Dr. Rose-Marie Muzika for helping in various aspects of organizing this meeting and preparing the proceedings.

The editors thank the following branches of the U.S. Dept. of Agriculture Forest Service who funded the publication of these proceedings:

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# Pheromone mass trapping: does it protect windfalls from attack by *Ips typographus* L. (Coleoptera: Scolytidae)?

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**ABSTRACT** Five sites containing windfalls were selected in Southern Belgium in the winter 1992-93. Trees in each site had been attacked in 1992 (total: 168 trees attacked during the second flight). These trees had shed a large amount of infested bark before their removal in the winter, leaving therefore a large residual overwintering bark-beetle population. Traps and/or trap-trees were set up in each site. After the first flight, in late spring, a model was first established from the sampling of six trees. It yielded a function describing the number of entrance holes to be expected at each position along the trunks, permitting estimation of total numbers of entrance holes per tree and per site. Sex-ratio per site was also estimated. Combining estimates of total numbers of holes per tree and sex-ratios, total numbers of beetles colonising the windfalls could be estimated at each site. A total of ca 202,000 beetles colonised 38 windfalls over 6 sites and therefore escaped trapping. At one of the sites, total catches in trap trees were also estimated: they amounted to ca 32,000 *Ips typographus* whilst at the same site 5 windfalls out of 8 were attacked by a total of 28,000 beetles. A significant relationship was found between windfall protection and trapping effort (ratio trap trees: trees attacked on previous year), suggesting that adequate trapping effort could provide efficient protection.

**KEY WORDS** *Ips typographus*; mass trapping; pheromones; trap trees; windfalls

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HIGH NUMBERS OF pioneer *Ips typographus* beetles and their symbiotic fungi are necessary to overcome the defenses of healthy spruce trees (Mulock and Christiansen 1986), while poorly defended hosts such as windfelled trees can be easily colonised. If this kind of breeding material becomes abundant, bark beetle populations may increase beyond epidemic threshold, and healthy, standing trees can be successfully attacked (Christiansen and Bakke 1988). Recurrent field observations illustrate this sequence. For example, Figure 1 (M. Dolmans unpublished) shows the progress of an outbreak at Mellier (Southern Belgium), where 70 trees had been windfelled in February 1990 and were left lying during the whole year. The beetles attacked first all the windfalls and then, during the flight of the first generation of the year, they turned to neighbouring live trees. One classical way to minimise these disastrous events is to remove or peel susceptible material before it can yield a new generation. However, as in the previous example, *Saubere Wirtschaft* (clean forestry) is not always implemented, due to either shortage in manpower or limited site accessibility.

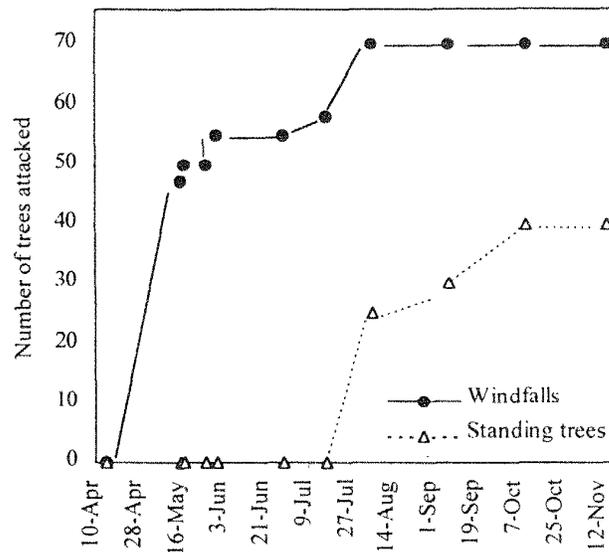


Figure 1. Shift of *Ips typographus* from windfalls to standing trees (Mellier 1990; M. Dolmans, unpublished)

Pest management would be greatly facilitated if pheromone mass-trapping could provide an alternative to forest hygiene under these conditions. Abgrall and Schvester (1987) tested this approach in the French Alps, where they surrounded several large windblown areas (ca 100 ha each) with high numbers of pheromone traps (49 to 108) and with felled, pheromone-baited poisoned trap trees. Millions of beetles were counted in the traps and trap trees, but the windfalls were nevertheless attacked and, in the two following years, live trees were killed.

In the experiments which are reported here, we tried to analyse further the potential of mass-trapping to protect windfalls. The following point were considered:

- How many insects attacked the windfalls?
- What proportion of the windfalls were protected by pheromone trapping?
- If windfalls were attacked, did this competition affect the performances of traps and trap trees?

To answer these questions, the following steps were followed: a) select windfall areas in winter; b) establish traps or trap trees; c) sample trees attacked in spring, to determine attack density and sex-ratio; d) model density of attacking beetles on an individual tree trunk; e) estimate how many beetles established on windfalls and, when possible, compare with trap catches; f) count how many windfalls escaped from attack; g) estimate how many windfalls were potentially protected by trapping.

**Table 1. Characteristics of the five experimental sites in Saint-Hubert**

Sites	Number of trees killed (summer 1992) [1]	Number of windfalls (winter 1992-93)	Number of trap trees [2]	Number of traps [3]	Ratio ([2]+[3]): [1]
A - "Ortho dh"	20	8	6 (standing)	6	0.36 <sup>1</sup>
B - "Ortho db"	8	14	3 (lying) <sup>2</sup>	-	0.38
C - "Ortho gh"	8	13	5 (lying)	-	0.63
D - "Ortho gb"	26	24	6 (lying)	-	0.23
E - "Mochamps"	106	18	13 (lying)	-	0.12
Total	168	77	33	6	

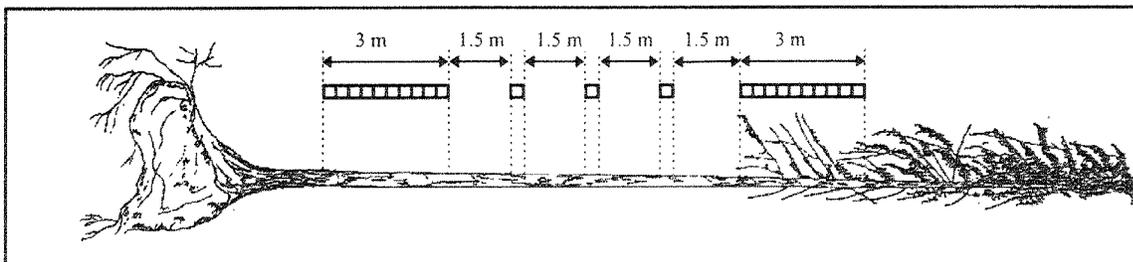
<sup>1</sup> In site A, the six traps have been converted into "trap-tree equivalents" counting 5.42 traps for 1 trap tree

<sup>2</sup> Previous experiments (unpublished) showed no differences in catches between standing and lying trap trees.

### Materials and Methods

**Experimental set-up.** Five sites containing windfalls (large trees of ca 1.5 m<sup>3</sup>) were selected at Saint-Hubert (Southern Belgium) in the winter 1992-93. Each site had been attacked in 1992 (total: 168 trees attacked during the second flight in 1992). These trees had shed much infested bark before their removal in the winter, leaving therefore a large residual overwintering bark-beetle population. In early April, traps (Theysohn) and/or insecticide-treated, pheromone-baited traps-trees (Drumont et al. 1992, Raty et al. 1995) were set up in each site (Table 1). Each trapping device was equipped with one *Pheroprax* pheromone dispenser (Shell Agrar).

**Sampling.** After the first flight in late spring, six attacked windfalls were randomly selected (one in sites A and D; two in sites B and E). 30 x 30 cm phloem samples were taken on each tree along two lateral lines, one on each side, following two patterns: a) on both ends of the trees, 10 samples side by side over 3 m starting at the point on the trunks where infestation began or stopped, b) on the central portion of the infested part of the trunks, one sample every 1.5 m, starting from the end of the lower 3 m portion (Figure 2). The numbers of entrance holes were counted on each sample. Trunk circumference along the sampled trees was also recorded. On four trees, the numbers of maternal galleries were counted, to establish a sex-ratio. As sex-ratio did not significantly vary between sites ( $\text{Chi}^2 = 0.253$ ;  $p > 0.05$ ; 3 df), an average sex-ratio f:m of 2.12 was used for all sites. Trunk circumference at lower and upper ends of the attacked portion of the trunk, as well as total length of attack were also



**Figure 2. Sampling design for assessing densities of entrance holes per tree**

measured on all unsampled trees.

**Catches in site A.** Numbers of insects caught in site A were determined by direct counting in the traps. In the trap trees, the numbers of insects caught in four funnels (diam. 30 cm) nailed to the base of the trunk (one just under the pheromone dispenser, the three others at right angle to each other) were used to estimate total catches following the method described by Raty et al. (1995). Comparing catches in traps to those in trap trees, a “trap-tree equivalent” [“TTE”, ratio of the catches (trap:trap tree)] was calculated:  $5037/27322 = 1:5.42$ .

## Results

**Table 2. Attacked windfalls in the experimental sites**

Sites	Attacked	Unattacked
A	5	3
B	6	8
C	4	9
D	10	14
E	13	5
Total	38	39

**Windfalls escaping from attack.** Total protection failed in all five sites (Table 2).

**Numbers of insects attacking the windfalls.** A function describing the distribution of attacks along the infested part of the trunks was established (Figure 3). This function is similar to the one developed by Mayyasi et al. (1976) for *Dendroctonus frontalis*:

$$d = [(a+b(h/H)).[h/H-(h/H)^2]^c$$

where:

d: number of entrance holes/dm<sup>2</sup>

h: height in the attacked portion of trunk (cm)

H: total length of attacked portion of trunk (cm)

The values for parameters a, b and c were established using the least squares method (a: 1.324557; b: -0.31153; c: 0.112154).

The trunk circumference was found to vary linearly along the trunks and could adequately be determined at each point on the trunks using the function:

$$C = C_0 + (C_1 - C_0) \cdot (h/H)$$

where:

C: circumference at height h (cm)

$C_0$ : circumference where attacks start

$C_1$ : circumference where attacks end

Integrating the product of these two functions on the total attacked trunk length, an equation was obtained, giving the total number of penetration holes (N) of each windfall according to its characteristics:

$$N = H(0.487822 C_0 + 0.449375 C_1)$$

The total number of insects per tree was then established by taking the females into account via the calculated sex-ratio:  $N_{\text{tot.}} = 3.12N$ . Total figures for each site are given in Table 3. An estimated 202,278 beetles attacked the windfalls.

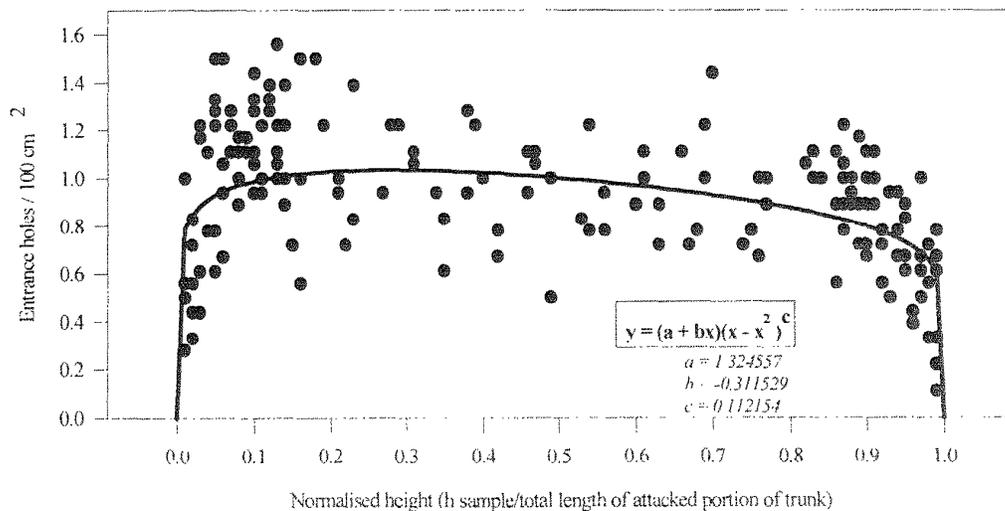


Figure 3. Estimated numbers of entrance holes of *Ips typographus* on each tree

**Trapping efficiency.** In site A, total estimated catches were 32,359 beetles while 28,067 insects attacked the windfalls. Working with trap-tree equivalents [ $n = 7.107$ , i.e. 6 trap trees + (6 traps/5.42)], the average number ( $\pm$  SD) of insects caught per TTE was  $4,548.9 \pm 2,051.9$ . The average number of insects per windfall in site A was  $5,613.6 \pm 1548.4$ . These figures suggest that, in site A, each trap tree prevented attack of one windfall.

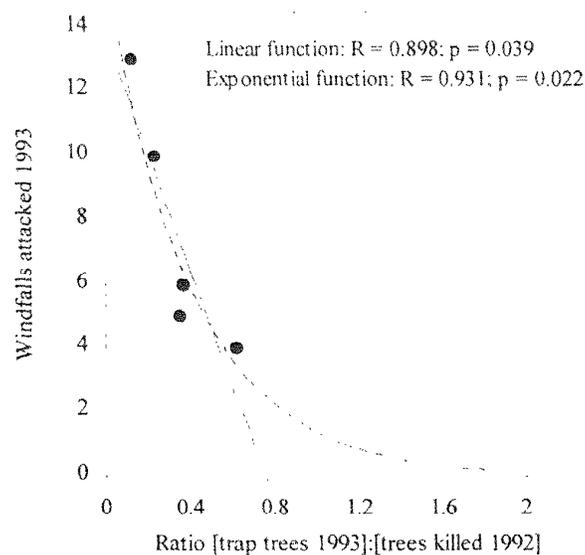
In another location nearby (Chanly) with comparable past history (ca 30 trees attacked in the summer of 1992) but devoid of windfalls, 8 trap trees caught an average  $4,445.9 \pm 1,638.8$  beetles. These catches are not significantly different from those in site A (t-test;  $t =$

**Table 3. Estimated numbers of *Ips typographus* that attacked the windfalls**

Site	Mean per tree ( $\pm$ S.D.)	Total per site
A	5613.6 $\pm$ 1548.4	28,067
B	4819 $\pm$ 2560.2	28,914
C	6443.3 $\pm$ 1318	25,773
D	5220.9 $\pm$ 1729.4	52,210
E	5177.9 $\pm$ 2024.8	67,314
Total	5323.1 $\pm$ 1881.9	202,278

0.09;  $p = 0.93$ ; 13 d.f.). Trapping efficiency therefore does not appear to be influenced by competition from the windfalls.

As the experimental set-up had not taken into account any estimate of the beetle population in the sites, partial failure to protect the windfalls could have been due to deployment of inadequate numbers of trap trees. Since the trees in all five sites were nearly of the same age, and of comparable size (ANOVA on basal circumferences of the windfalls in the five sites:  $F = 1.41$ ;  $p = 0.25$ ; 4 d.f.), and since they had been attacked at the same time on the previous year and taken out of the stand at the same period and by the same manner, we used the numbers of trees attacked in each site during the summer 1992 as a measure of beetle populations. We also used the ratios:  $[number\ of\ trap\ trees\ 1993]:[number\ of\ trees\ killed\ 1992]$  or, in site A,  $[number\ of\ trap-tree\ equivalents\ 1993]:[number\ of\ trees\ killed\ 1992]$  as a measure of the trapping effort to protect the windfalls in each site. In Figure 4 these values were plotted against the numbers of windfalls attacked in 1993. The significant relationships observed suggests that, if the trapping effort is high enough, windfalls could be effectively protected.



**Figure 4** Relationship between numbers of windfalls attacked and trapping effort

### Discussion

Windfalls offer no resistance to *Ips typographus*. As soon as a pioneer beetle lands on anyone of them it can start attracting conspecifics and the tree under attack competes with the protective traps or trap trees. Moreover, the windfalls possibly emit primary attractants not produced by the standing trap trees or the artificial traps: Austarå et al. (1986) report an enhanced effect of synthetic pheromones in the presence of logging waste. In our experiments, windfalls were attacked in all sites, as considerable numbers of insects escaped from trapping. However, competition from the windfalls did not seem to reduce the performances of the trap trees which, in site A, each caught as many beetles as each trap tree in another site where no windfall was present. On the other hand, over the whole trapping period considered (15 April to 30 July), the total numbers of beetles caught by the poisoned, pheromone-baited trap trees were not higher than those of insects establishing on the windfalls. This is intriguing, as the effect of insecticide is supposed to prevent the bark beetles from establishing on the trap trees and producing anti-aggregation pheromones, which should result in protracted attractivity of the pheromones and thus in larger catches.

When trapping effort is taken into account, it seems that windfalls could be protected by mass-trapping, provided that sufficient investments are made. In our experiments, this effort would have amounted to 0.8 - 2 TTE per tree attacked on the previous year (Figure 4). If the trees attacked in 1992 had not been removed during the winter 1992-93, local beetle populations would have been larger, and trapping efforts would have had to be higher. The trapping effort required for windfall protection can thus be prohibitive if large amounts of trees have been attacked during the previous year. However, if clean forestry cannot be

implemented, especially in cases where windfalls have been preceded by few or no attacks, mass-trapping might constitute an efficient option.

In this perspective, further work is still needed to confirm and expand these first results. In particular, it would be important to know what is the temporal sequence of beetle colonisation (successive or simultaneous response to trap trees and windfalls ?), in order to establish whether pheromone trapping in a site so far devoid of *Ips typographus* might increase the risks for the windfalls to be colonised. Another priority would be to determine an optimal relationship between trapping efforts and the stand's past history.

### Acknowledgements

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# Silvicultural methods of *Lymantria dispar* L. management: effects on *Agrilus bilineatus* (Weber) populations

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**ABSTRACT** The abundance of twolined chestnut borer, *Agrilus bilineatus* (Weber), adults were sampled using sticky panels over a 6-year period in a mixed hardwood forest in West Virginia. Sixteen stands (average size 10.5 ha) were used in the study; eight of these were silviculturally thinned in 1989, the remainder were uncut. During 1990 and 1991, populations of gypsy moth, *Lymantria dispar* L., reached outbreak levels. Densities of *A. bilineatus* adults peaked in 1992, the year following the second defoliation year (1992), and were always greater in thinned than unthinned stands, however overstory mortality was greater in unthinned stands. Correlations between twolined chestnut borer abundance and tree mortality were not strong, nor were the relationships between defoliation and twolined chestnut borer.

**KEY WORDS** *Agrilus bilineatus*; silviculture; mortality; *Quercus*; defoliation

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FOR AT LEAST the past 100 years, the two-lined chestnut borer, *Agrilus bilineatus* (Weber), has been recognized as a significant source of mortality to oaks (*Quercus* spp.) and to American chestnut, *Castanea dentata* (Chittenden, 1909, Haack and Acciavatti 1992). *Agrilus bilineatus* is frequently associated with trees that have been stressed through defoliation. As a major cause of defoliation for hardwood trees in the Northeastern United States, *Lymantria dispar* L. (gypsy moth), provides an initial stress to its preferred hosts, i.e. *Quercus*, and has been followed by *A. bilineatus* and *Armillaria mellea* as secondary mortality agents (Wargo 1977).

Silvicultural approaches to managing gypsy moth impacts have been proposed several times over the last 100 years (Fisk 1913, Clement and Munro 1917, Behre 1939, Bess et al. 1947, Gottschalk 1993). The intent of this approach is to minimize damage if defoliation does occur or reduce the likelihood of defoliation. Few studies have examined the effect of silviculture on the secondary mortality agents of gypsy moth host trees. The objective of this study was to determine if silvicultural treatments affected *A. bilineatus* adult population densities. Because portions of the study area was defoliated by the gypsy moth, we were also able to examine the relationships among *A. bilineatus* abundance, defoliation, and tree mortality.

## Methods

The study took place on the West Virginia University Forest (WVUF), located in Monongalia and Preston Counties, West Virginia. This oak-mixed hardwood forest (ca. 3075 ha) is along the Chestnut Ridge anticline, in the Appalachian Plateau physiographic province (Fenneman 1938). Average elevation of the WVUF is 591 m, but ranges from 318 m to 796 m. Overstory vegetation ranges from stands with a diverse assemblage of mixed-hardwood species to those dominated by oak. Variation in composition of overstory tree species corresponds in part to elevation -- percentage of oak increases with elevation. The 16 forest stands studied ranged in size from 7.8 to 12.6 ha, with an average size of 10.5 ha. The stands were physically selected to be arranged as eight pairs; one of each pair was thinned.

Within each stand, square plots (0.4 ha) were located within a stratified grid; each plot was separated by at least 100 m. Stands had 10 to 19 plots, depending on their size. The boles of two oaks associated with each stand were wrapped with a cardboard band impregnated with resin and coated with Tanglefoot™. Bands were 22.9 cm wide and were placed at 1.4 m above ground. The bands were placed on trees in mid-May, and the diameter, species and vigor condition of the tree were recorded at that time. Bands were removed in mid-August at which time all adult *A. bilineatus* were removed and counted. The number of *A. bilineatus* adults / m<sup>2</sup> were calculated to adjust for the diameter of the tree.

Bands were first deployed in 1989 and the study continued until 1994. No data were collected in 1990, however. During the winter of 1989-90, 8 of the 16 stands were thinned to reduce susceptibility or vulnerability to the gypsy moth. During 1990 and 1991, six stands (three thinned and three unthinned) were defoliated by gypsy moth. Each of the six stands incurred more than 50% defoliation of preferred species and more than 40% defoliation of all species for 2 years. Defoliation in the other stands, i.e. background defoliation level, was less than 15% of all species, including preferred. The data on *A. bilineatus* from 1989, then, represents base-line information prior to treatment or defoliation effects.

## Results and Discussion

When grouped by treatment, it is apparent that 1989 levels of *A. bilineatus* were similar among all stand types (Table 1). However, following defoliation in 1990 and 1991, the abundance of *A. bilineatus* increased significantly in the defoliated stands. Relative to control stands, the thinned stands also showed an increase in *A. bilineatus* populations in 1991, presumably due to the thinning effect, i.e. thinning may have damaged or stressed some trees, thereby attracting the insect (Dunn et al. 1986). Despite an increase in *A. bilineatus* in thinned stands, mortality of overstory species was minimal for stands that were not defoliated.

**Table 1. Average number of *Agrilus bilineatus* in each of four treatments in West Virginia University Forest. The first year of defoliation was 1990, and silvicultural thinnings took place during the winter of 1989 - 1990.**

	1989	1991	1992	1993	1994
Treatment	#/m <sup>2</sup>				
Thinned	8.68	30.36	50.87	19.14	2.82
Control	12.33	3.27	16.96	20.19	6.90
Defoliated	5.69	85.78	533.34	92.89	4.47
Defoliated and Thinned	11.91	111.23	899.31	65.64	7.65

Figure 1 describes the temporal pattern of defoliation, abundance of *A. bilineatus* and overstory mortality. These data represent the pair of stands that was most heavily defoliated, but the trend resembles that of the other defoliated stands. Although defoliation was comparable in both thinned and unthinned stands, the abundance of *A. bilineatus* was greater in the thinned stand, however, overstory mortality was greater in the unthinned stand. One possibility for the lower mortality in thinned stands is the overall increased vigor of the trees. Because the objective of the thinning was to remove trees of low vigor, residual overstory trees generally were more healthy in thinned than unthinned stands. Attacks of *A. bilineatus* may not have been successful in healthy trees, thus there was no resulting increase in mortality. Further, the greater number of borers in thinned stands also may represent a higher concentration of *A. bilineatus*, i.e., more borers but on fewer trees.

Abundance of *A. bilineatus* reached a maximum in 1992, but most of the overstory mortality occurred in 1991. The high population level resulted from the tree stress as a result of high levels of defoliation in 1990 and 1991. The pulse in mortality in 1991 reflected an increase in successfully attacked trees, that is, the large number of trees from which adult borers emerged. As a result of the mortality, the number of available hosts declined in subsequent years, contributing to a decrease in *A. bilineatus* abundance.

To understand the relationship between *A. bilineatus* and defoliation and the relationship between the insect and overstory mortality, we derived correlation coefficients using 1992 data on *A. bilineatus* with defoliation and mortality data for various years. The relationships between the borer and defoliation (Table 2) generally were weak, and often inverse. Correlations between 1992 levels of *A. bilineatus* and defoliation in were relatively strong only for stand 8 in the three defoliation years.

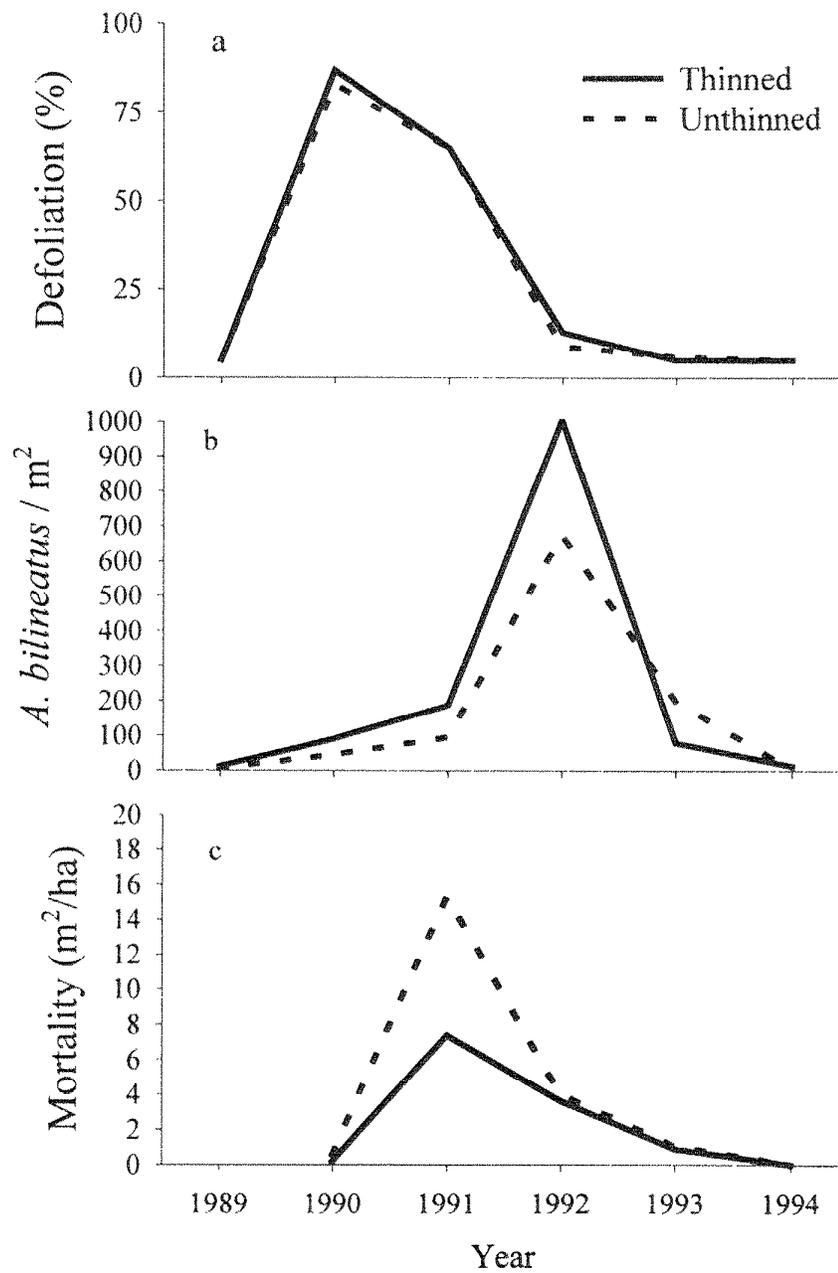


Figure 1. Trends in a pair of defoliated stands from 1989 to 1994 on the West Virginia University Forest in (a) defoliation of overstory trees (b), abundance of *Agrilus bilineatus* (c), and overstory mortality.

**Table 2. Pearson correlation coefficients of 1992 plot-level abundance of *Agrilus bilineatus* and defoliation.**

Stand No.	Defoliation year		
	1990	1991	1992
7	-0.143	-0.549	-0.185
8	0.409	0.801	0.630
13	0.093	-0.155	0.072
14	-0.103	-0.529	-0.275
15	-0.252	0.084	0.268
16	-0.141	0.190	0.065

The relationship between *A. bilineatus* and overstory mortality generally was better than those with defoliation (Table 3). The highest correlations were between 1992 *A. bilineatus* and 1993 mortality in stand 8, and between 1992 *A. bilineatus* and 1992 mortality in stand 15. Given the life history characteristics of the insect, it is not surprising to find a good relationship between *A. bilineatus* abundance in one year and with overstory mortality in the next. However, *A. bilineatus* abundance rarely accounted for mortality in the same year unless populations have been increasing in the previous year. In stand 15 there was a strong relationship between 1992 borer abundance and tree mortality for all three years: 1991, 1992, 1993. Some trees may take up to 3 years to die following initial attack by *A. bilineatus* (Haack and Acciavatti 1992). Thus, the pattern could be consistent for several years in succession. The most notable finding was the lack of a relationship between *A. bilineatus* and overstory mortality in most stands, for most years. These coefficients were generated using plot-level data, so it is possible that the plot-level relationship is insufficient to explain the dynamics of *A. bilineatus* in these stands. The plot and stand-level correspondence of borer abundance with defoliation and mortality may have more to do with attraction, dispersal, and aggregation – variables not addressed here.

**Table 3. Pearson correlation coefficients of 1992 plot-level abundance of *Agrilus bilineatus* and mortality for stands that were defoliated.**

Stand No.	Mortality Year				
	1990	1991	1992	1993	1994
7	-0.348	-0.417	0.186	-0.371	0.000
8	-0.302	0.368	0.715	0.895	-0.231
13	-0.341	-0.246	0.211	0.017	-0.203
14	0.330	0.016	0.446	-0.405	0.381
15	-0.393	0.550	0.752	0.555	-0.231
16	-0.140	-0.091	-0.001	-0.332	0.006

The abundance of *A. bilineatus* was consistently greater in thinned than in unthinned stands. The likely reason for this is stress from the logging operation, namely damage to residual trees or soil compaction. Several studies have shown that injured oaks attract more adult borers than uninjured oaks (Dunbar and Stephens 1975, Cote and Allen 1980, Haack and Benjamin 1982). Another possible explanation for an increase in *A. bilineatus* abundance in thinned stands is an increase in light in the canopy which in turn caused an increase in adult activity in thinned stands. Although thinning may promote activity of adult *A. bilineatus* and subsequent population buildup, it does not result in corresponding overstory mortality. Under circumstances where stress is minimal, and defoliation is not imminent, reducing overstory trees of low vigor and low starch reserves (Dunn *et al.* 1990), may keep populations of twolined chestnut borer low, in addition to reducing overstory mortality.

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## Augmentation of *Dendroctonus frontalis* parasitoid effectiveness by artificial diet.

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**ABSTRACT** *Dendroctonus frontalis* (Coleoptera: Scolytidae) is native to southeastern, USA, pine forests and has a rich complex of insect parasitoids. Natural enemies, and especially parasitoids, do not currently appear effective in regulating *D. frontalis* populations within rapidly expanding infestations. We believe forest stand structure, coupled with improper forest management strategies, are the primary reasons for this apparent lack of regulation.

We monitored *D. frontalis* and parasitoid populations over an 18-month period in a large infestation in east Texas and noted that although parasitoid numbers tracked *D. frontalis* population growth and decline, percent parasitism never exceeded 10% and averaged 5 to 6%. Why were parasitoids not able to better respond to increasing *D. frontalis* host populations? Our data suggest that both longevity and fecundity of parasitoid adults are severely constrained when food is not available.

Our research with a synthetic food, Eliminate™, developed by Entopath Inc., substantiates our hypothesis that longevity and egg production of adult *D. frontalis* parasitoids is increased when they are fed a nutrient-rich diet. We are currently testing field applications of this diet as an applied biological control tactic for southern pine beetle.

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During the past 2 years we have been studying the role of adult nutrition in the biology of parasitoids of the southern pine beetle, *Dendroctonus frontalis* Zimmermann, to test whether an artificial source of nutrition for the adult parasitoids will enhance their effectiveness as mortality agents of *D. frontalis*. The impetus for this research is based on a hypothesis (Stephen 1995) that the parasitoid complex of *D. frontalis*, when deprived of nutrition, is not successful in the control of beetle populations. The key point of this hypothesis is that parasitoids currently are not effective in regulating *D. frontalis* populations because parasitoid adults, in improperly managed southern pine forests (those which are overstocked, homogeneous in age and species composition and protected from fire), are limited in reproductive capacity and longevity by lack of suitable nutrition from natural sources. In this paper we summarize evidence that we believe supports this hypothesis.

Years of field-based observations of rapidly growing *D. frontalis* infestations, supported by a variety of published research, leads us to some specific observations about their dynamics (Table 1). Of particular interest to us is the fact that in all actively expanding infestations the rapid within-tree development of *D. frontalis* immatures, coupled with continuously re-emerging parent adults and emerging brood adults (Coulson et al. 1979; 1980; 1985), results in cohesive "spots" that contain a multitude of *D. frontalis* larvae that can serve as hosts for parasitoids.

**Table 1. Summary of pertinent information about large, rapidly growing southern pine beetle infestations.**

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A rich complex of *D. frontalis* parasitoids is always present.

A continuous supply of beetles, from brood adult emergence combined with re-emerging parent adults, produce an almost constant source of pheromone around trees under attack.

Continuous, rapid colonization of new trees yields overlapping beetle generations with all life stages present within the infestation.

Synchronous beetle development within neighboring trees results in thousands of fourth-stage larvae/pupae concentrated in closely adjacent trees.

Parasitoid host-selection behavior enables identification of and aggregation on those trees with susceptible hosts.

Parasitoid life cycles can be completed in approximately one-half the time of their hosts.

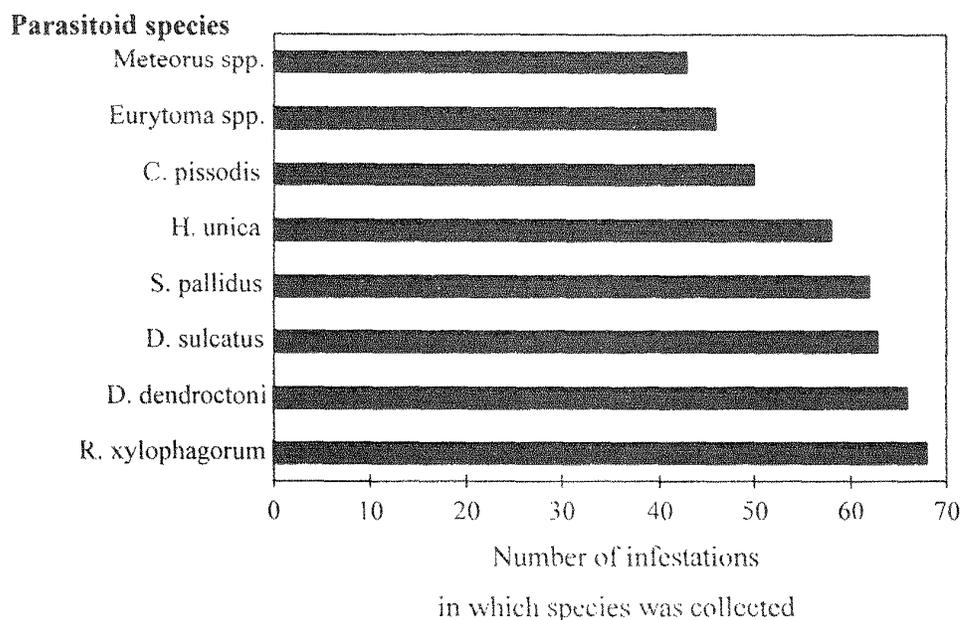
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Also, our collection records indicate that there are eight common species of parasitoids (Table 2). We have sampled intensively in a wide variety of infestations between 1975 and 1992, and a cursory examination of those collection data (Fig. 1) suggest that most of those species are nearly always present (Berisford 1980; Goyer & Finger 1980; Moser et al. 1971; Stephen et al. unpublished) in these infestations. It is also commonly observed that those parasitoid adults aggregate at trees with susceptible hosts (Camors & Payne 1973; Dixon & Payne 1979; Berisford et al. unpublished); and that during summer, most species can complete development in about two weeks, or one-half the time of their *D. frontalis* hosts (Jones and Stephen 1994). This suggests that parasitoids should have a greater opportunity to numerically respond to growing *D. frontalis* populations than we observe in large infestations.

**Table 2. Common Guild of *D. frontalis* Parasitoids**

Family	Species
Braconidae	<i>Coeloides pissodis</i>
	<i>Dendrosoter sulcatus</i>
	<i>Spathius pallidus</i>
	<i>Meteorus species</i>
Chalcidoidea	<i>Roptrocerus xylophagorum</i>
	<i>Dinotiscus dendroctoni</i>
	<i>Heydenia unica</i>
	<i>Eurytonia species</i>

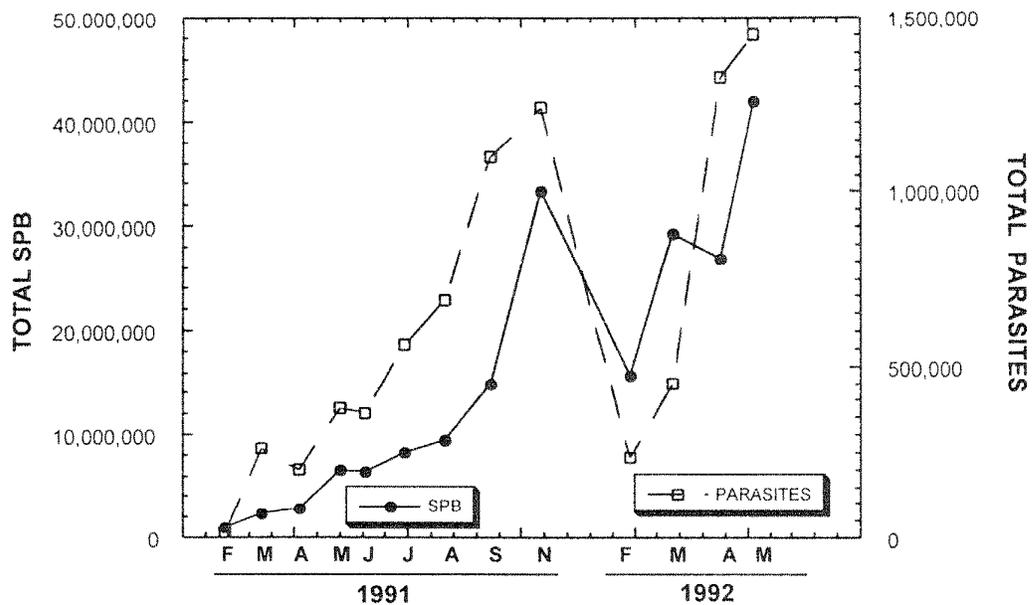
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**Figure 1.** Number of times each of the eight common *D. frontalis* parasitoids was collected from a total of 72 infestations that were sampled between 1975 and 1992.

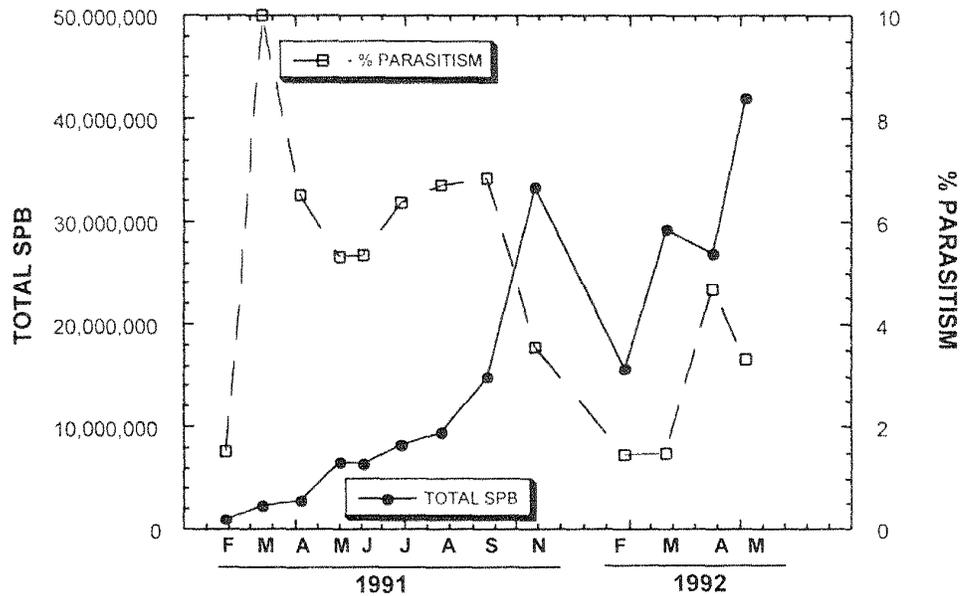
Research that provides estimates of parasitoid-caused mortality to *D. frontalis* populations is extremely limited. Those data that do exist support the conclusion that parasitoids do not cause high amounts of mortality, and despite many years of intensive research there are no published data that relate *D. frontalis* infestation growth over time and changes in parasitoid-caused mortality.

During 1991 and 1992 we intensively studied a large *D. frontalis* infestation by sampling infested trees and concurrently monitoring total infestation growth and size on the Indian Mounds Wilderness Area in east Texas (Fig. 2).



**Figure 2.** Numbers of adult *D. frontalis* (SPB) and adult parasitoids estimated in Spot 3, Indian Mounds Wilderness Area east Texas, over a series of sampling periods beginning in February 1991 and continuing to May 1992.

The infestation contained 74 currently infested trees in April 1991. It grew rapidly throughout the summer until by late September 1991 it consisted of 895 currently infested trees (and nearly 2600 cumulative dead trees). Beetle population levels declined over the winter, but the infestation began to grow again in the spring, and continued to grow until our final samples were taken in May 1992. In April 1991 we estimated approximately 2.8 million adult *D. frontalis*, and the rapid population growth that occurred from that period until November resulted in about 33.5 million beetles present at the start of the winter. Our sampling in February indicated about 15.8 million adults, but rapid increase in population led to nearly 42 million by May 1992. Total parasitoid numbers grew from less than 200,000 in April, 1991, to about 1.2 million in November, declined over the winter, then grew to about 1.45 million by May 1992. A visual comparison of increase and decrease in parasitoid numbers in relation to *D. frontalis* numbers indicates that patterns of change are closely related. Although parasitoid population abundance continually increased throughout spring and summer, percent parasitism was between 6 and 7% in both April and September (and fluctuated at about those levels in all intervening months) suggesting that although actual numbers of parasitoids increased in relation to changing beetle numbers, a numerical response probably did not occur (Fig. 3).



**Figure 3.** Numbers of adult *D. frontalis* (SPB) and percent parasitism estimated in Spot 3, Indian Mounds Wilderness Area, east Texas, over a series of sampling periods beginning in February 1991, and continuing to May 1992.

Our conclusion is that parasitoids inflicted variable, but relatively low mortality and did not exhibit a numerical response to increasing *D. frontalis* populations. When this conclusion is examined in relation to: (1) superabundance of continuously available *D. frontalis* host larvae; (2) parasitoid adults need only to traverse minimal distances within spots to locate these hosts; (3) observation of parasitoid aggregation at trees with suitable host larvae; and (4) parasitoid immature development rates that are nearly twice as rapid as their hosts (Table 1), it is perplexing that over several months of infestation growth a proportionally greater amount of parasitization did not occur.

Recently completed research designed to investigate egg load parameters in the complex of *D. frontalis* parasitoids (Hanano and Stephen, unpublished) indicates that among the different species the average number of eggs in newly emerged females ranged from about 5 to 17, with most species possessing less than a dozen eggs. Furthermore, these females rapidly resorb their eggs in the absence of nutrition (Table 3). In addition, Mathews et al. (unpublished) have determined that adult parasitoid survivorship is negatively influenced by lack of nutrition, and, in the absence of food, these adults are relatively short lived even under ideal lab conditions (Table 3).

**Table 3. *D. frontalis* parasitoids are synovigenic.**


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Have a limited number of eggs when they emerge as adults.
Resorb their eggs to prolong their lives if food (or hosts?) are not available.
Require nutrition as adults to produce new eggs.
Are short lived without food or water.
Can produce more eggs with a nutrient rich diet.

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These conclusions are in agreement with our hypothesis that lack of food for adult parasitoids may be the primary reason for the observed failure of parasitoids to adequately respond to increasing host densities. Carrying only the eggs at the time of emergence, adult females who do not receive additional nutrition cannot parasitize enough *D. frontalis* immatures to proportionally increase their abundance in relation to their hosts' density.

Entopath, Inc. has recently developed a nutritional supplement, Eliminate™, that specifically addresses the nutritional needs of adult hymenopterous parasitoids. We have used this product in our assessments of the role of nutrition for *D. frontalis* parasitoid egg production and longevity. Numerous authors have discussed the effects of forest management, or the lack of management, on the likelihood and severity of *D. frontalis* infestations. Silvicultural guidelines for reducing losses to *D. frontalis* are summarized by Belanger (1980). Pine stands that are highly susceptible to *D. frontalis* problems often are even-aged, single-species forests, that are overmature and over-stocked. Some of these conditions may be associated with poor forestry in the past and even some current intensive forest management practices (Table 4). Turchin et al. (1991) suggest that *D. frontalis* problems are becoming more severe. Perhaps pre-1900 forests, opened by fire, provided a more favorable environment for *D. frontalis* parasitoids because of greater diversity and structure that yielded an abundance of nectar-producing flowering plants encouraging parasitoid survival and reproduction when beetle infestations were initiated.

**Table 4. Improperly managed southern pine forests may be....**


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Predominantly a single pine species.
Even-aged.
Densely stocked.
Closed in canopy structure.
Protected from fire.
Blanketed with a thick pine-straw litter layer.
Barren with respect to flowering annuals.

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Our current research efforts are designed to field test the effectiveness of Eliminate™ as a nutritional supplement for *D. frontalis*. It is our intent to determine whether food supplements can enhance the effectiveness of the existing parasitoid complex of the bark beetle, and thus create an applied biological control tactic to reduce losses to *D. frontalis* that can be used alone or in combination with other IPM tactics. If Eliminate™ is effective, we anticipate that it will be a useful tool for forest pest managers as a method for direct control, as an aid in salvage operations, and useful in environmentally sensitive areas where salvage or cut-and-leave are not desirable alternatives.

### Acknowledgements

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# Spruce aphid population dynamics in relation to canopy character: scope for cultural regulation.

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**ABSTRACT** The dynamic relationships between annual population densities of the spruce aphid in plantations of Sitka spruce are reviewed. The aphid is anholocyclic in western Europe and unlike many aphids on trees, it can be strongly affected by winter weather. In general, mild winters may be followed by higher aphid populations which are capable of causing widespread defoliation, but overcompensating density dependence between years is also indicated and among those processes responsible are behavioural responses of aphids to increased crowding in spring.

Alate aphids were found to accumulate on foliage bearing low initial aphid populations, but it was also significant that they preferentially accumulated on tree canopies which were more exposed (apparent) than those under normal plantation conditions (cryptic). From initially similar population densities of aphids, larger aphid populations were shown to develop on apparent trees than on cryptic trees of the same provenance. The redistribution of alate aphids can therefore be seen as a significant (although not the only) process responsible for generating differences in aphid numbers between trees. The process is density dependent but different canopy types could support different equilibrium densities of aphids.

The consequences of differences in canopy exposure in plantations (edges or spacing between trees) may be an increased risk of aphid damage, and this should be considered in silvicultural planning, particularly as better interactive models for the growth of Sitka spruce plantations become available and the economic effects of the aphid become better understood.

**KEY WORDS** *Elatobium abietinum*, dispersal, Sitka spruce, *Picea sitchensis*, plantations

THE GREEN SPRUCE aphid *Elatobium abietinum* (Walker) is an important pest in Britain and in other maritime regions of western Europe. The insect is probably native to Norway spruce (*Picea abies* (L.) Karst.) on which it causes little damage, and problems are more or less confined to the exotic Sitka spruce *Picea sitchensis* (Bong.) Carr.. There is some irony in the fact that Sitka spruce is unlikely to be out-performed in the British Isles by other fast-growing timber trees (Low, 1987) but it is also one of the spruce species on which the aphid performs best (Nichols, 1987).

Damage to spruce foliage is caused during feeding when an injected toxin generates localised chlorosis (Fisher, 1987) and leads to premature needle abscission. The rate of needle loss corresponds closely to aphid population density (Day and McClean, 1991) and in turn results in a reduction in tree growth (see Straw, 1995 for a recent review). New foliage produced in the year of damage is not severely attacked (Jackson and Dixon, 1997) and trees are rarely killed, so the aphid remains a perennial pest. Populations persist even on severely defoliated trees and fluctuate within a plantation from year to year.

Density related processes are commonplace in the population dynamics of tree-dwelling aphids (Dixon 1990) but the origins of such density dependence are often less well

understood because of the complex age and morph structure in aphid populations. Spruce aphid population changes in maritime parts of western Europe are particularly difficult to interpret because, unlike other tree-dwelling species, the aphid here has no egg stage forming a convenient end-of-season point of reference. Growth and reproduction are possible year round. Nevertheless, it is becoming increasingly evident that population levels from year to year are, in part, a function of previous population densities. Some elements of the annual density dependent response of spruce aphid populations is thought to arise from differential aphid dispersal (Day, 1986).

Aphids undertake kinetic movements in response to the variable quality of the environment (Dixon, 1985) and these movements may involve aggregation or centrifugal dispersal in response to local resource status and the presence of other aphids. In this paper we look firstly at the patterns of alate production in a plantation forest and at the effect of population densities on the maintenance of alates on the tree at a time when damage is most likely to result. In addition we seek a relationship between the maintenance of alates and canopy exposure.

Natural boreal forest is characteristically even-aged (Peterken, 1987), and forests dominated by species such as Sitka spruce are less prone to disturbance, and hence local patchiness, than others, but it is also true that natural forest shows a greater diversity of canopy form and juxtaposition than its plantation counterpart. In plantations, trees are systematically spaced and re-spaced during a rotation to improve maximum mean annual increment (Lowe, 1987) and the physical relationships between adjacent canopies are often uniform. Sitka spruce thrives particularly well in closed stands and achieves high productivities through a foliar geometry which favours good light interception even in shaded positions (Cannell 1987). At present we have little idea how aphid pests respond to the silvicultural options open to plantation foresters. It is particularly important, for example, to explore the balance in economic gains achieved through respacing, and the losses which may arise from increased pest activity under different silvicultural conditions. As a first stage, this requires information on how pests respond to trees growing closer or further from one another.

Some accounts suggest that larger populations of the green spruce aphid, and consequently greater levels of foliar damage, develop on isolated trees, trees at the plantation edge and on trees prior to canopy closure at the so-called thicket stage of the rotation (Bevan 1966). This paper briefly reviews observations on the relationship of aphid populations to spruce canopies in a forest plantation where gaps between some trees have developed and given rise to different canopy types. Observations focus on the brief period in May when alate virginoparae are found in populations and when redistribution of aphids between trees is possible.

### Methods

Populations of aphids were studied in field plantations of Sitka spruce in Clare Forest, Co. Antrim and in Springwell Forest, Co. Londonderry, Northern Ireland. The general field methods employed and forest sites have been described in Day (1984a & b). Samples of year  $n-1$  age shoots were removed from the same trees at regular intervals through a season, or in the case of longer-term monitoring, once a year at the end of May when the population was

known to be at its peak level. Aphids were removed from the foliage, counted in the laboratory and assigned to seven growth stages and morphs.

Recruitment rate was estimated from the ratio between adult aphids (virginoparae) present in the samples and the number of first instar aphids. The insects pass through the first instar in a day or so at this time of year so it is thought to be a good reflection of population fertility and anticipated population growth rate. The production of alates occurs during a relatively short period in May and is initiated by increasing daylength (Fisher, 1982). A comparison of the relative numbers of aphids entering the alate developmental pathway, and the numbers of alate aphids subsequently found in samples from the same trees, provided an index of net alate accumulation on a tree. Alate adults are capable of leaving shoots at almost any time, and are also capable of arriving from elsewhere. It was not possible to distinguish between immigrants and those which remained on their natal shoot, so net migration was the estimated function. This was termed the index of migration. The ratio of the integrated numbers of alate to apterous morphs was calculated from abundance curves of instar IV and adults throughout the season. The curves (eg. Fig 5) were plotted on a physiological time scale (accumulated day degrees above a developmental threshold of 4 °C from January 1st) which adjusts the data for the temperature dependence of developmental rates. Areas under the abundance / physiological time curves were designated as follows:

al     alate adults  
 al4    alatform instar four nymphs  
 v     apterous adults  
 ins4   apteriform instar four nymphs

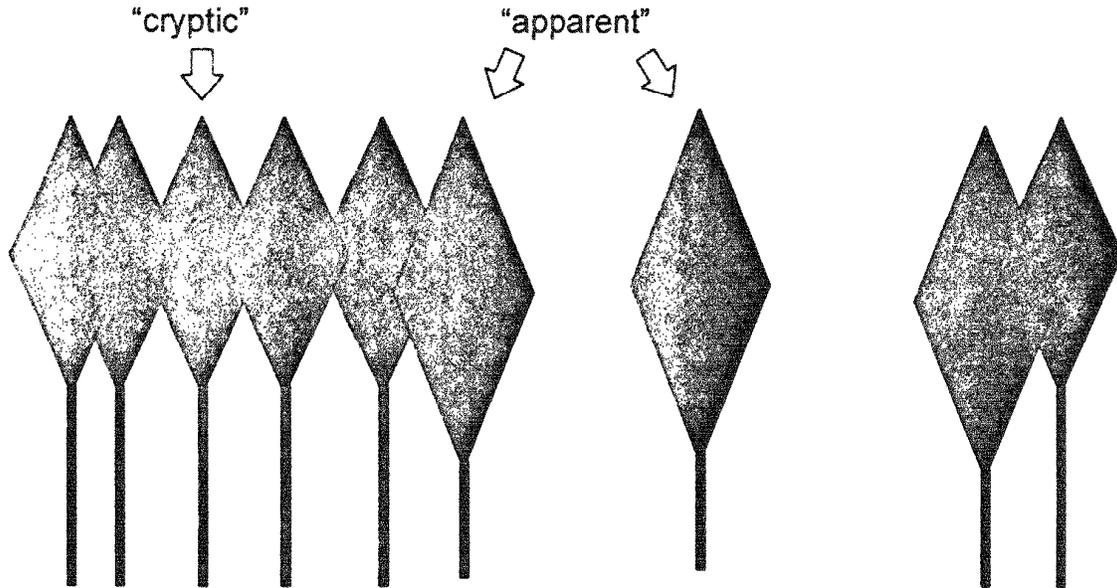
If the relative loss of alate adults by emigration was balanced by immigration, and there was therefore no net migration, the expected integrated abundance of alate adults would be given by:

$$al_{\text{expected}} = [(v) \times (al4)] / ins4$$

$$\text{and an index of migration} = \log (al_{\text{observed}}) - \log (al_{\text{expected}})$$

The index of migration actually indicates the outcome of migration and alate aphid survival for each tree studied.

The trees studied were of two main canopy types which reflected differences in their physical appearance (Fig 1). Where gaps had arisen in the forest plantation, or where trees were positioned at the edge of the forest, regardless of aspect, the canopies had developed with a third or more of their canopy perimeter at breast height without close proximity to other canopies ("apparent").



**Fig. 1. Representation of canopy types based on differences in their physical apparency. Cryptic canopies formed part of the normal plantation pattern at 2m spacing of stems and canopies developed juxtaposed and in contact with those of adjacent trees. Apparent canopies developed with a third or more of their perimeter in gaps within the crop or at plantation edges.**

Trees growing at normal 2m spacing from others had canopies at breast height which were completely surrounded by others ("cryptic"). A second series of observations was made on trees at Springwell forest in a collection of IUFRO Sitka spruce seed origins. Regular estimates of aphids were made on replicate trees of several provenances and we report here the monitored changes in population in six trees of a single Californian provenance. Here, three apparent and three cryptic trees started with rather similar aphid population densities before the aphid flight period in mid-May. The objective was to see if different population

levels developed in the two canopy types where tree origin was better defined and where initial aphid densities were comparable.

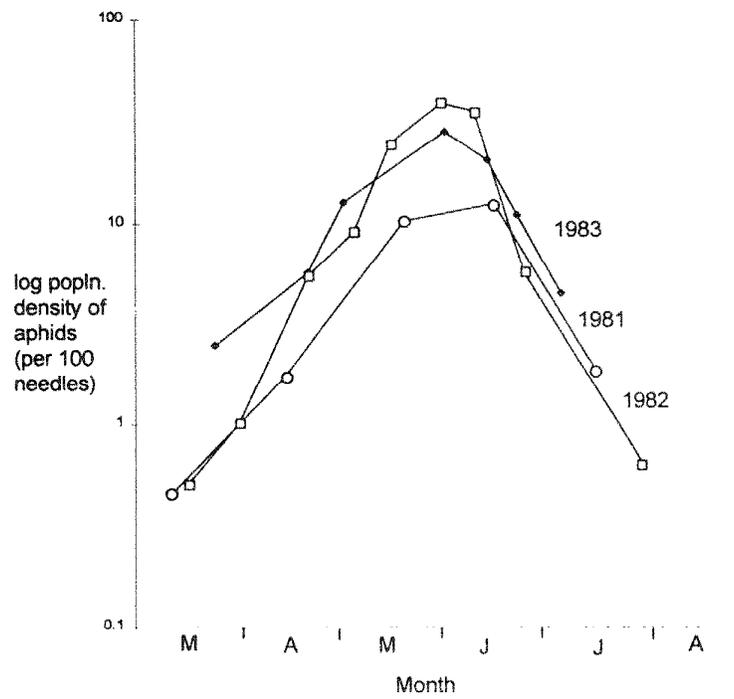
### Review of Population Dynamics

In the British Isles and most other parts of Europe where the aphid has become a pest, the seasonal patterns of aphid abundance are rather characteristic (Parry, 1974 and Fig.2). Aphid numbers start to increase in March when temperatures exceed a developmental threshold of 4°C (Crute and Day, 1990) and reach a peak towards the end of May (Day and Crute, 1990). A decline in sap nutrient quality following budburst results in the population falling to low levels by the beginning of July (Day, 1984a). Although translation of the population trajectory to a physiological time scale allows comparison of similar trends in different years (Fig. 2), it is the timing of budburst in any year which governs when the population is most likely to fall. In Northern Ireland this timing tends to be rather constant (Day, 1984a).

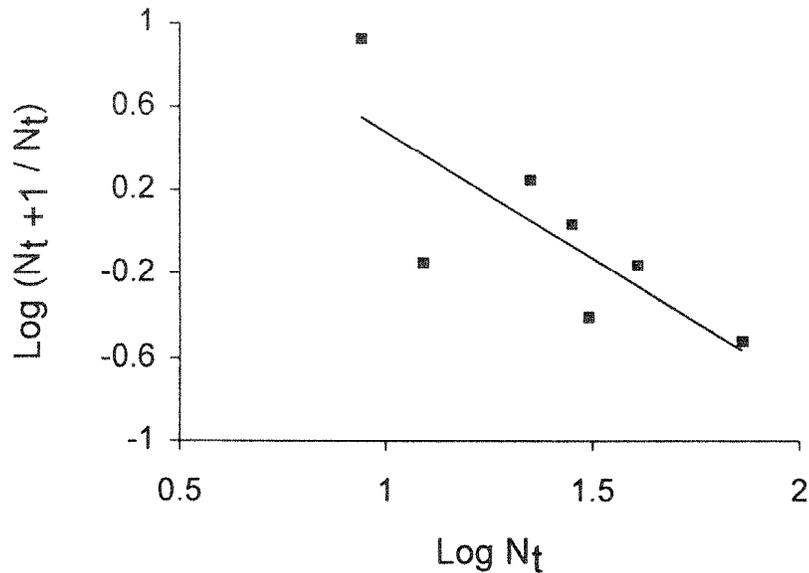
The population peak is of particular interest since it determines the level of foliar damage in a forest. The amplitude of the peak varies from year to year, and is determined by factors and processes which can be broadly summarised as follows. Firstly, there is an inverse relationship between the rate of population change between years ( $\log [N_{t+1} / N_t]$ ) and population density ( $\log N_t$ ) (Fig. 3). This explains about 60% of the variation in population density and may comprise a number of processes acting on the population of aphids throughout the year, and whose joint effect is overcompensating density dependence (Day and Crute, 1990). The statistical validity of this relationship is dubious but there is some comfort in the knowledge that, although the axes are not strictly independent, more rigorous analyses of similar relationships in other aphids provide similarly significant results (Dixon, 1990; Wellings *et al.* 1985).

Secondly, the population of anholocyclic aphids which enters the winter will respond in a variety of ways to warmer or colder conditions (depending on the year or the locality) before population growth becomes exponential once more in the following April. In some cases the result will be a reduction in recruitment, and in others there will be mortality. Some of the critical conditions for a range of European forests are currently being analysed (Day, in prep.) and are summarised by Day and Crute (1990) and in Table 1.

Jointly, overcompensating density dependence and the three temperature conditions explain a very high proportion of the annual variation in peak aphid population density. A quite independent analysis of spruce aphid catches derived from the Rothamsted Insect Survey has revealed similar relationships with the previous year's catch and winter temperature conditions (Thacker, 1996). Stepwise regressions for 18 suction trap sites in Great Britain were significant for more than half the sites, although density dependence between years appeared to be undercompensating. Nevertheless, the similarity of the result is encouraging considering that the trap catches were quite coarse representations of actual population data.



**Fig. 2. Mean population densities of spruce aphids estimated from foliage samples.**



**Fig. 3. The relationship between the rate of population change and population density in consecutive years, based on estimates of maximum aphid population density in summer.**

**Table 1 Winter and spring temperature conditions which are associated with lower population densities of spruce aphids at the following summer peak**

condition	critical temperatures	seasonal prerequisite	$r^2$ for regression on residuals of dd relationship
PHYS	physiological time (see text) accumulated before budburst (low spring temperature means aphids fail to capitalise on high sap nutrient levels)	cool springs	0.77
CHILL	frequencies of periods of 14 consecutive days with a daily mean temperature $\leq 5^\circ\text{C}$ (prolonged existence below the threshold for development causes chill coma)	cool winter	0.72
FREEZE	accumulated day degrees below $-7^\circ\text{C}$ (ice nucleation leads to freezing and death)	cold winter	0.70

Surprisingly, we know little about the processes which contribute to the overcompensating density dependent response of aphids to summer population densities. Plant effects and the actions of natural enemies, even at times of the year when aphids themselves are quite rare on the needle leaves, cannot be ruled out. Here we explore the potential for density dependence at the level of individual trees and in terms of the relative losses or gains (net migration) of alate aphids, before looking at a further effect of canopy type on this relationship.

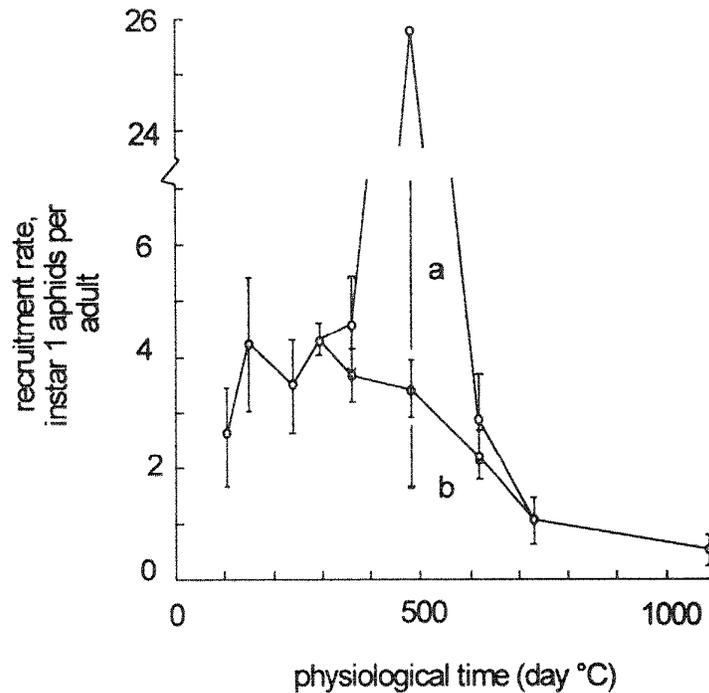
### Results

Aphid populations are reported during the part of the season from March to July when they were conspicuously present on spruce foliage. At other times of the year aphid populations may be barely detectable by routine sampling. It was no surprise that recruitment rate increased prior to budburst and then gradually declined as the summer progressed (Fig 4, line b). Since the alates of many aphid species are thought to larviposit only after a migratory flight and the majority of alates are lost during migration, the recruitment rate was recalculated with the assumption that the alates present made no contribution to recruitment (Fig 4, line a). Comparison of the two lines strongly suggests that this assumption is wrong, and that a more likely interpretation is that alates contribute to reproduction at least as much as apterous virginoparae. Their relative loss from a tree would therefore be consequential to subsequent population growth (or decline).

A population which experiences almost equal recruitment of alate instar IV nymphs and alate adult aphids is illustrated in Fig. 5. These data represent the aphids sampled on one of the trees in the study. On a tree where the relative losses of alate adults was high, the shaded sector "al" on Fig. 5 for adults would have a smaller area than for the equivalent sector for instar IV above.

The converse would be the case for a tree on which relative gains of alate aphids were made. In this way the index of migration rate was calculated for each tree and plotted against initial aphid density in Fig 6.

Clearly the most important effect on net migration is initial population size, and the components of net migration rate appear to act in a density dependent manner. Alate aphids appear either to leave trees on which population density is increasing rapidly, or to settle preferentially on trees with lower aphid levels. Differential mortality is an unlikely explanation since the calculation of the migration index has taken any minor relative differences in survival of apterous morphs into account. Although alate morphs may have higher rates of mortality than those of apterae, it is hardly likely that, relative to one another, they will differ in respect of population density. Since alates have a much greater capacity to arrive on or leave trees by flight this is the probable explanation for the primary relationship in Fig. 6.



**Fig. 4.** The seasonal pattern of recruitment rate (ratio of first instar nymphs in samples to adult virginoparae), calculated a) on the assumption of no contribution from alatae and b) on the assumption that all virginoparae in samples contribute to recruitment.

A second influence on net migration is the apparency of the tree canopy. The slope of regressions through data representing the two canopy types are significantly different ( $P < 0.005$ ) and suggest that equilibrium densities of aphids will be higher on trees with apparent canopies. Of course, spruce aphid populations are rarely in equilibrium, rather they change quite rapidly during the early summer. Nevertheless, it is anticipated that cryptic canopies will support fewer aphids per foliage unit at the time of the population peak.

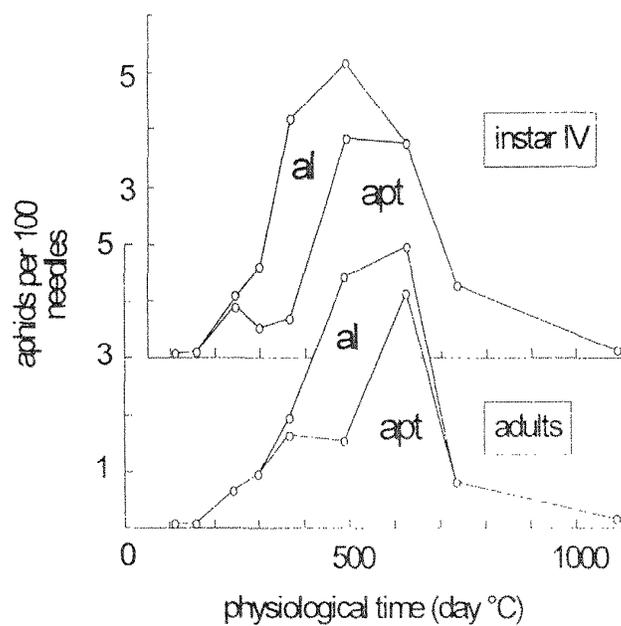
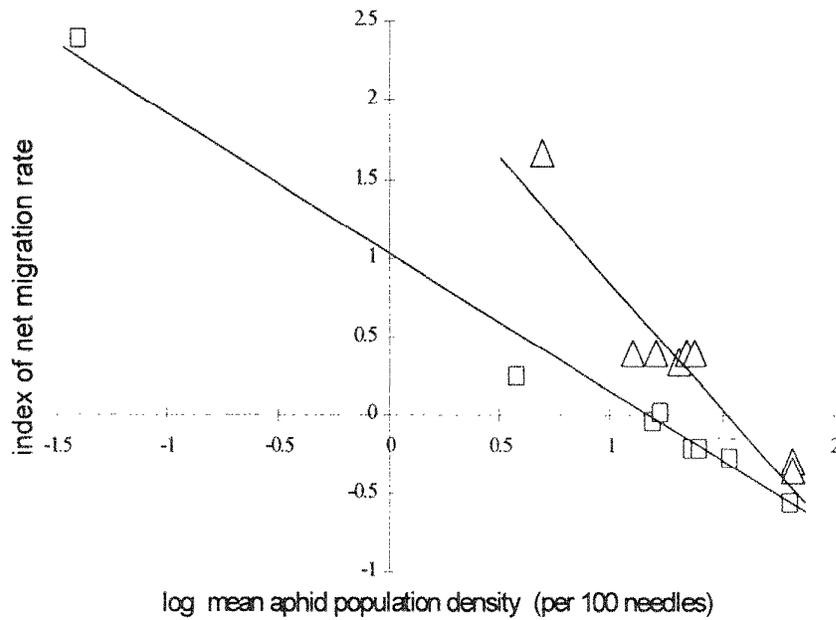
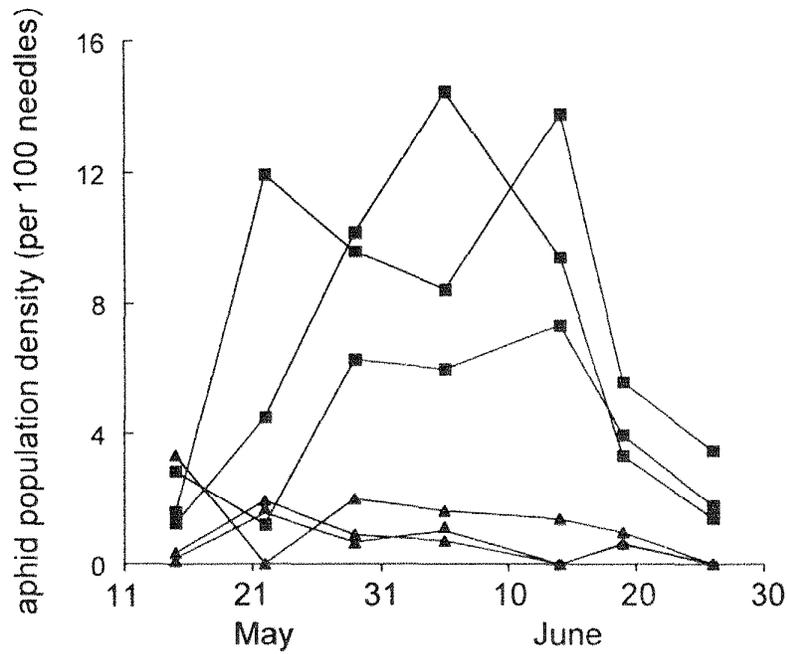


Fig. 5. The seasonal pattern of abundance of apterous and alate morphs in a population of spruce aphids estimated from the same tree. The shaded area represents alate or apterous morphs in both cases.



**Fig. 6.** Changes in net migration rate (based on the relative production of alate instar IV nymphs and the subsequent occurrence on a tree of alate virginoparae) in relation to initial (April) population densities of aphids estimated for a tree.

A separate series of trees were selected for their canopy types and studied at Springwell forest. Trees were of the same provenance and initially (prior to alate production) supported similar population densities of aphids. The expectation was that trees with apparent canopies would support larger aphid numbers by the end of May. This was indeed the case for the six trees reported in Fig. 7.



**Fig. 7.** The development of aphid populations on six trees of the same Californian provenance, where three trees were apparent (■) canopy types and three were cryptic (Δ) canopy types. Data represent mean population density based on shoot samples from each tree.

### Discussion

Other aphids on deciduous trees also experience overcompensating density dependence (Barlow and Dixon, 1980; Wellings *et al.*, 1985) but this occurs within years, whereas between year dynamics are governed by strong density dependence. Intraspecific competition operating through changes in aphid quality appears to be the main process

responsible for regulation, together with additional effects of natural enemies (Dixon, 1990). So far we have no knowledge of annual differences in spruce aphid quality, although when aphids were examined on trees supporting a range of population densities a crude measure of fecundity failed to show corresponding variation (Day, 1986). Loss of needle habitat may play a part, particularly since the rate of needle loss is proportional to aphid density (Day and McClean, 1991) and it appears that some needles are lost even at low aphid population density (Straw, in prep.). However, adult aphids are particularly vagile (Day, 1986) and may be expected to move from needles prior to abscission; the proximal cause of population change may therefore be losses of more mature aphids (with greater reproductive value) but the underlying process may be the response of the plant to aphid feeding. Results here suggest another contribution to density dependent regulation of aphid populations is at least possible when comparing dynamic responses between trees. Relative accumulation of alate aphids, known to play a major role in subsequent recruitment, was related to initial population density.

Canopy type or exposure was also important in appearing to determine different equilibrium aphid levels. It is a possibility that the clear differences in population development on trees of the same (Californian) provenance were simply the result of microclimate. Higher temperatures can cause quite large differences in mean relative growth rate at this time (Armour, in prep.). Trees growing close to edges experience differing exposure and edaphic factors altering insect survival as well as tree physiology and phenology. *Neodiprion sertifer*, for example, is frequently more abundant in unthinned stands (Pitman *et al.*, 1982). Temperature differences would only explain the canopy effect in the study at Clare forest if they affected aphid net migration.

It is interesting that isolated sycamore trees support fewer *Drepanosiphum platanoidis* because they sustain much higher losses from dispersal than do trees growing in clumps (Dixon, 1990). Here the effect is reversed compared with the spruce aphid, but then the migratory strategies of the two aphids are thought to be quite different, sycamore aphids undertaking only local flights between trees (Dixon, 1985) and spruce aphids capable of longer range dispersal which results in frequent interception by suction traps some distance from spruce forests (Thacker, 1995).

There are numerous examples in the literature of aphids selecting plants on the basis of background or of plant canopy spectral reflectivity (Berlandier and Cartwright, 1996). One of the changes that takes place in spruce canopies as aphid population density increases is that older foliage turns yellow before being lost entirely. Such changes may be profoundly important to immigrant aphids selecting new habitat, but would not explain different responses of alates to variations in canopy exposure. Perhaps aphids perceive and respond more favourably to canopies juxtaposed with habitats of contrasting physical character. As mentioned earlier, exposed canopies may provide a warmer microclimate than those which are closely juxtaposed and alate aphids may use this as a selection criterion. It is perhaps not surprising that aphids are capable of selecting new habitat on the basis of its current occupancy or its surface physical characteristics; the evolution of relationships between aphids and trees may have been strongly influenced by the aphids' perception of the relative surface area of specific plant parts (Dixon *et al.* 1995).

Spruce aphids undoubtedly affect the long-term growth of Sitka spruce crops (Day and McClean, 1991; Day and Cameron, 1997; Straw, 1995) and the results of periodic

defoliation are currently being incorporated in plantation growth models (T. Randle and T. Ludlow, pers. comm.). Where thinning and respacing are components in Sitka spruce silviculture (Low, 1987), consideration might be given to the trade-off between potential gains in productivity through competitive release of trees and the effects of increased aphid loads on timber growth. Further work is needed on the development of aphid populations at several crop ages and under a range of thinning régimes in order to estimate costs and benefits of cultural management with greater precision.

### Acknowledgements

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# Integrating Tree Felling with Application of an Inhibitor Pheromone for Suppressing Southern Pine Beetle Infestations\*

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**ABSTRACT** Recent efforts to develop a pheromone-based suppression tactic for southern pine beetle (SPB) are reported here. The suppression tactic relies on the use of the inhibitor pheromone verbenone to reduce or halt spread of southern pine beetle infestations. Verbenone-only and verbenone-plus-tree felling treatments were evaluated over a two-year period. In 1994, the verbenone-only treatment was effective in the eastern part of the SPB range, yet ineffective in Texas. Verbenone-plus-felling options were effective in all test areas. The ineffectiveness of verbenone-only treatment in Texas is attributed to a lower application rate of verbenone compared to rates used in the other test areas. This led to the development of a standardized protocol of verbenone application rates for 1995. Using the new protocol, the efficiency of all verbenone treatments increased in all test areas. Verbenone-only is recommended for infestations that are small in size and where felling or salvage of trees is not desired. Verbenone-plus-felling all active trees is more effective in larger infestations than verbenone-only, and does allow for salvaging of dead trees. In preparation for the release of these behavioral chemical tactics for operational use, we identify and discuss several issues that remain to be addressed.

**KEY WORDS** southern pine beetle, suppression, pheromones, verbenone, tree felling

THE SOUTHERN PINE beetle, *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae) continues to be the most serious insect pest of southern pines in the USA. In fact, 1995 was considered the most severe outbreak year in modern history, with regional losses estimated at \$250 million (1996 Southern Forest Insect Work Conference Committee Report). Traditional direct control tactics such as 1. cut-and-remove (fell and remove attacked trees plus a buffer strip of unattacked trees); 2. cut-and-leave (fell infested trees plus a buffer strip of uninfested trees and leave them at the site); 3. cut-and-spray infested trees with insecticide; and 4. cut, pile, and burn infested trees, are used to treat infestations (Swain and Remion 1981). Yet during outbreak years, limited personnel and equipment make it very difficult to treat all infestations. In addition, forest managers would prefer an alternative that either doesn't include tree felling or reduces the amount of volume felled (Salom et al. 1997). This is especially true in pre-commercial stands and remote areas with limited access.

A new tactic employing the application of an inhibitor pheromone to SPB infestations will soon be available to forest land managers. It has been a long time coming, considering that the use of semiochemicals in pest management for SPB was first suggested 25 years ago (Vité 1971). Experimentally, pheromone-based techniques for suppressing SPB infestations have included: 1. treating trees with the aggregation pheromone frontalin and cacodylic acid (Vité 1971); 2. attempting to prevent aggregation and infestation growth by treating dead trees in the infestation with the SPB aggregation pheromone, frontalin (Payne et al. 1985) or by aerial application of frontalin (Vité et al. 1976); and 3. placing the inhibitor pheromone verbenone at the active head to prevent infestation spread (Payne et al. 1992, Billings et al. 1995). To date, the inhibitor-based suppression tactic has been the most effective and economical of the tactics utilizing pheromones.

Verbenone, the pheromone used in this tactic, is an oxygenated terpene derived from *trans*-verbenol, whose identity (Renwick 1967) and function (Renwick and Vité 1970) suggested that it may have potential use in management of SPB. Successful tests of the compound in field trials by Payne et al. (1978) and Richerson and Payne (1979) led to the development of a verbenone-based suppression tactic (Payne and Billings 1989, Salom et al. 1992, Payne et al. 1992, Salom et al. 1995; Billings et al. 1995). This paper reports on the latest continued evaluation and comparison of verbenone-only and verbenone-plus-felling options of the suppression tactic. In addition, recent efforts to standardize infestation level release rates of verbenone and size of treatment buffer strips for all verbenone treatment options are discussed.

#### **Protocol for Verbenone Suppression Tactics**

Generalized procedures used in applying verbenone and evaluating success of two verbenone suppression tactics follow:

1. Identify active SPB infestations with < 120 currently infested trees.
2. Count the number of currently infested trees and verify the presence of fresh attacks.
3. Assess whether the infestation will continue to grow. Continued growth can be determined based in part on the number of fresh-attacked trees (trees where eggs have not yet been laid) and continued availability of susceptible trees in front of the active head (zone of most recent SPB attacks) (see Billings and Pase 1979).
4. Make decision whether or not to treat.
5. If the decision is to treat, apply one of the following available options:
  - a. *Verbenone-only*: treat fresh-attacked trees and a buffer strip of unattacked trees with verbenone.
  - b. *Verbenone-plus-tree felling all actively infested trees*: Fell all actively infested trees and treat buffer strip of unattacked trees with verbenone.
  - c. *Verbenone-plus-felling fresh-attacked trees*: fell all fresh-attacked trees and treat buffer of unattacked trees with verbenone
6. Monitor infestation for 6 weeks to determine treatment effectiveness. Categories include:
  - a. *Total suppression*: no new trees attacked beyond treated buffer strip during the 6-week post-treatment period.

- b. *Partial suppression:* new trees attacked beyond treated buffer strip, yet infestation growth decreased by  $\geq 50\%$ .
- c. *No suppression:* new trees attacked beyond treated buffer strip and infestation growth decreased by  $< 50\%$ .

**Verbenone Elution Device.** Verbenone with the enantiomeric ratio of 34%(+): 66%(-) was used for all treatments (Salom et al. 1992). 5 ml of verbenone was placed in white 1.2 mil polyethylene bags (8 x 13 cm) provided by Phero Tech, Inc., Delta B.C. The bag provided an elution rate of ca. 9.2 mg/h for 40 to 50 days during summer months (C.W. Berisford et al., unpublished data).

#### Comparisons Among Different Verbenone Treatment Options in 1994

The collaborators in this project were the Texas Forest Service (TFS), University of Georgia (UGA), and Virginia Tech (VT). The TFS evaluated sites in Texas, UGA in Alabama and Georgia, and VT in Virginia, North Carolina, and South Carolina. Three verbenone treatment options plus a check were evaluated as follows: verbenone-only (17 sites), verbenone-plus-felling all attractive trees (9 sites), verbenone-plus-felling all fresh attacked trees (8 sites), and no treatment checks (13 sites).

- a. *Verbenone-Only-* In SPB infestations, all fresh-attacked trees plus a buffer strip (3 trees deep and 10 m surrounding the active head) were treated with verbenone. Bags were attached to trees at a height of 3 m. The number of bags attached to trees were based on tree diameter at breast height (d.b.h.). This relationship was applied differently between the TFS and the VT/UGA groups (Table 1). The TFS tended to apply fewer bags per tree d.b.h. than VT/UGA for trees with  $\leq 28$  cm d.b.h.
- b. *Verbenone-Plus-Felling All Actively Infested Trees -* All actively infested trees were felled toward the older part of the infestation. A buffer strip of unattacked green trees, similar in size as used in the treatment above, was treated with verbenone. With the exception of the buffer, this treatment mimics a conventional cut-and-leave treatment that serves to open up the stand. The drastically different environmental conditions that result from opening the stand is believed to promote dispersal rather than aggregation. Brood in felled timber may be susceptible to increased radiant heat near the opened forest floor, resulting in a higher level of mortality. In addition, felling fresh-attacked trees reduces the production of secondary attractants.
- c. *Verbenone-Plus-Felling Fresh-Attacked Trees-* In this option only freshly-attacked trees were felled. The same sized buffer strip of unattacked trees at the active head of the infestation was treated with verbenone. This treatment is aimed primarily at eliminating sustained production of beetle- and host-produced attractants within the treated infestation. The felling of freshly-attacked trees open up the stand, but to a lesser degree than when all infested trees are felled.
- d. *Check-* SPB infestations that met treatment criteria but could not be treated due to various constraints were left untreated and monitored for 6 weeks.

**Table 1. Recommended number of verbenone bags placed on trees in southern pine beetle infestations by the Texas Forest Service and Virginia Tech/Univ. of Georgia during 1994 field season.**

<u>Texas Forest Service</u>			<u>Virginia Tech/Univ. of Georgia</u>		
<u>d.b.h. Range</u>			<u>d.b.h. Range</u>		
<u>Inches</u>	<u>cm</u>	<u># Bags/Tree</u>	<u>Inches</u>	<u>cm</u>	<u># Bags/Tree</u>
≤ 6	≤ 15	1	≤ 4	≤ 10	1
> 6 - 11	> 15 - 28	2	> 4 - 9	10 - 23	2
> 11 - 15	> 28 - 38	3	> 9 - 15	23 - 38	3
> 15 - 18	> 38 - 46	4	> 15 - 18	38 - 46	4
> 18 - 20	> 46 - 51	5	> 18 - 20	46 - 51	5
> 20	> 51	6	> 20	> 51	6

**Results** *Verbenone-Only* - The efficacy of this treatment was quite variable in 1994. In the eastern portion of the range (NC, GA, and AL), infestation growth was reduced by an average of 62% in 5 infestations (Table 2). Four infestations were completely suppressed while one was unaffected by the treatment. In Texas, the verbenone-only treatment was essentially ineffective (Table 2). Complete suppression occurred in only 1 of the 12 treated infestations, and infestation growth was slowed by at least 50% in one other infestation.

We attribute the relative ineffectiveness of the 1994 verbenone-only treatment in Texas to a lower amount of verbenone used for each treatment (Table 1). In 7 randomly selected infestations from the 1994 field season (ranging in size from 23 - 129 actively infested trees), the number of bags recommended by the TFS was 23% less than the number of bags recommended by the VT/UGA group. These differences in application rates were addressed during the 1995 field season. The modified protocol and the ensuing results will be presented in a later section of this report.

*Verbenone-Plus-Felling All Actively Infested Trees* - Infestation growth over all 9 infestations was reduced 70% (Table 2). Although the percent reduction in spot growth was less than in previous years (Billings et al. 1995), the tactic was completely effective in 8 of the 9 infestations by the end of the post-treatment monitoring period.

*Verbenone-Plus-Felling Fresh-Attacked Trees* - This tactic was completely effective in 4 of 5 infestations in Texas and partially effective in the other (Table 2). In Alabama, the treatment was effective in one of two infestations.

*Check* - Thirteen infestations were used as controls to ensure that most untreated infestations would continue to expand. Nine infestations increased in size by > 1 tree/day, and 10 added more than 10 trees during the monitoring period (Table 2).

*Relationship Between Verbenone Release Rate and Treatment Effectiveness* - To help explain why treatment effectiveness differed between Texas and other areas in the SPB range, we looked at the relationship between the amount of verbenone applied to a treatment and the percent reduction in infestation growth from data collected in 1993 (Billings et al. 1995) and 1994. A significant relationship was observed for verbenone-only (Figure 1a), but

Table 2. Growth rates of southern pine beetle infestations before and after application of suppression treatments in 1994.

Treatment	Infestation No.	Mean DBH inches (cm)	Pre-treatment				Post-treatment				
			New Trees Attacked	No. of Days	Trees Killed/Day	No. Active Trees at Treatment	Verb used m <sup>2</sup> /ft <sup>2</sup>	New Trees Attacked <sup>1</sup>	No. of Days	Trees Killed/Day	% Growth Reduction
Verbenone Only (East)	NC-1	13.3 (33.8)	9	8	1.1	46	21.2	19 <sup>a</sup>	43	0.4	63.6
	NC-4	12.3 (31.2)	14	10	1.4	79	14.3	45 <sup>c</sup>	40	1.1	21.5
	GA-2	4.5 (11.9)	4	6	0.7	37	25.0	8 <sup>a</sup>	42	0.2	71.4
	GA-3	8.6 (22.6)	4	6	0.7	29	58.3	2 <sup>a</sup>	45	0.04	94.3
	AL-4	5.0 (12.7)	6	5	1.2	47	50.0	17 <sup>a</sup>	36	0.5	58.3
	TX-26	7.9 (20.1)	39	7	5.3	140	27.5	171 <sup>c</sup>	42	4.1	22.6
	TX-27	8.1 (20.6)	8	8	1.0	47	23.3	46 <sup>c</sup>	42	1.1	-9.9
	TX-28	8.0 (20.3)	15	7	2.1	86	21.4	58 <sup>c</sup>	42	1.4	33.3
	TX-37	15.7 (39.9)	17	8	2.1	53	10.0	52 <sup>c</sup>	42	1.2	42.9
	TX-39	11.5 (29.2)	7	8	0.9	76	16.4	49 <sup>c</sup>	42	1.2	-25
(West)	TX-36	8.2 (20.8)	28	33	0.8	41	29.6	42 <sup>c</sup>	45	0.9	-11.2
	TX-43	15.4 (39.1)	8	21	0.4	24	12.5	8 <sup>a</sup>	30	0.3	25
	TX-30A	8.3 (20.3)	4	7	0.6	63	21.1	51 <sup>c</sup>	41	1.2	-50
	TX-30	8.5 (21.6)	18	6	3.0	86	22.2	53 <sup>b</sup>	42	1.3	56.7
	TX-27A	8.8 (22.4)	6	7	0.8	50	25.7	19 <sup>c</sup>	41	0.5	37.5
	TX-26A	7.2 (18.3)	80	15	5.3	252	13.1	187 <sup>c</sup>	41	4.6	13.2
	Mean	9.8 (25.0)	18.1	9.9	1.6	69.1	24.5	46.9	41.1	1.2	38.6 <sup>2</sup>
	Verbenone + Fell	VA-1	6.3 (16.0)	6	8	0.8	44	32.6	3 <sup>a</sup>	43	0.07
All Actively Infested Trees	VA-2	7.5 (19.1)	8	6	1.3	24	36.5	2 <sup>a</sup>	41	0.05	96.2
	NC-3	11.4 (29.0)	4	8	0.5	23	23.3	7 <sup>a</sup>	40	0.2	60
	SC-1	7.2 (18.3)	52	9	5.8	115	32.2	5 <sup>a</sup>	35	0.1	98.3
	SC-2	8.0 (20.3)	16	7	2.3	115	13.8	11 <sup>a</sup>	36	0.3	87
	GA-1	6.6 (16.8)	16	25	0.6	129	9.8	32 <sup>c</sup>	42	0.8	-25
	AL-3	6.4 (16.3)	7	14	0.5	96	19.2	17 <sup>a</sup>	42	0.4	20
	TX-66	7.9 (20.0)	5	6	0.8	56	19.8	0 <sup>a</sup>	42	0.0	100
	TX-68	7.4 (18.8)	17	7	2.4	107	25.8	0 <sup>a</sup>	42	0.0	100
Mean	7.6 (19.4)	14.5	10	1.7	78.8	23.7	8.6	40.3	0.2	69.8	

Table 2.(Cont'd)

Treatment	Infestation No.	Mean DBH inches (cm)	Pre-treatment				Post-treatment				
			New Trees Attacked	No. of Days	Trees Killed/Day	No. Active Trees at Treatment	Verb used ml/ft <sup>2</sup>	New Trees Attacked <sup>1</sup>	No. of Days	Trees Killed/Day	% Growth Reduction
Verbenone+Fell All Fresh Attacks	AL-1	5.5 (14.0)	8	8	1.0	24	116.2	14 <sup>a</sup>	49	0.3	70.0
	AL-2	7.8 (19.8)	11	14	0.8	87	--	42 <sup>c</sup>	36	1.2	-33.3
	TX-61	7.7 (19.6)	11	14	0.8	34	24.5	0 <sup>a</sup>	40	0.0	100
	TX-100	6.9 (17.5)	11	6	1.8	60	33.1	20 <sup>a</sup>	41	0.5	72.3
	TX - 14	8.5 (21.6)	31	14	2.2	86	22.1	11 <sup>b</sup>	29	0.4	82.8
	TX - 27	8.7 (22.1)	13	18	0.7	40	22.0	1 <sup>a</sup>	29	0.03	95.7
TX - 29	6.2 (15.7)	31	14	2.2	60	31.3	1 <sup>a</sup>	29	0.03	99.6	
Mean		9.2 (18.6)	16.6	12.6	1.4	55.9		12.7	36.1	0.35	69.6
Untreated Check	NC-2	8.7 (22.1)	4	7	0.6	43		1	41	0.02	
	GA-4	5.6 (14.2)	20	7	2.9	250		99	41	2.4	
	TX-29C	7.7 (19.6)				51		46	42	1.1	
	TX-31C	7.5 (19.1)				189		144	36	4.0	
	TX-32C	13.1 (33.3)				35		6	21	0.3	
	TX-33C	17.0 (43.2)				33		51	22	2.3	
	TX-34C	15.5 (39.4)				37		39	35	1.1	
	TX-36C	8.2 (20.9)				24		28	33	0.8	
	TX-38C	12.6 (32.0)				77		177	54	3.3	
	TX-312	7.2 (18.3)				222		197	32	6.2	
	TX-332	17.0 (43.2)				81		118	38	3.1	
TX-342	15.7 (39.9)				57		67	32	2.1		
TX ---C	14.3 (36.3)				23		0	32	0.0		
Mean		11.5 (29.3)			86.3		74.8	35.3		2.1	

<sup>1</sup> <sup>a</sup> Total suppression (no new trees attacked beyond treated buffer during 6-week post-treatment period).

<sup>b</sup> Partial suppression (new trees attacked beyond treated buffer, yet infestation growth decreased by  $\geq 50\%$ ).

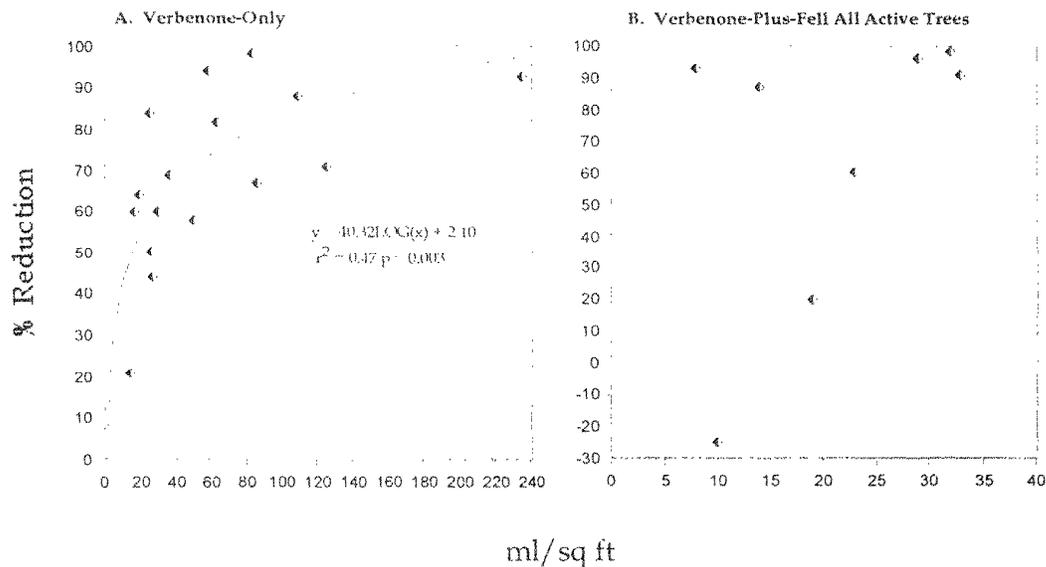
<sup>c</sup> No suppression (new trees attacked beyond treated buffer and infestation growth decreased by  $< 50\%$ ).

<sup>2</sup> Mean values were calculated by summing % reduction for each infestation and dividing by the number of infestations.

not for the verbenone-plus-felling all active trees treatment ( $F_{1,6} = 1.767$ ;  $p = 0.232$ ) (Figure 1b).

### Comparisons Among Different Verbenone Treatment Options in 1995

Two treatments were evaluated in 1995 were verbenone-only and verbenone-plus-fell all active trees. Verbenone-plus-fell fresh-attacks was not evaluated due to time constraints from trying to carry out enough replicates of the other two treatments. We determined it was more important to focus on the verbenone-only and verbenone-plus-fell all active trees treatments, and thus have two field-tested and efficacious treatments to carry into a technology transfer program. We evaluated verbenone-only in 20 sites, verbenone-plus-fell all active trees in 19 sites, and 8 check sites.



**Figure 1. Relationship between verbenone application rate and percent reduction in infestation growth during the 6-week post-treatment monitoring period for treatments A. the verbenone-only and B. verbenone-plus-fell all active trees.**

**Standardized Verbenone Application Rates.** Application rates of verbenone were increased for both verbenone-only and verbenone-plus-felling treatments for the 1995 season. The rates were modified from previous procedures (Billings et al. 1995) and based partially on data from Figure 1. Verbenone application rates were established to deliver 40 ml/ft<sup>2</sup> of basal area of actively infested trees for verbenone-only and 25 ml/ft<sup>2</sup> for verbenone-plus-felling all active trees (Table 3). Table 3 was designed to provide potential users with the number of bags required to treat infestations based on number of trees and mean tree diameter. Minimum buffer strip sizes of 12.2 m and three trees deep were used for verbenone-only and 7.6 m and two trees deep for verbenone-plus-felling all active trees. If the application rates listed above failed to meet the minimum buffer requirements, additional bags were added to treat all trees within the buffer. The number of bags attached to each tree

ranged from 1 - 6, based on tree diameter size. The recommendations for bags/tree from VT/UGA section of Table 1 were used by all collaborators in 1995.

**Results.** *Verbenone-Only* - Infestation size averaged 42 trees, ranging from 15 - 88 trees at the time of treatment. Overall, infestation growth was reduced by 77% (Table 4). Not only was greater reduction (17%) observed in the eastern states when compared to data from 1994, was met in 14 of the infestations. In general, the data suggest the importance of a higher application rate.

*Verbenone-Plus-Felling All Actively Infested Trees* - Infestation growth rate was reduced 89% (Table 4). This was not significantly different from the verbenone-only treatment ( $t_{0.05(2),37} = 1.99$ ;  $p = 0.054$ ). Out of 19 infestations, 16 (84%) were completely

*Check* - Of the eight infestations used as controls, six expanded by > 1 tree/day (Table 4). Check infestations grew an average of 3.1 trees killed/day, versus 0.3 and 0.1 trees killed/day for verbenone-only and verbenone-plus-felling active trees treatments, respectively.

**Table 3. Minimum number of verbenone bags recommended for treating southern pine beetle infestations for A. verbenone-only<sup>1</sup> and B. verbenone-plus-fell all active trees<sup>2</sup> in 1995.**

**A. Verbenone -Only (40 ml/ft<sup>2</sup>)**

Avg. d.b.h.	Number of Actively Infested Trees							
	10	20	30	40	50	60	70	80
6	50	50	50	63	79	95	110	126
8	50	56	84	112	140	168	196	224
10	50	88	131	175	218	262	306	349
12	63	126	189	252	315	377	440	503
14	86	171	257	342	428	513	599	684
16	112	224	335	447	559	670	782	894
18	142	283	424	566	707	848	990	1131
20	175	349	523	698	873	1047	1222	1396

<sup>1</sup>Number of bags = (mean d.b.h/2)<sup>2</sup> . no. active trees . 0.1745

**B. Verbenone-Plus-Felling All Active Trees (25 ml/ft<sup>2</sup>)**

Avg. d.b.h. -----	Number of Actively Infested Trees											
	10	20	30	40	50	60	70	80	90	100	110	120
6	50	50	50	50	50	60	70	80	90	100	109	118
8	50	50	54	70	88	105	122	140	158	175	192	210
10	50	55	82	109	137	164	191	218	246	274	300	328
12	50	80	120	160	200	240	280	320	360	400	432	472
14	54	107	161	214	267	322	374	428	481	534	588	642
16	70	140	210	280	349	419	489	558	628	698	768	838
18	89	177	265	354	442	530	618	707	795	883	972	1061
20	109	218	327	436	545	654	763	872	981	1090	1200	1310

<sup>2</sup>Number of bags = (mean d.b.h/2)<sup>2</sup> . no. active trees . 0.1091

Table 4. Growth rates of southern pine beetle infestations before and after application of suppression treatments in 1995.

Treatment	Infest. No.	Mean DBH inches (cm)	Pre-treatment				Post-treatment				
			New Trees Attacked	No. of Days	Trees Killed/Day	No. Active Trees at Treatment	Verb. used (ml/ft <sup>2</sup> )	New Trees Attacked <sup>1</sup>	No. of Days	Trees Killed/Day	% Growth Reduction
Verbenone Only	GA-1	5.2 (13.2)	27	14	1.9	35	86.2	29 <sup>a</sup>	42	0.7	63
	GA-2	6.0 (15.2)	26	14	1.8	41	96.6	18 <sup>a</sup>	42	0.4	78
	GA-5	7.6 (19.3)	8	7	1.1	27	58.9	19 <sup>c</sup>	33	0.6	45
	AL-1	10.0 (25.4)	9	7	1.3	29	51.9	13 <sup>a</sup>	42	0.3	77
	AL-2	6.0 (15.2)	18	7	2.6	64	48.6	27 <sup>a</sup>	42	0.6	77
	AL-4	5.8 (14.7)	21	14	1.5	55	40.1	10 <sup>a</sup>	42	0.2	87
	AL-5	8.6 (21.8)	19	7	2.7	63	25.6	13 <sup>a</sup>	42	0.3	89
	MS-2	17.4 (44.2)	6	7	0.9	23	21.3	14 <sup>c</sup>	29	0.5	44
	TX-1	9.6 (24.4)	8	11	0.7	41	54.9	7 <sup>a</sup>	42	0.2	74
	TX-2	4.8 (12.2)	21	11	1.9	56	73.5	9 <sup>b</sup>	42	0.2	87
	TX-3	6.9 (17.5)	20	6	3.3	71	42.3	9 <sup>a</sup>	42	0.2	93
	TX-5	8.2 (20.8)	3	7	0.4	20	48.6	1 <sup>a</sup>	42	0.02	95
	TX-6	8.2 (20.8)	4	7	0.6	17	48.2	3 <sup>a</sup>	42	0.1	88
TX-7	17.4 (44.2)	2	6	0.3	15	26.2	8 <sup>c</sup>	22	0.4	25	
TX-8	18.3 (46.5)	7	11	0.6	29	33.5	12 <sup>a</sup>	42	0.3	55	
TX-9	19.4 (49.3)	4	11	0.4	25	23.0	4 <sup>a</sup>	42	0.1	72	
TX-10	8.0 (20.3)	12	8	1.5	48	43.2	2 <sup>a</sup>	42	0.05	97	
TX-11	10.1 (25.7)	11	14	0.8	41	28.8	0 <sup>a</sup>	42	0.0	100	
TX-12	6.8 (17.3)	12	7	1.7	27	67.4	0 <sup>a</sup>	42	0.0	100	
TX-13	9.7 (24.6)	18	8	2.3	88	40.9	0 <sup>a</sup>	42	0.0	100	
Mean		9.7 (24.6)	12.8	9.2	1.5	42.2	48.0	9.4	39.9	0.3	77.3 <sup>2</sup>

Table 4 (Cont'd)

Treatment	Infest. No.	Mean DBH inches (cm)	Pre-treatment				Post-treatment				
			New Trees Attacked	No. of Days	Trees Killed/Day	No. Active Trees at Treatment	Verb. used (ml/ft <sup>2</sup> )	New Trees Attacked <sup>1</sup>	No. of Days	Trees Killed/Day	% Growth Reduction
Verbenone +	NC-1	8.1 (20.6)	11	7	1.6	35	25.6	0 <sup>a</sup>	42	0.0	100
Fell All	NC-2	8.4 (21.3)	23	7	3.3	122	22.3	21 <sup>a</sup>	40	0.5	85
Actively	NC-3	7.2 (18.3)	21	7	3.0	125	25.5	94 <sup>c</sup>	40	2.4	20
Infested	NC-4	8.5 (21.6)	32	7	4.6	122	23.6	38 <sup>b</sup>	42	0.9	80
Trees	NC-5	16.0 (40.6)	14	13	1.3	35	18.4	14 <sup>b</sup>	42	0.3	77
	NC-8	8.9 (22.6)	6	5	1.2	52	23.1	0 <sup>a</sup>	42	0.0	100
	NC-10	9.3 (23.6)	10	12	0.8	37	24	1 <sup>a</sup>	42	0.02	98
	GA-3	6.3 (16.0)	17	14	1.2	48	27.4	0 <sup>a</sup>	42	0.0	100
	GA-4	7.3 (18.5)	17	7	2.4	72	20.6	5 <sup>a</sup>	42	0.1	95
	GA-6	7.2 (18.3)	12	7	1.7	58	49.1	0 <sup>a</sup>	34	0.0	100
	AL-3	9.5 (24.1)	26	14	1.9	38	29.4	5 <sup>a</sup>	42	0.1	95
	FL-1	9.4 (23.9)	18	7	2.6	81	24.4	24 <sup>a</sup>	42	0.6	77
	FL-2	7.5 (19.1)	16	7	2.3	54	36.1	17 <sup>a</sup>	41	0.4	83
	TX-14	11.1 (28.2)	2	8	0.3	30	29.4	0 <sup>a</sup>	39	0.0	100
	TX-15	12.8 (32.5)	17	12	1.4	78	18.9	0 <sup>a</sup>	42	0.0	100
	TX-16	11.0 (27.9)	20	18	1.1	46	26.4	0 <sup>a</sup>	42	0.0	100
	TX-17	7.4 (18.8)	6	9	0.7	31	28.0	0 <sup>a</sup>	41	0.0	100
	TX-18	7.4 (18.8)	6	9	0.7	41	28.5	0 <sup>a</sup>	42	0.0	100
	TX-19	8.1 (20.6)	59	6	9.8	351	19.0	26 <sup>a</sup>	42	0.6	94
Mean		9.0 (22.9)	17.5	9.3	2.2	77	26.3	6	41	0.1	89.1

Table 4 (Cont'd)

Treatment	Infest. No.	Mean DBH inches (cm)	Pre-treatment				Post-treatment				
			New Trees Attacked	No. of Days	Trees Killed/Day	No. Active Trees at Treatment	Verb. used (ml/ft <sup>2</sup> )	New Trees Attacked <sup>1</sup>	No. of Days	Trees Killed/Day	% Growth Reduction
Untreated	NC-6	13.0 (33.0)				73	-	179	42	4.3	-
Control	NC-7	10.0 (25.4)				158	-	230	42	4.3	-
	NC-9	10.8 (27.4)				85	-	306	40	7.7	-
	NC-12	10.8 (27.4)				88	-	78	48	1.5	-
	NC-13	12.3 (31.2)				38	-	19	42	0.5	-
	NC-14	9.6 (24.4)				79	-	31	14	2.2	-
	GA-8	11.5 (29.2)				27	-	85	42	2.0	-
	GA-10	6.4 (16.3)				18	-	24	28	0.9	-
	Mean	10.6 (26.9)				70.8		119	37.3	3.1	

<sup>a</sup> Total suppression, no new trees attacked during the last two weeks of monitoring period.

<sup>b</sup> Partial suppression, infestation growth decreased by > 50%.

<sup>c</sup> No suppression

Mean values were calculated by summing % reduction for each infestation and dividing by the number of infestations.

## Conclusions and Future Needs

The inconsistency in the results observed between Texas and the eastern states in 1994, encouraged us to increase and standardize application rates of verbenone for both the verbenone-only and verbenone-plus-felling all active trees. These increased rates proved to be extremely effective for both treatments options in 1995. These revised rates in easy-to-use tables (Tables 3A & B) should enable forest land managers to treat SPB infestations without supervision. The verbenone-only treatment provides a control option in areas where felling timber is not permitted or desired (ie. precommercial stands, state parks or other protected areas). Where felling is a viable option, the verbenone-plus-felling treatment is an effective alternative to all felling treatments currently recommended and used. In general, it can be used in larger-sized infestations than the verbenone-only treatment, thus giving forest land managers more treatment options.

As these tactics approach operational status, there are still some technical issues that need to be addressed. One of the most important issues is the testing of a new verbenone bag. Currently the present bag elutes verbenone as soon as it is made and must be kept frozen prior to application. A new dispenser is being developed that will not release verbenone until it is attached to the tree. This will greatly ease shipping, storage, and handling of the bags.

Another issue we will consider is application height. Currently, verbenone is attached to trees 3-4m above ground on the tree bole. The rationale behind this is to position verbenone near the location on the bole where beetles first attack the tree (Dixon and Payne 1979). However, a special application tool, the Hundle Hammer, must be used to make this application. If the tactic can remain effective when attaching bags to the bole of the tree with a staple gun at arms reach, it will simplify the application procedure and reduce the application time. Promising results were obtained by the Texas Forest Service when they used this application approach for the verbenone-plus-felling treatment prior to 1994 (Billings unpublished data). Further tests of application height are planned.

The promising results obtained with the verbenone-plus-fell fresh-attacked trees in 1994 should merit further evaluation of this treatment. With standardized application rates of verbenone, there is no reason why this treatment could not be as effective and useful as the other two treatment options evaluated.

An issue currently being addressed is the registration of the verbenone bags with the U.S. Environmental Protection Agency (E.P.A.). The present status is that virtually all tests that have been requested have been conducted. Tests on immune response and an avian dietary study may still be requested. Once that issue is resolved, a registration package will be submitted for evaluation by E.P.A. (Steve Burke, Phero Tech, pers. commun.).

Lastly, the issue of technology transfer must be addressed. For the verbenone tactics to become accepted and used by foresters, efforts must be made to train foresters in their use and convince them that verbenone is a viable alternative to currently recommended SPB treatments. If the verbenone treatments are applied improperly, and as a result are ineffective, foresters may be reluctant to accept this new technology. Clark et al. (1997) address the issue of technology transfer for SPB in more detail.

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# A user-friendly PC-based GIS for forest entomology: an attempt to combine existing software

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**ABSTRACT** We present a combination of existing software which should facilitate the use of GIS by forest entomologists. The use of existing GIS by ecologists who want to take advantage of the spatial component of their analyses is often hindered by the difficulty of use and cost of such tools. Moreover, it might be useful to have a system which can be carried to remote locations where access to a mainframe computer or powerful workstations is unavailable. It is now possible to have a good system running on a single personal computer due to the increasing power and the low cost of this type of hardware. We have gathered programs characterised by their simplicity, low cost, and performances. IDRISI is a simple and inexpensive GIS which has a simple file structure that allows the user to create his/her own analysis scripts with basic knowledge in computer science. VARIOWIN is a geostatistical package which performs exploratory variography and 2D modelling. SURFER is a surface mapping system able to create and to display grids using several methods of spatial interpolations including two dimensional anisotropic kriging. FRAGSTATS is a program which performs landscape analyses and finally, COREL DRAW is a vector-oriented package that can be used for output of both bitmap and vector output. These programs were not designed to work together and problems may occur due to the heterogeneous nature of the system. Conversion file difficulties were encountered and we were faced with the complexity of using different programs to perform one analysis sequence. An additional module is being developed to solve these problems and the whole system should be able to manage data, analyze their spatial component and display map output in a simple and user-friendly way.

**KEY WORDS:** GIS, Spatial analysis, geostatistics, software.

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GEOGRAPHICAL INFORMATION SYSTEMS (GIS) are widely used in environmental management (Burrough 1993). In ecology and particularly in forest entomology they may be of considerable interest for the study of spatial pattern and insect spatial distribution (Liebhold et al. 1993, Coulson et al. 1993, Turner 1989). For example, the measurement of spatial dependence is essential in sampling methodology (Rossi et al. 1992, Legendre 1993, Fortin et al. 1989). Moreover, the interaction between insects and their environment always bears a spatial component (Borth and Hubert 1987, Hohn et al. 1993).

A GIS is a computer program designed to collect, retrieve, transform, display, and analyze spatial data. GIS can incorporate georeferenced data to produce maps or layers. Usually, a map layer or a theme is composed of only one type of data. GIS have the ability to import and manage data from different sources: mapped data, alphanumeric data, remotely sensed data. These types of data may then be combined to build a GIS database. Using this database, the user may create map outputs or display views relative to specific questions. These systems have recently improved their abilities to carry out spatial analyses integrating new built-in functions (spatial interpolation, spatial autocorrelation, overlay analysis, etc.). Furthermore, the user may create his own analysis functions with personal scripts.

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Pages 54-61 in J.C. Grégoire, A.M. Liebhold, F.M. Stephen, K.R. Day, and S.M. Salom, editors. 1997. Proceedings: Integrating cultural tactics into the management of bark beetle and reforestation pests. USDA Forest Service General Technical Report NE-236.

New GIS users often must choose between the performances of their system and the time that they will spend to be able to use it. Simple systems are easy to learn, but often lack integrated functions which obliges the user to write his/her own script to achieve specific goals.

Powerful systems are created for a diversity of purposes. They bear useful built-in functions, but users must become familiar with the whole GIS environment to use them properly. These powerful systems usually run on workstations. This type of hardware and associated software are expensive and demand knowledge of a new operating system environment. For example, the use of an important application software such as ARC/INFO demands knowledge in the UNIX operating system, knowledge of the ARC/INFO file structure and topology, of the ARC/INFO high number of commands and of the AML (Arc Macro Language).

However, users who just want to take advantage of the spatial component of their data have different hardware and software requirements than users who are planning complete GIS research projects involving extensive data census. The first kind of users can not afford expensive systems to add a spatial analysis component to their ecological studies. This is why an inexpensive system working on a single PC might interest such users. Moreover, the increasing power of PCs makes GIS more and more efficient on this hardware. Finally, a system running on a single PC might be useful on the field or to remote locations where access to mainframe computer or powerful workstations is unavailable (Carver et al. 1995).

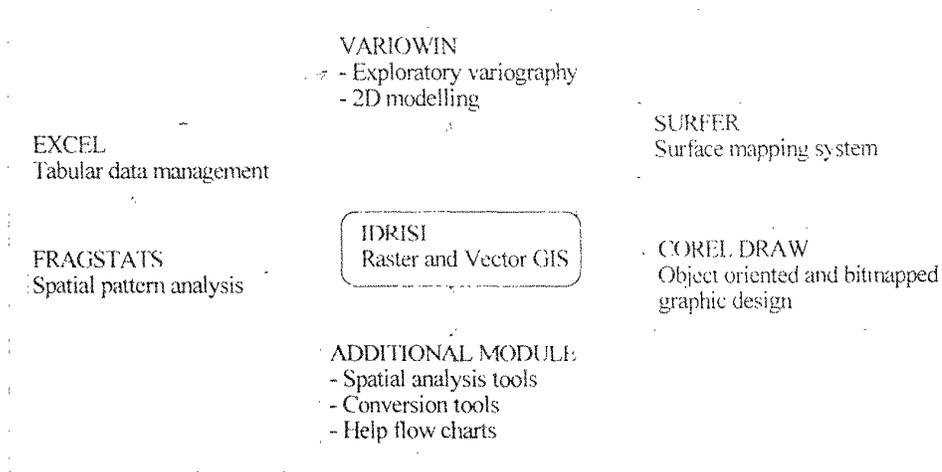
We present a combination of inexpensive and user-friendly PC-based software which should help potential users to integrate spatial components to their ecological studies.

### **System Presentation**

First, information about existing software was collected, mostly on the Internet in Web pages. Additionally, user discussions available in newsgroups related to each software were followed.

The software applications were tested on a Pentium 90 MHz PC with 8 Mbytes of RAM, under the WINDOWS 95 operating system. ARC/INFO PC, MAPINFO and IDRISI have been tested for GIS functionality. VARIOWIN, Geostatistical Toolbox, Geo-EAS, FRAGSTATS and SURFER were tested as additional spatial analysis tools. These applications were first tested with external sample data and secondly with our own data. GIS were tested for their ability to create a new database, to manage it and especially to exchange data with other sources. Spatial analysis software were tested with the author's instructions.

The chosen combination of software is presented in figure 1. IDRISI for WINDOWS (Clark University, Eastman 1988, Cartwright 1991) is a raster GIS which includes vector-data management and display. It is highly user-friendly and bears a lot of built-in spatial analysis functions. Its very simple file structure facilitate the creation of new analysis scripts. IDRISI for Windows includes a database manager which allows users to relate geographic features to a database (DBase, Access, text files). We used it in our system because of its simple file structure in both vector and raster formats and its ability to import and export data in a large range of formats (raster or vector geographical data or database data). This software is very inexpensive and will be used as the central geographical data manager of our system.



**Figure 1: Structure of the system showing inputs and outputs between software.**

VARIOWIN, written by Yvan Pannatier (University of Lausanne - Switzerland, Pannatier 1994) has been released with a manual (Pannatier 1996). Its aim is to compute geostatistical analyses and variogram modelling in 2D. There are three modules. The first creates a pair-comparison file on the basis of an ASCII file containing XY co-ordinates and attributes. The second module computes variogram surfaces, directional variograms, and a general variogram. It is also possible to estimate the semi-variogram with other estimators like the non-ergodic covariance or the non-ergodic correlogram which are often used in ecology (Sokal and Oden 1978(a), 1978(b), Johnson 1989). Moreover, the user may also create H-scatterplots and identify interactively potential outliers affecting the measure of spatial continuity. The last module offers an excellent tool to interactively model the semi-variogram.

SURFER (Golden Software, Inc.) is a surface mapping system designed to manage and display 3D raster-based data. Its first aim is to build surfaces by spatial interpolation on the basis of georeferenced data points. These interpolation methods include kriging but an input model created with another software has to be specified to perform it. The input and output files of VARIOWIN are fully compatible with the SURFER format and their combination has proved to be excellent to practice geostatistics. It is possible to export the interpolated grid in a format readable by IDRISI. The last version of SURFER has the capability to perform 2D anisotropic kriging with three nested structures.

FRAGSTATS is a DOS-based spatial analysis program for quantifying landscape structure written by K. McGarigal and B. J. Marks (Oregon State University). Landscape ecology involves the study of the landscape pattern which can be associated with other ecological characteristics, including vertebrate and invertebrate populations (Saunders *et al.* 1991, Turner 1989, Wiens *et al.* 1993). FRAGSTATS has been developed to quantify landscape structure by offering a comprehensive choice of landscape metrics. The PC version creates IDRISI raster-format files.

COREL DRAW (Corel Corporation) is a well known object-oriented vector and bitmapped graphic design software which is able to import and export in most of the graphic file formats. It is very flexible and can be efficiently used to manipulate and print map output.

EXCEL (Microsoft) is another well known software which is installed on many PCs. It may be used to manage input tabular data and output graphs and statistics.

### Test With Our Own Data

This combination of software has been tested in two study cases. The aim of this test was to assess the system inadequacies in specific analyses and to list any problems encountered. These test studies concerned the spatial distribution of *Pulvinaria regalis* Canard in the city of Oxford (Speight et al. 1996) and *Dendroctonus micans* (Kug.) in the Massif central (unpublished). The use of the combined software in both cases is presented in Table 1. In both studies, IDRISI was used to manage the spatial data, VARIOWIN was used to calculate variograms, correlograms, correlogram surfaces, and for 2D isotropic and anisotropic modelling. SURFER was used to process kriging and to generate surfaces and map outputs. COREL DRAW was used to assemble the final map outputs. FRAGSTATS has not yet been tested with actual data.

**Table 1: Use of the software for different stages of the study cases.**

Software	<i>Pulvinaria regalis</i> in the city of Oxford	<i>Dendroctonus micans</i> in the Massif Central
EXCEL	Data encoding Exploratory Data Analysis Graph outputs	Data encoding Exploratory Data Analysis Print output of the correlogram
IDRISI	Database construction Plotting of the samples on a map Quadrat analysis Moving-Windows analysis	Database construction Plotting of the samples on a map Quadrat analysis Moving-Windows analysis
SURFER	Print output of the correlogram surface Anisotropic 2D kriging Map output of the density distribution	Isotropic 2D ordinary kriging Creation of a Digital elevation model Map output of the density distribution
VARIOWIN	Creation of a Pair Comparison File Semi-variogram and semi-variogram surfaces 2D anisotropic semi-variogram modelling	Creation of a Pair Comparison File Semi-variogram and semi-variogram surfaces 2D isotropic semi-variogram modelling
COREL DRAW	Digitizing streets contour lines Map output of the samples points	Map output of the sample points Digitizing forest stands contour lines Digitizing altitude contour lines

### Results And Discussion

The use of this combination of software is very easy to learn and use. The interactivity of the exploratory variography performed with VARIOWIN is an excellent method for becoming familiar with the basics of geostatistics and is highly recommended to beginners. The kriging function of SURFER is elementary and other software must be used to perform other types of kriging (Varekamp *et. al.* 1996). Moreover, the user must take care not to use the kriging function of SURFER as a black-box tool; users should be aware of the hypotheses and assumptions involved in a kriging process (Isaaks and Srivastava 1989). The surface-management and the map-output abilities of SURFER are highly complementary to a

GIS such as IDRISI. FRAGSTATS has not been tested with our data but its use with data with the software provided is very easy. EXCEL and COREL DRAW are well known software and we do not need to comment on them. Taken as a whole, the system met all the requirements of these two case studies and we plan to carry on with almost the same configuration for further studies. The proposed combination of software allowed us to perform file input, data management, spatial analyses and map outputs.

However, considerable time was spent to solve computing problems. Basically, problems were caused by the fact that these applications were not designed to work together. First, some spatial analyses are not covered by this software combination. For example, a simple quadrat analysis might be used to determine whether sample spatial distribution is aggregative or not (Myers 1978). Second, the file formats used by the software are often different and conversion may involve a very detailed knowledge of the different software file structures. Fortunately, IDRISI allows the conversion of data from/to a wide range of formats. However we had problems even with the proper tools. For example, the missing data value used in the \*.grd files used by VARIOWIN is not the same in the \*.grd SURFER files (these files are described as having the same format). The grid files used by SURFER are binary files and must be first converted to ASCII files to be converted to IDRISI files. These problems are not serious if they can be easily identified, but they may otherwise cause important time losses. Sometimes, the automatic data transformations were not possible and we had to proceed manually within a text file. Third, due to the modular and heterogeneous structure of our system, we had to use different software to carry out an analysis sequence. For example, a basic geostatistical analysis involves exploratory data analysis (Tukey 1977) which can be computed with EXCEL, map output of the samples created with IDRISI, moving-windows analysis to detect sample-point aggregation and proportional effects calculated with separated programs (not included in the IDRISI analyses scripts), calculation of the estimated semi-variogram and its modeling carried out with VARIOWIN, and finally ordinary kriging processed with SURFER. This sequential analysis procedure was split into different small procedures within each software, with its own file input and output characteristics. Without an excellent knowledge of each software use and limitations, much time may be wasted.

To meet these problems, we plan to write scripts in Visual Basic gathered in one new additional module. First, they compute spatial analyses which are not covered by the other software (e.g. quadrat and moving-windows analyses). Second, to simplify the file conversions, we will write flow charts indicating steps to convert files. These flow charts should underline sensitive steps (e.g. replacement of one no-data value by another). If a file-conversion tool does not exist in the software combination, we plan to write it. Finally, we plan to write flow charts for typical spatial analysis procedures. These flow charts will be designed to help users to know how and where they can perform a given analysis. This additional module (figure 1) should complement the system in a user-friendly way: the additional tools will complement the existing software, conversion procedures and the flow charts should reduce the wasted time needed to become familiar with all the individual programs.

Varekamp et al. (1996) showed that it was possible to perform a wide range of geostatistical procedure with public-domain software available on the Internet (Englund and Sparks 1988, Pebesma 1993, Deutsch and Journel 1992). Their system is based on the use of

DOS executable programs or FORTRAN routines which provide more geostatistical analysis functions than our system. We have chosen to focus on user-friendly and basic software. The kriging abilities of SURFER are limited, but if a user wants to do more than two dimensional ordinary kriging, he can refer to other more powerful software (e.g. GSLIB) which is more complex and involves a better knowledge of spatial interpolation methods used in geostatistics. However, we insist on the fact that VARIOWIN is excellent for users to perform basic explorative and interactive variography and can be highly suggested for beginners users with geostatistics. Carver et. al. (1995) showed the advantages of having a GIS like IDRISI installed on a portable PC for expedition fieldwork (i.e. ability to develop sampling strategy as a result of immediate data visualisation). Additional spatial analysis modules enhance these advantages by a direct spatial analysis treatment of the data. For example, a strong spatial discontinuity in a species spatial distribution or a detection of data outliers might reveal interesting local environmental discontinuities. Such discontinuities detected afterwards are difficult to explain or interpret. Such fieldwork use of the GIS might then be of a considerable interest.

Our system is basically designed for beginners in GIS and geostatistics, but we believe that even experienced users will find interest in a portable and inexpensive system which allows small budget projects. Moreover, experienced users may use the same combination of software as a base which can be supplemented with additional software whenever they reach limitations. The flexible structure of the system and the simple file structure used should facilitate the integration of additional modules.

### Conclusion

Taken as a whole, this system could be used as a reliable, portable, and inexpensive PC-based GIS and spatial analysis tool. Problems due to the heterogeneous nature of the system have been encountered but they can be solved easily by a good knowledge of each software characteristics. An additional module should facilitate the use of this system by beginners. The flexible and simple structure of the system will facilitate the integration of additional modules by experienced users interested in different aspects of spatial analysis.

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