Progress Report

1 October 2001 – 31 March 2003

CHEMICAL ECOLOGY AND MANAGEMENT OF FOREST INSECTS

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Executive Summary

This two-year project is supported by mainly by an NSERC Cooperative Research and Development Grant for $250,000 which matches equal contributions from the forest industry (19 companies collectively), and B.C. government agencies, Forest Renewal B.C. and its successor, Forestry Innovation Investment (FII). Award of NSERC funding for the final six months is contingent on my obtaining continuing support from FII.

The research on forest insects supported by this funding has three objectives:

1. to make fundamental discoveries based on rigorous experiments;
2. to identify those discoveries that have practical potential in forest pest management; and
3. to work with clients to develop, test and implement new technology arising from fulfillment of the first two objectives.

Pursuit of these objectives in 10 major projects and four minor ones has led to many deliverables that fall into two broad categories, Contributions to Scientific and Technical Knowledge, and Operational Deliverables. In the former category there are 18 significant contributions.

1. Demonstration of marked differences in the bark and foliage volatile spectra of Douglas-fir (coast and interior), interior spruce, interior fir and lodgepole pine that could be used in host discrimination by tree-killing bark beetles.
2. Finding of primary attraction of Douglas-fir and spruce beetles to synthetic blends of host volatiles, the first such demonstration for either species.
3. Confirmation that myrcene is a better synergist for mountain pine beetle pheromones than a synthetic blend of lodgepole pine volatiles.
4. Discovery of new repellents for bark beetles, including *trans*-verbenol, acetophenone and 1-octen-3-o1 for the Douglas-fir beetle, MCH and 1-octen-3-ol for the mountain pine beetle, and 1-octen-3-ol for the spruce beetle.
5. Proof that Phero Tech's new high-dose verbenone pouch can deter attack in lodgepole pine stands by the mountain pine beetle in 0.16 ha plots treated with 16 pouches, and that deterrence can be significantly increased by adding a seven-component nonhost volatile blend, both treatments being suitable immediately for small-scale implementation.

6. Verification that MCH and 2-phenylethanol reduce catches of the mountain pine beetle in pheromone-baited traps, but discovery that only the latter compound is partially effective in deterring attack on pheromone-baited trees.

7. Finding that fatty acids and vegetable oils are competitive with a four-component nonhost volatile blend in delaying attack by ambrosia beetles on conifer logs, but realization that fatty acids and oils are impractical to work with and have little commercial value.

8. Preliminary finding that among an array of seven bark beetle pheromones that are perceived by ambrosia beetle antennae, MCH is so repellent to the striped ambrosia beetle that it is being tested in 2003 as a log protectant alone and in combination with our nonhost volatile blend.

9. Additional finding that attraction by the striped ambrosia beetle to the pheromone lineatin is enhanced by the bark beetle pheromones ipsenol and ipsdienol, suggesting that they may be used to improve the efficacy of commercial trapping programs.

10. Demonstration that lightweight flexible plastic traps of both cross-vane and pipe design are effective in trapping large woodborers, but realization that marketing of the traps must be delayed until durability is assured, and minor adjustments in design are tested.

11. Finding that the host volatiles ethanol and conophthorin interact with the pheromone tirathol to result in optimal attraction of the birch-infesting ambrosia beetle, *Trypodendron betulae*.

12. Morphological and molecular characterization of fungi associated with B.C.'s four native ambrosia beetles in the genus *Trypodendron*.

13. Demonstration by a weevil caging experiment of high susceptibility to the poplar and willow borer of one hybrid poplar clone (*trichocarpa x nigra*), and absolute resistance in another (*nigra x maximowiczii*).

14. In contrast to results in the field (13), lack of absolute discrimination in the laboratory by the poplar and willow borer among cut stem sections of hybrid poplar clones, suggesting that resistance expressed in the field by intact plants is induced by weevil oviposition.

15. New findings of pheromones of coniferophagous bark beetles in the bark of angiosperm trees, e.g. *trans*-verbenol, sulcatone and frontalin in *Populus tremuloides*, and conophthorin in 28 of 36 species examined to date.

16. Verification that grandisol is a male-produced pheromone that attracts female white pine weevils, and that grandisoic acid in combination with host volatiles is attractive to males.

17. Discovery of the spruce budworm sex pheromone component (*E*)-11-tetradecanal, and the saturated aldehyde tetradecanal, in the oral exudate of budworm larvae.
18. Elucidation in collaboration with Phero Tech of the impact and infestation dynamics of overwintering alder bark beetles in Weyerhaeuser Canada's Stillwater Division on the Sunshine Coast.

Operationally there are five major deliverables, as follows.

1. Set up and operation of over 45 experiments in over 20 separate research sites throughout the southern half of B.C., involving direct collaboration with personnel in Lignum Ltd., Phero Tech Inc., and UNBC, and interaction with 16 cooperators in four companies, two government agencies, one non-governmental organization and one university.
2. Liaison in collaborative research and development with two scientists in Canadian Forest Service laboratories at Sault Ste. Marie and Fredericton, and one U.S. Forest Service scientist in Athens, Georgia.
3. Administration of over $400,000 in external research funding, including the support and supervision of three postdoctoral scientists, three research technicians, seven graduate students, and eight research assistants, as well as a fleet of six vehicles which logged over 100,000 km, purchase and deployment of over $25,000 in semiochemicals and release devices, and maintenance of a large inventory of laboratory and field equipment.
4. Contribution to scientific and technical training through the graduation of one Ph.D. student, who is now a Postdoctoral Fellow at Cornell University, and one M.P.M. student, who is now Woodborer Program Manager for Phero Tech Inc., and the supervision of five other graduate students.
5. Communication of activities and results through the following:

- 18 papers published or in press in refereed journals;
- 2 chapters published in books, and one in press;
- 3 non-refereed publications;
- 13 presentations at scientific and professional meetings; and
- extensive interaction with Phero Tech Inc., the company that will develop marketable products and services arising from this research

Acknowledgments

I and my students and professional employees are most grateful to: Kevin Carvill RPF, who guided us through the final days of Forest Renewal B.C. and facilitated the transition to funding by Forestry Innovation Investment (FII); Fred Lowenberger RPF, who has done his utmost to make administration by FII user-friendly to researchers; Alison Janidlo and Linda Martin of NSERC who understood the uncertainty of funding from multiple sources and made it possible for research to proceed in the face of this uncertainty; and Barb Sherman of my department at SFU, who expertly oversees financial and administrative management of the research program. We also thank all the companies and industrial associations that have generously and loyally supported this research during a time of extraordinary hardship for Canada's forest industry.

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I. ADMINISTRATION

This two-year CRD project was started on 1 October 2001 after termination on 30 September 2001 of my 10-year NSERC Industrial Research Chair. It will terminate on 30 September 2003, one month after the date of my mandatory retirement from SFU. The major contribution of $125,000 per year from NSERC is matched by equal contributions of $62,500 from 19 forest industries, and $62,500 shared by Forest Renewal BC (FRBC) and it successor BC Forestry Innovation Investment (FII). The full amount of the first FII award has been spent, and will be accounted for separately by the SFU Finance Office. The final six months of funding from FII has been applied for, along with a request for a further six months of support. Additional industrial contributions to the overall research program were made by the Cariboo and Interior Lumber Manufacturers Associations, the Northern Forest Products Association, Ainsworth Lumber Co. Ltd., Louisiana Pacific Canada Ltd., Phero Tech Inc., Scott Paper Ltd., and Weyerhaeuser Canada Ltd. via sponsorship of GREAT Scholarships from the Science Council of B.C. to two to Ph.D. students, Deepa Pureswaran and Cindy Broberg. Also included in overall program funding is a $50,000 Discovery Research Grant from NSERC. During the first six months of the two-year CRD program, research on woodborers reported herein overlapped research on the same subject under FRBC Grant no. PA97511-0RE, which terminated on 31 March 2002.

As I near official retirement, there are no new graduate students or postdoctoral personnel in my laboratory. Postdoctoral Fellow Dean Morewood left for Pennsylvania State University on 1 April 2002. The employment of Drs. Harold Pierce and Aileen Wardle was terminated on 30 September 2002, after 28 and 11 years, respectively, working in my laboratory. This has left Research Technicians Leslie Chong, Regine Gries and Kathy Simmonds (nee Hein) coordinating overall field research, chemical-analytical activities, and woodborer management studies, respectively. Two Ph.D. students are wrapping up their research and will defend their theses in 2003-4. My last M.P.M. and M.Sc. students will defend their theses in the summer semester. A final Ph.D. student, Cindy Broberg will have research to complete in the summer of 2004.

Working with the three technicians and several research assistants, I will increasingly conduct much of the hands-on field research myself.

II. OBJECTIVES

Three objectives are paramount in my research program and guide all of the research therein. These are:

1) to make fundamental discoveries on natural phenomena by conducting experimental research of the highest possible standard;
2) to determine experimentally whether any of these discoveries have the potential to be exploited in new or improved methods of forest pest management; and
3) to work with industrial and governmental clients to facilitate the operational development, testing and implementation of new technology arising from fulfillment of the first two objectives.

III. GENERAL METHODOLOGY

My laboratory has developed, employed, adapted and refined what is now proven methodology. With excellent technical support, well-maintained equipment, and few restrictions on the flow of materials and supplies, we have had considerable success. We strive to construct perceptive hypothesis on how natural phenomena work, and then reconstruct the mechanisms that govern them.

We are expert in: volatile capture methodologies; coupled gas chromotographic-electroantennographic detection analysis (GC-EAD), GC-mass spectrometry (GC-MS) and other methods of volatile analysis; laboratory bioassays using various types of olfactometers; field forestry techniques including collection of mensurational data; field-trapping, tree-baiting and tree- and log-protection experiments using randomized complete block layouts and numerous types of lures and traps; and statistical analysis using ANOVA, Ryan's Q test, linear regression, chi-square and many other parametric and non-parametric tests. When our technical capacity is exceeded, we have a long history of successful collaboration with other laboratories.

IV. RESEARCH

A. HOST AND NONHOST CONIFER RECOGNITION IN FOUR SPECIES OF TREE KILLING BARK BEETLES

Investigators Deepa Pureswaran (Ph.D. student), Harold Pierce, Regine Gries, John Borden

Cooperators Ben Wilson, RPF (Babine Forest Products), Gwen Baker (Riverside Forest Products), Lorraine Maclauchlan RPF (BC Ministry of Forests), Ionut Aaron (Malcom Knapp Research Forest).

Problem Statement

Past research has elucidated the perception of response to nonhost angiosperm bark volatiles by tree-killing bark beetles in B.C. This has led to the development of a repellent nonhost volatile blend that we now recommend for use in combination with the antiaggregation pheromone verbenone against the mountain pine beetle, *Dendroctonus ponderosae*. Very little is known about the perception and response to host and nonhost conifer volatiles by B.C.'s four major tree-killing bark beetles, *D. ponderosae* , the Douglas-fir beetle, *D. pseudotsugae*, the spruce beetle, *D. rufipennis*, and the western balsam bark beetle, *Dryocoetes confusus*. Knowledge of this aspect of chemical ecology could lead to a better understanding of primary attraction to uninfested trees, secondary attraction involving both host volatiles and aggregation pheromones, and nonhost avoidance. It could also lead to the discovery of new attractants and repellents that have potential for operational application.

Research Accomplished

- Deepa has completed a replicated analysis by GC of the foliar and cortical volatiles of coastal and interior Douglas-fir, lodgepole pine, subalpine fir and interior spruce. In each case 10 trees ≥ 500 m apart were sampled. The results show a striking difference in both bark and foliage volatile spectra between coastal and interior Douglas-fir, and distinct differences among species in both ratio of volatiles, the presence or absence of some, e.g. □-phelladrene, limonene, bornyl acetate, and also the presence or absence of certain enantiomers of chiral compounds, e.g. (+)-□-pinene. These results indicate that there is ample information in the volatile spectra of the four conifer species to justify testing the hypothesis that the bark beetles specific to these species use these volatiles to distinguish between host and nonhost trees during host selection. A paper on this subject is in preparation for Phytochemistry.

- The results of 25 field trapping experiments in the summers of 2001 and 2002 to test the above hypothesis have now been analyzed. For the Douglas-fir beetle synthetic blends of bark and foliage volatiles from subalpine fir and lodgepole pine reduced catches in traps. In one experiment interior beetles responded significantly to blends of host volatiles alone, confirming primary attraction. In contrast blends of Douglas-fir and spruce volatiles did not increase catches significantly over those in traps baited with ethanol and the pheromones frontalin and MCOL. Spruce beetles also showed primary attraction to their host volatiles, but western balsam bark beetles were most attracted to volatiles of Douglas-fir than those of interior fir. For the mountain pine beetle neither host nor nonhost volatiles had any effect on the response to traps baited with the pheromones *trans*-verbenol and *exo*-brevicomin. Conversely, myrcene, which is only a minor constituent of lodgepole pine bark and foliage volatiles, and was excluded from the synthetic test blends, had a huge synergistic effect in combination with the pheromones. This led Deepa to propose the hypothesis that populations of mountain pine beetle in B.C. co-evolved with ponderosa pine which has a much higher myrcene content than lodgepole pine.

- In 2002 Deepa also ran two additional experiments for the mountain pine beetle on Red Plateau, near Kamloops. These tested more complete synthetic blends of lodgepole pine bark and foliage volatiles than in 2001, which included trace amounts of myrcene. Analysis of the trap catches showed that myrcene was again a better synergist than the blends of volatiles from lodgepole pine, the principal host of the beetle in B.C. Following up the hypothesis that the mountain pine beetle in B.C. may have evolved as a ponderosa pine specialist and may be more attracted to its volatiles than those of lodgepole pine, Deepa has collected foliage and bark samples of ponderosa pine from the southern interior. These will be processed for chemical analysis to determine their myrcene content.

B. RESPONSES BY FOUR SPECIES OF TREE-KILLING BARK BEETLES TO SEMIOCHEMICALS FROM HETEROSPECIFIC BEETLES

Investigators Deepa Pureswaran, John Borden, Regine Gries

Cooperators Ben Wilson RPF (Babine Forest Products), Gwen Baker (Riverside Forest Products), Lorraine Maclauchlan RPF (B.C. Ministry of Forests)

Problem Statement

Until recently research on behavioural disruptants for bark beetles has focussed on antiaggregation pheromones produced by conspecific beetles. For several years my laboratory has shifted part of its focus to investigating the role of volatiles from heterospecifics. Many of these compounds act as synomones, semiochemicals that are naturally beneficial to both the producing and the perceiving species. In bark beetles they may deter one species from attacking a host already attacked by another, relieving both from the threat of interspecific competition for the limited resources offered by the inner bark. When known and tested for repellency these synomones have considerable potential for use in combination with other repellents in protecting trees, and possibly stands, from attack.

Research Accomplished

- Deepa Pureswaran and Regine Gries have used GC-EAD to determine which compounds released by both sexes of Douglas-fir, mountain pine, spruce and western balsam bark beetles are perceived by the antennae of both sexes of each of the four species. Armed with this information, Deepa conducted experiments in the summers of 2001 and 2002 to elucidate the potential behavioural activity of each of the antennally-active compounds. Analysis of the data from these experiments, completed in the fall of 2001, has revealed several new repellents. 1-Octen-3-ol, which is produced by female *Dendroctonus* spp., and has been found previously in a European bark beetle, was highly repellent to Douglas-fir beetles, mountain pine beetles and spruce beetles, and thus can be classed as a new antiaggregation pheromone. MCH (3-methylcycohex-2-ene-1-one), which is an antiaggregation pheromone for Douglas-fir and spruce beetles, was significantly repellent to mountain pine beetles, indicating that in this case it acts as an interspecific synomone. Acetophenone, also identified in the volatiles of all three species, was moderately repellent to Douglas-fir beetles. *trans*-Verbenol, an antiaggregation pheromone of the mountain pine beetle, decreased the response of both sexes of Douglas-fir beetles. No results were obtained for western balsam bark beetles. The results on the three *Dendroctonus* species will by submitted for publication in Chemoecology in April or May 2003.

C. PROTECTION OF LODGEPOLE PINE FROM ATTACK BY THE MOUNTAIN PINE BEETLE USING HIGH DOSES OF VERBONENE IN COMBINATION WITH NONHOST VOLATILES.

Investigators John Borden, Leslie Chong, Tracy Earle RPF (Lignum Ltd.), Dezene Huber (Forest Sciences, UBC)

Problem Statement

As far back as 1989, the antiaggregation pheromone verbenone released from bubble caps at 1.8 mg/24 h at 20ºC (Phero Tech Inc.) showed great promise in protecting stands of lodgepole pine from attack by *Dendroctonus ponderosae*. However, research in Canada and the USA demonstrated that verbenone applications were of inconsistent efficacy over time, place and species of tree. Two approaches to improving the efficacy of verbenone-based disruption treatments have been pursued. My laboratory developed a nonhost angiosperm bark volatile blend that was repellent alone, and in preliminary single- or paired-tree experiments significantly enhanced protection from attack over that achieved with verbenone alone. The other approach was to increase the dose of verbenone. In their efforts to develop an efficacious verbenone treatment against the southern pine beetle Phero Tech devised a high-dose pouch that released verbenone at 25 mg/24 h at 20ºC. This research project combined both approaches in a single treatment.

Research Accomplished

- In June 2001, a 10-replicate, five-treatment experiment was initiated on 50 plots near Williams Lake, B.C. in collaboration with Lignum Ltd. and Phero Tech. It carried over into 2002 with respect to field evaluation, data analysis and writing. A seven-component nonhost volatile (NHV) blend tested in this experiment was comprised of guaiacol, benzaldehyde, salicyladehyde, nonanal, (*E*)-2-hexen-1-ol, (*Z*)-3-hexen-1-ol, and benzyl alcohol. Release devices containing antiaggregants (verbenone or NHVs) were deployed at 16 points on a 10 m grid in 40 x 40 m plots. In 10 control plots with no antiaggregants, single pheromone-baited trees at the plot centre were all mass-attacked by the mountain pine beetle by early October (Table 1), as were 26.6% of the 432 lodgepole pines within the boundaries of the plots (Table 2). In contrast, in plots treated with a high dose of verbenone plus NHVs, two of the central pheromone-baited trees escaped any attack whatsoever, four of 10 plots had no surrounding trees attacked and only 2.1% of the total of 523 surrounding trees were mass-attacked (Tables 1,2). Density of attacked and mass-attacked trees was highest within 5 m of the central baited tree in all treatments, indicating that those beetles that breached the antiaggregant grid were then drawn toward the baited tree. Operational efficacy should thus be improved in the absence of baited trees within a treated area. We conclude that high-dose verbenone plus NHV treatments could be implemented operationally as a minor component of an integrated pest management strategy for large infestations, particularly in a push-pull tactic in which beetles are pushed from one area by the antiaggregant treatment and drawn into another with attractive baits. However, primarily because of cost, the principal use would be in short-term protection of small, high-value stands or stands of high ecological or social value. A manuscript reporting these results is in press in Forestry Chronicle. After a diversion in 2002 testing MCH and 2-phenyl ethanol as potential disruptants (see IV, D) we will return to operational research in 2003, focussing on lowering the cost of antiaggregants by simplifying the nonhost volatile blend and reducing the density per ha of release devices.

Table 1. Effect of treatment with verbenone at two release rates, with and without NHVs on attack by mountain pine beetle on baited and surrounding lodgepole pine in 40 x 40 m plots.

		Baited trees	
Treatment	No. plots	No. mass attacked ($\geq$31.25 attacks/m^2)	No. replicates with attack on surrounding trees
Control	10	10	10
Low verbenone	9	9	9
Low verbenone & NHVs	10	9	8
High verbenone	10	10	8
High verbenone & NHVs	10	8	6

Table 2. Comparison of proportions of available lodgepole pine ≥17.5 cm dbh surrounding the central baited tree that were attacked (≥1 attack) and mass-attacked (≥31.25 attacks/m^2) in 2001.

Treatment	No. trees	Proportion[a]	
		Attacked	Mass-attacked
Control	432	26.6 a	21.3 a
Low verbenone	561	14.1 b	11.6 b
Low verbenone & NHVs	437	17.2 b	15.3 ab
High verbenone	521	7.7 c	6.0 c
High verbenone & NHVs	523	3.3 c	2.1 d

[a] Proportions within a column with the same letter are not significantly different, chi-square test for multiple proportions, $P<0.05$.

D. NEW CANDIDATE DISRUPTANTS FOR THE PROTECTION OF LODGEPOLE PINE FROM ATTACK BY THE MOUNTAIN PINE BEETLE

Investigators John Borden, Lisa Poirier (UNBC), Deepa Pureswaran

Cooperators Gordon Craigie RPF (Weyerhaeuser Canada), Chuck Carter RPF (Canadian Forest Products)

Problem Statement

While high-dose verbenone plus NHVs constitute an efficacious treatment for protecting lodgepole pine from attack by the mountain pine beetle (see IV,C above), both disruptants are costly, and the potential use is thus limited. One approach to reducing cost is to reduce the density of disruptants from 100/ha (10 x 10 m spacing) to 25/ha (20 x 20 m spacing) or even 16/ha (25 x 25 m spacing). Another approach is to investigate other less costly disruptants that might improve the efficacy of a low-dose verbenone blend. Three candidate disruptants were considered; 1-octen-3-ol (see IV,B above), MCH (see IV,B above) and 2-phenylethanol (a potent antiaggregation pheromone discovered by Deepa Pureswaran in her M.Sc. research). On the advice of Steve Burke of Phero Tech we discarded 1-octen-3-ol because of its high toxicity to vertebrates. This left us with MCH and 2-phenylethanol.

Research Accomplished

- Two 12-replicate trapping experiments were set up near the East Gate of Manning Park. These were to verify the results of past trapping experiments and to test low dose verbenone (V), MCH and 2-phenylethanol (2PE) in binary and ternary combinations for their ability to disrupt catches of mountain pine beetles in traps baited with the pheromones *trans*-verbenol and *exo*-brevicomin and the host kairomone myrcene (bait). Treatments in the two experiments were as follows:

Exp.1	Exp. 2
unbaited control	unbaited control
bait	bait
bait + V	bait + V + MCH
bait + MCH	bait + V + 2PE
bait + 2PE	bait + MCH + 2PE
bait + V + MCH + 2PE	bait+ V + MCH + 2PE

- Trapping Exp. 1 and 2 were exactly replicated twice as tree baiting experiments (except that myrcene was not included in Phero Tech tree baits), once at Whipsaw Creek near Princeton, and once on the 1400 Road south of Prince George, with respective numbers of replicates as follows: 25, 20, 20 and 17. In mid and post-attack assessments, the attack density on the treated trees was counted in 20 x 40 cm panels on the east and west faces of the trees, and all trees ≥17.5 cm dbh within 5 m of the baited tree were evaluated as unattacked, lightly-attacked (attack density <31.25/m^2) or mass-attacked (attack density ≥31.25/m^2,or many pitch tubes and copious amounts of frass in bark crevaces, cobwebs and around the root collar).
- In the trapping experiments the repellency of both MCH and 2-phenylethanol was verified, but only the latter was competitive with verbenone; the temary combination reduced the catches to a level not significantly different from that in unbaited control traps (Table 3). The tree baiting experiments (Tables 4, 5) demonstrated why it is unwise to rely only on trapping experiments, a fault that has plagued other research groups. In tree-baiting Exp. 1 no treatment was better than verbenone alone, although 2-phenylethanol appeared to have some ability to protect trees from attack. In Exp. 2 at Princeton, all combinations that included verbenone were effective in preventing mass attack on baited trees as well as attack on surrounding trees. At Prince George, the beetle pressure was so high that the unbaited control trees were frequently attacked, probably obscuring significant treatment effects. One

pertinent conclusion, that can be reached, is that MCH has no potential as a operational protectant against attack by *D. ponderosae*. On the other hand, one might tentatively conclude that it is worth working further with 2-phenylethanol. A manuscript on these experiments is planned for the Canadian Entomologist.

Table 3. Ranked catches of mountain pine beetles in multiple-funnel traps baited with attractant baits (*trans*-verbenol, *exo*-brevicomin and myrcene) alone or with MCH, 2-phenyl-ethanol (2PE) or verbenone (V) alone or in ternary combination (Exp. 1) and with the candidate antiaggregants in all possible binary and the ternary combination (Exp. 2). N=12 in both experiments.

Exp. no.	Treatment	Number of Beetles captured($\bar{x}$ ±SE)[a] Males	Females
1	bait	137.8 ± 47.4 a	86.5 ± 38.8 a
	bait + MCH	44.9 ± 8.9 b	24.4 ± 8.2 b
	bait + 2-PE	4.7 ± 1.1 c	4.3 ± 1.2 c
	bait + V	3.5 ± 1.2 cd	2.3 ± 1.5 cd
	bait + MCH +2PE +V	3.5 ± 0.5 cd	1.1 ± 1.0 d
	unbaited control	0.8 ± 0.4 d	0.8 ± 0.3 d
2	bait	76.2 ± 29.8 a	41.3 ± 16.0 a
	bait + MCH + V	2.2 ± 1.5 b	1.1 ± 0.6 b
	bait + MCH + 2PE	1.7 ± 0.7 b	1.6 ± 0.7 b
	bait + 2PE + V	0.5 ± 0.2 b	0.2 ± 0.2 b
	bait + MCH + 2PE + V	0.4 ± 0.2 b	0.6 ± 0.2 b
	unbaited control	0.1 ± 0.1 b	0.3 ± 0.1 b

[a] Means within a column and experiment followed by the same letter are not significantly different, Ryan, Einot, Gabriel, Welsh multiple Q test, $P<0.05$

Table 4. Attack by the mountain pine beetle in tree-baiting Exp. 1 and 2 on trees treated with *trans*-verbenol and *exo*-brevicomin (bait) alone or with MCH, 2-phenylethanol (2PE) or verbenone (V) alone or in ternary combination (Exp. 1,) or MCH, 2PE and V in all possible binary and ternary combinations (Exp. 2)

Exp. no.	Location	Treatment	No. trees	% Trees attacked (≥ 1 attack)[a]	%Trees mass-attacked (≥31.25/m2)[a]	Attack density/m^2 on attacked trees[b]
1	Princeton	bait	25	100.0 a	100.0 a	125.5 a
		Bait + MCH	25	96.0 ab	84.0 b	112.5 a
		Bait + 2-PE	23	75.0 b	66.7 b	108.1 a
		Bait + V	25	0.0 c	0.0 c	na
		bait + MCH + 2-PE + V	27	11.5 c	0.0 c	6.3 b
		unbaited control	26	0.0 c	0.0 c	na
	Prince George	bait	20	95.0 a	95.0 a	91.4 ab
		bait + MCH	20	90.0 ab	80.0 ab	105.4 a
		bait + 2-PE	20	90.0 ab	75.0 abc	77.3 ab
		bait + V	20	65.0 ab	35.0 c	52.9 c
		bait + MCH + 2-PE + V	20	55.0 b	40.0 bc	60.9 bc
		unbaited control	20	55.0 b	40.0 bc	62.5 bc
2	Princeton	bait	20	100.0 a	100.0 a	114.1 a
		bait + MCH + 2-PE	20	70.0 b	60.0 b	73.2 ab
		bait + MCH + V	19	31.6 bc	5.3 c	17.8 b
		bait + 2PE + V	20	25.0 c	0.0 c	8.8 b
		bait + MCH + 2-PE + V	20	30.0 bc	0.0 c	6.3 b
		unbaited control	20	5.0 d	0.0 c	6.3 b

Prince	bait	17	94.1 a	94.1 a	64.6 a
George	bait + MCH + 2-PE	17	52.9 b	23.5 b	26.6 ab
	bait + MCH + V	17	41.2 b	23.5 b	26.6 ab
	bait + 2PE + V	17	58.8 ab	35.3 b	38.2 ab
	bait + MCH + 2-PE + V	17	70.6 ab	47.1 b	26.6 b
	unbaited control	17	64.7 ab	29.4 b	35.4 ab

[a] Proportions within a column, category and experiment followed by the same letter are not significantly different, chi-square test for multiple proportions, $P < 0.05$.

[b] Means within a column, category and experiment followed by the same letter are not significantly different, Ryan, Einot, Gabriel, Welsh multiple Q test, $P < 0.05$.

Table 5. Attack by the mountain pine beetle in tree baiting Exp. 1 and 2 on surrounding trees within 5 m of trees treated with *trans*-verbenol and *exo*-brevicomin (bait) or with MCH, 2-phenylethanol (2PE) or verbenone (V) alone or in ternary combination (Exp. 1), or MCH , 2PE and V in all possible binary and ternary combinations (Exp. 2).

Exp. no.	Location	Treatment	No. trees	% Trees attacked (≥ 1 attack)[a]	% Trees mass-attacked (≥31.25/m^2)[a]
1	Princeton	bait	103	30.1 a	15.5 ab
		bait + MCH	119	33.6 a	23.5 a
		bait + 2PE	104	10.6 b	4.8 b
		bait + V	117	0.0 c	0.0 c
		bait + MCH + 2PE + V	127	0.0 c	0.0 c
		unbaited control	100	0.0 c	0.0 c
	Prince George	bait	69	73.9 a	47.8 ab
		bait + MCH	65	59.0 ab	31.3 ab
		bait + 2PE	62	43.5 bc	24.2 b
		bait + V	70	40.0 bc	27.1 ab
		bait + MCH + 2PE + V	75	33.3 c	18.7 b
		unbaited control	65	69.2 a	49.2 a
2	Princeton	bait	96	51.0 a	26.0 a
		bait + MCH + 2PE	93	24.7 b	15.1 a
		bait + MCH + V	87	2.3 c	1.1 b
		bait + 2PE + V	89	0.0 c	0.0 c
		bait + MCH + 2PE + V	105	1.0 c	0.0 c
		unbaited control	103	1.0 c	0.0 c
	Prince	bait	52	67.3 a	44.2 a

George	bait + MCH + 2PE	52	59.6 ab	36.5 ab
	bait + MCH + V	51	51.0 ab	25.5 ab
	bait + 2PE + V	61	37.7 b	23.0 ab
	bait + MCH + 2PE + V	47	46.8 ab	25.5 ab
	unbaited control	67	35.8 b	17.9 b

[a] Proportions within a column, category and experiment followed by the same letter are not significantly different, chi-square test for multiple proportions, $P < 0.05$.

E. PROTECTION OF CONIFER LOGS FROM ATTACK BY AMBROSIA BEETLES

Investigators John Borden, Leslie Chong, Aileen Wardle

Cooperators Ionut Aaron (Malcom Knapp Research Forest)

Problem Statement

Since the withdrawal of all chemical insecticides as log protectants against ambrosia beetles, there has been a lengthy quest for alternative agents. Our research has shown that nonhost angiosperm bark volatiles have considerable promise as new-age protectants. However research completed by Leslie Chong and me in the spring and summer of 2001 at the Malcom Knapp Research Forest indicated that attack by ambrosia beetles could be delayed, but not prevented, by treating logs with devices releasing four repellent nonhost angiosperm bark volatiles: 1-hexanol, benzyl alcohol, methyl salicylate and salicylaldehyde. In considering what to do next an apparent breakthrough in our thinking arose from revisiting a 1983 publication in which W.W. Nijholt of the Canadian Forest Service, Pacific Forestry Centre, reported that spraying logs with oleic acid resulted in three weeks of protection from attack by *Trypodendron lineatum.* We also put together our observations and those of Dr. Lee Humble of PFC that scolytid beetles bury their dead at the ends of empty galleries with findings by our laboratory and others that cockroaches, ants and aphids use oleic and linoleic acid as death recognition signals. We hypothesized that Nijholt's early success with oleic acid occurred because landing ambrosia beetles perceived a signal of pervasive death and did not proceed with attack until the signal had dissipated.

Research Accomplished

- Leslie Chong, Aileen Wardle and I tested the above hypothesis in two 10-replicate experiments involving 140 logs laid out 10 m apart in pairs along forestry roads at the Malcom Knapp Research Forest. The experiments were set up on 2-3 April 2002. A pheromone bait releasing lineatin and sulcatol was placed on a stake midway between the logs in each pair to induce beetles to orient toward the logs and to challenge them to choose between an experimental and a control log. In one experiment the experimental log was sprayed with ca. 2 L of oleic acid, treated with a 6.75 m-long polyflow tube releasing the four repellent nonhost volatiles (NHVs), or received both treatments. In the other experiment the experimental log in the pair was sprayed with oleic acid, linoleic acid, canola oil (rich in oleic acid) or safflower oil (rich in linoleic acid). The vegetable oils are much cheaper than the purified fatty acids, but contain the acids bound in triglycerides. Landing on sticky cards and attack was monitored thoughout the spring and early summer. Beetle flight was monitored throughout the season in multiple-funnel traps.

- In the first experiment (Table 6), the NHVs gave two weeks of protection from attack (1 of 10 logs attacked), but protection broke down by the third week (8 of 10 logs attacked). Oleic acid provided three weeks of protection, and there was no synergistic effect of combining NHV's with oleic acid. In the second experiment (Table 7), both fatty acids and both oils provided three weeks of protection. These results verify Nijohlt's 1980 results with oleic acid and expand them to other fatty acid-based materials. However, one season of working with these obnoxious agents has convinced us that they are too costly and inconvenient to use operationally. Were it not for new results with bark beetle pheromones (see IV,F below), this would have been our last year in the log protection business.

Table 6. Timing of first observable attack by ambrosia beetles on western hemlock logs in paired-log experiment, with untreated logs (UN) and logs treated with nonhost volatiles (NHVs), oleic acid (OA) or both NHVs and oleic acid (BOTH) 10 m apart, with a pheromone bait on a stake midway between them. Treatments done on a 2-3 April 2002 and logs checked weekly thereafter.

	No. of logs attacked (N=10)					
Week	UN	NHVs	UN	OA	UN	BOTH
1	7	1	7	1	3	0
2	9	1	7	1	4	0
3	10	8	10	1	9	0
4	10	10	10	5	10	4
5	10	10	10	9	10	5
6	10	10	10	10	10	10

Table 7. Timing of first observable attack by ambrosia beetles on western hemlock logs in paired-logs experiments, with untreated logs (UN) and logs treated with oleic acid (OA), linoleic acid (LA) canola oil (CO) (rich in oleic acid) or safflower oil (SO) (rich in linoleic acid) 10 m apart, with a pheromone bait on a stake midway between them. Treatments done on 2-3 April 2002 and logs checked weekly thereafter.

	No. Logs attacked (N=10)							
Week	UN	OA	UN	LA	UN	CO	UN	SO
1	0	0	1	0	0	0	0	0
2	3	0	3	0	3	1	4	0
3	5	0	8	1	4	2	6	1
4	10	6	9	10	10	9	10	10
5	10	9	10	10	10	10	10	10

F. RESPONSE BY AMBROSIA BEETLES TO BARK BEETLE PHEROMONES

Investigators Stuart Campbell, John Borden, Regine Gries

Cooperators Brian Drobe, RPF (Weyehauser Canada)

Problem Statement

There is one record in the literature on the response of an ambrosia beetle to a bark beetle pheromone, a finding by an undergraduate student in my laboratory that *Trypodendron lineatum* in the B.C. interior apparently uses the *Dendroctonus* pheromone frontalin as a weak host-finding kairomone. In one experiment in 2001, M.Sc. student Stuart Campbell found that the mountain pine beetle was moderately repelled from attractant-baited traps to which the ambrosia beetle pheromone lineatin had been added. Because ambrosia beetles do not infest trees killed by the mountain pine beetle until 9-10 months after attack, when the trees are no longer suitable for mountain pine beetles, a repellency to lineatin would be highly adaptive. Conversely, Stuart reasoned that it would be adaptive for ambrosia beetles to be repelled by pheromones released by bark beetles at the time they attack living trees, when they are not yet suitable as an ambrosia beetle habitat.

Research Accomplished

- Working with Regine Gries Stuart collected *T. lineatum*, *T. rufitarsus* and *T. retusum* at Deep Gulch (near Princeton) on 1-2 May 2002 and subjected them to GC-EAD analysis with an array of bark beetle pheromones. The antennae responded to only some of these compounds. For example *T. lineatum* antennae responded to ipsenol, ipsdienol, *cis*-verbenol, verbenone, MCOL, MCH, and seudenol, but not to *exo*- and *endo*-brevicomin, *trans*-verbenol, or (curiously) frontalin.
- As time permitted (this is not in his thesis topic), Stuart tested the bioactivity of antennally-active compounds in three experiments with pheromone-baited traps. Because of the strongly negative response of mountain pine beetles to 2-phenylethanol (Table 3), this compound was added to the list. In one experiment adding MCH to lineatin-baited traps reduced the catch of *T. lineatum* and *T. rufitarsus* combined (both are conifer-infesting species) by a highly

significant 84% compared to catches in traps baited with lineatin alone (Table 8). Seudenol, the parent alcohol of the ketone MCH, also caused a significant reduction.. Because lineatin

Table 8. Comparison of ranked catches of *T. lineatum* in traps baited with the attractive pheromone lineatin alone or in combination with one of 10 bark beetle pheromones.

Exp. no.	Treatment	No. reps.	No. of beetles captured ($\bar{x}$ ±SE)[a] Males	Females
1	lineatin + ipsdienol	10	464.0 ± 87.5 a	395.7 ± 78.0 a
	lineatin + verbenone	10	341.2 ± 67.9 ab	179.8 ± 31.3 b
	lineatin	9	272.6 ± 70.9 b	185.6 ± 43.3 b
	lineatin + *trans*-verbenol	10	250.8 ± 47.1 b	166.0 ± 38.3 b
	unbaited	10	0.3 ± 0.2 c	0.3 ± 0.2 c
2	lineatin + MCOL	10	376.7 ± 80.3 a	209.9 ± 35.3 a
	lineatin + frontalin	9	350.0 ± 24.1 a	244.1 ± 20.5 a
	lineatin	10	283.5 ± 37.8 ab	218.9 ± 27.7 a
	lineatin + seudenol	10	173.7 ± 10.0 b	104.8 ± 10.7 b
	lineatin + MCH	9	35.0 ± 0.4 c	22.8 ± 4.1 c
	unbaited	8	0.6 ± 0.4 d	0.3 ± 0.2 d
3	lineatin + ipsenol	10	376.7 ± 80.3 a	227.4 ± 16.0 a
	lineatin	10	223.9 ± 23.5 b	140.2 ± 16.5 b
	lineatin + *exo*-brevicomin	10	216.6 ± 19.6 b	138.3 ± 13.0 b
	unbaited	10	0.1 ± 0.1 c	0.1 ± 0.1 c
4	lineatin	8	478.0 ± 129.9 a	338.7 ± 111.1 a
	lineatin + 2-phenyl ethanol	8	272.1 ± 52.3 a	177.4 ± 41.7 a
	2-phenyl ethanol	8	1.1 ± 0.5 b	0.8 ± 0.4 b

unbaited	8	0.4 ± 0.3 b	0.3 ± 0.2 b

[a] Means within a column and experiment followed by the same letter are not significantly different, Ryan, Einot, Gabriel, Welsh multiple Q test, $P < 0.05$.

is such a potent pheromone, and because the repellency of MCH was so pronounced, this partial result alone was enough to induce us to test MCH alone and in combination with nonhost volatiles as a log protectant. Log protection experiments with corroborating trapping experiments are now in progress at Maple Ridge and Salmon Arm. Among the positive attributes of MCH are its low toxicity to vertebrates, and the fact that as a Phero Tech product MCH has recently been registered as a pesticide in the USA.

- The other intriguing result is that the response to pheromone-baited traps by interior *T. lineatum* was significantly enhanced by the addition of either ipsenol or ipsdienol (aggregation pheromones of secondary bark beetles in the genus *Ips*), while the beetles were indifferent to *exo*-brevicomin, frontalin, MCOL, 2-phenyl ethanol and *trans*-verbenol (aggegation pheromones of primary bark beetles in the genus *Dendroctonus*) (Table 8). Thus *T. lineatum* responds positively to the pheromones of secondary bark beetles that attack weakened hosts suitable for ambrosia beetles, and is indifferent to or repelled by pheromones of primary bark beetles that attack living hosts unsuitable for ambrosia beetles. The ecological and evolutionary implications of these results suggest that these highly adaptive responses could by reliably exploited in pest management. Therefore, in addition to further experiments with MCH, extending its potential bioactivity to *Gnathotrichus* species, we plan to test ipsenol and ipsdienol alone and together against all three species of economically important ambrosia beetles on both the coast and the interior.

G. A BETTER TRAP FOR LARGE WOODBORERS

Investigators Kathy Hein, John Borden, Steve Burke (Phero Tech), Dave Wakarchuk (Phero Tech), Jennifer Burleigh (Phero Tech), Nicole Jeans-Williams (Phero Tech)

Cooperators Ron Ferrier (Weyerhaeuser Canada, Okanagan Falls), Bob Carmichael (Weyerhaeuser Canada, Vavenby), Gary Greyell (Riverside Forest Producsts, Westbank)

Problem Statement

Large wood-boring beetles in the families Cerambycidae and Buprestidae, and woodwasps in the family Siricidae collectively cost interior B.C. lumber producers at least $34 million per year. The multiple-funnel traps currently used in operational trapping programs in B.C. and Alberta catch ambrosia beetles exceedingly well, but many large woodborers are not captured, and some of those that are escape. Therefore, for several years we have been working with Phero Tech, as well as Dr. Peter de Groot at the Canadian Forest Service's Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, to design, manufacture and field test traps that would be efficacious alternatives to multiple-funnel traps. We had earlier discarded a highly-effective trap consisting of cross-vane panels standing in a water-filled receptacle because of the excessive labour involved, their susceptibility to wind, the large number of small mammals captured, and the stinking mess of captured insects that had to be processed. Therefore, in recent years we have retained the cross-vane barrier design, but have investigated various types of "escape proof" collecting containers. Results from the summer of 2001 indicated that cross-vane traps with a black collecting bucket were superior to traps with a white bucket, four vanes were superior to three vanes, and a tall, wide, vertical, black silhouette was superior to a short, narrow one. However, the "puck board" cross vanes, while very durable, are heavy, expensive and difficult to assemble in the field. Therefore, a lighter, but still durable, material was needed. With these guiding principles we are working with Phero Tech to design and test lightweight pre-commercial cross-vane traps and sleeve traps specifically targeted at *Monochamus* spp. and *Xylotrechus* spp., the two most damaging groups of large woodborers.

Research Accomplished

- Kathy Hein worked at Phero Tech for eight weeks in the spring of 2002 to manufacture two prototype lightweight traps from 8 mil. polyethylene. The first was a 30 cm diameter 1.2 m long "pipe" attached to a deep polyethylene funnel, at the bottom of which was the bottom funnel of a Lindgren multiple-funnel trap with a double-length collecting cup. The second was similar to the cross-vane puck-board trap modified by Dr. Dan Miller of the U.S. Forest Service in Athens, Georgia. It consisted of four 21 cm x 1.2 m 8 mil. polyethylene panels suspended over an identical capture and collecting assembly as used in the pipe trap. Ten randomized complete block replicates of four trap types (the two new traps above, the conventional Phero Tech multiple-funnel trap, and the 2001 puck-board cross-vane trap that we developed) were set up in early June at each of three sites: Weyerhaeuser Canada's mill yards at Okanagan Falls and Vavenby, and Riverside Forest Product's 4-Mile Bear Creek Dryland Sort near Westbank. Available results Okanagan Falls and Vavenby (Table 9) indicate large numbers of beetles captured by all trap types. When the captures were brokene down by numerical ranking (with no stastistical tests done to date) the 2002 cross-vane trap was clearly superior, with 15 first place rankings (of 24 possible), a score of 3.42 and the highest number of total beetles captured (5,172) (Table 10). In contrast, the conventional multiple-funnel trap ranked the lowest by all three criteria, and the 2001 cross-vane and 2002-pipe traps were at an intermediate performance level. However, as the trapping season progressed the plastic in both 2002 traps began to suffer wind- and heat-induced distortion and weakness, and some of the metal hardware wore through or broke. Moreover the cross-vane trap is too long for operational use. Therefore, a final year of pre-commercial testing in 2003 will emphasize more durable materials and reductions in trap size. Even so, Dr. Jon Sweeney, of the Canadian Forest Service's Maritimes Forestry Centre in Fredericton, N.B., found that the CV-2002 trap caught 3.9 times more brown spruce borers, *Tetropium fuscum*, than the next best trap, which is commercially available. Thus in addition to its practical potential in protecting stored timber in the west, our new trap has excellent potential for use in the eradication programs against this devastating introduced insect in the maritimes. We hope that it may find more general use in the detection and suppression of other quarantined invaders.

Table 9. Catches in 2002 of cerambycid beetles in an experiment testing four types of traps at Weyerhaeuser Canada's mill yards at Okanagan Falls and Vavenby. All traps were baited with commercial lures (Phero Tech Inc.) releasing ethanol and α-pinene. Traps were: multiple-funnel trap with a dry collecting cup used operationally for woodborer trapping (MF); 2001 cross-vane test trap with puckboard vanes and dry bucket receptacle (CV-2001); lightweight 8 mil. plastic pipe trap manufactured in 2002 in collaboration with Phero Tech (Pipe-2002); and lightweight 8 mil. plastic crossvane trap manufactured in 2002 in collaboration with Phero Tech (CV-2002).

			No. beetles captured			
Location	Species	Sex	MF	CV-2001	Pipe-2002	CV-2002
Okanagan Falls	*Monochamus scutellatus*	males	41	25	35	45
		females	23	17	16	17
	M. clamator	males	115	96	110	191
		females	115	98	115	184
	M. obtusus	males	570	210	221	671
		females	383	151	202	506
	Xylotrechus longitarsus	males	405	858	662	522
		females	295	721	455	426
	Arphopalus asperatus	males	11	26	28	21
		females	17	44	57	38
	A. productus	males	31	43	41	57
		females	25	35	34	45
	Asemum striatum	males	7	12	30	35
		females	16	23	45	51
Vavenby	*Monochamus scutellatus*	males	193	446	227	273
		females	125	218	202	212
	M. clamator	males	22	18	21	25
		females	17	36	17	18

Xylotrechus	males	595	832	845	879
longitarsus	females	396	614	544	507
Asemum	males	5	36	29	177
striatum	females	20	60	37	231
Tetropium	males	5	15	14	16
velutinum	females	2	15	13	25

Table 10. Comparison of numerical ranking for each entry by sex and species in Table 9 for numbers of cerambycid beetles caught in four types of traps tested in 2002. Combined score is based on a 4-point scale, in which a rank of first = 4, second = 3, third = 2, and fourth = 1, taken as a mean of 24 possible rankings.

	Number of instances by rank			
Rank	MF	CV-2001	Pipe-2002	CV-2002
First	1	6	2	15
Second	6	9	2	4
Third	1	4	15	5
Fourth	16	5	1	0
Score	1.67	2.67	2.38	3.42
Total no. beetles captured	3,434	4,649	4,000	5,172

H. VISUAL DISRUPTION OF HOST FINDING BY BARK AND TIMBER BEETLES

Investigators Stuart Campbell, John Borden

Cooperators Ionut Aaron (Malcom Knapp Research Forest), Gwen Baker (Riverside Forest Products)

Problem Statement

This study, follows up the discovery by a U.S. Forest Service Scientist, Dr. Brian Strom that southern pine beetles are inhibited form responding positively to attractive pheromones when they are released from white-painted traps or trees. In addition to elucidating the fundamental aspects of host selection, e.g. rejection by conifer-infesting insects of white nonhost species like trembling aspen and paper birch, this project is exploring the potential for visual disruption of host selection, e.g. whitewashing a log deck (believe it or not) to protect it from woodborer attack. It is also exploring whether there is a synergistic interaction between known olfactory repellents and deterrent visual stimuli.

Research Accomplished

- Stuart's results from the summer of 2001 are now analyzed. They indicate that in general conifer-infesting bark beetles and large woodborers were deterred from responding to attractive baits in white multiple-funnel traps, but ambrosia beetles were not. Ambrosia beetles infest primarily downed logs, have evolved potent pheromones and may not rely heavily on visual stimuli for host selection. Although large woodborers also infest downed hosts, they do not have long range pheromones, and may have evolved behavioural traits that rely more heavily on visual stimuli than ambrosia beetles.
- In 2002 Stuart conducted a large experiment aimed at elucidating the interplay between vision and olfaction in the selection of hosts by the mountain pine beetle. Clusters of four traps (two white, two black) were erected around a pole baited with attractive pheromones

exo-brevicomin, and *trans*-verbenol. The attractive kairomone myrcene was placed on 1) the black traps, 2) the white traps, 3) all four traps, and 4) neither, and 16 replicates of these four treatments were set up near Princeton, to determine whether vision, olfaction or both senses are utilized in selecting hosts in a small area redolent with beetle-produced pheromones. While the data are still being analyzed, visual inspection of the traps suggested the following tentative conclusions. 1) Myrcene is responsible for long range orientation to currently-attacked groups of trees. Almost no beetles were caught in clusters that did not have myrcene. 2) Having entered a cluster, beetles orient to candidate hosts on the basis of vision. In clusters with myrcene on white traps, there appeared to be more beetles in black traps. The same pattern was observed for clusters with myrcene on all four traps.

- Two experiments were conducted in 2002 on the Douglas-fir beetle in the Malcolm Knapp University of British Columbia Research Forest. In 2001, Stuart demonstrated that interior populations of this species are capable of using vision to avoid nonhost angiosperms. In contrast coastal beetles do not attack live, standing trees, and Stuart investigated whether this difference in host preference and aggressiveness was related to visual (Exp. 1) and visual + semiochemical (Exp. 2) nonhost angiosperm avoidance. The trap catches from these experiments have not yet been processed.

- Two experiments were conducted at Buck's Mountain, north of Kelowna, B.C. to determine whether the western balsam bark beetle would exhibit similar visual host preference as do two other tree-killing bark beetles, the Douglas-fir beetle and the mountain pine beetle. In 2001 both of these species avoided trap silhouettes that were similar in appearance to nonhosts such as aspen. In contrast to the hosts of the latter two species, *Abies lasiocarpa* and *A. bifolia* have bark that more closely resembles that of nonhost angiosperms. In Exp. 1 Stuart compared beetle responses to white and black traps baited with *exo*-brevicomin, with unbaited traps as controls. In Exp. 2 he compared responses to white and black traps baited with *exo*-brevicomin and a combination of □-pinene + ethanol. White and black traps baited with only *exo*-brevicomin and unbaited white and black traps were included as controls. Trap catches will be processed by May 2003.

I. CHEMICAL ECOLOGY AND REPRODUCTIVE ISOLATION AMONG FOUR NATIVE *TRYPODENDRON* SPECIES

Investigators Susanne Kühnholz, John Borden, Regine Gries, Bernie Crespi, Harold Pierce, Adnan Uzonovic (Forintek), Collette Breuil (Forest Sciences, UBC), Karen Jacobs (Forest Sciences, UBC)

Cooperators Lisa Poirier (UNBC), Lee Humble (PFC)

Problem Statement

Recent issues and events have made the study of ambrosia beetles of continuing importance. These include: international concern over importation and exportation of living ambrosia beetles and their symbiotic fungi in wood products; potential and realization of offshore exportation of forest products from interior Canadian forests where ambrosia beetles have traditionally not been considered to be a problem; emergence of value-added industries that demand blemish-free wood; the threat of non-tariff barriers to trade if ambrosia beetle infestations are found in Canadian forest products; alarmingly huge infestations in living European hardwoods of *Trypodendron domesticum* and *T. signatum* which normally infest logs; the discovery by Dr. Lee Humble of PFC that five species of exotic ambrosia beetles have become established in B.C.'s forests, including *T. domesticum* from Eurasia and *Xyloterinus politus* from eastern North America; and the increasing interest in native hardwood products that has transformed hardwood-infesting ambrosia beetles into potential pests. Accordingly, Ph.D. student Susanne Kühnholz is completing sstudy of the chemical ecology of *T. lineatum* and *T. rufitarisus* (which attack conifers), *T. retusum* (which attacks trembling aspen), and *T. betulae* (which attacks birches). She is also working on symbiotic fungi associated with each species and is using molecular techniques to determine the phylogenetic relationship among B.C.'s native species, and how they relate to the world fauna in this genus. Susanne's observations that *T. retusum* and *T. betulae* attack healthy trees is in opposition to all published reports, but they are consistent with our finding (corroborating Lee Humble's observations) that *T. domesticum* is also attacking living trees in B.C. A manuscript describing observations and potential for attack on living trees by secondary ambrosia beetles is in press in International Pest Management Reviews.

Research Accomplished

- Field trapping experiments with *T. betulae* were conducted in 2001 on the campus of the University of Northern B.C. with the new pheromone 2,2,6-trimethyl-6-vinyl-2H-pyran-3-ol (named tirathol after the genus of tropical moths from which it was first identified as a pheromone), indicated that the highest trap catches were obtained in response to a blend of the naturally-occurring *ESR* and *ZRR* stereoisomers. Inhibition of trap catches to the unnatural *ERS* and *ZSS* isomers suggested molecular interference at the receptor site. The antennally-active host volatile conophthorin in combination with tirathol enhanced trap catches. This research continued in 2002, adding ethanol as a potential attractant. The results indicate a positive synergistic interaction between tirathol, conophthorin and ethanol (Table 11). Tirathol is the first new ambrosia beetle pheromone to be discovered since the 1970's. Should any of the new exotic species, e.g. *X. politus*, prove to be pests, the expertise at SFU may be exploited to identify and develop new pest management tools.
- Response to the pheromone lineatin by the aspen-infesting species *T. retusum* was enhanced by the host volatile salicylaldehyde, which in turn inhibited responses to lineatin by the conifer-infesting *T. lineatum* and *T. rufitarisus*. Reciprocally, □-pinene enhanced responses by *T. lineatum* and *T. rufitarisus* and inhibited responses by *T. retusum*. Thus species specificity among three species that share the same pheromone is maintained in part by host and nonhost volatiles. We have no evidence for the involvement of semiochemicals in maintaining reproductive isolation between *T. lineatum* and *T. rufitarisus.*
- In collaboration with Dr. Adnan Uzonovic of Forintek, Susanne, has isolated 3-7 morphologically-distinct fungal isolates from each species of beetle. Drs. Collette Breuil and Karen Jacobs of UBC's Forest Science Department have collaborated with Susanne to verify three distinct species morphologically and four based on DNA analysis. Studies with Dr. Uzonovic have indicated that some isolates are weakly aggressive invaders of the wood and

bark of cut aspen bolts, suggesting pathogenic potential, but a tree inoculation study did not support this hypothesis, even though living fungi of all three isolates tested were recovered from the trees approximately six months after inoculation.

- Suzanne is currently working Dr. Bernie Crespi's laboratory at SFU using mitochondrial DNA to determine the relatedness or disparity among B.C.'s four native *Trypodendron*.

Table 11. Captures of *Trypodendron betulae* in multiple-funnel traps in two 2002 experiments on the UNBC campus. Statistical analysis not yet done.

Exp. no.	Treatment	No. beetles captured ($\bar{x}$ ±SE) Males	Females
1	unbaited control	0.6 ± 0.3	1.1 ± 0.4
	ethanol	3.9 ± 1.8	2.7 ± 0.9
	tirathol	2.0 ± 0.8	1.6 ± 0.7
	tirathol + ethanol	2.8 ± 1.3	4.2 ± 1.3
2	unbaited control	0.3 ± 0.2	0.1 ± 0.1
	tirathol + conophthorin	1.5 ± 0.8	1.4 ± 0.5
	tirathol + conophthorin + ethanol	11.2 ± 4.1	9.4 ± 3.6

species, and to set these species in context with most of the world species in this genus. In addition to providing data on the phylogenic relationships within the genus, this study will provide the basis for comparison of the phylogeny of beetle species and their symbiotic fungi, and may aid in determining the origin of exotic species or populations intercepted at ports of entry or established in B.C.'s forests.

- Susanne was on medical leave in the spring semester, and will be absent much of the summer of 2003 because of the birth of twin girls on 21 March 2003. Her thesis defense is anticipated in the spring or summer of 2004.

J. COMPARARTIVE CHEMICAL ECOLOGY OF TWO HARDWOOD WOODBORERS

Investigators Cindy Broberg, John Borden

Cooperators Dav Minhas RPF (Scott Paper), Gashaw Abebe (Scott Paper), Dan Carlson RPF (Scott Paper), Dave Piggin RPF (B.C. Ministry of Forests).

Problem Statement

Poplars are increasingly harvested for lightweight lumber, oriented strand board, paneling, moldings, chip board, furniture manufacture, engineered lumber and soft paper products. Poplars and willows are used for soil stabilization, livestock fodder, windbreaks and greenbelts, and may in the future be used for CO_2-neutral biomass energy production. Species in both genera are vital in maintaining biodiversity in forested landscapes. Yet very little is known about insect species that infest poplars and willows. In B.C. an exotic weevil, the poplar and willow borer, *Crytorhynchus lapathi*, frequently attacks willow, *Salix* spp., and black cottonwood, *Populus trichocarpa*, but there are only four records of it infesting trembling aspen, *P. tremuloides*. Conversely, the native cerambycid beetle, *Saperda calcarta* predominately attacks aspen, but can occur on poplar and willow. Ph.D. student Cindy Broberg set out in 2000 to study the comparative chemical ecology of *C. lapathi* and *S. calcarata*. However, *S. calcarata* has proven to be exceedingly hard to collect in the field or rear in the laboratory, making most laboratory studies impossible to date. Moreover, despite strong antennal responses in GC-EAD analyses to captured host volatiles, not one *S. calcarata* has been captured in a multitude of experiments employing black and white multiple-funnel traps baited with antennally-active synthetic host volatiles. Therefore with one exception this report focuses primarily on investigations in 2001-2002 involving *C. lapathi*.

Research Accomplished

- In 2001-2002 Cindy placed considerable emphasis clonal variation of hybrid poplars in relation to host selection and resistance to infestation by *C. lapathi*. In one 20-replicate, Latin square experiment, male-female pairs were caged in August 2001 on first-year whips of four hybrid poplar clones at Scott Paper's Harrison Bay nursery. The crosses to form the clones were:

  trichocarpa x nigra (TN)
  trichocarpa x maximowiczii (TM)
  trichocarpa x deltoides (TD)
  nigra x maximowcizii (NM).

  In December 2001, 10 replicates were cut down and destructively sampled for *C. lapathi* eggs. In July 2002, the remaining 10 replicates were cut and adult weevils were collected as they emerged from the whips in screened cages. There was no significant difference among clone in the number of eggs laid (Table 12). However, 97 weevils emerged from 9 TN whips, and none emerged from any of the 10 TN whips. These results were not backed up by pitfall olfactometer bioassays with cut stem sections, in which weevils did not strongly avoid NM, and paired twig feeding bioassays in which weevils fed just as readily on NM sections as they did on sections from wild *Populus trichocarpa*. This disparity strongly suggests that resistance in NM, and possibly TM as well, is induced and antibiotic, preventing embryonic development and hatching of eggs. Such resistance may be harder to overcome than antixenosis (nonpreference). These results suggest that new clones should be screened for resistance before any great effort is placed in propagation and the establishment of plantations**.** In addition to the importance of this research to Scott Paper, Potlach Forest

Products in Oregon has recently experienced severe damage by *C. lapathi* in their hybrid poplar plantations. Therefore, Cindy is continuing her research in 2003 to characterize physical and biochemical traits that could be involved in resistance, and has begun to collaborate with Dr. J. Bohlmann's laboratory at UBC to determine which, if any, of several genes known to be associated with induced resistance are activated by weevil feeding and oviposition.

- Cindy is also conducting pitfall and feeding bioassays comparing the preference of *C. lapathi* males and females for willow, trembling aspen, bigleaf maple, black cottonwood, red alder and a conifer, Norway spruce. Although these assays are still underway, preference for angiosperm samples over spruce in pitfall bioassays suggests that weevils find potential angiopserm hosts by olfaction, but that close-range discrimination is required for final host choice. This hypothesis is supported by a general preference for willows over other species in feeding bioassays. Porapak Q-captured volatiles from *Salix stichensis* were attractive to female *C. lapathi* at a dose of 69 gram-hours of aerated material, but males were responsive at 6.9 gram-hours. However, a blend of six host plant volatiles tested in the spring of 2002 induced no weevils to enter baited traps of three different designs. Cindy is aerating willows at different times in the season and is comparing captured volatiles from uninfested and infested hosts to determine if the spectra of potentially attractive volatiles changes, and to elucidate whether weevil adults and or larvae supplement host odour with an attractive pheromone that could cause the repeated attacks observed in nature.
- In the fall of 2002, Cindy and Regine Gries demonstrated that female *C. lapathi* produce conophthorin and frontalin in a 19:1 ratio, and that both sexes responded positively to this blend in a laboratory bioassay. Verification of this result, as well as field trapping experiments with conophthorin and frontalin are planned for 2003.
- Most research on *Saperda calcarata* has been terminated because it has been unproductive. In an attempt to return to the basics Cindy set up a 20-replicate field experiment north of Savona in June 2002 to determine if *S. calcarata* will attack artificially stressed aspens.

Treatments are as follows: 1) 2 axe cuts into the sapwood on opposite sides of the lower bole,

2) 2 axe cuts plus one ethanol bait (a sign of anaerobic metabolism), 3) ethanol bait alone, and 4) untreated control. All trees are ≥ 20 m apart. They will be monitored periodically for attack commencing in the summer of 2003. Research in 2003 will also follow up a 2002

Table 12. Results of weevil-caging experiment showing variation among four hybrid poplar clones to infestation by *Cryptorhynchus lapathi.*

Clone	No. eggs per tree (N=10) ($\bar{x}$ ±SE)[a]	No. trees producing adult weevils (N=10)	Total no. emerged weevils
TN	47 ± 11	9[b]	97
TD	34 ± 11	4	21
TM	25 ± 13	2	3
NM	14 ± 4	0	0

[a] No significant difference among means, PROC GLM, *P*=0.59

[b] One tree that might have produced weevils was attacked so severely that it died. Four others had basal breaks.observation that *S. calcarata* responded positively in the laboratory to the volatiles from leafy aspen branches.

K. PHEROMONES OF CONIFEROPHAGOUS BARK BEETLES IN ANGIOSPERM TREES

Investigators Cindy Broberg, Regine Gries, John Borden

Cooperator Carolyn Jones (Van Dusen Botanical Garden)

Problem Statement

We had previously demonstrated that the scolytid pheromone conophthorin is found in bark volatiles of paper birch, trembling aspen, black cottonwood and bigleaf maple (corroborrating its discovery in Sweden in two species of birch), and that another pheromone, frontalin, is found in the bark of red and Sitka alder. Cindy's GC-EAD work with Regina Gries has carried this research even further. She has also found frontalin in trembling aspen and conophthorin in willows. Even more surprising, two additional pheromones of coniferophagous bark beetles were discovered, *exo*-brevicomin (tentatively) in aspens, and chalcogran in aspen and willows. These findings raise profound questions as to how ubiquitous these compounds are, what their natural role in angiosperm trees is (they are complex and metabolically costly to synthesize), whether the biosynthetic pathways are similar, and how coniferophagous bark beetles avoid responding to them. Therefore, she has embarked on a collaborative study with Ms. Carolyn Jones of the VanDusen Botanical Garden in Vancouver to determine the extent of this phenomenon.

Research Accomplished

Cindy put together a carefully-considered list of trees to sample in 23 families, 32 genera and 46 species (Table 13). One palm and a ginko were added to the list of angiosperms, primarily out of curiosity. Volatiles have been captured from the cut branches and foliage of several species. Extracts of the Porapak Q-trapped volatiles are held in the freezer until sampled by co-chromatography with a comprehensive blend of known bark beetle pheromones. Tentative identifications are being verified by GC-MS. The preliminary results indicate that in addition to conophthorin and *exo*-brevicomin, *Populus tremuloides* also produces *trans*-verbenol, sulcatone, and frontalin. Moreover, she has also found conophthorin in 28 of 36 species examined to date, and chalcogran in 21 species.

Table 13. Taxonomic diversity of angiosperm trees, primarily growing at the Van Dusen Botanical Garden, that are being sampled for the presence of bark beetle pheromones in their bark and leaves.

Family	Genus	No. Species to be Sampled
Aceraceae	*Acer*	3
Anacardiaceae	*Rhus*	1
Aquifoliaceae	*Ilex*	1
Betulaceae	*Alnus*	2
	Betula	4
Caprifoliaceae	*Sambucus*	1
Cornaceae	*Cornus*	1
Ericaceae	*Arbutus*	1
Fabaceae	*Robinia*	1
(Leguminosae)	*Castanea*	1
	Fagus	1
	Quercus	4
Ginkoaceae	*Ginko*	1
Homamelidaceae	*Liquidambar*	1
Hippocasanaceae	*Aesculus*	1

Juglandaceae	*Carya*	1
	Juglans	1
Lauraceae	*Sassafrass*	1
Magnoliaceae	*Liriodendron*	1
	Magnolia	1
Moraceae	*Morus*	1
Oleaceae	*Fraxinus*	2
Palmae	*Washingtonia*	1
Platanaceae	*Platanus*	1
Rhamnaceae	*Rhomnus*	1
Rosaceae	*Crategus*	1
	Malus	1
	Prunus	1
Salicaceae	*Populus*	3
	Salix	3
Tiliaceae	*Tilia*	1
Ulmaceae	*Ulmus*	1

L. OTHER PROJECTS

Some research has not been successful in yielding useful data or comprehensive results to date. Other projects have yielded promising data, but have been terminated in anticipation of the closure of my laboratory. Examples of such projects follow.

- Regine Gries and Kathy Hein have carried out extensive GC-EAD analyses of volatiles captured from male zebra beetles, *Xylotrechus longitarsus*. We are now convinced that earlier recordings of male-specific compounds, that could have been sex or aggregation pheromones, were in fact artefacts. This line of research has been terminated.

- A final experiment by M.P.M. student Andrea Tanaka on the white pine weevil, *Pissodes strobi*, has now been analyzed. It verifies that the male-produced compound grandisol is an attractive pheromone for interior B.C. females, and that grandisoic acid in combination with host volatiles is attractive to males. We plan further testing of both of these compounds against coastal and interior weevils in 2004.

- Ph.D. student Sarah Bates, working with Harold Pierce and Regine Gries, has been able to identify four of five candidate sex pheromone components produced by male western conifer seed bugs, *Leptoglossus occidentalis*. However, the most antennally-active fifth component has defied identification by GC-MS, and the amounts produced are too small to use other analytical methods. This research is included as an appendix in Sarah's thesis, and will be left to others to complete. Also in Sarah's thesis is an Appendix reporting the antennal response in GC-EAD analyses by *L. occidentalis* antennae to nine pheromone components from sympatric cone-infesting moths and one midge. Field experiments with baited Japanese beetle traps at the Skimikin Seed Orchard in 2002 failed to capture a single bug, in contrast to promising results with Z-9-14:OAc in 2001. We intend to continue this research in 2003.
- Research Associate Aileen Wardle has been working with Regine Gries to identify the volatile components in the larval oral exudate (spit) of spruce budworm larvae. Using GC-EAD analysis on female western spruce budworms, they confirmed that the sex pheromone component (*E*)-11-tetradecanal, and the saturated aldehyde tetradecanal were both present in the larval exudate. However, Aileen was not able to obtain any consistent behavioural response by larvae to either or both compounds in a feeding bioassay or by adults in an oviposition bioassay. We will therefore report our findings, and leave future behavioural studies to others.

V. PUBLICATIONS

As in all ongoing programs, publications arising from research completed before the start date are now just appearing, and results from funded research will be published after the end date. Any *post hoc* attempt to match publications with the supporting grants would be futile. Therefore all papers published, submitted or in preparation since 1 October 2001 are listed.

A. PAPERS IN REFEREED JOURNALS PUBLISHED OR IN PRESS

1. Lait, C.G., S.L. Bates, K.K. Morrissette, J.H. Borden and A.R. Kermode. 2001. Biochemical assays for detecting damage to the seeds of lodgepole pine, and other conifers, resulting

from feeding damage by *Leptoglossus occidentalis* Hedimann (Hemiptera: Coreidae). Can. J. Bot. 79: 1349-1357.

2. Strong, W.B., S.L. Bates, and M.N. Stoehr. 2001. Feeding by *Leptoglossus occidentalis* Heidemann (Hemiptera: Coreidae) reduces seed set in lodgepole pine. Can. Entomol. 33: 857-865.
3. Allison, J. D. and J. H. Borden. 2001. Observations on the behaviour of *Monochamus scutellatus* (Say)(Coleoptera: Cerambycidae) in northern British Columbia. J. Entomol. Soc. B.C. 98: 195-200.
4. Poirier, L.M. and J.H. Borden. 2001. Qualitative analysis of larval oral exudate from eastern and western spruce budworms (Lepidoptera: Tortricidae). J. Entomol. Soc. B.C. 98: 243-250.
5. Broberg, C.L., J.H. Borden and L.M. Humble. 2002. Distribution and abundance of the poplar and willow borer, *Cryptorhynchus lapathi* (L.) on *Salix* spp. in British Columbia. Can. J. For. Res. 32: 561-568.
6. Bates, S.L., C.G. Lait, J. H. Borden and A.R. Kermode. 2002. Measuring the impact of *Leptoglossus occidentalis* (Heteroptera: Coreidae) on seed production in lodgepole pine using an antibody-based assay. J. Econ. Entomol. 95: 770-777.
7. Morewood, W.D., K.E. Hein, P.J. Katinic, and J.H. Borden. 2002. An improved trap for large woodboring insects with emphasis on *Monochamus scutellatus* (Coleoptera: Cerambycidae). Can. J. For. Res. 32: 519-525.
8. Bates, S.L., W.B. Strong and J. H. Borden. 2002. Abortion and seed set in lodgepole and western white pine conelets following feeding by *Leptoglossus occidentalis* (Heteroptera: Coreidae). Environ. Entomol. 31: 1023-1029.
9. Burleigh, J.S., R.I. Alfaro, J.H. Borden and S. Taylor. 2002. Historical and spatial characteristics of spruce budworm *Choristoneura fumiferana* (Clem.) (Lepidoptera: torticidae) outbreaks in northeastern British Columbia. For. Ecol. Manage. 168: 301-309. 10.
10. Morewood, W.D. K.E. Hem, J.H. Borden and l.M. Wilson. 2002. □-Pinene and ethanol: key host volatiles for Xylotrechus *Iongitarsus* (Coleoptera: Scolytidae). J. Entomol. Soc. B.C. 99: 117-122.

11. Allison, J.D., W.D. Morewood, J. H. Borden, K.E. Hein, and I.M. Wilson. 2003. Differential bio-activity of *Ips* and *Dendroctonus* pheromone components for *Mononchamus clamator* and *M. scutellatus* (Coleoptera: Cerambycidae). Environ. Entomol. 32: 23-30.

12. Wardle, A.R., J. H. Borden, H.D. Pierce, Jr. and R. Gries. 2003. Volatile compounds released by disturbed and calm adults of the tarnished plant bug, *Lygus lineolaris*. J. Chem. Ecol. (in press).

13. Borden, J.H., L.J. Chong, T.J. Earle and D.P.W. Huber. 2003. Protection of lodgepole pine from attack by the mountain pine beetle, *Dendroctonus ponderosae* (Coleoptera:Scolytidae), using high doses of verbenone in combination with nonhost volatiles. For. Chron. (in press).

14. Borden, J.H., L.J. Chong, R. Gries and H.D. Pierce, Jr. 2003. Potential for nonhost volatiles as repellents in integrated pest management of ambrosia beetles. Integr. Pest Manage. Reviews (in press).

15. Kühnholz, S., J.H. Borden and A. Uzonovic. 2003. Secondary ambrosia beetles in apparently healthy living trees: adaptations, potential causes and suggested research. Integr. Pest Manage. Reviews (in press).

16. Tomlin, E.S., R.I. Alfaro and J. H. Borden. 2003. Overstory shading limits consititutive and induced resinosis of Sitka spruce against the white pine weevil. For. Ecol. Manage. (in press).

17. Huber, D.P.W. and J.H. Borden. 2003. Comparative behavioral responses of *Dryocoetes confusus* Swaine, *Dendroctonus rufipennis* (Kirby) and *Dendroctonus posderosae* Hopkins (Coleoptera: Scolytidae) to angiosperm tree bark volatiles. Environ. Entomol. (in press).

18. Evenden, M.L., L.E. Delury, G.J.R. Judd and J.H. Borden. 2003. Assessing the mating status of male obliquebanded leafrollers, *Choristoneura rosccana* (Lepidoptera: Tortricidae), by dissection of male and female moths. Ann. Entomol. Soc. Am. (in press).

B. MANUSCRIPTS SUBMITTED TO REFEREED JOURNALS

1. Lait, C. G., D. R.Miller, S. L. Bates, J. H. Borden and A. R. Kermode. Biochemical assay detects feeding damage to loblolly pine seeds caused by the leaffooted pine seed bug, *Leptoglossus corculus*. J. Entomol. Sci.

2. Pureswaran, D. S. and J. H. Borden. Tests of host specificity in four tree-killing bark beetles. Environ. Entomol.

3. Pureswaran, D.S. and J. H. Borden. Is bigger better? Size and pheromone production in the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae). J. Insect Behav.

4. Miller, D. R. and J. H. Borden. Responses of *Ips pini*, *Pityogenes knechteli* and associated beetles (Coleoptera) to host monoterpenes in stands of lodgepole pine. J. Entomol. Sci.

5. Morewood, W. D., K. E. Simmonds, R. Gries, J. D. Allison and J. H. Borden. Dispruption by conophthorin of the kairomonal response of sawyer beetles to bark beetle pheromones. J. Chem. Ecol.

6. Pureswaran, D. S., R. Gries and J. H. Borden. Antennal responses of four species of tree-killing bark beetles (Coleoptera: Scolytidae) to volatiles from conifers and beetles. Chemoecology.

7. Burleigh, J.S., J. H. Borden and R.I. Alfaro. Impact of the spruce budworm, *Choristoneura fumiferana* (Clem.), on the increment and distribution of volume in white spruce, *Picea glauca* (Moench) Voss, in northeastern British Columbia. Can J. For. Res.

8. Pureswaran, D. S. Group level effects and the evolution of cooperation among nonrelatives: pheromone mediated regulation of aggregation in tree killing bark beetles. Evol. Ecol. Res.

C. CHAPTERS

1. Alfaro, R.I., J.H. Borden, J.N. King, E.S. Tomlin, R.L. McIntosh and J. Bohlmann. 2002. Mechanisms of resistance in conifers against shoot infesting insects. pp. 101-106. In: Mechanisms and deployment of resistance in trees to insects. M.R. Wagner, K.M. Clancy, F. Lieutier and T.D. Paine (eds.). Kluwer Academic Press, Dordnecht, The Netherlands.

2. Borden, J.H. 2002. Allelochemics. pp. 14-17. In: Encyclopedia of pest management. D. Pimental (ed.) Marcel Dekker, New York.

3. Borden, J.H. 2002. Forest pest and fire management. In: Encyclopedia of life support systems. UNESCO, EOLSS Pub. Co., UK (in press).

D. NON-REFEREED PUBLICATIONS

1. Borden, J.H. 2001. Ramblings. pp. 211-219. In: Boreal odyssey: Proceedings of the North American Forest Insect Work Conference May 14-18, 2001, Edmonton, Alberta. W.J.A. Volney, J.R. Spence and E.M. Lefebvre (eds). Canadian Forest Service, Northern Forestry Centre, Edmonton.
2. Borden, J. H. 2003. *Dryocoetes confusus*. CAB International, Data Sheet on Quarantine Pests (in press).
3. Borden, J. H. 2003. *Ganthotrichus sulcatus*. CAB International, Data Sheet on Quarantine Pests (in press).

VI. COMMUNICATION AND EXTENSION

In addition to publication of results with dispatch in high-quality, accessible, peer-reviewed journals, my laboratory follows other means of communication of results as needed to ensure that results are available to users. These are summarized beginning on 1 October 2001.

A. PAPERS PRESENTED AT SCIENTIFIC AND PROFESSIONAL MEETINGS

1. Bates, S.L., C.G. Lait, , J.H. Borden and A.R. Kermode. 2001. Developing damage prediction formulae for the western conifer seed bug, *Leptoglossus occidentalis*, in lodgepole pine. Entomological Society of Canada Annual Meeting, Niagara Falls, Ontario, 21-24 October, 2001.
2. Pureswaran, D.S., J.H. Borden, and R. Gries. 2001. Semiochemical-based host selection among four coniferophagous tree-killing bark beetles (Coleoptera: Scolytidae). How different do the trees smell? Entomological Society of America Annual Meeting, San Diego, CA, 25-29 November, 2001.
3. Morewood, W. D. 2002. Building a better beetle trap for big borers in British Columbia. Professional Pest Management Association of B.C. Annual Meeting, Burnaby, B.C., 6 February 2002.

4. Tanaka, A. 2002. The *Pissodes* problem; is there a semiochemical salvation? Professional Pest Management Association of B.C. Annual Meeting, Burnaby, B.C., 6 February 2002.
5. Borden, J.H. 2002. Who left the logs out? FERIC/FORINTEK/PAPRICAN Seminar. Wood Storage: Issues and Solutions.
    - 26 March 2002, Montreal (by video conferencing).
    - 27 March 2002, Edmonton (in person).
6. Borden, J.H. 2002. Research update. Phero Tech Technical Seminars.
    - Prince George, 11 April 2002.
    - Mackenzie, 12 April 2002.
7. Pureswaran, D.S. 2002. Host selection in tree-killing bark beetles. Unraveling the intricacies of a complex communication system. Western Forest Insect Work Conference, Whitefish, Montana 23-25 April 2002. (WFIWC Memorial Scholarship Winner, Invitational Presentation).
8. Campbell, S.A. and J.H. Borden. 2002. Visual and semiochemical deterrence of host seeking forest coleoptera. Western Forest Insect Work Conference, Whitefish Montana, 23-25 April 2002 (poster).
9. Bates, S.L. 2002. Detection, impact and management of the western conifer seed bug *Leptoglossus occidentalis* Heidemann, in lodgepole pine seed orchards. Pacific Branch, Entomological Society of America, Annual Meetings Lake Tahoe CA, 16-19 June 2002. (Comstock Award Winner, Invitational Presentation).
10. Borden, J. H., L. J. Chong, T. J. Earle and D. P. W. Huber. 2002. Protection of lodgepole pine from attack by the mountain pine beetle, *Dendroctonus ponderosae* (Coleoptera: Scolytidae), using high doses of verbenone and nonhost bark volatiles. Entomological Society of America Annual Meeting, Fort Lauderdale FL, 17-20 November 2002.
11. Pureswaran, D. S., R. Gries and J. H. Borden. 2002. Interspecific communication and host selection in tree-killing bark beetles. Entomological Society of America Annual Meeting, Fort Lauderdale FL, 17-20 November 2002.

12. Borden, J. H. 2003. Protection of lodgepole pine from attack by the mountain pine beetle. Seminar organized by Lignum Ltd., Williams Lake, B. C., 13 January 2003.
13. Campbell, S. A., R. Gries and J. H. Borden. 2003. Response of the striped ambrosia beetle, *Trypodendron lineatum* (Coleoptera: Scolytidae), to bark beetle pheromones. Professional Pest Management Association of B. C. Annual Meeting, Burnaby, B. C., 19 February 2003 (Best Student Paper Award).

B. WORKING MEETINGS AND COLLABORATION WITH PHERO TECH INC.

Because Phero Tech Inc. is our principal industrial sponsor and the potential developer and marketer of new technology arising from research, some member of our laboratory is in at least weekly contact with the company. More formal interaction with the company since 1 October 2001 has been as follows.

1. Research Planning Meeting, 28 November 2001, SFU, attended by Phero Tech personnel.
2. Woodborer Research Meeting, 15 January 2002, Phero Tech, attended by J.H. Borden, L.J. Chong, W.D. Morewood, K.E. Hein, S. Kühnholz, C. Broberg, and S.A. Campbell.
3. Woodborer Trap Design Meeting, 12 February 2002, Phero Tech, attended by J.H. Borden, W.D. Morewood and K.E. Hein.
4. Participation in technical seminars for forestry workers (see A, 6).
5. K. Hein seconded to Phero Tech 8 weeks in March - May 2002 to participate in design and manufacture of woodborer traps.
6. Research review and planning meeting, 10 September 2002, J.H. Borden meeting with J. Burleigh, A. Gustafsson, S. Burke and D. Wakarchuk.
7. Meeting at Phero Tech on 15 October 2002 between J. H. Borden, J. S. Burleigh and A. Gustafsson to discuss alder bark beetle project.
8. Research Planning Meeting, 16 December 2002, attended by all laboratory personnel, at Phero Tech.
9. Collaborative work on alder bark beetle contract by J. H. Borden (SFU), J. S. Burleigh and A. Gustafsson (Phero Tech) with N. Hughes RPF (Weyerhaeuser Canada, Stillwater

Division) and R. Brewer RPF (GFC forest Management, Powell River), 2-5 December 2002 and 20-24 January 2003.

C. REPORTS TO SPONSORING COMPANIES

The CRD project annual report was sent in late October 2002 to the following 20 industrial sponsors, which have contributed financially directly to the CRD grant program: Abitibi Consolidated Inc., B.C. Hydro, Bugbusters Pest Management Inc., Canadian Forest Products Ltd., Gorman Bros. Ltd., International Forest Products Ltd., Lignum Ltd., Manning Diversified Forest Products Ltd., Millar-Western Forest Products Ltd., Phero Tech Inc., Riverside Forest Products Ltd., Slocan Forest Products Ltd., Tembec Forest Industries Ltd., TimberWest Ltd., Tolko Industries Ltd. (Nicola and Quest Wood Divisions), Weldwood of Canada Ltd., West Fraser Mills Ltd., Western Forest Products Ltd., and Weyerhaeuser Canada Ltd. The report was also sent to the industrial sponsors of Science Council of B.C. GREAT Scholarships for two students, Deepa Pureswaran and Cindy Broberg. Deepa is supported by the Cariboo Lumber Manufacturers' Association, the Interior Lumber Manufacturers' Association, the Northern Forest Products Association and Phero Tech Inc. Cindy is supported by Louisiana Pacific Canada Ltd., Scott Paper Ltd., Weyerhaeuser Canada Ltd., Ainsworth Lumber Company Ltd., and Phero Tech Inc. Both students also sent individual reports to their sponsors.

D. COLLABORATION WITH INDUSTRIAL SPONSORS AND OTHER ORGANIZATIONS

Most of our field research takes place within the operating areas of one or more of our industrial sponsors. We are often assisted by their forestry personnel, who become aware through grass roots technology transfer of our objectives, methodology and results. As documented in Section IV, in 2001-2002 this grass roots interaction involved 16 cooperators, who represent four companies, two government agencies, one nongovernmental organization and one university. In addition, in 2001 - 2002 we collaborated directly on a mountain pine beetle project with Lignum Ltd., and one of their foresters, Ms. Tracy Earle RPF, is a co-author of a publication submitted to

Forestry Chronicle on this work. Dr. Lisa Poirier of UNBC is a collaborator on our current mountain pine beetle project.

VII. RESEARCH PERSONNEL

Postdoctoral Personnel

H.D. PIERCE, Jr., University Research Associate

Degrees: B.Sc., Ph.D., Illinois.

Subject Area: Volatile capture and extraction, analytical and synthetic organic chemistry, advising graduate students.

Present Position: Unemployed as of 30 September 2002.

A.R. WARDLE, Research Associate

Degrees: B.Sc., UBC; MPM, Ph.D., SFU.

Subject Area: Protection of logs from woodborer attack, bioactivity of budworm oral exudate.

Present Position: Unemployed as of 30 September 2002.

W.D. MOREWOOD, Postdoctoral Fellow

Degrees: B.Sc., M.Sc., Ph.D., Univ. Victoria

Subject Area: Chemical ecology and management of wood-boring beetles.

Present Position: Research Associate, Department of Entomology, Pennsylvania State University.

Research Technicians

L.J. CHONG

Degree: B.Sc., SFU

Subject Area: Support services and research coordination, set up and maintenance of field experiments, data processing.

R. GRIES

Degree: M. Agr., Göttingen, Germany
Subject Area: GC-EAD analysis, bioassays, maintenance of GC-EAD laboratory and coordination of laboratory services.

K.E. SIMMONDS (nee HEIN)

Degree: B.Sc., SFU

Subject Area: Chemical ecology of wood-boring beetles.

Ph.D. Students

S. KÜHNHOLZ

Degree: Dip. Univ. Wurbug
Awards: SFU Graduate Fellowship
Subject Area: Chemical ecology and interaction between four species of *Trypodendron* native to British Columbia

S.L. BATES

Degrees: B.Sc., Univ. Guelph; MPM, Ph.D., SFU
Awards: NSERC Graduate Scholarship; Entomological Society of Canada Graduate Scholarship; Science Council of B.C. GREAT Scholarship
Subject Area: Impact assessment of the western conifer seed bug on lodgepole pine.
Present Position: Postdoctoral Fellow, Cornell University Agricultural Experiment Station, Geneva NY.

D.S. PURESWARAN

Degrees: B.Sc., Madras Christian Coll.; M.Sc., SFU
Awards: SFU Graduate Fellowship; Science Council of B.C. GREAT Scholarship
Subject Area: Role of tree and beetle volatiles in maintaining host specificity and reproductive isolation in coniferophagous bark beetles.

C.L. BROBERG

Degree: B.Sc., Okanagan Univ. Coll. In coop with UBC, MPM, SFU

Awards: NSERC Graduate Scholarship; Entomological Society of Canada Graduate Scholarship; Science Council of B.C. GREAT Scholarship

Subject Area: Comparative chemical ecology of the poplar and willow borer and *Saperda calcarata* on willow, aspen and cottonwood.

Master of Pest Management Students

A. GUSTAFSSON

Degree: B.Sc., Concordia, MPM , SFU

Awards: Government of Sweden Graduate Scholarship

Thesis: A test of sequential semiochemical baiting to contain and concentrate infestation of the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae). Defended August 2002.

Present Position: Woodborer Program Manager, Phero Tech Inc., Delta, B.C.

J.A. TANAKA

Degree: B.Sc., SFU

Subject Area: Chemical ecology of the white pine weevil.

Present Position: Research Assistant, Agriculture Canada, Agassiz, B.C.

M.Sc. Student

S.A. CAMPBELL

Degree: B.Sc., SFU

Subject Area: Visual disruption of host selection in bark beetles and woodboring insects.

Research Assistants

P. MOREWOOD, MPM, SFU

S.H. NAGLA, Biological Sciences Major, SFU

M.C. TAI, English and Biological Sciences Major, SFU

B. MOON, Biological Sciences Major, SFU

S. VANDER MEER, Biological Sciences Major, SFU

N. VANDER WAL, Biological Sciences Major, SFU

C. SILVA, B.Sc. SFU

G. REYES, B.Sc. Dalhousie

A. KRICKAN, Biological Sciences Major, SFU

M. LEFLER, B.Sc., SFU

VIII. DELIVERABLES

Deliverables for the 18 months beginning on 1 October 2001 are separated for convenience into contributions to scientific and technical knowledge, and operational deliverables associated with such activities as research administration, experimentation, reporting and networking.

A. CONTRIBUTIONS TO SCIENTIFIC AND TECHNICAL KNOWLEDGE

We have not in the past 18 months completed research that has resulted directly in marketable products and services. The pace of research in forestry is necessarily slow, because it relies principally on gradual transformation of practices and policies based on large volumes of accumulated knowledge and skills. Nonetheless, several of the projects listed under Section IV, will have a very practical outcome, and some may have commercial potential. The most significant of the contributions to date are itemized below.

1. Demonstration of marked differences in the bark and foliage volatile spectra of Douglas-fir (coast and interior), interior spruce, interior fir and lodgepole pine that could be used in host discrimination by tree-killing bark beetles.
2. Finding of primary attraction of Douglas-fir and spruce beetles to synthetic blends of host volatiles, the first such demonstration for either species.

3. Confirmation that myrcene is a better synergist for mountain pine beetle pheromones than a synthetic blend of lodgepole pine volatiles.
4. Discovery of new repellents for bark beetles, including *trans*-verbenol, acetophenone and 1-octen-3-o1 for the Douglas-fir beetle, MCH and 1-octen-3-ol for the mountain pine beetle, and 1-octen-3-ol for the spruce beetle.
5. Proof that Phero Tech's new high-dose verbenone pouch can deter attack in lodgepole pine stands by the mountain pine beetle in 0.16 ha plots treated with 16 pouches, and that deterrence can be significantly increased by adding a seven-component nonhost volatile blend, both treatments being suitable immediately for small-scale implementation.
6. Verification that MCH and 2-phenylethanol reduce catches of the mountain pine beetle in pheromone-baited traps, but discovery that only the latter compound is partially effective in deterring attack on pheromone-baited trees.
7. Finding that fatty acids and vegetable oils are competitive with a four-component nonhost volatile blend in delaying attack by ambrosia beetles on conifer logs, but realization that fatty acids and oils are impractical to work with and have little commercial value.
8. Preliminary finding that among an array of seven bark beetle pheromones that are perceived by ambrosia beetle antennae, MCH is so repellent to the striped ambrosia beetle that it is being tested in 2003 as a log protectant alone and in combination with our nonhost volatile blend.
9. Additional finding that attraction by the striped ambrosia beetle to the pheromone lineatin is enhanced by the bark beetle pheromones ipsenol and ipsdienol, suggesting that they may be used to improve the efficacy of commercial trapping programs.
10. Demonstration that lightweight flexible plastic traps of both cross-vane and pipe design are effective in trapping large woodborers, but realization that marketing of the traps must be delayed until durability is assured, and minor adjustments in design are tested.
11. Finding that the host volatiles ethanol and conophthorin interact with the pheromone tirathol to result in optimal attraction of the birch-infesting ambrosia beetle, *Trypodendron betulae*.
12. Morphological and molecular characterization of fungi associated with B.C.'s four native ambrosia beetles in the genus *Trypodendron*.

13. Demonstration by a weevil caging experiment of high susceptibility to the poplar and willow borer of one hybrid poplar clone (*trichocarpa x nigra*), and absolute resistance in another (*nigra x maximowiczii*).
14. In contrast to results in the field (13), lack of absolute discrimination in the laboratory by the poplar and willow borer among cut stem sections of hybrid poplar clones, suggesting that resistance expressed in the field by intact plants is induced by weevil oviposition.
15. New findings of pheromones of coniferophagous bark beetles in the bark of angiosperm trees, e.g. *trans*-verbenol, sulcatone and frontalin in *Populus tremuloides*, and conophthorin in 28 of 36 species examined to date.
16. Verification that grandisol is a male-produced pheromone that attracts female white pine weevils, and that grandisoic acid in combination with host volatiles is attractive to males.
17. Discovery of the spruce budworm sex pheromone component (*E*)-11-tetradecanal, and the saturated aldehyde tetradecanal, in the oral exudate of budworm larvae.
18. Elucidation in collaboration with Phero Tech of the impact and infestation dynamics of overwintering alder bark beetles in Weyerhaeuser Canada's Stillwater Division on the Sunshine Coast.

B. OPERATIONAL DELIVERABLES

1. Set up and operation of over 45 experiments in over 20 separate research sites throughout the southern half of B.C., involving direct collaboration with personnel in Lignum Ltd., Phero Tech Inc., and UNBC, and interaction with 16 cooperators in four companies, two government agencies, one non-governmental organization and one university.
2. Liaison in collaborative research and development with two scientists in Canadian Forest Service laboratories at Sault Ste. Marie and Fredericton, and one U.S. Forest Service scientist in Athens, Georgia.
3. Administration of over $400,000 in external research funding, including the support and supervision of three postdoctoral scientists, three research technicians, seven graduate students, and eight research assistants, as well as a fleet of six vehicles which logged over

100,000 km, purchase and deployment of over $25,000 in semiochemicals and release devices, and maintenance of a large inventory of laboratory and field equipment.

4. Contribution to scientific and technical training through the graduation of one Ph.D. student, who is now a Postdoctoral Fellow at Cornell University, and one M.P.M. student, who is now Woodborer Program Manager for Phero Tech Inc., and the supervision of five other graduate students.
5. Communication of activities and results through the following:
   - 18 papers published or in press in refereed journals;
   - 2 chapters published in books, and one in press;
   - 3 non-refereed publications;
   - 13 presentations at scientific and professional meetings; and
   - extensive interaction with Phero Tech Inc., the company that will develop marketable products and services arising from this research.

Exp. no.	Treatment	No. beetles captured ($\bar{x}$ ±SE) Males	Females
1	unbaited control	0.6 ± 0.3	1.1 ± 0.4
	ethanol	3.9 ± 1.8	2.7 ± 0.9
	tirathol	2.0 ± 0.8	1.6 ± 0.7
	tirathol + ethanol	2.8 ± 1.3	4.2 ± 1.3
2	unbaited control	0.3 ± 0.2	0.1 ± 0.1
	tirathol + conophthorin	1.5 ± 0.8	1.4 ± 0.5
	tirathol + conophthorin + ethanol	11.2 ± 4.1	9.4 ± 3.6