The white pine weevil in British Columbia: Basis for an integrated pest management system

by Rene I. Alfaro[1], J.H. Borden[2], R.G. Fraser[3], and A. Yanchuk[4]

Research programs to date in British Columbia on the biology, damage and control of the white pine weevil, *Pissodes strobi* (Peck), a pest of spruce, *Picea* spp. and pine, *Pinus* spp., are reviewed. Significant progress has been made in the areas of genetic resistance, silvicultural and chemical control. An integrated pest management (IPM) system is formulated which combines silviculture-driven and resistance-driven tactics. The system relies on accurate hazard rating of plantation sites and requires continuous monitoring of attack levels and the forecasting of plantation productivity under various IPM tactics through the use of a decision support system. Research needs which would increase effectiveness of the IPM system are reviewed and organized in the context of the plantation productivity cycle.

Key words: insect control, *Pissodes strobi*, IPM, genetic resistance, silvicultural control, chemical control, decision support system

Les programmes de recherche à ce jour en Colombie-Britannique portant sur la biologie, les dommages et le contrôle du charançon du pin blanc, *Pissodes strobi* (Peck), un ravageur des épinettes, *Picea* spp. et des pins, *Pinus* spp., ont fait l'objet d'une étude. Des progrès significatifs ont été enregistrés au niveau de la résistance génétique et du contrôle sylvicole et chimique. Un système de gestion intégrée des ravageurs (GIR) est formulé et combine des tactiques découlant de la sylviculture et de la résistance des arbres. Le système repose sur une évaluation précise du risque relatif aux sites de plantation et nécessite une surveillance continue des niveaux d'attaque et de la productivité des plantations en fonction de diverses tactiques de GIR grâce à l'utilisation d'un système de prise de décision. Les domaines de recherche qui pourraient accroître l'efficacité d'un système GIR sont révisés et situés dans le contexte d'un cycle de productivité d'une plantation.

Mots clés: contrôle des insectes, *Pissodes strobi*, GIR, résistance génétique, contrôle sylvicole, contrôle chimique, système de prise de décision

Introduction

The white pine weevil, *Pissodes strobi* (Peck), causes severe problems to reforestation programs throughout Canada. In coastal British Columbia (BC) Sitka spruce, *Picea sitchensis* (Bong.) Carr., a valuable timber tree, is so severely damaged that planting of this species is currently not recommended in most areas. The current planting guidelines for coastal BC allow only 20% Sitka spruce in medium and high hazard areas[1]. In the interior of B.C. and Alberta there is increasing concern that plantations of white spruce, *Picea glauca* (Moench) Voss, and Engelmann spruce, *Picea engelmannii* Parry, created in recent years may also be at risk (Taylor *et al.* 1991). In eastern North America, the most important species damaged by *P. strobi* are eastern white pine, *Pinus strobus* L., Jack pine, *Pinus banksiana* Lamb., and Norway spruce, *Picea abies* (L.) Karst.

After overwintering in the duff, *P. strobi* adults emerge in early spring and move to the 1-year-old terminal shoot (leader), where the females lay eggs in oviposition punctures in the bark near the apical bud. If the weevil larvae become established, they move downwards, mining and consuming the phloem, and eventually killing the leader (Silver 1968). Repeated leader destruction causes height-growth loss and stem deformities which reduce tree value, often to zero (Alfaro 1992). Although most trees survive the attack, stunted trees are suppressed, and sometimes killed, by competing vegetation (Alfaro 1982).

The current recommendations for control of *P. strobi* in BC (British Columbia Ministry of Forests 1989) rely on prevention of the problem by reducing the proportion of host trees ha^{-1} during spacing and precommercial thinning. The possibility of direct control through leader clipping or chemical sprays is also identified.

Integrated pest management (IPM) is an ecological approach to pest control with the objective to use a combination of various tactics to *reduce damage* rather than to eliminate the pest. An important goal is to minimize environmental impact (U.S. National Academy of Sciences 1969). These systems are usually consolidated into a unified program which specifies strategies and tactics in the context of the crop productivity cycle.

The desirability of IPM is based on the fact that pest management specialists have realized that relying on simplistic approaches based on a single control method have been generally ineffective and can lead to problems. For example, excessive dependence on chemical pesticides induced pesticide resistance in numerous agricultural pests (Georghiou and Saito 1983). Similarly, exclusive, large-scale use of insect resistant tree genotypes could increase evolutionary pressures on insects, resulting in the evolution of biotypes with the ability to overcome plant resistant mechanisms (Gould 1988; Raffa 1989). IPM tries to avoid these problems by adopting a more integrated approach, based on an understanding of pest-host interactions to reduce selection pressures on the pest.

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[1] Pacific Forestry Centre, Canadian Forest Service, 506 West Burnside Road, Victoria, British Columbia, Canada V8Z 1M5.
[2] Centre for Pest Management, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6.
[3] Pacific Forests Products Ltd., 8067 East Saanich Rd., Saanichton, British Columbia, Canada V0S 1M0.
[4] Research Branch, British Columbia Ministry of Forests, 31 Bastion Square, Victoria, British Columbia, V8W 3E7.

[1] Heppner, D.G. and G.M. Wood. 1984. Vancouver Region Sitka spruce weevil survey results (1982–1983) with recommendations for planting Sitka spruce. Internal Report PM-V-5. B.C. Ministry of Forests.

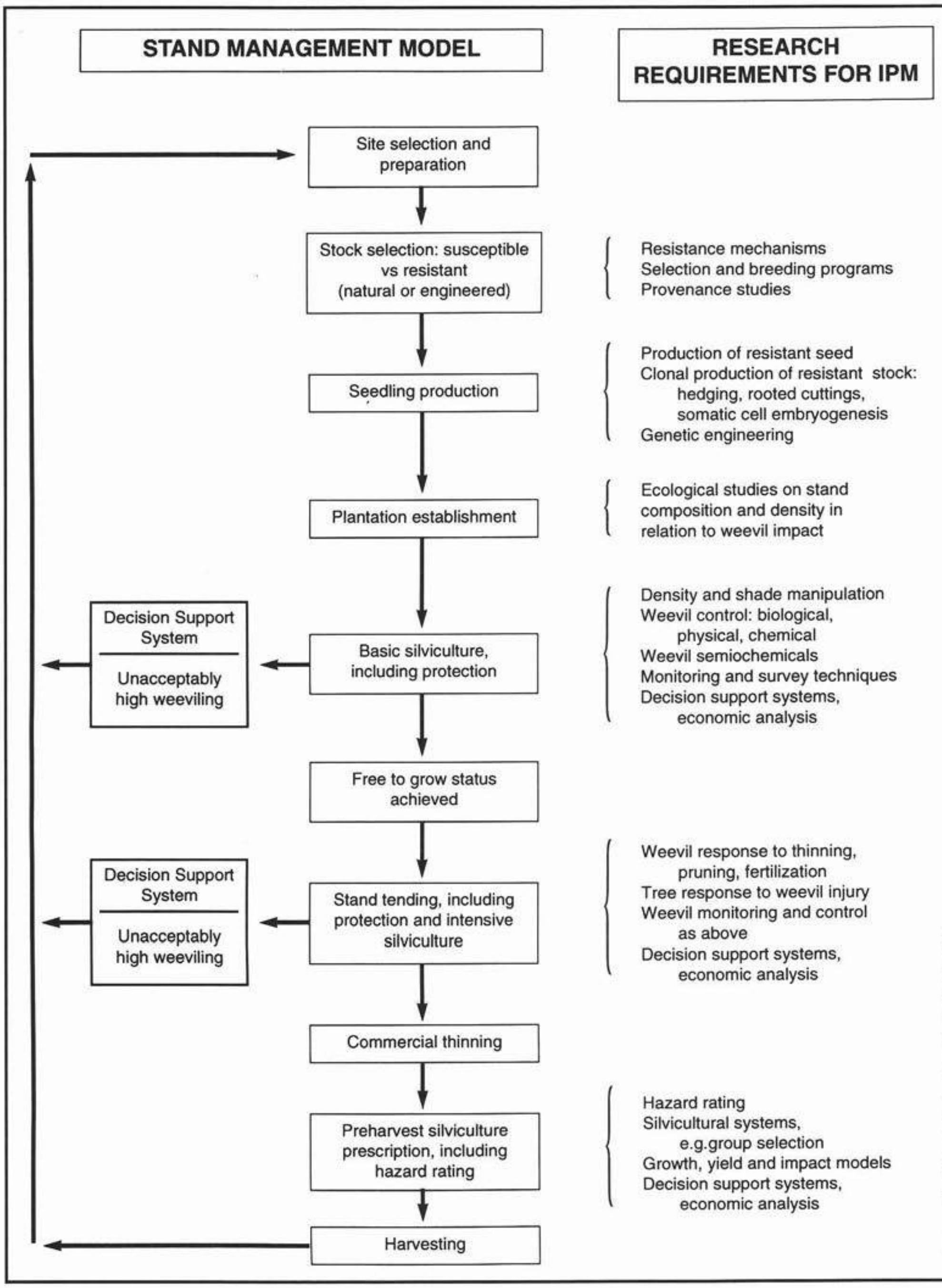

Figure 1. Stand management model for Sitka and interior spruces in British Columbia showing how unacceptably high damage by the white pine weevil, analyzed by a Decision Support System, can recommend abandonment of plantations before maturity (left hand loops), and on the right various research needs for an intensive research and development program for integrated management of *Pissodes strobi*.

IPM programs in forestry are generally less advanced than in agricultural systems. The difficulty lies in that, relative to agriculture, forest ecosystems are more complex and of a much larger scale. One recent example is the IPM program devised for the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, in BC.[2] This program identifies six broad management strategies, under which any appropriate combination of 25 different tactics can be applied. The strategies range from prevention of future problems to active suppression of current infestations, and the various tactics include such actions as aerial surveys, hazard and risk rating, selective cutting regimes, semiochemical-based manipulation of populations, and direct control by felling and burning of infested trees or treating them with chemical pesticides. A decision support system to evaluate management options for this pest is currently under development at the Pacific Forestry Centre.

Another notable example is the comprehensive IPM system for the management of the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McD), in the western United States (Brookes *et al.* 1978) and British Columbia (Shepherd and Otvos 1986). These systems rely on early detection through egg mass surveys and pheromone trapping. Stands are ranked in terms of degree of outbreak hazard to ensure early detection in the most likely areas. Biological control with microbial insecticides

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[2] Safranyik, L. and P.M. Hall. 1990. Strategies and tactics for mountain pine beetle management. Unpublished report prepared for the mountain pine beetle task force. B.C. Ministry of Forests, Victoria.

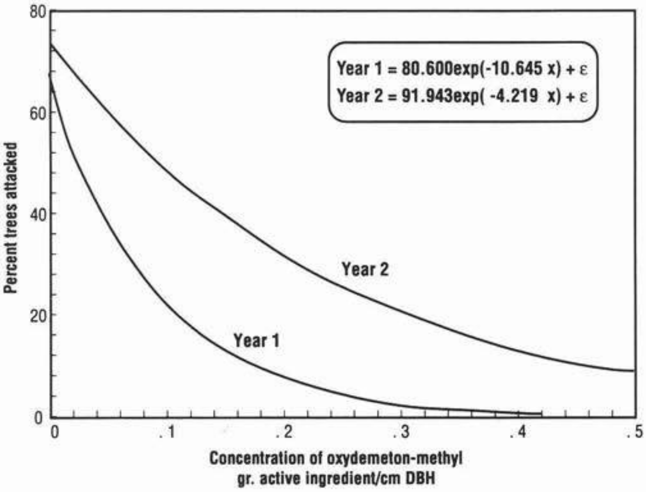

Figure 2. Percentage of Sitka spruce trees attacked two years after treatment with stem implants of the systemic insecticide oxydemeton-methyl at 0, 0.1, 0.2, and 0.4 g.a.i. cm^{-1} DBH.

is applied if appropriate. In the U.S.A., models were developed to project insect populations and stand development under various control alternatives and to evaluate socioeconomic impacts.

The objective of this study was to review current progress in *P. strobi* research in BC, and based on this, to formulate a possible IPM system. With reference to the silviculture of Sitka and interior spruce in BC (Fig. 1), this review could also provide a basis for an intensive research and development program for this pest. The last review of the subject was conducted 10 years ago by Cozens[3] who summarized weevil biology and research progress.

Direct Control

Three decades ago DDT sprays were recommended for direct control of the white pine weevil (Connola 1961). Wide scale conventional chemical control of this type has been abandoned because, although it can be effective, it is considered environmentally undesirable. However, experimental systemic insecticide injections have been used recently to achieve two years of control in treated trees (Fraser and Heppner 1993; Fraser, unpublished report[4]) (Fig. 2). Because only individual crop trees are injected, harmful effects of pesticides on non-target organisms are minimized. Work is presently continuing in BC to develop systemic insecticide injection formulations of longer duration and higher effectiveness.

Extensive clipping operations to remove infested leaders were conducted in BC in the 1980s with the goal of reducing weevil populations. Although removal of the infested leader may improve tree form (Lavallée and Morissette 1989), weevil infestations were not reduced (L. Rankin, BC Min. of Forests, Williams Lake, B.C. pers. comm.). Clipping operations have now been largely discontinued because they are expensive and logistically difficult (Smith and McLean 1993).

The possibility of using biological control has been considered and several studies of the predators and parasitoids of *P. strobi* have been conducted (Alfaro and Borden 1980; Hulme *et al.* 1986, 1987; Hulme 1989, 1990). However, to date, no agents are available for biological control. Current research on this subject in B.C. includes the development of methods of natural enemy enhancement and biological control by importation of parasitoids from European *Pissodes* species for use against *P. strobi*. The usefulness of microbial insecticides (bacteria and virus) for weevil control has received little attention in Canada.

Because the number of weevils ha^{-1} during the mating season is low, attractive semiochemicals, if discovered, could be used to mass trap *P. strobi*. However, although pheromones are known for *P. nemorensis* (Phillips and Lanier 1986) and *P. castaneus* (Pajares and Guerrero 1992), attempts to isolate and identify pheromones in *P. strobi* have been so far unsuccessful (Phillips and Lanier 1986).

Silvicultural Control

Management of weevil populations by stand manipulation has long been hypothesized to be a viable alternative (Sullivan 1961). The objective is to modify stand microclimate to make it unsuitable for successful attack or for weevil survival. Silvicultural treatments, such as pruning or thinning, could also be modified to minimize the impact of the weevil on attacked trees and stands.

Wallace and Sullivan (1985) reviewed early work on the influence of stand conditions on the behaviour of *P. strobi* in eastern white pine, *Pinus strobus* L. They concluded that dense stands and shaded habitats are unfavorable for weevil development because adult weevils require certain conditions of temperature and humidity for feeding and oviposition. These activities are restricted by the low temperatures prevailing in dense, shaded stands. Low temperatures also retard larval development, which probably increases exposure of larvae to attack by parasitoids and predators. In conditions where heat accumulation is insufficient for completion of larval development, a Sitka spruce stand cannot sustain viable weevil populations (McMullen 1976).

In Ontario, Stiell (1979) reported reductions in weevil damage to eastern white pine when it was mixed with deciduous species. McLean (1989) demonstrated lower rates of weevil damage in Sitka spruce under an overstory of red alder, *Alnus rubra* Bong., than in the open. Alfaro and Omule (1990) found significantly lower attack rates (Fig. 3) and better stem form, even in attacked trees, in Sitka spruce plantations started at the closest of three spacings. Stiell (1979) also demonstrated low attack rates in dense eastern white pine stands and proposed a thinning regime to release the unattacked trees, thus ensuring a sufficient amount of undamaged timber ha^{-1}. Recently, new experiments have been initiated in BC to examine the influences of density and species mixtures on weevil damage and tree growth.

With the widespread adoption of clearcutting and reforestation, extensive plantations of nearly pure Sitka spruce were created on the coast which provided conditions extremely favorable for weevil outbreaks. There were virtually unlimited feeding and oviposition niches. Similar conditions have been created apparently in many spruce plantations in the interior of BC. Pure

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[3] Cozens, R. 1983. The spruce weevil, *Pissodes strobi* Peck (Coleoptera: Curculionidae): a review of its biology damage, and control techniques with reference to the Prince George Timber Supply Area. Internal Report PM-PG-3. B.C. Ministry of Forests.

[4] Fraser, R.G. 1992. User of oxydemeton-methyl (Metasystox-R) and dimethoate capsules applied with an Ezject lance for Sitka spruce weevil (=white pine weevil) control. November 1992. Pacific Forest Products, Saanich, B.C.

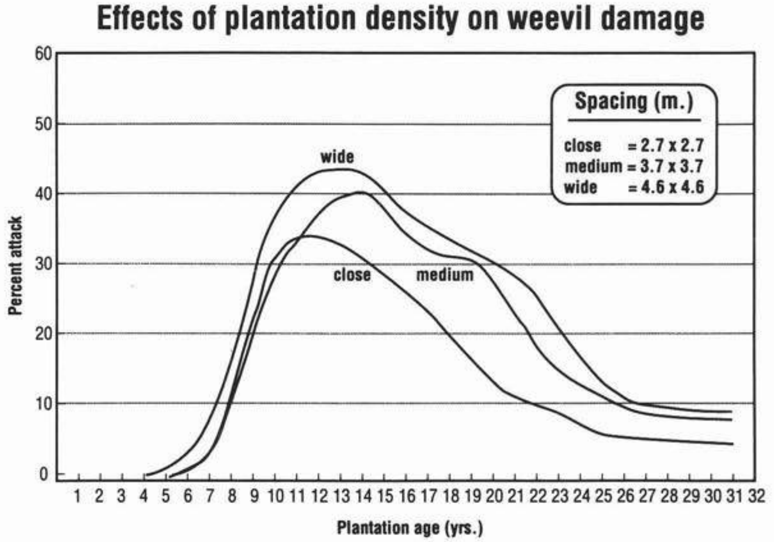

Figure 3. Epidemiology of *P. strobi* under three plantation spacing regimes. In typical infestations, attacks rise sharply to 30–50% of trees year^{-1}. This is followed by a period of insect/host equilibrium which can last several years. Infestations ultimately decline due to reduction in leader sizes, elimination of the host and changes in plantation microclimate.

spruce plantations should not be initiated in high hazard areas. Also, it is of critical importance to determine weevil epidemiology in alternative silvicultural systems such as single tree and group selection and shelterwood systems. The relation between site factors (moisture, soil type, etc.) and weevil damage should be investigated. Work underway in Quebec as well as Taylor *et al.* (1991) indicate that heavier attack is associated with certain site conditions.

Genetic Resistance

Of the several alternatives for management of *P. strobi*, the use of genetic resistance might have the most beneficial effect (Fig. 4). Analysis of field trials in British Columbia demonstrated genetic variation in the resistance of both white and Sitka spruce to weevil damage (Kiss and Yanchuk 1991; Alfaro and Ying 1990; Ying 1991; Brooks and Borden 1992; Alfaro *et al.* 1993; Alfaro 1982). These analyses indicate that individual wild trees, as well as groups of trees from certain families and provenances, show resistance in the form of reduced numbers of successful weevil attacks. For example, trees from the Haney provenance (40 km east of Vancouver, BC) established in trials at Sayward and Fair Harbour, on Vancouver Island, grew well and were the least damaged (Alfaro and Ying 1990; Ying 1991). For interior spruce, family variation in weevil resistance is high, and resistant families are typically the fastest growing (Kiss and Yanchuk 1991).

In eastern North America, several studies demonstrated variation in susceptibility or resistance to *P. strobi* in eastern white pine (Wright and Gabriel 1959; Plank and Gerhold 1965; Connola 1966; Soles *et al.* 1969, 1970). Based on field observations and caging experiments, these researchers also detected genetic variation in susceptibility of white pine from different populations and among different *Pinus* species and their hybrids.

Ying (1991) noted that provenances yielding resistant Sitka spruce are located in areas of high weevil hazard, such as Haney or Squamish (44 km north of Vancouver, BC) on the BC mainland, where Sitka spruce is rare. He hypothesized that spruce may have been partially eliminated by the weevil in these areas and, therefore, the survivors may have higher resistance than the population average.

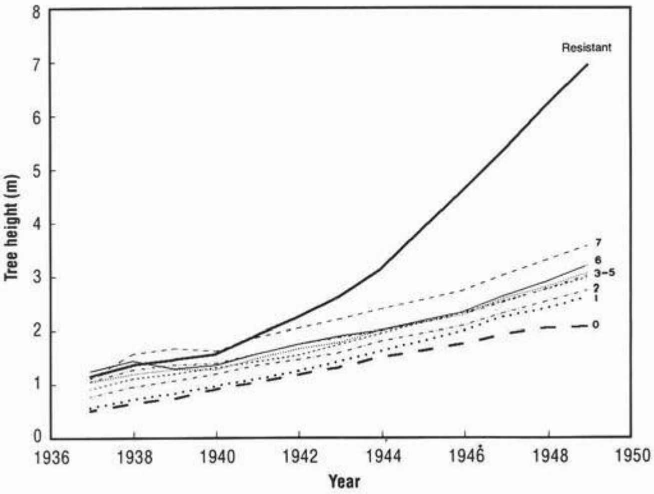

Figure 4. Height growth from 1937 to 1949 of Sitka spruce trees in an experimental plot (N = 182) at Green Timbers, Surrey, BC. Curves represent average growth of trees which sustained zero to seven or more attacks in the period. Note segregation of the height growth curves showing the preference of *P. strobi* for the fastest growing trees in a plantation, and the lack of attacks on very slow growing trees (Zero). This particular plot contained one resistant tree (Resistant). This tree was fast-growing and was never attacked. From unpublished data collected by K. Graham, M. Prebble, D. Smith and W. Mathers of the Dominion Forestry Laboratory (now Pacific Forestry Centre), Victoria, BC.

Another potential source of resistance may be by hybridization, as differential susceptibility among different *Picea* spp. has been reported (Mitchell *et al.* 1990; G. Kiss, BC Min. of Forests, Vernon, BC, pers. comm.). In some areas "Lutz" spruce, a Sitka × white spruce hybrid, exhibits resistance (Mitchell *et al.* 1990). Alfaro and Ying (1990) identified the Skeena River area of BC as one area where naturally resistant hybrid individuals could be found.

Alfaro *et al.* (1993), Ying (1991) and Brooks and Borden (1992) hypothesized that resistance probably has a multi-allelic or multigenic basis, with the possible existence of several resistance mechanisms which act in concert, possibly in a synergistic fashion, but which vary according to differences in trees, families or provenances. Resistant genes in interior spruce seem to be segregated to different degrees among the progeny of wind-pollinated families and hybrids. However, until appropriate studies are undertaken to examine the modes of inheritance of resistance mechanisms, this remains largely speculation.

Recent studies of the resistance mechanisms in Sitka spruce have disclosed that resin canals are significantly more dense in resistant than in susceptible Sitka spruce (Tomlin and Borden 1993). In addition, Alfaro (unpublished) described a hypersensitive reaction in spruces in response to feeding and oviposition by *P. strobi*. This reaction consists of the formation of traumatic resin canals in the developing xylem. The reaction was significantly more intense in resistant than in susceptible trees. In accordance with the observation that *P. strobi* will feed on resistant clones but eventually leave these trees (M. Hulme, Pacific Forestry Centre, Victoria, BC, pers. comm.), T.S. Sahota (Pacific Forestry Centre, Victoria, BC, pers. comm.) proposed an antibiosis resistance mechanism in which resistant trees can inhibit or reverse reproductive processes controlled by juvenile hormone in adult weevils, i.e. an effect similar to that induced by precocene (Bowers *et al.* 1976) as well as other substances. Brooks and Borden (1992) developed a prototype, three-component resistance index for Sitka spruce based on feeding deterrence and foliar monoterpene profiles. They proposed that when other resistance mechanisms or characteristics are known, they could be quantified and incorporated into a definitive, multi-component resistance index.

Alfaro and Ying (1990) also demonstrated variation in tolerance, i.e., the ability of trees to recover from weevil damage, as defect type varied by provenance and family. Trees in some provenances had more attacks tree^{-1} but were able to develop into merchantable trees. Tolerance to weevil damage is exemplified in the Big Qualicum provenance (10 km north of Parksville); some trees in this provenance were among the tallest at the Sayward trial even though they sustained repeated attack.

Current research on weevil resistance in BC is addressing the following subjects: elucidation of the mechanisms of resistance, selection and breeding of resistant genotypes, development of methods to identify and mass propagate resistant material, and molecular genetic studies of host trees and weevils. One aspect of critical importance is to ascertain the level of variability in weevil populations with respect to their ability to overcome the tree's resistance mechanisms.

Hazard Rating

A climate-based hazard rating system for *P. strobi* on Vancouver Island was developed by McMullen (1976). Heppner and Wood[1] established weevil hazard zones for Vancouver Island and the coastal mainland of BC based on the distribution of *P. strobi*, and developed planting guidelines. These systems, plus a detailed temperature-based hazard rating system under development for interior spruce (Sieben and Spittlehouse 1991) will prove valuable for reforestation planning and for prioritizing areas for control treatments and for deployment of resistant genotypes. Hazard rating could be incorporated into a geographic information system (GIS) as part of an overall expert system for white pine weevil decision-making.

Decision Support Studies

Assessment of the impacts of the white pine weevil is a critical prerequisite to determining the levels of expenditures to be committed for weevil management and research. This information is important in pest management to determine warning, action and damage thresholds. Alfaro (1992) developed a stand simulator (Spruce Weevil Attack Trials, or SWAT) capable of assessing the effects of different levels of weevil damage on Sitka spruce plantation productivity. Results from a SWAT trial were used by Errico (1990) to calculate the effects of weevil on the timber supply of the Kalum District in the Prince Rupert Region of BC SWAT simulation was also used by T. Ebata, (BC Min. of Forests, Smithers, BC, pers. comm.) to produce an economic assessment method. Research is continuing to integrate the SWAT model into the Tree and Stand Simulator (TASS) model, which is used routinely for forecasting the yield of managed stands in BC (Mitchell 1975). The combined model is expected to be useful for assessing plantation productivity under different scenarios of weevil population intensity, and for assessing alternative plantation management strategies such as sanitation thinning or the performance of mixtures of susceptible and resistant stock.

By definition, IPM requires accurate estimates of economic damage (including quality losses) so that the necessary management steps can be prescribed. In forestry, the relevance of a pest infestation for a particular stand depends on the extent to which the management objectives for the stand will be affected. Expected damage to every resource must be measured and projected to the time of harvest. A particular management technique will be beneficial only if its addition to an IPM program is cost-effective and significantly increases the possibilities of attaining the management target. In the end, management decisions are made through the process of forest planning, which allows managers to examine the feasibility of attaining these objectives under various constraints (Simmons *et al.* 1984). The damage caused by weevils and the benefits of alternative control options should enter this iterative process along with other natural resource information, including inventory data, yield tables, effects of silvicultural treatments, data on non-timber forest resources, and financial information.

A Preliminary Integrated Pest Management System for *P. strobi* in B.C.

We believe enough information exists in BC to enable the formulation of a preliminary IPM system for this pest. The system we propose comprises two broad strategies and numerous specific tactics for IPM in existing and in new plantations. A salient feature of this IPM system is the combination of tactics based on silviculture and genetic resistance, with other tactics added as needed, when economically feasible, and when proven to be effective (Table 1). Central to this system is the continuous monitoring of weevil populations and forecasting of weevil impacts on forest productivity through a computerized decision support system (DSS), to evaluate the need for, and possible benefits of, a given tactic.

Choice of tactics for the management of existing susceptible plantations will be based on economic analysis considering value of the crop, present levels of weevil damage, fore-

Table 1. Strategies and tactics for integrated pest management of *Pissodes strobi* in existing and new plantations of Sitka and interior spruce in BC

Strategies	Tactics
• Manage existing plantations of mainly susceptible trees to reduce weevil incidence or impact	• Favor non-host species in spacing and thinning.
	• Interplant with non-host conifer species in young plantations.
	• Interplant with non-host deciduous (shade) trees in young plantations, or conserve shade trees that have regenerated naturally until spruces reach height at which susceptibility diminishes.
	• Delay spacing and thinning to maintain high stand density.
	• Interplant with resistant trees, if available, in young plantations.
	• Monitor weevil populations.
	• Model weevil impacts and effects of control actions.
	• Apply stem injections of insecticide to crop trees.
	• Clip leaders to remove weevils and enhance stem form.
	• Conserve parasitoids in clipped leaders.
• Develop and manage new plantations so as to minimize susceptibility to weevils and to reduce weevil incidence or impact	• Hazard rate sites prior to harvest to guide selection of management tactic.
	• Model weevil impacts and effects of control actions.
	• If ecologically and economically sound, and effective in reducing weevil incidence, implement alternative silvicultural systems, e.g. conventional and group selection, shelterwood.
	• Practice high-density planting.
	• Mix spruce with non-host conifers.
	• Mix spruce with non-host deciduous (shade) trees.
	• Plant resistant stock mixed with susceptible stock.
	• Implement brush control and intensive silvicultural treatments so as to minimize weevil incidence or impact.
	• Monitor weevil populations.
	• Apply stem injections of insecticide to crop trees where necessary.
	• Clip leaders to enhance stem form, remove weevils and conserve parasitoids.
	• Mass-trap weevils with semiochemicals (if/when available).
	• Augment parasitoid populations (if/when possible).

casts of future insect populations and estimates of damage at rotation. If management tactics are, or would be, unsuccessful in maintaining the productivity of a site, the decision support system may recommend abandonment of an existing plantation and its replacement by alternative tree species. The objective of the IPM system is, however, to avoid these situations before they arise by selecting the appropriate path to lead to a profitable crop. The economic value of the various possible combinations of tactics, provided by the DSS system, will assist foresters in their path selection.

Tactics for the protection of new plantations will depend on a preliminary weevil hazard rating, as part of required pre-harvest silviculture prescriptions. In low hazard areas, silviculture-driven tactics such as mixed species planting and increased planting density may be sufficient to produce a successful crop. In high hazard areas, the silvicultural prescription should be resistance-driven, i.e. it should include the use of resistant stock or resistant species. However, we expect that resistance will be most effective if applied in combination with other tactics.

Several levels of resistance could be utilized depending on the deployment strategy. Seed collected from naturally-resistant provenances, e.g., Big Qualicum wild seed collections, should produce stock with an increased level of resistance over that of normal wild seed. This low-level and variable resistance may be adequate in medium hazard sites, particularly in combination with increased plantation density, intensive silviculture (sanitation thinning) and direct control if necessary. Increased levels of resistance will be available from cuttings from hedged, resistant trees, from seed-orchards, from micropropagation of cloned seedlings produced by somatic cell embryogenesis, and, in the future by cloning of genetically engineered genotypes. However, any silvicultural system involving resistant genotypes should take into consideration the need for avoiding the risk of insect evolution leading to biotypes capable of overcoming genetic resistance. To reduce this risk, Ying (1991) noted the desirability of developing resistant varieties which combine several resistance mechanisms, as the risk of overcoming resistance by single gene mutations may be reduced. Hence, the optimal deployment of resistant trees in managed plantations or forest ecosystems should not be simple imitations of historical agricultural systems (Namkoong *et al.* 1988). Rather, as pointed out by Raffa (1989), it should lean towards the creation of "genetic mosaics" involving multi-component resistance mechanisms, a susceptible tree component, and a variety of tactics (Table 1) that will enhance and exploit the use of resistant stock.

Implementing IPM

Critical testing of this IPM system is beginning in British Columbia. An experimental plantation is being initiated in 1994 in which a mixture of resistant and susceptible genotypes are planted at dense spacing. Sanitation thinning and corrective pruning will be implemented when deemed profitable. The crop trees will be injected with insecticide as needed based on close monitoring and output of the SWAT/TASS decision support system. In separate trials, Mr. Ken Day (University of British Columbia Research Forest, Williams Lake, BC) has established spruce plantations under two silvicultural regimes of mixed species planting. To test the various IPM tactics that are available, it is imperative that trial plantations such as these be established under different conditions of weevil pressure and in different ecoregions. New components could be added as new research results became available. These might include the use of semiochemicals and augmentation of natural parasitoid populations (Table 1). Various research topics (Fig. 1) that should be addressed in an intensive research and development program to increase the effectiveness of the system are provided. We contend that systematic investigation of these research questions and application of the results in an integrated, ecosystem-based IPM system will restore Sitka spruce as a species of choice in many sites of coastal BC, and will reduce the mounting risk of weevil damage in interior spruce plantations.

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References

Alfaro, R.I. 1982. Fifty-year-old Sitka spruce plantations with a history of intense weevil attack. J. Entomol. Soc. B.C. 79: 62-65.

Alfaro, R.I. 1992. Forecasting weevil damage. pp. 10–16. *In* Spruce weevil Symposium Proceedings, Terrace, B.C., March 12, 1992. B.C. Ministry of Forests, Prince Rupert Region, Smithers, B.C.

Alfaro, R.I. and J.H. Borden. 1980. Predation by *Lonchaea corticis* Taylor on the white pine weevil, *Pissodes strobi* Peck. Can. Entomol. 112: 1259-1270.

Alfaro, R.I. and S.A.Y. Omule. 1990. The effect of spacing on Sitka spruce weevil damage to Sitka spruce. Can. J. For. Res. 20: 179-184.

Alfaro, R.I. and C.C. Ying. 1990. Levels of Sitka spruce weevil, *Pissodes strobi* (Peck), damage among Sitka spruce provenances and families near Sayward, British Columbia. Can. Entomol. 122: 607-615.

Alfaro, R.I., M. Hulme and C.C. Ying. 1993. Variation in attack by Sitka spruce weevil, *Pissodes strobi* (Peck), within a resistant provenance of Sitka spruce. J. Entomol. Soc. B.C. 90: 24-30.

Bowers, W.S., T. Ohta, J.S. Cleere and P.A. Marsella. 1976. Discovery of insect anti-juvenile hormones in plants. Science 193: 542-547.

British Columbia Ministry of Forests. 1989. Weevils and other pests. *In* Protection Manual. Volume II, Chapter 11. Victoria.

Brookes, M.H., R.W. Stark and R.W. Campbell. 1978. The Douglas-fir Tussock moth: A synthesis. USDA For. Serv. Tech. Bull. 1585. 331 p.

Brooks, J.E. and J.H. Borden. 1992. Development of a resistance index for Sitka spruce against the white pine weevil, *Pissodes strobi*. Canada-British Columbia FRDA Report No. 180. Victoria, B.C.

Connola, D.P. 1961. Portable mistblower spray tests against white pine weevil in New York. J. For. 59: 764-765.

Connola, D.P. 1966. Preliminary studies on resistance in Eastern white pine to the white pine weevil, *Pissodes strobi* (Coleoptera: Curculionidae) in New York. Ann. Ent. Soc. Amer. 59: 1011-1012.

Errico, D. 1990. Estimating the effects of reforestation pests on long-term wood supply. pp. 216–225. *In* Proc. XIX IUFRO World Congress, Book 2. Montreal, Canada, Aug 5-11, 1990.

Fraser, R.G. and D.G. Heppner. 1993. Control of white pine weevil, *Pissodes strobi* on Sitka spruce using implants containing insecticides. For. Chron. 69: 600-603.

Georghiou, G.P. and T. Saito. 1983. Pest resistance to pesticides. Plenum Press, New York.

Gould, F. 1988. Evolutionary biology and genetically engineered crops. BioScience 38: 26-33.

Hulme, M.A. 1989. Laboratory assessment of predation by *Lonchaea corticis* (Diptera: Lonchaeidae) on *Pissodes strobi* (Coleoptera: Curculionidae). Environ. Entomol. 18: 1011-1014.

Hulme, M.A. 1990. Field assessment of predation by *Lonchaea corticis* (Diptera: Lonchaeidae) on *Pissodes strobi* (Coleoptera: Curculionidae) in *Picea sitchensis*. Environ. Entomol. 19: 54-58.

Hulme, M.A., A.F. Dawson and J.W.E. Harris. 1986. Exploiting cold-hardiness to separate *Pissodes strobi* (Peck) (Coleoptera: Curculionidae) from associated insects in leaders of *Picea sitchensis* (Bong.) Carr. Can. Entomol. 118: 1115-1122.

Hulme, M.A., J.W.E. Harris and A.F. Dawson. 1987. Exploiting adult girth to separate *Pissodes strobi* (Peck) (Coleoptera: Curculionidae) from associated insects in leaders of *Picea sitchensis* (Bong.) Carr. Can. Entomol. 119: 751-753.

Kiss, G. and A. Yanchuk. 1991. Preliminary evaluation of genetic variation of weevil resistance in interior spruce in British Columbia. Can. J. For. Res. 21: 230-234.

Lavallée, R. and J. Morissette. 1989. Le contrôle mécanique de Charançon du pin blanc. Forêts Canada. Centre forestiere des Laurentides. Feuillet d'information. Min. des Approvisionnements et Services Canada No. Fo29-4/25-1989F

McLean, J.A. 1989. Effect of red alder overstory on the occurrence of *Pissodes strobi* (Peck) during the establishment of a Sitka spruce plot. pp. 167–176. *In* R.I. Alfaro and S. Glover (eds.), Proc. IUFRO Working Group Meeting on Insects Affecting Reforestation. Vancouver, B.C. Canada. Pacific Forestry Centre, Victoria, B.C.

McMullen, L.H. 1976. Spruce weevil damage. Ecological basis and hazard rating for Vancouver Island. Environ. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-X-141.

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. For. Sci. Monogr. 17.

Mitchell, R.G., K.H. Wright and N.E. Johnson. 1990. Damage by the Sitka spruce weevil (*Pissodes strobi*) and growth patterns for 10 spruce species and hybrids over 26 years in the Pacific Northwest. USDA, For. Serv. Res. Pap. PNW-RP-434.

Namkoong, G., H.C. Kang and J.S. Brouard. 1988. Tree breeding: principles and strategies. Mono. Theor. Appl. Gen. 11. Springer-Verlag, New York.

Pajares, J.A. and A. Guerrero. 1992. Semiochemical mediated attraction in the small banded pine weevil, *Pissodes castaneus* (Col: Curculionidae). Proc. XIX Internat. Congr. Entomol., Beijing, China, 1992.

Phillips, T.W. and G.N. Lanier. 1986. Interspecific activity of semiochemicals among sibling species of *Pissodes* (Coleoptera: Curculionidae). J. Chem. Ecol. 12: 1587-1601.

Plank, G.H. and H.D. Gerhold. 1965. Evaluating host resistance to the white pine weevil (*Pissodes strobi*) (Coleoptera: Curculionidae) using feeding preference tests. Ann. Entomol. Soc. Amer. 58: 527-532.

Raffa, K.F. 1989. Genetic engineering of trees to enhance resistance to insects. BioScience 39: 524-534.

Shepherd, R.S. and I.S. Otvos. 1986. Pest management of the Douglas-fir tussock moth: procedures for insect monitoring, problem evaluation and control actions. Can. For. Serv., Pac. For. Cent. Rep. BC-X-270. 14 p.

Sieben, B.G. and D.L. Spittlehouse. 1991. Effect of climate change on spruce weevil infestation hazard. p. 123. *In* Implications of climate change for Pacific Northwest Forest Management. Dept. Geog. Public Series. Occ. Paper No. 15. Univ. of Waterloo.

Silver, G.T. 1968. Studies on the Sitka spruce weevil, *Pissodes sitchensis*, in British Columbia. Can. Entomol. 100: 93-110.

Simmons, G.A., W. Cuff, B. Montgomery and J.M. Hardman. 1984. Integrated pest management. pp. 11–20. *In* D. Schmitt and J. Searcy (Eds.), Managing the Spruce budworm in Eastern North America. USDA, For. Serv. Agric. Handbook 620: 11-20.

Smith, J.H.G. and J.A. McLean. 1993. Methods are needed to prevent devastation of Sitka spruce plantations by the Sitka spruce weevil *Pissodes strobi* Peck. pp. 81–93. *In* Proc. of the IUFRO International Sitka Spruce Provenance Experiment. Edinburgh, Scotland Sept. 2-7, 1984.

Soles, R.L., H.D. Gerhold and E.H. Palpant. 1969. Testing white pine seedlings for weevil resistance. Proc. 2nd FAO/IUFRO World Consult. For. Tree Breed., Washington. No. FO-FTB-69-5/9. 4 p.

Soles, R.L., H.D. Gerhold and E.H. Palpant. 1970. Resistance of western white pine to white pine weevil. J. For. 68: 766-768.

Stiell, W.M. 1979. Releasing unweevilled white pine to ensure first-log quality of final crop. For. Chron. 55: 142-143.

Sullivan, C.R. 1961. The effect of weather and the physical attributes of white pine leaders on the behaviour and survival of the white pine weevil, *Pissodes strobi* Peck, in mixed stands. Can. Entomol. 93: 721-741.

Taylor, S., R.I. Alfaro and K. Lewis. 1991. Factors affecting the incidence of white pine weevil damage to white spruce in the Prince George Region of British Columbia. J. Entomol. Soc. B.C. 88: 3-7.

Tomlin, E.S. and J.H. Borden. 1993. Relationship between leader morphology and resistance or susceptibility of Sitka spruce to the white pine weevil. Ms. submitted to Can. J. For. Res.

U.S. National Academy of Sciences. 1969. Principles of plant and animal pest control. Volume 3: Insect-pest management and control. National Academy of Science Pub. No. 1695, Washington, D.C.

Wallace, D.R. and C.R. Sullivan. 1985. The white pine weevil, *Pissodes strobi* (Coleoptera: Curculionidae): A review emphasizing behaviour and development in relation to physical factors. Proc. Entomol. Soc. Ont. 16(Suppl.): 39-62.

Wright, J.W. and W.J. Gabriel. 1959. Possibilities of breeding weevil resistant white pine strains. USDA For. Serv. Sta. Pap. Northeast For. Exp. Stn. No. 115, 35 p.

Ying, C.C. 1991. Genetic resistance to the white pine weevil in Sitka spruce. B.C. Ministry of Forests Res. Note No. 106. Victoria, B.C. Canada.