Integrated Management of Bark Beetles: Economic Contributions of Peter Berck and Foundational Entomological Research

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1 Introduction

Bark beetles (Coleoptera: Curculionidae, *Scolytinae*) are a major threat to coniferous forests across much of the northern hemisphere, especially in a warmer and drier climate (Fettig et al., 2013). Control of bark beetle outbreaks to protect forests has been a recurring quest for more than a century, with varying success. In the 1970s and 1980s, considerable efforts were directed toward resolving controversies over the application of persistent pesticides as the principal method to manage outbreaks. Advances in research on pheromones of bark beetles and other behavioral compounds during these decades were incorporated into more ecologically benign approaches to managing stands. What emerged was integrated pest management. "Integrated pest management is a process of synthesis where all aspects of the pest-host system are studied and evaluated to provide the resource manager with an information base for decision-making. These aspects include the ecological and socioeconomic components of the system, its interrelations with other resources, treatment tactics to be used, and their effects on the pest and other components of the ecosystem. Evaluation of the decisions implemented is the end of the process

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and the beginning of a new one, refining the various components of the system to improve the decision support base for future decisions" (Stark & Waters, 1985, pp. 50–52).

Development of integrated pest management (IPM) of pine bark beetles was a subprogram of a large multidisciplinary, multiyear program named "The Principles, Strategies and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems." Funding came primarily from the National Science Foundation (NSF) and Environmental Protection Agency (EPA) but also from the United States Department of Agriculture (USDA), the California Agricultural Experiment Station, and California's IPM program. Participants worked at the University of California at Berkeley, Texas A&M University, the University of Arkansas, the University of Idaho, Virginia Polytechnic University, and the Intermountain Forest and Range Experiment Station and Pacific Southwest Forest and Range Experiment Station of the USDA's Forest Service.

The bark beetle subprogram focused on three insect-host ecosystems: (1) the western pine beetle (WPB), *Dendroctonus brevicomis* LeConte, in California's ponderosa pine forests; (2) the mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins, in lodgepole pine forests of the Northern Rocky Mountains; and (3) the southern pine beetle, *Dendroctonus frontalis* Zimmerman, in loblolly pine forests of the southeastern United States (Waters, 1985). David Wood was the leader of a part of the subprogram, the part that focused on western pine beetles. Peter Berck, his colleague, contributed an economic perspective to the development of integrated management of bark beetles in North American forests.

After joining the faculty in the Department of Agricultural and Resource Economics at the University of California at Berkeley in 1976, Peter began to participate in the NSF-EPA program. Peter contributed to the teaching of the group in integrated pest management (IPM) for forest ecosystems. Members of the IPM group developed a first-ever course in integrated forest pest management for graduate and upper-division undergraduate students. Peter and others who taught the course represented the disciplines most important to forest management: entomology, pathology, dendrology, and economics.

Peter also contributed his expertise in forest economics to the program's research. In one collaboration, he and William Leuschner described impacts of attacks by bark beetles on the uses and ecosystem services of forests (Leuschner & Berck, 1985a). In a related collaboration, Peter and three others simulated an important impact, namely, timber production with and without tree mortality caused by the western pine beetle, and then estimated the net present value of the differences in timber production (Liebhold et al., 1986). In their second collaboration, Peter and William Leuschner used ideas and methods of environmental economics, decision analysis, and finance to describe benefit-cost analyses of treatment of bark beetle attacks (Leuschner & Berck, 1985b).

2 System Structure

In addition to co-authoring the two chapters in *Integrated Pest Management in Pine-Bark Beetle Ecosystems* and the article in *Forest Science* (Liebhold et al., 1986), Peter collaborated with many other colleagues to describe the structural system of forest pest management. Informally called the "Berkeley Box," the model of the system comprises rectangles and circles connected to each other (Fig. 1). Each rectangle or circle represents a sub-model that is a complex system itself (Fig. 1). "The interrelations between the components and the linkages of sub models in the system are indicated by the arrows. The heavier arrows indicate the direction of information flow for planning and decision in the operational system" (Stark & Waters, 1985, pp. 52–53). The model "was developed at the start in order to facilitate the organization of research to be conducted in each of the three subprograms and to provide a common orientation to program goals" (Waters, 1985, p. 5). The book chapters by Leuschner and Berck (1985a, b) and the forest science article by Liebhold et al. (1986) specifically relate to the rectangles "impact on resource values" and "benefit/cost integration."

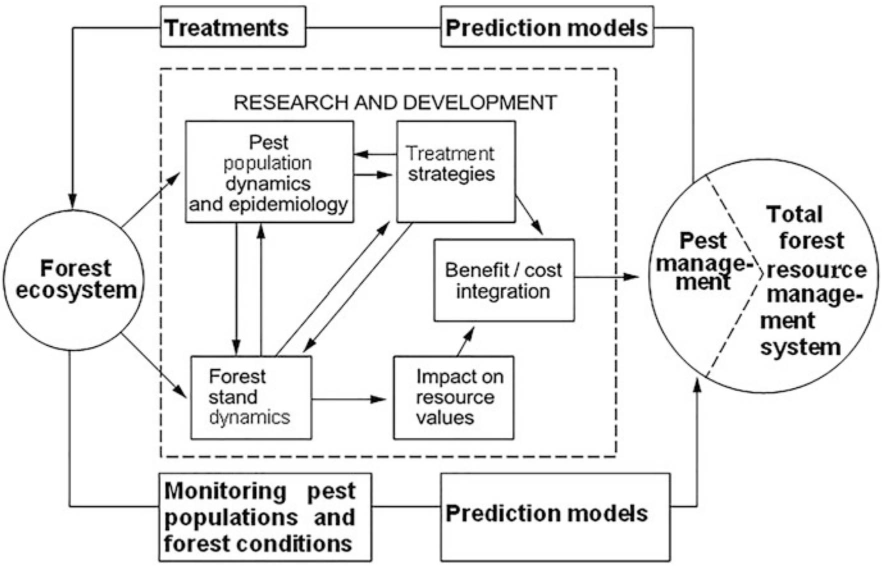

Fig. 1 System structure of forest pest management. (Waters and Cowling (1976) as cited in Stark and Waters (1985, p. 53))

Fig. 2 Western pine beetle infestation in a ponderosa pine stand, with typical spotty distribution of killed trees and different stages of foliage discoloration. (Courtesy of the U.S. Forest Service as published in Waters et al. (1985))

3 Treatment Strategies and Tactics

The foundation of policy-relevant, benefit-cost analyses of treatment of bark beetle attacks is field-tested strategies and tactics. Treatment to control outbreaks of bark beetles has focused on two of the most damaging beetle species in western forests: the western pine beetle and the mountain pine beetle. The western pine beetle is one of the most studied bark beetles, because it causes extensive mortality of ponderosa pines, *Pinus ponderosa*, in southern and central British Columbia, southward to northern Mexico, and eastward to North and South Dakota and Nebraska (Fig. 2). This species also kills Coulter pine, *P. coulteri*, in California. The biology and control of this bark beetle are comprehensively discussed in Miller and Keen (1960), Stark and Dahlsten (1970), Waters et al. (1985), and Wood and Bedard (1976).

The mountain pine beetle is the most widespread and destructive bark beetle in the western United States (Furniss & Carolin, 1977). Its principal hosts are lodgepole pine (*P. contorta*), sugar pine (*P. lambertiana*), western white pine (*P. monticola*), ponderosa pine, Coulter pine, pinyon pine (*P. edulis*), single-leaf pinyon pine (*P. monophyla*), and whitebark pine (*P. albicaulis*). Other hosts include sensitive high-elevation species of concern, such as foxtail pine (*P. balfouriana*), bristlecone pine (*P. longaeva*), and limber pine (*P. flexilis*), which are at increased risks of mountain pine beetle attack due to the impacts of global warming and an introduced tree-killing fungus (white pine blister rust).

3.1 Stand Treatments: Thinning

Thinning of stands, an "indirect treatment," has been shown to be the most durable treatment to reduce stand susceptibility to bark beetle attacks, but it is challenging in terms of cost, logistics, and public acceptance (Wood et al., 1985; Gillette et al., 2014b). Therefore, much research has emphasized "direct treatments" that reduce beetle populations either by lethal means or by repelling them from stands. "Treatments aimed at reducing the damage caused by bark beetles through stand manipulations have been subject to extensive investigation and controversy for many years . . . The capacity to schedule and conduct treatments in stands prior to infestation by bark beetles not only permits the manager to reduce the chances of bark beetle-caused loss, but to recover trees before deterioration by microorganisms and wood borers, and to protect adjacent stands from infestation by beetles breeding in high hazard stands . . . many studies have indicated that bark beetle infestations are correlated with high stand density... Thinning has been viewed as a means of increasing the resistance (vigor) of the residual stand to infestation by insects and pathogens . . . Lowering stand density through thinning is one of the few silvicultural techniques available to resource managers to lower the hazard to bark beetle infestations . . . " We selected two studies out of many that illustrate the value of thinning. "In eastern Oregon, Sartwell and Stevens (1975) and Sartwell and Dolf Jr. (1976) show greatly reduced incidence of MPB-caused mortality in thinned plots of ponderosa pine compared to untreated plots . . . " (Wood et al., in Waters et al., 1985, pp. 123–124).

3.2 Pest Population Treatments

The two principal treatments aimed at mitigating damage by reducing pest populations (rather than stand health and resilience) are insecticides and semiochemicals. Miller and Keen (1960) observed in their summary of early research on the western pine beetle that "Direct control measures aimed at killing beetle populations have been quite fully explored and applied over vast areas for many years . . . However, all results from applied control indicate that the killing of beetles, no matter by what method, has only a limited effect in reducing tree mortality . . . ".

3.2.1 Insecticides

Koerber (1976) summarizes the literature describing the effectiveness and controversies arising from the use of lindane (and other toxic compounds) to reduce tree mortality. More recently, a number of less persistent insecticides have shown efficacy for tree protection, but their use remains limited because of concerns

Table 1 Explanation of the bark beetle emergence/attack numbering system

Generation number/code	Year of attack	Year of emergence
1969 (3) 69(3)	Fall 1969	Spring 1970
1970 (1) 70 (1)	Spring 1970	Early summer 1970
1970 (2) 70 (2)	Early summer 1970	Fall 1970
1970 (3) 70 (3)	Fall 1970	Spring 1971
1971 (1) 71 (1)	Spring 1971	Early summer 1971

about nontarget effects, environmental contamination, and human health concerns (Gillette et al., 2014b).

3.2.2 Semiochemicals

The two primary semiochemical approaches to mitigating bark beetle damage are mass trapping, using aggregation pheromones, and repellency, using anti-aggregation pheromones to repel beetles from forest stands.

3.2.2.1 Mass Trapping with Aggregation Pheromones: The Bass Lake Study

Discovery of the pheromone of the female western pine beetle enabled mass trapping of bark beetles as a possible tactic to reduce tree mortality (Silverstein et al., 1968). The identification of the blend of compounds called EFM (*exo*-brevicomin, frontalin, myrcene) as the most attractive aggregation pheromone blend for *D. brevicomis* is discussed in Bedard and Wood (1974, p. 443) and in references cited therein.

The following discussion concerns a large mass-trapping study near Bass Lake (Madera County), California.

> Sequential aerial photography was used to detect ponderosa pine trees killed by successive generations of the western pine beetle (WPB), *Dendroctonus brevicomis* Lec., over a three-year period [1970–1972] during a study to evaluate the effectiveness of attractive pheromones for the suppression and survey of WPB . . . Infested trees at the beginning of the suppression treatment, including both treated and untreated stands, totaled 283. Attacks by three successive WPB generations in 1970 killed 90, 83, and 91 trees, respectively. [See Table 1 for an explanation of the numbering system]. The first generation in 1971 killed 47 trees and the two subsequent generations combined killed a total of 49 trees. During the suppression treatment, the tree mortality was concentrated into the suppression plots in comparison to the check plots and the surrounding area. (DeMars et al., 1980, p. 883)

By 1972, tree mortality distribution in both treated and untreated stands returned to its original pattern, but at one-tenth the original level as shown by maps (DeMars et al., 1980).

> In the Bass Lake experiment traps were deployed in two configurations over 65 Km^2 in 1970 (Bedard & Wood, 1974). About 600,000 western pine beetles were trapped during

> the suppression period. The mortality attributed to western pine beetle in the generation preceding treatment was 283 +/– 46 trees (DeMars et al., 1980). Following treatment, WPB was found infesting 90 +/– 16 dead trees. Ponderosa pine mortality decreased to about 30 trees by late 1971, and tree mortality remained low for the next 4 years over the entire experimental area. (Wood et al., 1985, p. 130)

> Tree size and bark surface area infested in trees killed by the western pine beetle (WPB), *Dendroctonus brevicomis* Leconte, and the density of attacking and emerging WPB were measured on 91 trees spanning five consecutive generations of the insect. The emergence densities of six natural enemies were also estimated. Heights to top of infestation (HTI) averaged 16.0 m, but were significantly lower in trees attacked by the second [70(1)] and third [70(2)] generations, during synthetic pheromone elution, than in the first [69(3)], or fourth [70(3)], and fifth [71(1)] generations *before* and *after* the treatments, respectively. (DeMars Jr et al., 1986)

> WPB attack density declined steadily from 4.36 beetles/dm^2 in generation 69(3) to 0.86 beetles/dm^2 in 71(1) . . . Densities of attacking and emerging WPB were found to be uncorrelated with tree diameter, indicating that density was not a function of tree size and that these two variables may be treated as independent random variables when used in product models to estimate area-wide population totals . . . Sampling errors for natural enemies were quite large, ranging up to 400%, therefore few conclusions could be drawn . . . WPB productivity increased with decreasing density/square decimeter of attacking beetles . . . The WPB population at Bass Lake would be released from endemic to epidemic status at the equilibrium point reached at a density of attacking adults of $\log_e$ 1.65 beetles/dm^2. (DeMars Jr et al., 1986, pp. 881–882)

There have been two other large-scale efforts to suppress bark beetle outbreaks, in Scandinavia and McCloud Flats (Siskiyou County), California. In response to a large outbreak of *Ips typographus* in Norway spruce (*Picea abies*) forests in Norway and Sweden in the late 1970s, both governments set out 930,000 pheromone-baited traps to reduce the beetle populations, with the goal of reducing tree mortality (Lie & Bakke, 1981). An estimated 4.5 billion beetles were caught, with large reported reductions in trees killed. Suppression of the western pine beetle by mass-trapping in ponderosa pine forests in the Mt. Shasta area was implemented in 1970–1973 (Lindahl Jr., 1989). In this study, synthetic pheromones were used in an attempt to draw beetles into suppression plots, although there was no detected effect on tree mortality within these suppression zones. Several statistical estimators of tree mortality exhibited relatively high levels of variability. Numbers of attacking and emerging beetles were estimated from individual trees; emergences were better predictors than attacks (Lindahl Jr., 1989). Both of these operations, as well as the Bass Lake effort, lacked the replication that is considered to be essential for scientific studies.

3.2.2.2 Anti-aggregation Pheromones

The use of pheromones and other behavioral chemicals as anti-attractants is an effective tactic for several bark beetle species (Seybold et al., 2018). Most bark beetles have been shown to utilize a strong aggregation pheromone to overcome host resistance to attack by attracting many thousands of beetles to synchronously

Table 2 Reduction in bark beetle attack rates following treatment with anti-aggregation pheromones verbenone and MCH

Location	Pheromone	Host tree[a]	Beetle[b]	Percentage attack reduction
Idaho, USA	Verbenone	LPP	MPB	62.5
California, USA	Verbenone	LPP	MPB	65.2
Wyoming, USA	Verbenone	WBP	MPB	38.1
Washington, USA	Verbenone	WBP	MPB	76.1
California, USA	Verbenone	LPP	MPB	65.5
Washington, USA	Verbenone	WBP	MPB	74.0
Colorado, USA	Verbenone	LPP	MPB	86.6
Montana, USA	Verbenone	LPP + WBP	MPB	89.0
Washington, USA	MCH	DF	DFB	95.2
Chihuahua, Mex.	MCH	DF	DFB	100.0

Redrawn from Gillette and Fettig (2021)
[a]*LPP* lodgepole pine, *WBP* whitebark pine, and *DF* Douglas-fir
[b]*MPB* mountain pine beetle and *DFB* Douglas-fir beetle

attack single trees so that they cannot "pitch out" the beetles with their resin exudates. Verbenone, an anti-aggregation pheromone produced by a number of North American pine bark beetle species, interrupts the response of beetles to their aggregation pheromones (Seybold et al., 2018). Aerially applied and ground-applied verbenone in a slow-release formulation reduces the attack rate of mountain pine beetles by 38–89%, as reported in a series of studies targeting mountain pine beetles in lodgepole pine, whitebark pine, and limber pine (Table 2) (Gillette et al. 2009, 2012a, b, 2014a, summarized in Gillette & Fettig, 2021). MCH, the principal anti-aggregation pheromone for the Douglas-fir beetle, is even more effective. The efficacy of the treatment depends on application rate and timing, tree stress, the tree and bark beetle species treated, and background beetle population size. For example, verbenone treatments targeting either western pine beetle or mountain pine beetle in ponderosa pine have not been proved consistently effective (Negron et al., 2006; Seybold et al., 2018), while significant protection is provided for all other pine species tested. In general, verbenone has been shown to be most effective for low to moderate bark beetle populations (Table 2) (Gillette & Fettig, 2021). More research is needed to assess the efficacy of verbenone treatments using larger treatment areas, higher application rates, and synergistic adjuvants (Gillette & Fettig, 2021).

4 Synthesis and Future Research

The time and location of strategies to manage bark beetle outbreaks and the extent to which the strategies are effective impact people's uses of the treated forests and the ecosystem services they provide (e.g., Leuschner & Berck, 1985a). These strategies are designed to mitigate or prevent damages from such outbreaks. Damages include reductions in people's uses of forests, such as timber production and recreation, and impairment of ecosystem services, such as water yield and erosion control. In turn, changes in monetary values of timber production and in people's willingness to pay for recreation and ecosystem services from treated forests are likely to occur and can be estimated (e.g., Leuschner & Berck, 1985a, b). Changes in values were indeed estimated in a few instances 35–40 years ago (e.g., Liebhold et al., 1986; Michalson, 1975).

Since the publication of Waters et al. (1985), however, methods that can be used to estimate monetary damages from insect pests in forests have been refined (e.g., Freeman III et al., 2014; Johnston et al., 2017, 2021) and actually used in at least 16 studies (Cohen et al., 2016; Rosenberger et al., 2012, 2013). For example, a refinement in Hotelling, Clawson, and Knetsch's travel-cost model (Clawson & Knetsch, 1966) has been used to estimate people's willingness to pay for recreation at multiple sites in Rocky Mountain forests with tree densities that vary for reasons that include beetle infestations (Walsh et al., 1989). Contingent valuation (e.g., Mitchell & Carson, 1989), a method that was rarely used to value non-timber amenities of forests during the time of the IPM project, has subsequently been used to estimate people's willingness to pay for protection of spruce-fir forests (Kramer et al., 2003). Hedonic models of house prices have been used with refinements to estimate how much home owners value changes in the health of trees that are affected by insect attacks on or near their residential properties (e.g., Cohen et al., 2016; Holmes et al., 2006). Benefits transfer, the use of previous estimates of willingness to pay for similar amenities, has been used to estimate recreational damages resulting from infestations of mountain pine beetle in Rocky Mountain National Park (Rosenberger et al., 2013). These advances in methods to estimate monetary values of damages of bark beetle outbreaks can also be used to estimate benefits of reductions in the damages, that is, benefits of bark beetle treatments. Moreover, "cost estimates [of treatments] are, in most cases, somewhat easier to make than benefit estimates" (Leuschner & Berck, 1985b, p. 185).

Benefit-cost analyses of direct treatments of pest populations do not, however, represent the breadth of information that economists and other social scientists can provide for integrated management of forest insect pests. Management of insect pests in forests is a component of management of forest resources (Fig. 1). Ownership of forests critically affects timber harvests and other aspects of management (e.g., Berck, 1979; Bohn & Deacon, 2000; Fretwell & Regan, 2015; Siry et al., 2010). Given that ownership affects management of forests, does ownership specifically affect bark beetle outbreaks? In particular, are outbreaks less likely to occur on privately owned and managed forests than on publicly owned and managed forests that usually are less frequently thinned, logged, and prescriptively burned? Do bark beetle outbreaks last longer or spread more widely on publicly owned and managed forests than on privately owned and managed forests? Rigorous empirical answers to these questions could help policy makers decide whether changes in regulations would improve integrated management of bark beetles and which mix of strategies and tactics would be most beneficial to society, given their limited budgets for treatment of bark beetles.

In spite of advances in geospatial and statistical methods that improve the design and implementation of large-scale field studies, forest entomologists will rarely, if ever, have sufficient funding for randomized, controlled, and replicated experiments to evaluate strategies and tactics to manage bark beetles. For similar reasons, economists will rarely, if ever, be able to present forest managers with exhaustive analyses of the impacts and benefit-cost evaluations of the possible indirect and direct treatments for integrated management of bark beetles. What, then, should scientists who can provide only limited information to forest managers do? The now 35–year-old book, to which Peter co-contributed two chapters, has this insightful advice:

> The preceding impact analyses only partially cover all possible impacts. Also, some were made in only a few geographic areas and then extrapolated to entire regions. Extrapolation to wider regions, or lack of study replications, is not desirable. Most of the authors recognized this shortcoming. However, we are faced with the choice of either presenting available evidence, regardless of its adequacy, or presenting no evidence and having decisions made anyway. We choose to present the available evidence with the caution that it is limited and may not apply to all the diverse cases that can exist within the wide geographical ranges covered by bark beetles and their forest host types. (Leuschner & Berck, 1985a, p. 120)

The advice – provide the best available evidence with caveats – still makes sense today.

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