

Adaptive Management Experiments in Vertebrate Pest Control in New Zealand and Australia

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Abstract

Government conservation agencies in New Zealand and the Australian state of Victoria spend 20% and 4%, respectively, of their annual budgets to manage a small part of the problem caused by introduced mammals. Managers' uncertainty about the optimal strategies for applying pest control has led to major differences in management practices within the single pest control programs in both countries. Monitoring under a trial-and-error approach has not removed uncertainty but has led managers to support the application of adaptive management for their pest control. Control of brushtail possums (*Trichosurus vulpecula*) in New Zealand and red foxes (*Vulpes vulpes*) in Victoria, Australia, is conducted over large areas in many operations, but individual managers apply different control regimes based on the perceived benefits and opportunity costs. We report on the processes used to set up the first adaptive management experiments in pest control in New Zealand or Australia that combine the competing models approach (used when only a single management regime can be applied at one time) with an experimental approach (made possible when different management regimes are applied simultaneously in different places) with the aim of elucidating benefits and costs of the different strategies used to control the 2 pests. (WILDLIFE SOCIETY BULLETIN 34(1):229–236; 2006)

Key words

adaptive management, Australia, brushtail possums, red fox, New Zealand, pest control, *Trichosurus vulpecula*, *Vulpes vulpes*.

The optimal way to manage complex biological systems is almost always unclear because of uncertainties imposed by largely unmanageable extrinsic or environmental factors, lack of complete knowledge about how the system actually functions, and intrinsic errors in any monitoring used to assess the outcomes of management. Walters (1997) defined the purpose of adaptive management as the systematic acquisition and application of reliable information on which to make management decisions in the face of these uncertainties.

The original concepts of adaptive management as proposed by Holling (1978) and developed during the 1980s and 1990s (Walters and Holling 1990) focused on harvesting regimes for fisheries (Hilborn and Walters 1992) and game birds (Williams et al. 1996, Johnson et al. 2002), and the difficulties in sustaining them when the size of the sustainable harvest was uncertain or disputed. More recently, the process has been suggested for threatened species management (Smallwood et al. 1999), insect pest and weed management (Shea et al. 2002), habitat conservation (Wilhere 2002), wildlife management (Rutledge and Lepczyk 2002), and ecosystem management (Carpenter et al. 1998).

Most of these management systems involved a single management system (e.g., national set of harvesting regulations, a legal requirement to protect a threatened species, or a single river system) and debate on the best ways to change the management system to achieve some goal. Adaptive management in these cases has used modelling to predict outcomes if different feasible management options were applied. Monitoring data were then used to compare the ability of alternative models to mimic the dynamics of the system using model selection tools and decision theory tools (Ellison 2004, Johnson and Omland 2004).

However, other biological systems are managed in different ways

at different places, and that allows adaptive management to use experimental design (i.e., replication, randomization of treatments, and nontreatments; Sit and Taylor 1998). Competing management regimes for similar problems are almost inevitable when any large institution undertakes the management of many large, complex systems with imperfect knowledge or different or unclear goals. Use of management differences as experimental treatments is attractive in ecological systems particularly where uncertainty arising from ecological processes and disturbances can only be sensibly investigated at field management scales (Walters and Green 1997, Rempel et al. 1997, Wigley and Roberts 1997).

The logic required to set up such an adaptive management experiment is similar to any experiment. There has to be uncertainty about how the system works and some ideas or hypotheses about how it might work. The best way forward is to couple sensible modelling with experiments that have good statistical power (Walters 1993). In such an adaptive management experiment, these uncertainties are expressed in different management regimes (i.e., treatments) spatially as replicates where multiple management units are available. Within this framework, the reasons for the different management regimes (i.e., hypotheses) need to be formalized in conceptual or quantitative models. Managers tend to have qualitative models about why they act differently, and scientists tend to have more quantitative models that purport to predict the outcomes of different management treatments. The effects of these management differences are then monitored and, provided the right questions were asked and decision-makers were paying attention, better management decisions (or at least more transparent ones) should result. Adaptive management also recognizes that the results of an experiment are unlikely to remove all uncertainty. In fact, an adaptive management process may well increase management

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uncertainty in the short term, and so further iterations of the process may be needed to reduce uncertainty (Walters 1986).

The objective of our studies was to use differences in management of 2 introduced vertebrate pest species (brushtail possums [*Trichosurus vulpecula*] in New Zealand and red foxes [*Vulpes vulpes*] in Victoria, Australia) as treatments in an adaptive management experiment aimed at elucidating the benefits and costs of applying control at different frequencies and intensities.

Vertebrate Pest Control in New Zealand and Victoria

Thirty percent of New Zealand and 16% of Victoria, Australia, are reserved primarily for conservation of indigenous biodiversity. In these areas direct threats to biodiversity from extractive land use are absent or limited by legislation, but the indirect threats from exotic pests and weeds remain a significant problem (Anonymous 1997, Department of Conservation 2000).

New Zealand and Victoria have 31 and 14 species, respectively, of introduced mammals with wild or feral populations (King 1990, Menkhorst 1995). A substantial part of the business of government conservation agencies in both states consists of deciding which exotic species will be managed as pests, where, when, and how to control them, and how often, how much to spend doing it,

who should do it, and who should pay. The New Zealand Department of Conservation and Parks Victoria spend about \$20 million (20%) and \$5 million (4%), respectively, of their annual budgets controlling mammalian pests, and both invest substantial sums each year (\$6 million in New Zealand and \$2 million in Victoria) on research into ways to manage pests more effectively (Anonymous 1997, Parkes and Murphy 2003). (All \$ quoted have been calculated as US dollars.)

Styles of Management for Pest Control

Current pest management programs in New Zealand and Australia are large-scale and usually need to be sustained in perpetuity because the pest populations cannot be eradicated. These programs involve high levels of uncertainty about the best tactics and strategies to use to control pests, the outcomes these actions achieve, and so the ability of institutions to sustain funding or persist with their current priorities and actually sustain individual operations. We identify 5 management styles (i.e., deferred action, risk-aversion, dogmatism, trial and error, and adaptive management) used in pest control in the 2 countries.

Deferring action until uncertainties are resolved is not an option favoured by pest managers, who usually believe that the effects of exotic biota on indigenous ecosystems are actually or potentially adverse and action is urgent. There are exceptions to this in New Zealand and Australia where the exotic animal is seen as both a pest and a resource. For example, conflicts over the status and appropriate management of deer introduced to New Zealand (*Cervus elaphus scoticus*, *C. e. nelson*, *C. unicolor*, *C. timorensis*, *Dama dama* and *Odocoileus virginianus*) and Australia (*C. elaphus scoticus*, *C. unicolor*, *C. timorensis*, *Dama dama*, *Axis axis* and *A. porcinus*) have resulted in suboptimal management regimes for groups who see the animals as pests and for those who see them as game or a commercial resource (Nugent et al. 2002a, Moriarty 2004). In New Zealand many decisions on deer management have been deferred despite successful templates for other species such as Himalayan thar (*Hemitragus jemlabicus*) (Department of Conservation 1993, Forsyth and Tustin 2002). In Australia deer are not managed as pests at all because of uncertainty about their impacts on native ecosystems (Moriarty 2004).

However, managers usually do manage the pest or threat in the face of uncertainty. Some take either a risk-averse approach or a dogmatic approach. The risk-averse approach in pest control “overharvests” the pest to minimize any possible impacts. Such an approach might be desirable in cases of high uncertainty (e.g., where the critical pest species or threat is unclear and all candidate threats are, therefore, managed) and high risk (e.g., as with the protection of some endangered species), (Innes et al. 1999), but has opportunity costs when budgets are limited (Choquenot and Parkes 2001). The dogmatic approach deliberately avoids any analysis of uncertainty or risk in case fixed policy positions are disturbed. It is usually driven by a “winner-take-all” fight between antagonistic stakeholders (Hughes 2000). Monitoring outcomes of management on the pest or resource is not a common feature under such management styles.

However, most managers do monitor outcomes and the subsequent “trial-and-error” or “learn-by-doing” is the dominant management process in pest control in New Zealand and Australia



Brushtail possum with juvenile offspring.



Red fox with bandicoot.

(Saunders and Norton 2001). Managers typically are prompted by some event (e.g., a new manager, a desire to be more efficient, imposition of some constraint or largesse from the government, plain curiosity, or occasionally by the results of research) to change the way they do things and see what happens. If managers like what happens, the new regime becomes best practice and they may even convince others to follow suit if they can demonstrate the benefits in a suitably powerful way. However, often the effect of the modified practice is not clear, not clearly linked to the changed management, or not clearly better than other options. While this form of management is better than management whose benefits are never monitored, it is inefficient and often ineffective in complex and uncertain systems such as pest management where intrinsic pest–resource–management dynamics and acute or chronic extrinsic events might or might not have predictable effects on the pest population, the resources it affects, or both (Caughley 1987, Coomes et al. 2003).

The solution, in our opinion, to improving efficiency and effectiveness in management with high risks and uncertainties is to develop more formal adaptive management experiments, which is what we have attempted for possum and fox control. We think government agencies have a predisposition toward adaptive management because of their successes with trial and error management (Anonymous 1997, Department of Conservation 2000).

Designing Current Possum and Fox Control as Adaptive Management Experiments

Current Management

Possums were introduced to New Zealand from Australia in 1858 to establish a fur industry and are now ubiquitous throughout the 3 main islands of New Zealand. Possums are herbivores and predators of native biota and are the main wildlife vector of bovine tuberculosis (Cowan 2001). The New Zealand Department of Conservation spends \$8 million each year on possum control in over 200 separate areas totalling 1 million ha, about 10% of the land under its tenure (Parkes and Murphy 2003). Managers have many control tools but most control is by aerial sowing of cereal-based baits containing compound 1080 or by ground-based poisoning with cyanide baits or with traps (Morgan and Hickling 2000). The general control strategy is to kill a high percent (typically >80%) of the possum population in an initial operation, usually using aerial baiting, followed by some maintenance control strategy at variable frequencies and intensities to maintain low possum densities. The maximum rate of increase (r_m) of possums is 0.3 (Barlow 1991) so populations take several years to recover from typical control events (Veltman and Pinder 2001). Frequent applications of maintenance control (a “press” strategy) generally use ground-based methods, while infrequent applications (a “pulse” strategy) generally use repeated aerial baiting (Parkes et al. 1997). Press strategies are designed mostly to protect threatened species, while pulse strategies are designed mostly to protect habitat infrastructure (e.g., forest canopy condition).

Foxes were introduced to Australia from England in the 1870s for sport hunting and to control rabbits (*Oryctolagus cuniculus*) and are now ubiquitous in Victoria and inhabit over 75% of the rest of

mainland Australia (Saunders et al. 1995). Foxes have contributed to the extinction and continuing decline of many small native marsupials and birds (Kinnear et al. 2002) and are predators of domestic lambs (Saunders et al. 1995).

Parks Victoria spends \$0.4 million/year controlling foxes in 70 separate operations over 64% of the land in conservation tenures (Anonymous 1998). Managers have only a single control tool: meat-based baits containing compound 1080 that are buried to reduce nontarget by-kills (Saunders et al. 1995). Fox control is designed to protect threatened species that are usually secondary prey of foxes, introduced rabbits being the primary prey (Pech et al. 1995). Because of this trophic position of the native prey and because r_m for foxes is 1.0 (King and Wheeler 1985), press strategies with frequent control are the norm but, with only one tool available, the policy issues relate to effectiveness and efficiency, rather than these plus the frequency of control as with possums. Can baiting be applied more cheaply for the same benefit and, thus, cover more areas for a fixed budget? The focus of the adaptive management project is, therefore, to measure benefits (in terms of native prey species viability) of fox control, to identify target densities for foxes and how to maintain these most efficiently.

Identifying the Management Differences Within Possum and Fox Control Operations

The issues and problems associated with possum and fox control worth addressing were identified by the managers at a series of workshops, 2 in 1999 for the possum project and 3 in 2001 for the fox project. At these workshops, a decision-tree method (Bosch et al. 1996) was used to clarify where managers differed in their possum or fox control and why they did so (i.e., they identified the key treatments for the experiment and constructed conceptual models of how they thought the pest-resource-management systems worked).

The key difference between possum control operations was the rationale or trigger used to determine the frequency of maintenance control. Some managers applied control at a set frequency, others based on possum densities, and others based on the condition or numbers of the native species being affected by the possums. These decisions led to control being applied from almost continuous up to 7-year intervals. The key differences between fox control operations were in the timing of bait application (i.e., seasonal or continuous) and in the density and layout of baits. Managers’ decisions on timing throughout the year were driven by the perceived seasonality of fox impacts on prey such as nesting birds or on constraints on management such as funding or access to the areas. Their decisions on how much bait to lay and where to lay it appeared to depend on a variety of local factors (e.g., habitat complexity, ease of access, surrounding land-use and the type of bait used). These management differences for both pests result in different costs/ha/year and are predicted to result in different average pest densities and different conservation outcomes. These costs and benefits are the response variables within the adaptive management experiments.

Treatments and Experimental Design

For possums, we selected 7 “treatments” each with 2 replicates based on the 3 types of trigger for maintenance control (J. P.

Parkes and D. Forsyth, Landcare Research, Lincoln, New Zealand, unpublished report). Six sites had maintenance control applied at set frequencies of 2, 4, or 7 years. Four sites had maintenance control applied when possum density indices reached certain levels as they recovered after each control event was the trigger. We selected low (10% trapcatch) and high (25% trapcatch) indices of density as these triggers. The trapcatch index is a standard method using leg-hold traps used to index possum densities in New Zealand (Meenken 2004), measured as the number of possums caught/100 trap-nights. This trigger was expected to result in control every 2 or 3 years for the lower index and 4 or 5 years for the higher index. Four sites had maintenance control applied according to some measure of the condition of the native biota affected by the possums. The standard method to assess this relies on the amount of possum browse or foliage density measured in the canopies of palatable tree species (Payton et al. 1999). We set a sensitive (or susceptible) and a robust (or less susceptible) measure, based on average foliage conditions of 2 common, palatable tree species: kamahi (*Weinmannia racemosa*) and mahoe (*Melicactus ramiflorus*). Both were present across all study sites, which we would expect to trigger control more or less frequently. The method is new and largely untested in this context (Nugent et al. 2002b), so we also covered (to some extent) our uncertainty about how the method would perform as an indicator by testing some alternative triggers based on the proportion of fallen leaves of kamahi and mahoe with signs of possum browse (Numata 1998). Measures of conservation benefits at each site also used the foliage condition index method on kamahi, mahoe and other palatable canopy species. We selected 14 study sites between 2,000 and 17,500 ha in North Island podocarp-hardwood forest types, and 1 of the 7 treatments was allocated to each. Three areas of forest without possum control were available as experimental controls.

We selected 3 bait densities and 3 timing strategies that, in all combinations, would allow comparisons of the costs and effectiveness of the range of management differences used in Victoria for foxes. We chose high (>0.6 baits/km²), medium (>0.2 but <0.6 baits/km²), and low (<0.2 baits/km²) bait densities, and applied baits continuously throughout the year, only during set seasons, or in pulses with breaks of several weeks throughout the year. Parks Victoria selected 6 national parks of 10,000 and 170,000 ha to apply the 13 control combinations. We established nontreatment sites for all high-density-continuous, low-density-continuous, and medium- and low-density-seasonal treatments, but there were no nontreatment areas for the pulsed bait density treatment. We used the abundance of selected native prey species at each site as the measure of benefit for each treatment. We based the selection of these species on a Multi-Criteria Decision Model that ranked species according to their potential risk to predation throughout the state (A. Robley and D. Choquenot, Arthur Rylah Institute, Victoria, Australia, unpublished report). While no common suite of prey species was available at all sites, those selected were classified under the policy definition for the control of foxes (Anonymous 1998) or were relatively common but restricted to refuge habitat and should respond to a reduction in predation pressure in 5–7 years.

Capturing the Issues in Models

We developed 2 models in the possum project: a nonspatial model designed to predict changes in possum densities after given levels of control and changes in the condition of the forest canopy as possum densities changed (Choquenot and Parkes 2000). We simulated possum population dynamics in an age-structured possum population (Brockie et al. 1981) growing logistically to carrying capacity through density-dependent changes in the proportion of females breeding and adult survival and density-independent survival of the young after emergence from the pouch (Barlow 1991). We modeled the impact of possums on canopy condition to predict changes in the condition of palatable tree species, measured as a foliage-cover index (Payton et al. 1999), where the predicted average canopy condition was treated as a function of its current condition and possum densities. The effect on possum densities of different control frequencies using 2 different standard control techniques whose costs were known was included in the simulations. We modelled the costs and effectiveness of 2 basic control methods, ground control and aerial poisoning using 1080 baits using data extracted from the literature (Warburton 2000). We also included the effect of different degrees of induced bait shyness (Morgan and Hickling 2000) that accumulated in the population dependent on the frequency of use of aerial poisoning with 1080 baits.

The second model was a spatial version of the Choquenot and Parkes (2000) model developed for each study site. We divided each site into 100-ha cells and possum densities were estimated by extrapolation (altitude alone explained much of the variation in possum density) from the monitored trapcatch indices before and after the initial control, respectively. We measured foliage cover indices before and usually annually after control. The predicted possum densities and canopy conditions in each cell were then taken from the Choquenot and Parkes (2000) model, the former with some simple density-dependent rules for immigration and emigration. These predictions will be compared with the actual results of ongoing monitoring as the treatments are repeated within a Geographic Information System (GIS) framework that managers can use as a decision support tool.

Spatially explicit models of pest animal control are useful for a wide range of reasons. In the possum project, the spatially explicit models were developed as stand-alone computer programs. This approach has 2 important limitations. First, the complexity of programming required means that these models tend not to be maintained or updated once the original programmer departs. Secondly, because these models tend to be highly specific in the way in which they pick up underlying geographic information (e.g., habitats, topography, tenure boundaries), they are difficult to generalize to other locations, situations, or pest species. To overcome these limitations, we have developed, for the fox project, a general process for implementing spatially explicit models of pest animal control through a GIS.

The fox project has built one spatially explicit predator-prey population model where the foxes are subjected to the reductions achieved by the different control regimes. Following this the models will be extended to include the response of selected fox prey species to various levels of control regimes. To predict changes in animal density across an area, it is divided up into 500-

ha cells. The model predicts changes in the density of the animal population within each of these cells by estimating the level of intrinsic recruitment into and emigration out of each cell, and the degree of immigration from other cells over time.

Measures of Costs and Benefits

Ultimately, the project will compare the net benefits of the different treatments with different funding rules, where the net benefits are the condition of the resources multiplied by the area treated. The policy issue for all pest control is simple but profound. For a limited national budget, a national policy manager can allow local managers to optimize the benefits at selected sites by applying intensive control frequently, a “press” strategy, and, perhaps, treat more of the pest species present. At the other extreme, managers could spread the control over more sites but treat each less intensively, or less often, and perhaps treat fewer of the pest species present. Third, the manager could design some mixture of the above extremes that might be better than either alone.

Applying intensive control frequently optimizes local benefits and in New Zealand is called the mainland island strategy (Saunders and Norton 2001). This approach sacrifices all values affected by pests at all untreated sites. Applying control infrequently allows managers to act at more sites but is likely to sacrifice some of the values susceptible to the pests even at the treated sites. The third strategy is probably the best (Parkes 1996). How to get the best national balance of sites and management levels is currently unresolved, but we think a wider adaptive management experiment using bioeconomic models would be the best way to obtain the answer.

The costs and benefits of the possum and fox campaigns can be modelled at any spatial scale using benefit-maximization or cost-minimization bioeconomic methods (Choquenot and Parkes 2000). Benefit-maximization identifies the control strategy that gives the best conservation result for a set budget, while cost-minimization identifies the cheapest way to achieve a desired conservation outcome. A true cost-benefit analysis was not considered because we had no sensible means of accruing the conservation benefits in the same currency as the control and monitoring costs.

For example, under a benefit-maximization approach with a set annual budget of \$6 million, the optimal control strategy to treat all 1.7 million ha of conservation land listed in the New Zealand national possum control plan depends on the frequency of control, the standard of protection desired, and the costs of and constraints on the control methods. If all the maintenance control is done by ground control (at \$10/ha for a 70% kill of possums) frequently enough to avoid canopy collapse (not a very ambitious goal), the predicted optimal net benefit is at a frequency of control every 2.8 years. In contrast, the optimal frequency using just aerial poisoning with 1080 under the above conditions depends very much on the extent of bait shyness induced by the technique. Detailed analyses of different bioeconomic predictions from the models are given in Choquenot and Parkes (2000).

Weaknesses in Our Approach

We were constrained in achieving the optimal experimental design in both projects because we could not allocate treatments at

random as most of the pest control operations were already under way. This weakens the inferences we can draw from the experiment but helps to sustain managers’ interest as propinquity between what they were doing and what we wanted them to do has reinforced their interest in the contest of ideas. In addition, limited project funding meant that only a subset of all operations (7% of possum operations but most of the large-scale ones for the fox project) could be included. To some extent this limitation reflects the fact that the impetus for both projects came from research agencies rather than the management agencies involved.

A second weakness is that the alternative models approach used in other forms of adaptive management was applied in an ad hoc fashion in our experiments. Although we could compare our possum cellular spatial model with alternatives based on individual animals’ behaviour (Efford 1996), they were developed in isolation and for different purposes that limit their utility in this framework.

Discussion

Large-scale sustained control of introduced vertebrate pests by government agencies for conservation purposes is common in Australia and New Zealand (Braysher 1993, Parkes and Murphy 2003). Some of these campaigns have been conducted under one guise or another for >50 years (Williams et al. 1995, Forsyth et al. 2003), but 1 general characteristic of them all is that government agencies have great difficulty in sustaining national plans and individual operations (Parkes 1996). Several strategic solutions are possible to overcome these difficulties, some of which may be appropriate for adaptive management and some not.

One solution advanced to avoid this risk is to plan for eradication of the species or at least isolated populations of them (Myers et al. 2000). This is not generally possible at a national scale for most widespread species because ≥ 1 of the rules to achieve it cannot be met: usually the risk of immigration is not zero (Parkes 1990). However, eradication is increasingly possible for populations with limited distributions (Gosling and Baker 1989, Parkes 1990) and for insular populations (Atkinson 2002) as techniques and planning improve and as managers’ confidence increases. Nevertheless, false confidence when it is clear from the outset that ≥ 1 rule is violated is one cause of fiscally unsustainable pest control; the failed eradication mutates into a de facto sustained control operation that is then abandoned when the initial goals are not met. Adaptive management experiments are not often possible in these eradication attempts as each case is unique and success precludes the option to test alternative models. However, incorporating the principles of uncertainty at the policy level to clarify “stop” or “change strategy” decisions in eradication attempts that are very risky (Parkes et al. 2002) is worth considering if only to sustain some of the benefits of unsuccessful eradication attempts.

A second solution to sustaining control is biological control. Adaptive management might be used to compare results of different release strategies, but biological control is by and large unmanageable once the agent is established and spread and so generally is not suitable for an adaptive management experiment.

The third solution to sustaining pest control is to maintain the control actions in perpetuity. Adaptive management is, we suggest, a key tool in assisting institutions to use this strategy.

First, adaptive management, as we have applied it, places the routine monitoring done by managers in a wider context by allowing managers to use the data to plan their next actions or to predict consequence, by coordinating data collection across different operations to improve the quality of routine procedures and analyses and by ensuring that business planning is driven by the biological needs of the systems rather than budgeting convenience. Our models are explicitly bioeconomic and provide predictions about costs and benefits in terms that managers at all scales can relate to. Second, adaptive management either decreases uncertainty in complex management systems or decreases the risk of failure (or unsustainability) by making the uncertainty more explicit.

In the possum and fox projects we have used direct trophic connections as our response variables to measure the benefits of pest control: a few common canopy tree species for the possum project and a few native prey species for the fox project. This sidesteps the criticism that adaptive management has little ability to provide mechanistic explanations of ecosystem functioning (Simberloff 1998). Whether the “response” species we have chosen were indicative of some wider ecosystem-level response to pest control was outside the scope of these projects. The tree species selected in the possum project are common canopy species and their induced absence would undoubtedly change the ecosystem, but whether they are keystone species (and so provide a link between a species focus and an ecosystem response) is unclear. The medium-sized mammal prey species chosen in the fox project are not now common in Victoria, and some have been proposed as possible keystone species (e.g., the fungivorous potoroos may have played such a role in constructing the eucalypt–mycorrhiza links in forest ecosystems; Claridge and May 1994).

Nevertheless, conservation managers in New Zealand and Victoria are expecting more complex solutions from their pest

management colleagues as they move from species management to ecosystem management paradigms. The levels of uncertainty implicit in ecosystem management are high. What is certain is that none of the various models advocated to predict ecosystem-level effects of management actions can provide the certainty about causes and effects that managers need if they are to control multiple sympatric pest species to provide measurable ecosystem-level benefits. There are complex interactions between sympatric pest species and between them and the native communities they affect. Even for systems with few species with well understood interactions, a satisfactory interactive model with several species across trophic levels is difficult to construct (Krebs et al. 2001). Alternative models such as use of keystone species as indicators of ecosystem change (Simberloff 1998), trophic-level numerical responses (Oksanen and Oksanen 2000), indicative changes in base trophic levels (Wardle et al. 2001), food-web structural analysis (Pimm 1991), or measures of ecosystem emergent properties such as resilience (Holling and Gunderson 2002) might provide some insights that would enable an adaptive management experiment for multiple pest species to be considered.

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