*Risk Analysis, Vol. 24, No. 4, 2004*

# What Can Decision Analysis Do for Invasive Species Management?

**Lynn A. Maguire***

Decisions about management of invasive species are difficult for all the reasons typically addressed by multiattribute decision analysis: uncertain outcomes, multiple and conflicting objectives, and many interested parties with differing views on both facts and values. This article illustrates how the tools of multiattribute analysis can improve management of invasive species, with an emphasis on making explicit the social values and preferences that must inform invasive species management. Risk assessment protocols developed previously for invasive species management typically suffer from two interacting flaws: (1) separating risk assessment from risk management, thus disrupting essential connections between the social values at stake in invasive species decisions and the scientific knowledge necessary to predict the likely impacts of management actions, and (2) relying on expert judgment about risk framed in qualitative and value-laden terms, inadvertently mixing the expert's judgment about what is likely to happen with personal preferences. Using the values structuring and probability-modeling elements of formal decision analysis can remedy these difficulties and make invasive species management responsive to both good science and public values. The management of feral pigs in Hawaiian ecosystems illustrates the need for such an integrated approach.

**KEY WORDS:** Decision analysis; Hawaiian ecosystems; invasive species; multiattribute analysis; risk management

## 1. INTRODUCTION

The purpose of this article is to suggest how a structured decision framework might be helpful for invasive species management. The framework that I use comes from decision analysis, specifically multiattribute utility analysis; this framework is especially helpful for decisions that are difficult because (1) the outcomes of possible management actions are uncertain; (2) there are several objectives for management, some of which may conflict; and (3) there are numerous parties interested in the management decision, each with its own view of what is likely to happen and with its own priorities among the many competing objectives for management. Invasive species management decisions are likely to suffer from all of these difficulties.

Since this article is part of a workshop on what theoretical ecology may offer to invasive species management, I will focus on (1) using decision analysis tools to facilitate a connection between results from theoretical ecology and management decisions and (2) using decision analysis to illuminate important elements of invasive species decisions that may be neglected by analyses that focus on theoretical ecology. Examples of the former include using population dynamics models to estimate the likelihood of various pest population sizes resulting from alternative management scenarios and using structured elicitation of expert opinion to supplement results from modeling and field studies of invasive species population dynamics. Examples of the latter include (1) using multiattribute utility analysis to articulate the many goals

* Nicholas School of the Environment and Earth Sciences, Box 90328, Duke University, Durham, NC 27708-0328, USA; tel: 919-613-8034; fax: 919-684-8741; lmaguire@duke.edu.

of invasive species management and express priorities among those goals and (2) using decision analysis as a framework to facilitate communication with stakeholders and other interest groups about invasive species biology and management alternatives.

## 2. INVASIVE SPECIES MANAGEMENT DECISIONS

For those who may not be familiar with invasive species management, it may be helpful to outline the types of decisions that managers are likely to face. Organizations and government agencies concerned with invasive species often divide decisions into two categories: (1) decisions about entry of potentially invasive species and (2) decisions about control of invasive species after they have arrived, whether through purposeful introductions or accidentally. The latter decisions often center around allocation of scarce resources: setting priorities for control among many invasive species and, for particular species, deciding which methods of control will provide the most benefit for the least cost.

Entry decisions include (1) decisions about whether and how to restrict potential routes of entry for organisms that may be introduced inadvertently in the course of some otherwise lawful activity, such as shipping or tourist travel, and (2) decisions about purposeful importation of organisms that are considered desirable by at least some constituencies, such as horticulturists or exotic animal enthusiasts. In the case of inadvertent introductions, some of the questions facing regulators include: What organisms might be introduced and in what numbers? Are they likely to spread beyond the immediate entry point? If they do spread, are they likely to be considered undesirable by at least some constituencies because they do harm to human interests or to native biota? Who or what is likely to be harmed and to what extent? What steps could be taken to minimize the likelihood of inadvertent introduction? Who would be harmed and who might benefit from taking those steps? What would they cost?

In the case of purposeful introductions, someone has already decided that the organism is desirable enough to warrant importing it. Regulators then face many of the same questions as for inadvertent introductions. In addition, they must ask: Do the risks of potential harm from this importation justify the costs that controls will pose for those who wish to import the organism? In addition, they may ask: If the introduction turns out to be harmful, would it be possible to retrieve the introduced organisms?[1] For both kinds of entry decisions, resources for gathering information needed to make decisions about restrictions and resources for monitoring potential points of entry to ensure that regulations are being followed are limited, obliging regulators to make a further set of decisions to allocate scarce resources where they are likely to do the most good.

Decisions about control of species after they have arrived are at least equally complex. Regulators must anticipate how likely an organism is to extend its range, how quickly, and in what numbers. They must project the likely effects of the organism at different population sizes and in different habitats on economic, ecological, and aesthetic values. These values are likely to differ among different human constituencies, raising equity concerns about the distribution of harmful, and of any beneficial, effects of the invasive species. Regulators must analyze potential methods of control and project the probabilities of achieving various levels of success, along with the likelihood of adverse side effects that, again, will likely differ among different human constituencies. Since the resources for monitoring and treatment of invasive species populations are inevitably limited, regulators must weigh all these uncertain costs and benefits in order to allocate scarce resources among candidates for control activities.

Decisions about management of invasive species thus exhibit all of the characteristics that decision analysis is supposed to be good for: uncertain outcomes; many, potentially conflicting, objectives; and multiple interest groups that may be affected differently by decisions taken. I will show how using decision analysis to represent these characteristics explicitly provides a conceptual (as well as a quantitative) framework to help managers use scientific data to their fullest advantage and to help scientists frame their work so that it will be most useful for management decisions.

## 3. FERAL PIGS IN HAWAII

To provide a context for this demonstration, I will use the management of feral pigs (*Sus scrofa*) in Hawaii, which exemplifies the complex interplay of human values and ecological interactions that make invasive species management decisions difficult. Pigs were brought to Hawaii both by the Polynesians who first settled in the islands[2] and later by European settlers. Descendants of these introduced animals established themselves throughout the islands, reproducing at incredibly rapid rates and damaging native ecosystems by uprooting native plants and facilitating the spread of introduced species.[3] In addition, tree cavities created by the pigs facilitate range expansion and population growth of mosquitoes (also nonnative), which carry avian diseases (malaria and pox) to which native forest birds are naïve, decimating native bird populations and encouraging range expansion of the many introduced bird species in Hawaii.[4] Even the range expansion of the feral pigs into higher elevations may be driven by the dynamics of other nonnative invaders, earthworms, which are a major food of the pigs.

The human side of this story is equally complex.[5] Managers of the increasingly scarce native forest in national parks, state natural area reserves, and private conservation areas, such as those owned by the Nature Conservancy, are desperate to protect remaining forests and, where possible, restore those that have already been degraded. Native Hawaiians interested in traditional medicinal and food uses of native plants also have an interest in forest preservation. Animal damage specialists from federal and state agencies are charged with finding humane and effective means of controlling undesirable introduced species such as pigs. Native Hawaiian hunters take pigs for subsistence and, perhaps more significantly, to celebrate major life events such as weddings and funerals. They attach a cultural significance to having wild pigs to hunt, preferably lots of them. State gamelands managers are in the awkward position of trying to manage for large numbers of pigs on lands adjacent to protected areas where other state managers are doing their best to eradicate pigs. Some of the methods used to kill feral pigs, including neck snares left unattended for long periods,[6] have attracted the attention of animal rights activists, both in Hawaii and internationally; these groups have used dramatic sit-ins and clandestine thefts of snares to protest what they view as inhumane control methods.

## 4. THE "PROBABILITY MODEL" PART OF DECISION ANALYSIS

It will be obvious to both managers and theoretical ecologists that one of the biggest difficulties in deciding how to manage invasive species is not knowing for sure what is going to happen—at the point of introduction, as the species spreads, or when controls are being applied. Articulating the range of things that might happen, and assigning some probabilities to the things that might happen, is one of the hallmarks of decision analysis; this is the "probability model" phase of decision analysis, a description of how the world works. This is perhaps the most obvious point where theoretical ecology could be helpful: developing predictions of what is likely to happen.

Population ecology is perhaps the most immediately likely contributor to invasive species management decisions, providing predictions of how many organisms might be found where and at what time. When a manager needs to make projections of the pattern and rate of spread of a potentially invasive species in order to make judgments about whether or not control measures or restrictions on imports need be put in place, results from population modeling can be used to parameterize the probability-model portion of a decision analysis. These results can be expressed in terms of a continuous distribution (Fig. 1A), a discrete approximation to a fundamentally continuous process (Fig. 1B), or a fundamentally discrete set of events, such as presence/absence (Fig. 1C). Similarly, population ecology could be helpful in projecting the likely impact on an invasive species population of a biological control agent, such as a predator or disease agent, or of a chemical control, via its impact on reproductive and/or mortality rates. A combination of population ecology and evolutionary ecology might be needed to carry projections into the longer term, where co-adaptive interactions of a biological control agent and an invasive species might modify the population dynamics of both target and control organisms. Any of these results would fit into the probability-modeling part of a decision analysis.

Other facets of theoretical ecology might contribute to invasive species management. Regulatory and management agencies have developed protocols to guide decisions on invasive species, some of which use species' ecological characteristics to help predict which are likely to have invasive potential (e.g., USGS 2000);[7] sometimes these are augmented by empirical studies of the factors associated with invasiveness.[8,9] These protocols can be formalized in decision trees where ecological characteristics are used to predict invasive spread and to decide whether or not to accept or reject purposeful introduction (e.g., Fig. 2). Community ecology may also shed some light on the types of ecological communities or ecosystems that are more vulnerable to invasion (e.g., islands, depauperate biota).

All of these contributions from theoretical ecology fit into the probability-modeling part of decision analysis and help clarify the range of possible

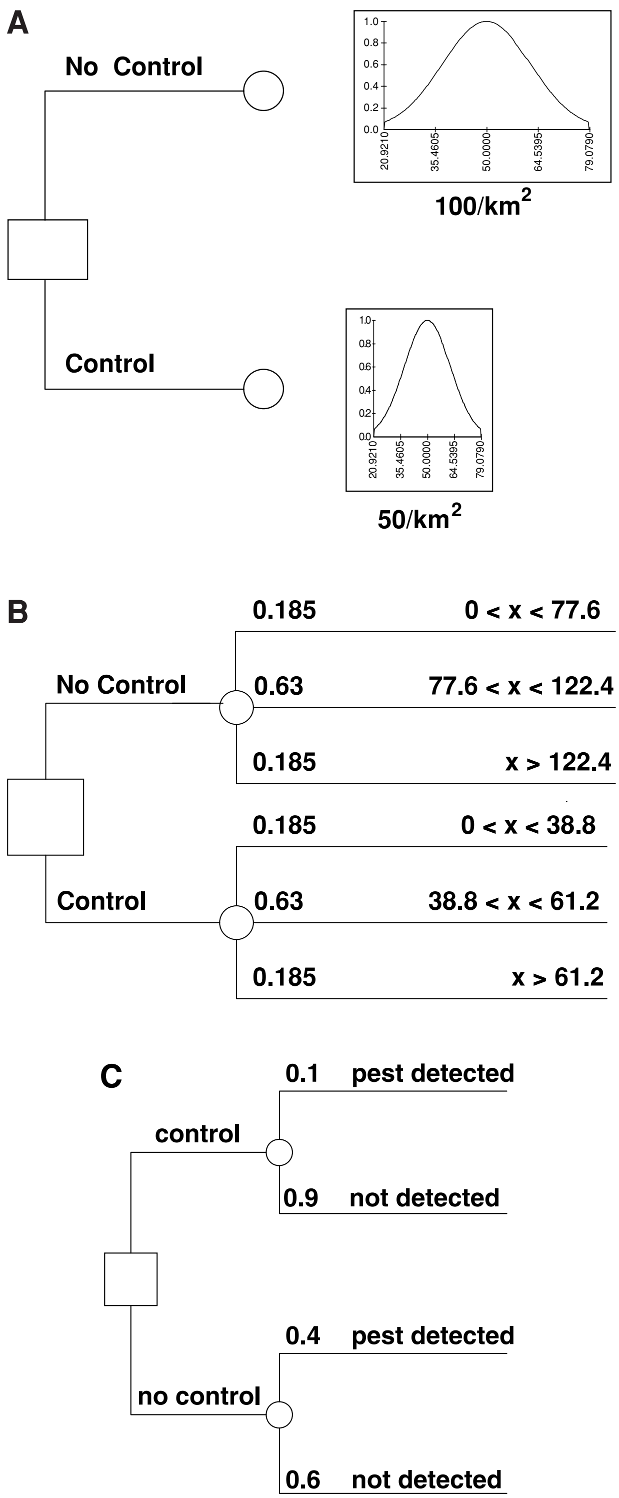


**Fig. 1.** Possible outcomes of control decisions shown as (A) continuous probability distributions of population size centered on 100 km$^{-2}$ for "no control" and 50 km$^{-2}$ for "control," (B) three-part discrete approximations to an underlying continuous distribution of population sizes, and (C) inherently discrete events.

outcomes from inadvertent introductions or from purposeful importation or control activities. It may be tempting to think that good knowledge about invasive species population dynamics will by itself provide a satisfying answer to management questions about what should be done, but it cannot perform that function in the absence of the other side of decision analysis: the modeling of values and preferences.

## 5. THE ROLE OF THE "VALUES MODEL" PART OF DECISION ANALYSIS

Decision analysis is concerned not only with predicting what is likely to happen, via the probability model, but also with guiding what, if anything, ought to be done about it; that larger task requires the analyst to model preferences over the range of things that might happen. The main feature that distinguishes invasive species like kudzu (*Pueraria montana* var. *lobata*) from invasive species like the seven-spotted lady beetle (*Coccinella septempunctata*) is that people by and large do not like the effects of the former and by and large do like the effects of the latter. Linking expressions of positive and negative impact on people's values to the description of what is likely to happen is essential to making good decisions about invasive species management. Decision protocols such as Reichard and Hamilton's[8] (Fig. 2) indicate which species to accept or reject on the basis of ecological characteristics, but they fail to incorporate information about the consequences of these choices in terms of ecological, financial, or aesthetic effects. Decisions to accept or reject are subject to error (accepting an invasive species or rejecting one that is not invasive) (Fig. 3). The consequences of these errors are likely to be both asymmetrical (i.e., the harm resulting from mistakenly accepting an invasive species is likely to be greater than benefits foregone when a noninvasive species is mistakenly rejected) and distributed differently among segments of the population (e.g., importers versus the general public). Decisions to accept or reject should weigh these differential consequences in conjunction with the likelihood of making an erroneous determination when setting standards for importation restrictions. Thomas and Randall's economic analysis[1] anticipates financial consequences of importation decisions, but not the many nonfinancial values that might be affected. Articulating the human values that are likely to be affected by introduction or spread of an invasive species is a necessary first step in determining the elements that must be included in the probability-modeling

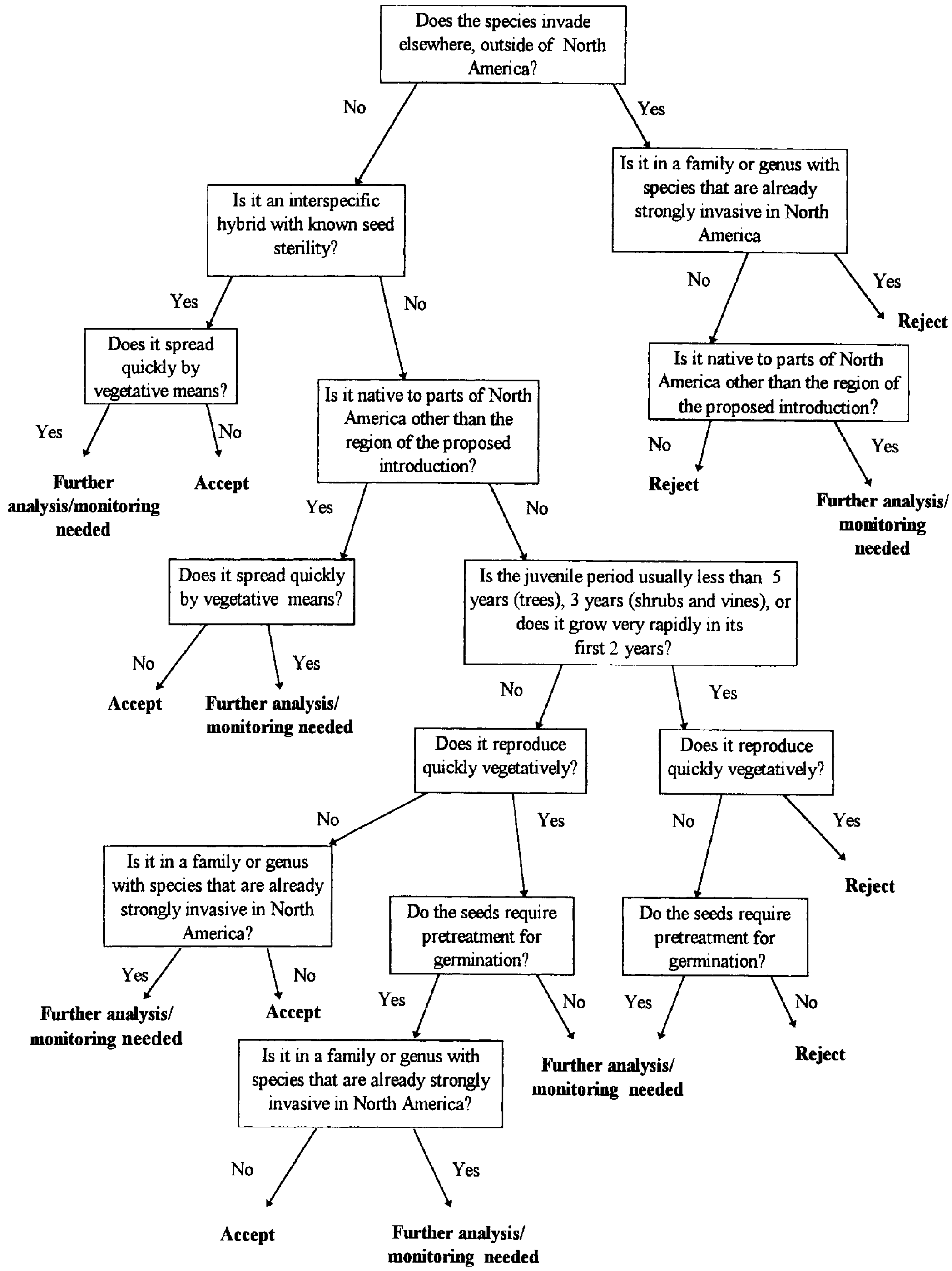


**Fig. 2.** Decision tree for woody North American invasive species (from Reference 8, with permission from Blackwell).

portion of a decision framework for invasive species management—how large a geographic region, how long a timeframe, what other species populations, and what physical parameters to model.

Multiattribute utility analysis, a framework for linking tradeoffs among conflicting objectives with uncertain predictions of how those objectives are likely to be affected by management alternatives,

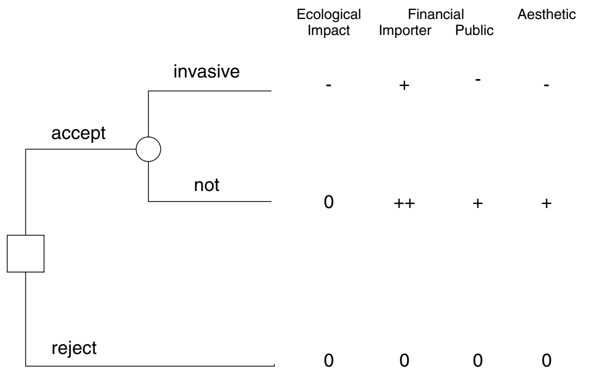


**Fig. 3.** Impact of errors in judgment about invasive potential of a candidate for purposeful introduction on ecological, financial, and aesthetic values. Symbols indicate the direction of change, if any, from the status quo.

starts with an objectives hierarchy representing the suite of goals being pursued by decision makers and affected parties. The objectives hierarchy is created by probing interested parties about their concerns and goals; those who make decisions about invasive species, those who might be materially affected by decisions taken, and those who could stand in the way of successful implementation of decisions taken are all interested parties. In decisions about control of feral pigs in Hawaii, interested parties include land managers for national parks, state natural area reserves, and private nature reserves, such as the Nature Conservancy; animal damage control personnel from state and federal agencies; game managers from state wildlife agencies; native Hawaiians interested in medicinal plants; native Hawaiian pig hunters; and animal rights activists from Hawaii and elsewhere.

Fig. 4 is an objectives hierarchy showing some of the goals of concern to parties interested in feral pigs in Hawaii. Each lower level on the hierarchy is an elaboration of higher-level goals, and the lowest level on the hierarchy is composed of measurable attributes that can be used to assess how well the goals represented in the hierarchy are being met.[10] These measurable attributes form important links between the values and preferences model and the probability-model parts of the overall decision analysis. To those who are modeling how the world works, they show exactly what sort of output from those models would be most useful for the management decisions at hand.

In the risk assessment and risk management framework used by the U.S. Environmental Protection Agency (EPA),[11] specifying an objectives hierarchy and a list of measurable attributes is part of the "planning" phase of risk assessment, where the managers and decision makers articulate the features of the world for which they need risk assessment information. In the case of feral pigs in Hawaii, it may be obvious that predicting the numbers of pigs in different locations will be important, but even more important will be extending those projections to predict the impact of those numbers of pigs on native plants, on the dynamics of nonnative competitors, on mosquito habitat, on mosquito populations, on disease organisms, on transmission to native birds, and so on. More difficult still is expressing preferences of various human constituencies over the range of ecological outcomes predicted by the probability models.

Best management for feral pigs

- Native flora and fauna
  - Forest birds
    - *Diversity*
    - *Density*
    - *Disease incidence*
  - Understory plants
    - *Density*
    - *Diversity*
- Hawaiian culture
  - Traditional medicine/food
    - *Plant diversity*
    - *Plant density*
  - Life event celebrations
    - *Pig density*
  - Respectful resource use
    - *Pigs killed but not eaten*
- Safety of nontargets
  - Humans
    - *Mortality*
    - *Injury*
  - Pets/hunting dogs
  - Nontarget fauna
- Humane methods
  - Minimum mortality
    - *Pigs killed*
  - Minimum suffering
    - *Time to death*
- Cost-effective
  - *$ to maintain low pig density*

**Fig. 4.** An objectives hierarchy showing goals and measures (in italics) for feral pig management in Hawaii. Indented entries are elaborations of the higher-level goal to the upper left.

For example, utility functions expressing relative preferences for different population densities of feral pigs or for different rates of extinction of native forest birds are likely to differ dramatically for Nature Conservancy land managers and for native Hawaiian hunters. The "values" model portion of decision analysis feeds back to the probability-modeling portion by showing where better predictions of what is likely to happen are necessary to discriminate among alternative management actions versus where decisions can be made with confidence even under considerable uncertainty.

## 6. RISK PROTOCOLS AND USE OF EXPERT OPINION: MIXING "FACTS" AND "VALUES"

When quantitative predictions of the population dynamics of the pest and its impact on socially valued goals are lacking, managers sometimes use qualitative rating scales to make invasive species management decisions. Agencies have developed protocols for making risk assessments for potentially invasive species consisting mainly of qualitative ratings of characteristics thought to be predictive of invasive potential. For example, the pest risk assessment protocol[12] used by the Animal and Plant Health Inspection Service (APHIS) to rate risks from pest organisms in solid wood packing material (SWPM) consists of seven elements rated high, medium, or low and a set of rules for combining these separate ratings into an overall assessment of high, medium, or low risk. For example, potential for economic damage is rated according to the number of risk factors present, such as known attacks on products of commercial value, ability to evolve more virulent strains, and lack of control measures.

Expert opinion is used throughout qualitative rating schemes wherever judgments are made about rating categories. For example, under "environmental damage potential" the SWPM risk assessment scheme asks respondents whether or not the pest organism is "expected to cause *significant* direct environmental effects such as extensive ecological disruption or large-scale reduction in biological diversity." Since there is no clear direction on what "significant," "extensive," or "large-scale" mean in practice, the expert's rating is inevitably an amalgamation of judgments about the biological behavior of the pest and personal definitions of these qualifying terms. Each person's definition of "significant" is necessarily tinged by personal values, which is no problem when each of us makes our own personal decisions, but becomes a problem when we are asked to provide such judgments on behalf of others who may hold quite different values. The APHIS rating system,[12] with its seven categories and rules for combining judgments, is a big improvement over completely unstructured uses of expert opinion, where the expert is asked to render a comprehensive opinion about whether or not a particular pest should be controlled with no articulation of the reasoning behind the opinion. Nevertheless, there are more systematic ways of using expert opinion that avoid the inadvertent mingling of the expert's opinions about the way the world works with personal values. Using expert opinion in a more systematic way bridges the gap between purely qualitative rating schemes and more quantitative analyses and eliminates the inadvertent co-mingling of facts and values in the decision protocol.

Structured methods for eliciting expert opinion and incorporating it into a decision framework can be found in texts such as Clemen,[13] Meyer and Booker,[14] and Morgan and Henrion (Chapters 6 and 7).[15] A central principle of using expert opinion well is to decompose the complex process the expert is being asked to assess into component parts that are more straightforward to assess and less likely to inadvertently mix assessments of fact with the influence of personal values. For example, instead of asking an expert in pig population dynamics to predict the population level of pigs in a given reserve under a specified level of snaring effort, ask the expert to answer a series of questions: What are your assumptions about the shape of the relationship between snaring effort and pig mortality? Will snares differentially capture pigs of different sexes and ages? How do these assumptions vary seasonally? With elevation? What are your assumptions about density-dependent mechanisms that may affect reproductive rates? In particular, what will happen to reproductive rates if snares are successful at reducing pig populations to very low densities? Decomposing a complex process into its component parts provides a natural avenue to link elicitation of expert opinion with models from theoretical ecology. Expert opinion can be used to develop the parameters, as well as the structure, of a population dynamics model; that is a more defensible use of expert opinion than eliciting an overall projection of population size.

Fig. 5 shows a Bayesian belief network for the pig dynamics described above (see Varis[16] for background on Bayesian belief networks for environmental problems, and Borsuk *et al.*[17] and Reckhow[18]

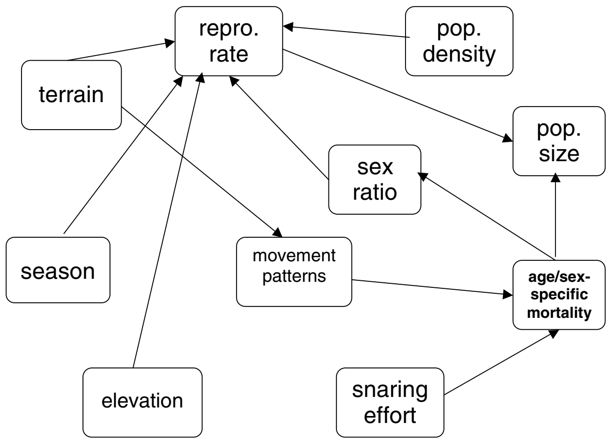


**Fig. 5.** A Bayesian belief network representing conditional probability relationships among factors determining the impact of snaring on pig population size. Note that this is not a dynamic model of these ecosystem processes, but instead a snapshot of statistical dependencies.

for additional examples). The arrows connecting the elements of the model represent conditional probability relationships (e.g., the probability distribution of pig movement patterns given a particular combination of season, elevation, and terrain). Where there are empirical data, these conditional probabilities can be estimated using regression or other statistical techniques. Where empirical data are lacking, a combination of expert opinion and ecological theory can be used to obtain the conditional probabilities. (Note that a Bayesian belief network represents a snapshot in time, not a dynamic model, and the arrows represent conditionality, not feedback or flows of energy or materials.) The Bayesian net framework organizes the use of expert opinion so that the expert can respond to clearly posed questions about the likelihood of clearly defined events. This approach to using expert opinion to fill in gaps in empirical data and theoretical understanding avoids the pitfalls of rating schemes that confound the expert's judgment about what is likely to happen with personal preferences about what outcomes are more desirable or how competing values (e.g., financial cost and environmental protection) should be balanced.

For most taxa of concern to invasive species managers, neither empirical data nor theoretical constructs are well-enough developed to provide guidance for control decisions unless augmented with expert opinion; for many species, expert opinion may have to supply most of the information on which management decisions will be based. Using structured protocols to carry out the assessment elevates expert opinion to a credible application of scientific method, rather than an unstructured display of "advocacy science" in pursuit of a predetermined management agenda. The steps of a structured use of expert opinion (modified from Clemen)[13] include: (1) Define the problem and identify the elements of the problem for which expert opinion is needed. (2) Identify and recruit the experts. (3) Motivate the experts' participation in the assessment. (4) Create a "mental model" for the chain of inference from the information to be elicited to the assessment results needed. (5) Provide the experts with a common pool of background information. (6) Train the experts in assessment protocols (e.g., methods for eliciting subjective probability distributions). (7) Elicit the assessments and verify the results by triangulation from several assessments. (8) Combine the judgments of several experts if needed (e.g., using Delphi methods).[19] (9) Document the assessment process. Use of expert opinion in practice is usually much sloppier than this and it is rare for assessments to follow all of these steps.

Even when Bayesian belief networks are not parameterized via a combination of expert opinion, theory, and empirical data, they serve a valuable purpose by making "mental models" of complex ecological processes available for scrutiny (e.g., Reference 20). Bayesian net models reveal the builder's assumptions about correlation, and sometimes cause and effect, in systems such as the pig-forest-mosquito-bird complex in Hawaii. Making these assumptions explicit is especially important where disputing parties see the problem differently and confusion about which parts of the disagreement are about matters of fact and which parts are about value differences impede solutions.

## 7. MODELING THE INTERESTS OF MULTIPLE PARTIES

This element of invasive species management, the influence of multiple groups with differing priorities on management decisions, may seem especially far removed from the realm of theoretical ecology. I have already described the many parties interested in management of feral pigs in Hawaii and some of their conflicting goals and differing priorities. Even in less-publicized cases, the roles of multiple stakeholders and multiple decision makers can exert as much influence over management decision making as scientific information on species population dynamics and ecological effects. Even in the decidedly uncharismatic case of pests that might be introduced in SWPM, managers must respond to the competing interests of (1) producers, importers, distributors, and consumers of the products being shipped in SWPM; (2) producers of the SWPM itself; (3) shippers and handlers of the products and packing materials; (4) users of the services and functions of species and ecosystems that might be affected by the spread of pests from SWPM; and (5) the general public and interests concerned with environmental integrity. Disagreements among interest groups commonly muddle disagreements about the factual basis for concern with differences in values and priorities.

In the case of SWPM pests, importers and environmentalists may disagree about the potential for harboring pests in SWPM and the potential for spread of any pests that may be imported accidentally. They will almost certainly disagree about what likelihood of introduction or likelihood of spread should trigger alarms and preventive actions. And, they certainly have different priorities among competing objectives, with short-term financial gain looming much larger for importers than for environmentalists, and the converse being the case for long-term effects on native biodiversity. These stakeholder values issues are usually seen as quite disjunct from the scientifically based risk assessment process, where the "facts" of the matter are articulated. The usual consequence of this disjunction is that science and values each have some influence on decisions about invasive species management, but those influences are often independent and uncoordinated. For example, EPA's risk assessment protocols[11] deliberately dissociate risk assessment (the "facts of the matter") from risk management (which incorporates values and preferences), except for rather narrowly defined interactions in the planning and reporting stages of an assessment, so that values issues will not compromise the scientific credibility of the risk assessment. Although EPA's worry is perhaps justified if science and values are muddled in the way they often are in unstructured decision processes, such as the unstructured use of expert opinion, a major purpose in using more structured decision tools like decision analysis is to allow both the facts and the values to play their appropriate role in the analysis, informing each other in a helpful way.

Making full use of the values modeling portion of decision analysis can provide a framework for negotiations among those interested in an invasive species management decision.[21,22] To do this, the objectives hierarchies described earlier should be "composite" hierarchies, incorporating the essential goals of all the interested parties in one hierarchy (e.g., Fig. 3) that lets all the parties see what goals must be addressed by any management scheme that is to enjoy broad support. The lowest level of the objectives hierarchy consists of measurable attributes, giving all the parties direction for gathering and analyzing technical information, such as population modeling results, to project likely outcomes of management activities. Creating a common stake in developing the technical basis for invasive species management decisions encourages "joint factfinding," a sharing of information and analyses, rather than secretive dueling among disputing parties with information selected to support their own positions.[23] A full multiattribute utility analysis expresses the preferences of each party over the range of possible management outcomes and the relative importance each places on each management objective. This articulation of differing values lets each party see why other parties prefer some management alternatives over others, and sets the stage for negotiating tradeoffs among conflicting objectives and for reconciling arguments about the distribution of positive and negative effects of management decisions. EPA has used stakeholder negotiations of this sort (sometimes called "negotiated regulations" or "negotiated rulemaking") to develop regulations for pesticide labeling and for toxics emissions,[24] although rarely with the explicit attention to values structuring that is described here. Negotiated solutions of this sort maintain a better link between the "facts" part of management decision making and the "values" part than does the more usual mode where the scientific analysis comes first and is then left behind in the wake of political pressures that reflect competing views on the proper tradeoffs among competing values.

## 8. SUMMARY

Invasive species management decisions are difficult because of uncertainty, multiple and conflicting objectives, and disputing parties. Decision analysis can help with each of these sources of difficulty. The probability-model portion of decision analysis explicitly represents sources of uncertainty, such as rates of spread of an introduced organism or effectiveness of control actions. The probability model is a natural place for results from theoretical ecology to enter invasive species management decision, by helping to predict the range of things that might happen and how likely each of those things is. The values modeling portion of decision analysis helps make the connection between theoretical ecology and management decision making by revealing the outcome measures that are meaningful to decision makers and, therefore, should be the endpoints of models based on theoretical ecology. When neither theory nor empirical data are sufficient to predict what is likely to happen, expert opinion can help fill the gap. Decision analysis structures the elicitation of expert opinion to take advantage of the expert's understanding of the ecological interactions affecting outcomes and to avoid inadvertent mixing of the expert's personal values with judgments about what is likely to happen.

The values structuring portion of decision analysis answers important needs in invasive species management that are outside the realm of theoretical ecology. Decision analysis can help articulate the many goals of those who have a stake in invasive species management decisions, their priorities among those goals, and their preferences among the possible things that could happen. The resulting structure can be used to facilitate negotiated agreements on management of invasive species that satisfy the essential goals of all parties. Such negotiated agreements do a better job of preserving the connection between the scientific input derived from theoretical ecology and private and public values than does the more usual mode of overriding science with political pressure.

## REFERENCES


1. Thomas, M. H., & Randall, A. (2000). Intentional introductions of nonindigenous species: A principal-agent model and protocol for revocable decisions. *Ecological Economics*, *34*, 333–345.
2. Olson, S. L., & James, H. F. (1984). The role of Polynesians in the extinction of the avifauna of the Hawaiian Islands. In P. S. Martin & R. G. Klein (Eds.), *Quarternary Extinctions: A Prehistoric Revolution* (pp. 768–780). Tucson, AZ: University of Arizona Press.
3. Katahira, L. D., Finnegan, P., & Stone, C. P. (1993). Eradicating feral pigs in montane mesic habitat at Hawaii Volcanoes National Park. *Wildlife Society Bulletin*, *21*, 269–274.
4. Cuddihy, L. W., & Stone, C. P. (1990). *Alteration of Native Hawaiian Vegetation: Effects of Humans, Their Activities and Introductions*. Honolulu: University of Hawaii Press.
5. Maguire, L. A., Jenkins, P., & Nugent, G. (1997). Research as a route to consensus? Feral ungulate control in Hawaii. In *Transactions of the 62nd North American Wildlife and Natural Resources Conference*, pp. 135–145.
6. Anderson, S. J., & Stone, C. P. (1993). Snaring to control feral pigs *Sus scrofa* in a remote Hawaiian rain forest. *Biological Conservation*, *63*, 195–201.
7. U.S. Geological Survey. (2000). *Alien Plants Ranking System, Version 5.1*. Available at http://www.npwrc.usgs.gov/resource/2000/aprs/aprs.htm. October 10, 2001.
8. Reichard, S. H., & Hamilton, C. W. (1997). Predicting invasions of woody plants introduced into North America. *Conservation Biology*, *11*, 193–203.
9. Maillet, J., & Lopez-Garcia, C. (2000). What criteria are relevant for predicting the invasive capacity of a new agricultural weed? The case of invasive American species in France. *Weed Research*, *40*, 11–26.
10. Keeney, R. L. (1992). *Value-Focused Thinking*. Cambridge, MA: Harvard University Press.
11. Environmental Protection Agency. (1998). *Guidelines for Ecological Risk Assessment*. Available at http://www.epa.gov/ncea/raf/pdfs/ecotxtbx.pdf. October 10, 2001.
12. U.S. Department of Agriculture. (2000). *Pest Risk Assessment for Importation of Solid Wood Packing Materials into the United States. Appendix C: Pest Risk Assessment Process*. Available at http://www.aphis.usda.gov/ppq/pra/swpm/appendixc.pdf. October 10, 2001.
13. Clemen, R. T. (2001). *Making Hard Decisions* (2nd ed. with Decision Tools). Pacific Grove, CA: Duxbury.
14. Meyer, M., & Booker, J. (1991). *Eliciting and Analyzing Expert Judgment: A Practical Guide*. London: Academic Press.
15. Morgan, M. G., & Henrion, M. (1990). *Uncertainty: A Guide to Dealing with Uncertainty in Qualitative Risk and Policy Analysis*. New York: Cambridge University Press.
16. Varis, O. (1995). Belief networks for modelling and assessment of environmental change. *Environmetrics*, *6*, 439–444.
17. Borsuk, M., Clemen, R., Maguire, L., & Reckhow, K. (2001). Stakeholder values and scientific modeling in the Neuse River watershed. *Group Decision and Negotiation*, *10*, 355–373.
18. Reckhow, K. H. (1999). Water quality prediction and probability network models. *Canadian Journal of Fisheries and Aquatic Sciences*, *56*, 1150–1158.
19. Linstone, H., & Turoff, M. (1975). *The Delphi Method: Techniques and Applications*. Reading, MA: Addison-Wesley.
20. Bostrom, A., Fischhoff, B., & Morgan, M. G. (1992). Characterizing mental models of hazardous processes: A methodology and an application to radon. *Journal of Social Issues*, *48*(4), 85–100.
21. Maguire, L. A., & Boiney, L. G. (1994). Resolving environmental disputes: A framework incorporating decision analysis and dispute resolution techniques. *Journal of Environmental Management*, *42*, 31–48.
22. Maguire, L. A., & Sondak, H. (1998). Can using decision analysis and dispute resolution techniques to solve environmental problems help promote equity? In D. J. Fletcher, L. Kavalieris, & B. F. J. Manly (Eds.), *Statistics in Ecology and Environmental Monitoring 2: Risk Assessment and Decision Making in Biology* (pp. 97–120). Dunedin, New Zealand: Otago University Press.
23. Fisher, R., Ury, W., & Patton, B. (1991). *Getting to Yes*, 2nd ed. New York: Penguin Press.
24. Harter, P. J. (1982). Negotiating regulations: A cure for malaise. *Georgetown Law Journal*, *71*(1), 31–42.