Prioritizing Invasive Species Threats Under Uncertainty

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Prioritizing exotic or invasive pest threats in terms of agricultural, environmental, or human health damages is an important resource allocation issue for programs charged with preventing or responding to the entry of such organisms. Under extreme uncertainty, program managers may decide to research the severity of threats, develop prevention or control actions, and estimate cost-effectiveness in order to provide better information and more options when making decisions to choose strategies for specific pests. We examine decision rules based on the minimax and relative cost criteria in order to express a cautious approach for decisions regarding severe, irreversible consequences, discuss the strengths and weaknesses of these rules, examine the roles of simple rules and sophisticated analyses in decision making, and apply a simple rule to develop a list of priority plant pests.

Key Words: invasive species, decision criteria, uncertainty

The U.S. Department of Agriculture (USDA) and the U.S. Department of Homeland Security (DHS) have programs to prevent or respond to the entry of damaging exotic pests or invasive species, which are non-native organisms that cause damages in excess of benefits. Program officials make important preparedness decisions concerning many organisms, such as whether or not to collect more information about specific organisms and their potential effects; implement surveillance programs; develop management practices or strategies; ban or restrict imports; require import inspections or treatments; implement offshore management programs; develop plans for eradication, containment, or control strategies in response to pest detections; or implement information or extension programs to help growers identify and respond to a pest. Officials with constrained budgets may have to make rapid decisions under extreme uncertainty. For these reasons, prioritizing invasive species threats and responses is an important resource allocation issue for government decision makers.

Different economic approaches can be applied to decisions concerning invasive species threats, ranging from sophisticated models that consider spatial, dynamic, stochastic, and other aspects of economic and biological systems, to simple decision rules using minimal information. Both sophisticated models and simple rules can have roles in decision making, depending on the decision to be made, available information, and time available for data collection and analysis. We develop a group of simple decision rules that use minimal information, discuss the strengths and weaknesses of those rules, examine potential roles for different rules in decision making, and apply a simple rule to develop a list of priority plant pests for preparedness activities.

In developing the simplified decision rules, we use the minimax criterion as a way to express a cautious approach for decision making, which Horan et al. (2002) suggest decision makers use for uncertain invasive species events with potentially severe, irreversible consequences. The relative cost criterion as applied in the economics of terrorism literature provides insight when there are severe uncertainties about the effectiveness of prevention and response options. Since government officials sometimes use a cautious approach

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for decision making under uncertainty, the economic implications warrant examination. For example, Michael Chertoff, Secretary of DHS, said that while the Department's risk analysis is based on threat, vulnerability, and consequences, "DHS will concentrate first and most relentlessly on addressing threats that pose catastrophic consequences" (Chertoff 2005).

Context of the Decision Problem

Prioritizing pests or invasive species generally focuses on identifying and ranking the worst threats. The National Invasive Species Council (2003) discussed guidelines for early detection and rapid response systems and cited the need for active detection networks to focus on high-priority species, pathways, and at-risk sites, and for preliminary risk assessment of high-priority species before detection in order to facilitate rapid response after detection. USDA's Animal and Plant Health Inspection Service (APHIS) annually prioritizes plant pests for the Cooperative Agricultural Pest Survey (CAPS) in order to allocate detection and surveillance resources to the greatest threats, using criteria for potential entry, establishment, spread, economic impact, and non-economic impact. Homeland Security Presidential Directive-9 (HSPD-9), in 2004, directed USDA, in coordination with other agencies, to develop a National Plant Disease Recovery System (NPDRS) in order to respond to high-consequence diseases of economically important crops by identifying pest control measures and developing emergency plans for their use.

From an ideal economic perspective, decision makers would consider the costs of prevention or management options and their effects on pest damages, simultaneously select the best approach for every pest, and allocate funds to pests and actions, subject to a budget constraint. However, decision makers often face extreme uncertainty, that is, sparse or unreliable information, about new pests, some of which may be imminent threats, and/or response options. There may be incomplete information about what crops a pest might damage, potential for entry, potential damage, crop area at risk, rates of increase and spread, and environmental and economic factors affecting entry, spread, and damage. In the most extreme cases, the identity of an organism as a pest may be uncertain, because there are undiscovered organisms that may become pests in new environments, while some known organisms, benign in their native environments because natural enemies or production practices mitigate infestations or damage, may cause significant damage in new environments. There also may be incomplete information about the cost-effectiveness of preventative or management methods for some pest threats, and in some cases, those options may be poorly understood or not available. Uncertainty about the likelihood and economic consequences of pest events hinders accurate assessment of threats, while uncertainty about the cost-effectiveness of prevention or management options hinders selection of a strategy. When detection or control methods are not available or are poorly understood, none can be selected.

Due to the time and costs of collecting information and analyzing pest threats and response options, agencies often respond to the threats as information becomes available to prevent major crop damage or loss of export markets. So, program managers might make a series of decisions. The sequential decision making process has characteristics of dual control or active learning where decisions are made to gain information (Kendrick 2005). Program managers may respond to new, passively or actively obtained information about exotic pest threats with active learning in order to reduce uncertainty about pest threats or to develop control or other preparedness methods, and later use that information to select appropriate methods for each pest, rather than simultaneously determining optimal strategies for all pests. For example, USDA agencies, such as the Agricultural Research Service and the Cooperative State Research, Education, and Extension Service, have programs to study new pest threats, develop control or preparedness methods, or disseminate information, which can be used by other decision makers. If control or preparedness methods are unknown or poorly understood, decision makers have no choice but to follow such a decision making process. Different decision rules can prioritize learning, preventative, or other response actions, depending on available information.

In some circumstances, decision makers might respond with provisional prevention or preparation measures, as well as active learning, when new, sparse information indicates that an exotic pest threat is highly damaging, irreversible, and imminent. The active learning could better quantify the threat or develop methods to detect or manage the pest, but could also indicate whether the measures should be continued, modified, or terminated to prevent misallocation of resources and complaints from other nations that the measures do not meet the standards of the Agreement on the Application of Sanitary and Phytosanitary Measures (World Trade Organization 1994).

Approaches to Managing Invasive Species Under Uncertainty

Primary differences in modeling efficient management of invasive species relate to the representation of uncertainty about the likelihood and economic consequences of events and the effects of preventative or management actions. The economic framework for risk management (risk management approach) is often used to address uncertainty in decisions. Shogren (2000) developed an optimal control model for reducing risks from invasive species while allocating scarce resources across market and non-market goods for the overall benefit of society. The model characterizes uncertainty through probabilities, a traditional approach that treats uncertainty as essentially the same as risk, and accounts for the effect of decisions and actions on probabilities. Risks can be reduced by mitigation (reducing the odds of a bad event) and adaptation (reducing the consequences of a bad event). Shogren's model is expressed as follows:

$$\text{(1)}\quad \underset{(x,Q)}{\text{Maximize}}\ EU = \int_a^b \left\{ \begin{array}{l} p(Q;\theta)\ V_0\left[m - c(x,Q)\right] \\ + \left[1 - p(Q;\theta)\right] \\ V_1\left[m - D(x;\theta) - c(x,Q)\right] \end{array} \right\} dF(\theta;\beta),$$

where EU is expected social welfare of the manager's nation, x is the manager's investment in adaptation (assumed to be a private good—exclusive and rival in consumption), Q is the manager's investment in mitigation (assumed to be a public good—non-exclusive and non-rival in consumption), $p(Q;\theta)$ is the probability of a good event, $V_0[m - c(x, Q)]$ is social welfare given a good event, m is endowed wealth, $c(x, Q)$ is the cost function for adaptation and mitigation activities, $[1 - p(Q;\theta)]$ is the probability of a bad event, $V_1[m - D(x;\theta) - c(x, Q)]$ is social welfare given a bad event, $D(x;\theta)$ is the money equivalent of damages if a bad event happens, θ is a random variable which takes values in the interval $[a, b]$ according to cumulative distribution function $F(\theta;\beta)$ and represents basic scientific uncertainty about the impact of an invasive species, and β is exogenous collective investments in research to reduce the uncertainty about the impact of an invasive species.

Eiswerth and van Kooten (2002) developed a firm-level, stochastic dynamic programming model for control of invasive weeds that recognizes several sources of uncertainty by using fuzzy sets, including lack of data, measurement error, variability in rate of spread, and impact of management measures, as well as the need to use categorical descriptions of uncertain events.

Horan et al. (2002) question the appropriateness of probabilities for representing uncertainty in the case of invasive species, suggesting that expected utility calculations, used in the risk management or Bayesian frameworks, may have limited value for analysis of some invasive species problems, and they identify these reasons: (i) the frequency of invasive species introductions may depend on trade levels and may be low, (ii) probabilities are difficult to assign to one-time events with no historical precedent, such as some invasive species introductions, and (iii) invasive species events may be very costly and irreversible. They developed a model of decision making under ignorance—where neither subjective probabilities nor detailed knowledge of the event space is available—based on Katzner (1998), Shackle (1969), and Vickers (1987). Their model features the notion of potential surprise, a measure of disbelief of potential future outcomes, and recognizes that inconceivable outcomes may occur. Decision makers would not focus on all outcomes and expected utilities, but rather on "the least unbelievable conjectured losses or gains from the activity," or "focus loss," without necessarily accounting for a probability distribution. However, catastrophic events with high potential surprise would not factor into the focus loss. Under this behavioral model, decision makers would take a cautious approach when considering uncertain outcomes so that low probability outcomes that are considered possible—those with low potential surprise—receive more prevention resources than under a risk management approach.

In addition to the concerns raised by Horan et al. (2002), a serious practical limitation of risk-based models is that it may be difficult or impossible to estimate or interpret probabilities and the novel circumstances that surround the introduction and establishment of potential invasive species, particularly those that have not yet entered or those that are poorly understood. Ouchi (2004) argued that there is no formally established methodology for treating expert judgment and that Bayesian and other approaches suffer from limitations in practical application. Even in cases where a historical record may suggest likelihoods, the prospect of intentional introductions or related challenges to biosecurity may render historical records largely unusable. Accounting for the effects of human activity on new pest entry and the susceptibility of agro-ecosystems to pests, as well as the endogenous effect of mitigation and adaptation activities on probabilities characterized in Shogren (2000), will increase the complexity of probability estimation.

Developing Criteria for Decision Making Under Uncertainty

When probabilities of events are not reliably measured or are not appropriate for representing uncertainty, as discussed above, traditional criteria for decision making under uncertainty include the maximin and maximax criteria, which represent polar extremes of optimism and pessimism, and the Laplace and Hurwitz criteria, which require information similar to probabilities (Render, Stair, and Hanna 2006). Info-gap methods are also applicable (Ben-Haim 2006). We selected the minimax criterion to represent a cautious approach to decision making regarding the adverse effects of invasive species and responses to those species when probabilities of events are unknown or are inappropriate for representing uncertainty, but other criteria could be used with different results. The following discussion shows how decision rules using that criterion follow from the traditional risk model through simplifying assumptions and economic logic when probability estimates and other important information, such as the cost-effectiveness of management options, are not available. As information becomes scarcer, decision making changes from selecting optimal actions to prioritizing pests.

Uncertainty criteria are often depicted in the context of decision analysis. The risk model, as represented in Shogren (2000), can be interpreted in a decision analysis framework by characterizing the choice set as a finite number of alternatives and basic scientific uncertainty as a discrete random variable. [A decision table based on Shogren's model is shown in Moffitt and Osteen (2004).] The choice set contains J possible pairs of investments in adaptation and mitigation, $((x_1, Q_1), (x_2, Q_2), \cdots, (x_J, Q_J))$. The basic scientific uncertainty concerning establishment of an introduced species, θ, is represented by a discrete random variable that takes on K different values denoted by $\theta_1, \theta_2, \cdots, \theta_K$, with the probability of the kth value denoted by $p(\theta_k)$. The optimal solution is the adaptation and mitigation pair corresponding to the largest EU. To develop a ranking of potential invaders for budgetary purposes, equation (1) would be solved to find the optimal action or program, (x, Q), for each potential invader, and the ranking would be based on the relative welfare improvements due to the optimal actions as compared to doing little or nothing, $(0, 0)$. Due to large information requirements, expression (1) may be very difficult to apply to many potential invaders, but it provides a foundation for modeling preparedness under uncertainty for invasive species.

The traditional model can be further simplified by assuming constant marginal social welfare and minimizing expected social cost (EC), measured as the sum of expenditures for preparedness actions and expected damage, which is a standard approach for pest control decision making:

$$(2)\quad \underset{(x,Q)}{\text{Minimize}}\ EC = c(x,Q) + \int_a^b \left[1 - p(Q;\theta)\right] D(x,\theta)\, dF(\theta;\beta).$$

Economic priorities associated with invasive species and the selection of adaptation and mitigation options could be ascertained by solving (2) for each possible invader. Priority rankings for budgets would be based on the reduction in *EC* for each pest due to the optimal choice of (x, Q) relative to doing little or nothing, (0, 0). The greater the reduction in *EC*, the higher preparedness action for a pest would rank. The information requirements associated with (2) are still significant, making it difficult to apply to many potential invaders.

If probabilities of events are not available, cannot be estimated, or are not appropriate for representing uncertainty, the decision considers only one θ_k at a time. In this framework, $c(x_i, Q_i)$ is interpreted as the cost of an action or program. Many actions or programs have aspects of both mitigation and adaptation. For example, eradication or containment can reduce damages at one location and prevent or slow the spread of damage to another. Effective prevention programs have a mitigating effect, but they prevent damages even if the probabilities of damages are unknown. For example, if a practice, such as methyl bromide fumigation or irradiation, is known to control a pest, treating potentially infested imports would prevent damages even if the probability of pest entry is unknown.

The minimax cost criterion selects the action (x_i, Q_i) that minimizes pest damage plus cost, given the value of θ_k that results in the worst pest damage and use of the action:

$$\text{(3)} \quad \underset{(i)}{\text{Minimize}}\left(\underset{(k)}{\text{Maximize}}\ \left(D\left(x_i,\ \theta_k\right)+c\left(x_i,\ Q_i\right)\right)\right).$$

If estimates of the costs of preventative and control actions and their effects on worst-case damages were available, then the minimax cost criterion would identify optimal actions for the worst state of nature. This criterion can consider multiple factors affecting damage under one state of nature and could be applied to obtain actions under other θ_k's, but outcomes would not be weighted by probabilities. Economic priority rankings for invasive species would be based on the reduction in worst-case damages plus costs for the optimal program as compared to doing nothing for each potential invader—the greater the reduction, the higher the ranking of preparedness for a species. The priorities would rank optimal actions for pests and also rank pests for more information about damage and states of nature.

Unfortunately, for many invasive species threats, information needed to apply the minimax criterion, as expressed in (3), may not be available. Program managers may face situations where there are few or no known preventative or control actions available or where there is little or no information about the effect of actions on pest damage. In these cases, selecting prevention and control actions for species becomes problematic. As a result, initial preparedness decisions will often focus on collecting information about pest threats and on the availability, cost, and effectiveness of prevention or control actions, in order to later facilitate the selection of actions.

The relative cost criterion, which is implicit in some economics of terrorism literature and based on the difference between damage estimates and action costs, could be combined with the minimax criterion to cope with this uncertainty. Some issues faced in the context of terrorism are remarkably similar to issues in crop protection (e.g., Cauley and Im 1988, Enders and Sandler 1993, Enders and Sandler 1996, Lapan and Sandler 1993, Lee 1988, Schwartz 1998, Slone 2000). A critical question is the prioritization of defense of potential targets, as well as prioritization of resources between preemptive and defensive measures (Endress 2002). For example, a comparison of damages resulting from a successful terrorist attack with the costs to terrorists of mounting an attack has led some economists to conclude that the marginal product of destructive activity greatly exceeds the marginal product of defense. In other words, potential damages to a target are thought to be large, and defensive measures are not expected to prevent all successful attacks. Therefore, some economists have concluded that resources should be directed at terrorist resources in a preemptive rather than a defensive effort (Madrick 2002). In such analyses, the likelihood that preemptive or defensive actions will prevent destructive activity is difficult to quantify, though the cost of the actions can be more easily determined.

The key consideration of the relative cost criterion is that selection of an action can be based on the magnitude of estimated damages associated with doing little or nothing relative to the cost of the action. When important elements such as the likelihood of consequences and the effectiveness of the action are highly uncertain, a decision maker using the reasoning of the relative cost criterion will select the action for which the difference between estimated damages and costs of action is the greatest. Moreover, if estimated damages utilized in the relative cost calculation reflect a worst-case scenario, then the minimax and relative cost criteria have been combined.

The principle underlying the combination of the minimax and relative cost criteria follows: under extreme uncertainty, if the damages under the worst-case scenario associated with doing little or nothing are large relative to program cost, then the program may be worthwhile even though the probabilities of outcomes and program effectiveness are largely unknown. Expression (4) combines the minimax and relative cost criteria:

$$\text{(4)} \qquad \underset{(i)}{\text{Maximize}}\left(\underset{(k)}{\text{Maximize}}\left(D\left(0, \theta_k\right) - c\left(x_i, Q_i\right)\right)\right).$$

The criteria expressed in (4) can be used to establish economic priorities for potential invaders by maximizing the difference between worst-case potential damages associated with doing nothing and the costs of known preparedness actions for an invader (other than doing nothing). In this case, the decision maker does not have an estimate of damage reduction due to (x_i, Q_i) but has reason to believe that the action may be effective. Potential damages would be measured by presuming that the most deleterious state of nature and θ_k causing the worst damage prevail. Based on the minimax/relative cost criteria, the greater that potential damage from an invader is relative to the action's cost, the higher would be its economic priority for preparedness, even though expected gain from the action cannot be determined.

The difference between the worst-case damage and cost of action is a measure of the maximum potential return resulting from the action or the maximum cost that can be incurred, including research, control, or other expenses. Actions for which the cost is greater than worst-case damage would not be feasible, but actions that pass this feasibility test might still be cost-ineffective. So, the priorities rank pests for research to measure the cost and effectiveness of actions and to assess new, poorly understood alternatives that are cheaper or more effective than a costly, well-understood one.

If no effective control actions are known or no cost-effectiveness information is available, the ranking using expression (4) would be based entirely on the estimate of maximum potential damage, which indicates a maximum potential return if a control were to become available. This special case of expression (4) is used subsequently for the empirical application in this paper. In this case, only pest threats can be prioritized; optimal preventative or control actions cannot be selected. Priorities rank pests for research to better understand pest damages and probabilities and to develop prevention, detection, or management actions before such actions can be selected. Scientists have used similar approaches to characterize pest risk. For example, Kolar and Lodge (2002) classified the worst exotic fish threats as "nuisance" (a measure of impact) with a "fast" rate of spread, without estimating probabilities of outcomes (p. 1235), which is similar to ranking pests by worst potential damage, except that threats were measured in non-monetary terms and not differentiated within a category.

Strengths, Weaknesses, and Implications for the Decision Making Process

The minimax criterion, which is included in (3) and (4), differs from the risk management approach by not explicitly addressing the likelihoods of damaging events. In addition, the combination of the minimax and relative cost criteria in (4) does not address rates of growth and spread or factors that limit area infested. The minimax and relative cost criteria and risk management approach identify similar rankings of threats and preparedness investments if (i) proportional pest damage estimates are the same or the rank-order of damages is the same for both approaches, (ii) pests can infest a high percentage of crop area, and (iii) rates of spread to full infestation are rapid. So, assuming agreement on the magnitude of proportional consequences, the minimax/relative cost criteria and the risk management approach would identify the same worst threats, where highly damaging pests rapidly infest high percentages of crop area. Inaccurate damage estimates, based on sparse or unreliable information or obtained from inconsistent sources, could result in inaccurate rankings of pest threats under both the risk management approach and minimax/relative cost criteria. Unknown pests or pests for which potential damages are poorly understood are difficult to prioritize, even though they ultimately could have large impacts. Similarly, both approaches can result in inaccurate ranking of prevention or control actions if cost-effectiveness estimates are inaccurate, and will obviously be unable to select prevention or control actions if none are available. The minimax loss criterion has been criticized for assuming that people cannot formulate subjective probabilities. Under subjective expected utility theory, it is assumed that people will use subjective probabilities when the probabilities are not objectively known (Savage 1954, Camerer and Weber 1992). However, while some individuals may quickly develop subjective probabilities, other literature indicates that some individuals do not quickly develop them and make decisions as if averse to ambiguity or uncertainty, which is different than risk aversion (Ellsberg 1961, Hsu et al. 2005, Rustichini et al. 2005).

The risk management approach will allocate resources more efficiently than the minimax and relative cost criteria will, if reliable probability and impact estimates are available. Due to the implicit assumptions and sparse information about important parameters, the minimax and relative cost criteria could lead to misallocations of resources to threats or actions. The criteria, as expressed in (3) and (4), may give too high a priority to less serious threats by not accounting for factors that reduce the likelihood or magnitude of damage. If only a small portion of crop area would be affected, the rate of spread were slow, or potential for entry or spread were low, the criteria would overestimate potential loss, identify a higher priority, and lead to more preparedness measures than the risk management approach would. Also, expression (4) would overestimate the potential return to control measures if available information underestimates their cost. In addition, the minimax criterion does not consider all states of nature and their probabilities, focusing on the worst state, so it is difficult to compare, for resource allocation purposes, uncertain threats to pests currently causing damages.

The simple minimax/relative cost approach may have an advantage over risk management based evaluations if decisions must be made quickly and if it is costly or difficult to obtain reliable probability estimates for entry or spread. In this circumstance, decision makers exercising caution regarding severe pest threats would prioritize—for costly research and development activities—threats with larger and potentially irreversible consequences higher than threats with potentially smaller consequences that might be more likely. While the risk management approach would allocate resources more efficiently than the minimax/relative cost criteria would if reliable probability and impact estimates were available, the time and cost requirements for satisfying the large information needs of the risk management approach, especially for sophisticated analyses using bioeconomic or stochastic dynamic control models, could be greater than those of the minimax/relative cost criteria, which can be more quickly estimated, due to smaller information requirements, and easily revised with new information.

The strengths and weaknesses of the minimax and relative cost criteria help define roles for different rules in the sequential decision making process discussed earlier. Simple economics-based decision rules can identify the worst pest threats, assuming that potential damage estimates are accurate, but there is a need for more information to separate the overrated threats from the worst threats and ultimately to select responses for specific pests. So, if simple rules are used, the decision making process should include the following steps in order to address the effects of inaccurate estimates or limited information: (i) collect important missing information to reduce uncertainty, (ii) reexamine threats and priorities based on new information, which may indicate more information needs, and (iii) select prevention and/or management strategies for high-priority pests, which may involve more sophisticated economic analyses, using information collected for those threats. These steps provide an opportunity to modify pest rankings and allocation of resources to research and development, and to evaluate the costs, effectiveness, and irreversible, adverse consequences of new preparedness or response alternatives, before the final selection of actions.

In effect, simple decision rules would prioritize pests for assessment of the likelihood and magnitude of threats, development of pest detection and management options, research on the costs and consequences of those options, or analyses to select such options, all of which are costly and subject to limited budgets. For example, the minimax criterion indicates that, if rapid response panels were organized to assess the subjective probabilities of the consequences of pest events and responses, pests with potentially large adverse consequences would have a higher priority for inclusion in the set of pests for assessment, even if the unknown probability of events might be small, than would pests with smaller but potentially more likely consequences. More sophisticated analyses using models that account for bioeconomic systems, time, space, or risk, and that have large data requirements, can be focused on high-priority threats in order to highlight decision trade-offs and help select actions.

Research on high-priority threats would also provide information to (i) re-estimate pest damage and reprioritize pest threats, which could identify other needs for research, (ii) examine the costs, effectiveness, and potential adverse effects of responses, and (iii) conduct more sophisticated analyses to select options. In the third case, when probabilities are appropriate for representing uncertainty of events and good estimates become available through the learning process, the traditional risk management approach, as expressed by equations (1) or (2), could be used to evaluate decisions. If probabilities are not available or appropriate for representing uncertainty but other relevant information is available, then the minimax criterion in expression (3) or other uncertainty criteria could be used to select actions.

Crop Protection Priorities

We developed a ranking of potential agricultural crop pests not currently or previously in the United States to demonstrate use of the combined minimax and relative cost criteria, as expressed in (4). A pessimistic presumption consistent with this approach is that significant pest problems in foreign locales will eventually lead to a similar significant domestic pest experience. While this presumption might not always be true, some empirical evidence supports using it. Reichard and Hamilton (1997) found that the most reliable characteristic for predicting invasiveness of woody plants was whether or not the species was known to invade elsewhere in the world. We assumed that no cost-effective options are available, so pests were ranked by worst-case damage estimates. A list developed with these procedures could be regarded as a first step in the decision making process, because it prioritizes pests for actions that obtain information about damage severity or the availability, cost, and effectiveness of exclusion or management actions in order to inform decisions that select such actions.

The procedure identified arthropod, weed, and disease pests that have never been in the United States but that could affect any of the 25 highest-value U.S. crops. Focusing the analysis on high-value crops assumes that prevention or management costs will be low relative to damage costs, which provides a rationale for preparedness actions. The procedure derived the 25 highest-value U.S. crops for a representative year, identified foreign countries where the crops are also produced, identified pests affecting the crops in the foreign countries, and recorded reported estimates of pest damage to the crops.

The list of the 25 highest-value crops produced in the United States for a representative year was derived by averaging published government statistics of crop values for 2001 and 2002 (U.S. Department of Agriculture 2003). A detailed search of international crop production records reported by the Food and Agricultural Organization of the United Nations (United Nations 2002) as well as reports found on the Internet related to crop production identified countries where any amount of the listed 25 crops is produced. Production amounts are small in some of the areas, but this illustrates that not just major production regions but all production areas were considered as potential sources of pests.

A large number of sources were examined to identify pest species and obtain damage estimates for each of the listed crops in each country where some production is reported. Then, a search was conducted to determine which foreign pest species are not currently or were not previously in the United States. Information sources included newspaper articles, trade journals, and some agency reports. However, online resources on the Internet proved to be the most valuable information source for both the identity and seriousness of pests in foreign countries. More than 22,000 Internet sites were examined. The exhaustive search effort yielded significant information in some cases and little in others. To maintain consistency with a minimax perspective, it was assumed that all the U.S. acreage of a crop would be affected at the maximum pest yield loss percentage for foreign locales. In cases where information was inadequate to estimate damage, pest species were not prioritized. Over 50 pest species were identified and analyzed, but additional pests could be examined. The list of the 25 most valuable crops in the United States is provided in a footnote to Table 1, while the underlying crop value statistics, countries reporting production, and potential invasive species for each of the 25 most valuable crops are shown in Moffitt and Osteen (2004).

Our priority list is comprised of five arthropod, two weed, and three disease pests, ranked by potential impact (Table 1). It is unclear if these are the worst threats facing U.S. agricultural crops, but they may warrant further attention. It could turn out that a damaging pest in a foreign locale cannot survive in the United States and that preparedness is not warranted. Alternatively, exotic pest damage in a new environment could be worse than in the native one.

Included in this priority list are three plant pathogens on USDA's list of biological agents with the potential to pose severe threats to plant health or plant products (Table 2): two strains of citrus greening disease (*Lieberobacter africanum, Lieberobacter asiaticum*) and Asian soybean rust (*Phakopsora pachyrhizi*). Two other pathogens on the USDA list of biological agents—citrus variegated chlorisis strain of *Xylella fastidiosa* and southern bacterial wilt (*Ralstonia solanacearum*)—were identified in developing Table 1 but not ranked in the top ten. Agents on the USDA list are subject to regulation of transfer under the Agricultural Bioterrorism Act of 2002 and are also priorities for the USDA's National Plant Disease Recovery System. USDA considered three criteria in identifying the selected agents: (i) effect on plant health or products, (ii) virulence of the pathogen (or toxicity of toxin) and the methods of transfer to plants, and (iii) availability of methods to treat or prevent disease caused by the agent. Plant pathogens that satisfy the criteria for selected agents will also rank high under the minimax/relative cost approach, which relies on potential damage estimates and is similar to the first of the USDA criteria. Differences, apart from any associated with decision criteria, follow from Table 1's exclusion of pests that have been or are now in the United States, and Table 2's inclusion of pathogens only.

Summary

Government decision makers sometimes must respond to pest threats in situations where there is limited information. Under extreme uncertainty, they may choose to conduct research to clarify the likelihood and severity of pest threats, develop prevention or control actions, and estimate their cost-effectiveness to inform later decisions about control strategies for specific pests.

Simple decision rules have a role in decision making about pest threats, as do risk assessments and sophisticated economic analyses. Sophisticated analyses are appropriate if reliable information is available, but simple rules may have a role when information is scarce and decisions must be made quickly. We used the minimax and relative cost criteria to develop simple decision rules based on the notion that decision makers might choose to exercise caution regarding the worst pest threats. We screened a number of exotic crop pest threats and applied this approach to develop a priority list. Other simple decision rules or measures of pest threat could be used, resulting in different rankings of threats and options. Our discussion is part of a work in progress, which we are extending by applying more general concepts developed by Ben-Haim (2006) to examine the robustness of decisions or the reliability of acceptable outcomes under extreme uncertainty and the trade-offs between robustness and performance measures. An advantage of the Ben-Haim approach over the minimax and similar criteria is that it can consider uncertainty about multiple states of nature and risk as an uncertain parameter.

While the minimax criterion, like other simple rules, can be relatively cheap and used quickly, it does not account for all outcomes and could misallocate resources. A recognition of the criterion's weaknesses implies that steps should be included in the decision making process to avoid or correct errors in identifying the worst threats or threats that are too costly to control. Simple decision rules

Table 1. Prioritization of Invasive Species by the Minimax/Relative Cost Criteria[a]

Pest	Crop	Worst-case cost ($ billions)
Larger grain borer (*Prostephanus truncatus*)	corn	17.6
Soybean rust (*Phakopsora pachyrhizi*)[b]	soybean	11.8
Phormium yellow leaf (*Phytophthora clandestina*)	hay/strawberry	9.4
Sunpest (*Eurygaster integriceps*)	wheat	5.8
Cleaver (*Galium aparine*)	wheat	3.5
Guatemalan moth (*Tecia solanivora*)	potato	2.9
Black – grass (*Alopecurus myosuroides*)	wheat	2.8
Andean potato weevil (*Premnotrypes spp*)	potato	1.7
Greening disease (*Lieberobacter africanum*; *L. asiaticum*)	orange	1.7
European wasp (*Vespula germanica*)	grape	1.7

[a] This list was developed by identifying exotic pests not currently or previously in the United States and estimating potential damages for the 25 highest U.S. value crops, averaged over 2001 and 2002: almonds, apples, barley, broccoli, carrots, corn, cotton, cottonseed, dry edible beans, grapes, hay, lettuce, mushrooms, onions, oranges, peaches, peanuts, potatoes, rice, sorghum, soybeans, strawberries, tobacco, tomatoes, and wheat.

[b] Soybean rust was discovered in the United States during November 2004 after this list was constructed.

can prioritize pest organisms for the collection of relevant information, including risk assessments and sophisticated economic analyses, to modify priorities and better inform decisions. Priorities would need to be reassessed as new information about pest threats becomes available. The advantage of such rules is that they can assist in the allocation of resources to the worst threats before it is too late or costly to address them.

Table 2. USDA Agent and Toxin List

Pest
Liberobacter africanus
Liberobacter asiaticus
Peronosclerospora philippinesis
Phakopsora pachyrhizi[a]
Plum pox potyvirus[a]
Ralstonia solanacearum, race 3, biovar 2
Sclerophthora rayssiae var. zeae
Synchytrium endobioticum
Xanthomonas oryzae pv. oryzicola
Xylella fastidiosa citrus variegated chlorosis strain

[a] Both pathogens have entered the United States, and APHIS removed them from the select agent list on March 18, 2005. *Phakospsora pachyrhizi* was removed to facilitate research to manage Asian soybean rust. Plum pox was removed because it would not spread easily by natural means and would be difficult to spread intentionally.

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