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Analysis

Application of portfolio theory to asset-based biosecurity decision analysis

Sonia Akter [a,*], Tom Kompas [b,c], Michael B. Ward [d]

[a] Lee Kuan Yew School of Public Policy, National University of Singapore, 469C Bukit Timah Road, Singapore 259772, Singapore
[b] Crawford School of Economics and Government, The Australian National University, Australia
[c] Centre of Excellence for Biosecurity Risk Analysis, University of Melbourne, Australia
[d] Department of Economics and Institute of Environmental Sustainability, Monash University, Melbourne, Australia

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ABSTRACT

A key challenge for biosecurity decision-making is how best to allocate scarce resources across multiple environmental assets. The allocation of funds for the best return from investment requires a careful assessment of expected return and uncertainty. In this paper, we applied a portfolio theory-based decision support tool that helps determine resource allocation in a way that maximizes expected return and minimizes uncertainty. Our framework offers three advancements to the literature. First, it helps in making resource allocation decisions across multiple pests that affect multiple environmental assets. Second, it incorporates multiple sources of uncertainty in the decision analysis including economic value uncertainty. Finally, it demonstrates a generic approach to design a choice experiment study to estimate monetary values of a broad group of environmental assets. We find that a portfolio-based framework applied in conjunction with a choice experiment study can be a useful tool to guide biosecurity resource allocation decisions. Our results show that disregarding value uncertainty may cause bias by underestimating true uncertainty in the opportunity set. The choice experiment study revealed substantial positive non-market values generated by environmental biosecurity in Australia. However, significant preference heterogeneity across respondents with regards to different biosecurity outcomes was observed.

1. Introduction

The continental biotas of the world had been isolated for millions of years. Globalization, especially the widening and deepening of international trade and human mobility across countries for holiday, travel, sports and business, dismantled the world's bio-geographic barriers, resulting in an exchange and redistribution of invasive pest species among and within continents (Perrings et al., 2010). Invasive exotic species inflict severe damage to native biodiversity, agriculture and social and recreational life. Environmental biosecurity measures prevent, control and eradicate the entry, establishment and spread of invasive species within a certain geographic boundary. Prevention efforts such as pre- and post-border quarantine restrictions limit the entry of invasive species in a country. Control measures such as trapping, fencing and shooting, and clearing contain the species within the infested areas and eradication measures completely eliminate the pest from an infested area.

A key challenge for biosecurity decision-making is how best to allocate scarce resources across multiple pest species in the face of limited knowledge of invasion dynamics and their potential implications for environmental assets (Perrings, 2005; Walshe et al., 2012; Yemshanov et al., 2014). The allocation of funds for the best return from investment and the best long-term outcomes for asset protection requires a careful assessment of expected return and uncertainty (Walshe et al., 2012). Biosecurity planners are therefore turning to tools that are capable of accommodating uncertainty in the decision analysis (Liu et al., 2011). Consequently, portfolio theory-based decision tools that account for uncertainty and allow efficient resource diversification are becoming increasingly popular in biosecurity policy planning (Prattley et al., 2007; Salo et al., 2011; Yemshanov et al., 2014). Portfolio theory, widely used for decades in the financial sector and economics research, is commonly used to determine investment allocation among a set of financial assets with uncertain returns in a way that maximizes expected return and minimizes volatility (uncertainty) (Markowitz, 1952; Salo et al., 2011).

Although portfolio theory has not been frequently applied in environmental decision and planning, its use has been steadily growing in the recent decade. The most frequent applications of portfolio theory within the environmental planning discipline were observed in biodiversity conservation, land-use planning and forest and water management (see for example Koellner and Schmitz, 2006; Crowe and William, 2008; Marinoni et al., 2011; Abson et al., 2013). Two studies used portfolio theory in invasive pest management (Prattley et al., 2007; Yemshanov et al., 2014). Prattley et al. (2007) considered spatial and temporal allocation of surveillance resources to increase the chance

* Corresponding author.
E-mail address: sonia.akter@nus.edu.sg (S. Akter).

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of detecting exotic animal diseases. Yemshanov et al. (2014) applied portfolio theory to allocate a fixed amount of surveillance resources among a set of geographical subdivisions in a way that maximizes the potential to detect a pest's existence in the study area.

The estimation of the potential monetary damage from pest incursions can be particularly difficult if the organism's anticipated impacts involve non-market goods and services. Monetary estimates of benefits obtained from marketed goods such as agriculture and commercial venture are fairly easily available (Reinhardt et al., 2003; Gong et al., 2009). Non-market benefits can be estimated using survey-based stated choice studies. Such studies were undertaken in the past using a species-specific approach focusing on one environmental asset (Beville et al., 2012). The species-specific approach offers context-specific economic impacts and thus informs policy decisions in case of a specific pest incursion. However, this approach is less useful when the decision makers are (1) applying an asset-based strategy to protect high-value environmental assets and/or (2) dealing with multiple invasion threats (e.g. a vertebrate versus invertebrate species) affecting a wide range of environmental assets. The asset-based strategy focuses on the protection of high-value environmental assets by controlling invasion in places where the benefit is the highest. This strategy is applied when a pest becomes so widespread that it is inefficient to control it everywhere it occurs. Further, a species-specific approach would require valuing the economic impacts of the threats posed by each pest organism individually, which is a resource- and time-intensive exercise. Biological invasions occur without much warning, allowing little or no time for a species-specific primary study. In most cases, authorities find themselves having to make urgent decisions using readily available information (i.e. value transfer method), which may lack precision yet provides some guidance.

Given this background, we present a general framework for biosecurity decision analysis that combines portfolio theory with the monetary benefits obtained from a stated choice study. Our framework offers three advancements to the previously applied frameworks. First, it illustrates an example of a portfolio analysis that is compatible with the asset-based strategy of biosecurity decision-making. This approach is particularly useful for making resource allocation decisions across multiple pests that affect multiple environmental assets. Second, it incorporates multiple sources of uncertainty in the decision analysis. Previous applications focused only on biophysical uncertainty. Uncertainty may also be embedded in the economic value estimate, which plays an important role in determining an efficient resource allocation decision. Finally, it demonstrates a generic approach to design a choice experiment study to estimate monetary values of a broad group of environmental assets. These generic values can be combined in a portfolio-based decision support tool to identify a set of efficient asset portfolios.

The rest of the paper is organized as follows. Section 2 presents the analytical framework. Section 3 describes the case study followed by the development of the stated choice exercise in Section 4. Section 5 describes the survey and sample characteristics. Section 6 sets out the results of the choice experiment. Section 7 presents the results obtained from the portfolio analysis. Section 8 discusses the results and draws concluding remarks.

2. Portfolio Theory Framework

To keep the illustration simple, we confine the scope of the portfolio analysis to non-market goods and to a homogeneous geographic region (e.g. a bioregion). Note that this exercise can be extended to multiple regions by adding an additional layer to allow spatial mapping (see Yemshanov et al., 2014 for more details). We present a hypothetical case using a portfolio (A) consisting of three environmental assets (j) namely, native plant and animal species, landscape and water bodies and recreational opportunities in backyard and outdoor areas. These environmental assets are vulnerable to invasion risk posed by three broad groups of exotic pests (S) namely vertebrate, invertebrate and terrestrial and aquatic weeds. We assume that vertebrate pests pose threat to native plant and animal species; terrestrial and aquatic weeds reduce esthetic and recreational values of landscape and water bodies; and invertebrate pests impede recreational opportunities in backyard and outdoor areas. The decision problem is to allocate a fixed amount of biosecurity budget (B) to alternative biosecurity measures in a way that would protect these assets from invasion risks.

Three sources of uncertainty are identified in the decision framework. They are scenario, impact and value uncertainty. Scenario and impact uncertainty refer to the biophysical aspects of invasion, that is, whether an invasion actually occurs and, if it does, the way it manifests in the biophysical system in terms of its duration, spread and extent of negative impacts on native species. Value uncertainty refers to the uncertainty about the economic value of an environmental asset. According to the random utility maximization model (McFadden, 1974), the indirect utility (U) obtained from an environmental asset can be partitioned into an observable (V) and an unobservable, or random, component (ε). Due to the presence and influence of the unobservable component, non-market values cannot be estimated with certainty.

The probability distribution function of pest S_j, which is harmful to asset j, to enter, establish and spread in a region is given by:

$$P(S_j) \sim f\left(\mu_{S_j}, \sigma^2_{S_j}\right) \tag{1}$$

where μ_{S_j} is the mean probability (or risk) and $\sigma^2_{S_j}$ is the measure of uncertainty. The magnitude of harm (X) that pest S_j inflicts on asset j can be expressed as:

$$X_j \sim g\left(\mu_{X_j}, \sigma^2_{X_j}\right) \tag{2}$$

where μ_{X_j} refers to the most likely (best guess) harm and $\sigma^2_{X_j}$ refers to the uncertainty around the most likely estimate of harm. Likewise, the non-market value of the harm to asset j can be written as:

$$Y_j \sim h\left(\mu_{Y_j}, \sigma^2_{Y_j}\right) \tag{3}$$

where μ_{Y_j} is the mean economic value of the harm measured in terms of household's willingness to pay to protect an environmental asset and $\sigma^2_{Y_j}$ is the variance or uncertainty around the mean economic value.

Central to portfolio theory are the expected returns of the individual portfolio assets, their standard deviations (uncertainty) and the correlation between the returns of the assets involved. However, the concept of 'returns' used in traditional investment portfolio models need some adjustments for it to be translated to a biophysical context. In the current context, 'return' is defined as the economic value of the avoided damage to an environmental asset (Hafi et al., 2013). In other words, it measures the difference in economic value of the expected damage under the status quo and a policy scenario.

Accounting for the three sources of uncertainty stated above, the expected avoided damage (D) to asset j is given by:

$$E(D_j) = \sum_{k=1}^{m} (P_k(S_j)) * E(\Delta X_j) * E(Y_j). \tag{4}$$

In Eq. (4), k ($=1, \ldots, m$) depicts a set of biophysical scenarios (e.g. wet versus dry condition) that allows altering the distributional assumption of the probability of invasion to occur in a specific geographical region. ΔX_j is the difference in physical harm to environmental assets between the current and changed policy option.

Information about the distributions of $P_k(S_j)$ and ΔX_j can be obtained from biophysical models (e.g. Caley et al., 2014, 2015). Estimates of Y_j can be obtained from a choice experiment study. Variance around D_j