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Optimizing provision of ecosystem services using modern portfolio theory

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ABSTRACT

Portfolio selection is a flexible tool that can be used to support natural resource decision-making to optimize provision of ecosystem services. The natural resource portfolio literature includes applications in fisheries, forestry, agriculture, spatial planning, invasive pest and disease surveillance, climate change adaptation, and biodiversity conservation, among others. We contribute to this growing literature by proposing a set of essential questions to guide the development and implementation of empirical portfolios for natural resource management that deal with (1) the nature and objectives of the portfolio manager, (2) the definition of assets to be included in the portfolio, (3) the way in which returns and risk are measured and distributed, and (4) the definition of constraints in the programming problem. The approach is illustrated using landings data from the Colombian Pacific, a data limited fishery, to set catch limits in fisheries at the ecosystem level. We also develop a set of constraints in the programming problem to simulate potential policy options regarding resource sustainability and social equity. The resulting efficient catch portfolios can be used to optimize the flow of provisioning ecosystem services from this fishery.

1. Introduction

Use of natural resources and the ecosystem service flows they provide often requires the balancing of alternative actions and their associated payoffs. Private users face choices with different costs, benefits, and levels of risk. For instance, farmers must choose among crops to be planted and fishers must choose which species to target while considering variation in weather, prices, input costs and other factors. But in a society where public trustees manage use of natural resources, the responsibility for many of these decisions rests almost entirely on policy-makers. Therefore, natural resource trustees must make the same choices that individual farmers, fishers, and foresters make daily, except at a larger scale that sometimes includes entire landscapes or seascapes, and for planning horizons which may affect multiple human generations. Portfolio selection is a tool that can aid natural resource managers in their decision-making by weighing returns and risks of different strategies to find the actions that optimize the provision of ecosystem service flows.

The portfolio approach has its roots in financial economics where investment managers choose from among a pool of assets with varying rates of return. Markowitz (1952) and Roy (1952) recognized that investors could ameliorate their risk by holding a variety of assets whose returns are not perfectly correlated. In addition, they proposed variations of the portfolio selection model to systematically choose the combinations of assets that would yield the maximum returns at the lowest possible risk. In recent years, the portfolio selection model has been proposed and illustrated as a tool for managing natural resources to yield the highest possible returns—in terms of ecosystem services—at minimum risk.

Modern portfolio theory has been proposed as a tool for managing a wide range of ecosystem services and related natural processes including biodiversity conservation (Figge, 2004; Koellner and Schmitz, 2006; Hoekstra, 2012), fisheries (Larkin et al., 2003; Edwards et al., 2004; Sanchirico et al., 2008; Johnson et al., 2013;

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Gourguet et al., 2014), forests (Knoke et al., 2005; Knoke and Wurm, 2006; Knoke, 2008; Matthies et al., 2015), agriculture (Castro et al., 2015; Knoke et al., 2015), spatial planning (Hills et al., 2009; Halpern et al., 2011), invasive pest and disease surveillance (Prattley et al., 2007; Yemshanov et al., 2014), and conservation under climate uncertainty (Crowe and Parker, 2008; Ando and Mallory, 2012a; Mallory and Ando, 2014; Shah and Ando, 2015). Ecologists have also recognized a portfolio effect at work in natural systems, by which communities with high diversity tend to produce more stable streams of ecosystem services (Tilman et al., 2006; Schindler et al., 2010; Anderson et al., 2013). Balvanera et al. (2014) provide an overview of the evidence linking biological diversity to stability in provision of ecosystem services. Akin to investors, ecosystems appear to benefit from holding a diverse set of assets, as the effects of natural variability are partially dampened by diversification.

To help guide the development and implementation of portfolios for natural resource management, we briefly review the portfolio selection model and develop a series of essential questions for using this approach to optimize provision of ecosystem services. We discuss the importance of these essential questions and how available data and intent of the decision-maker dictate how these questions are to be answered. These answers determine the type of portfolio model that results and the kind of management questions that can be analyzed with each model. Finally, we provide an illustration of the approach dealing with the choice of Total Allowable Catches (TACs) of different fish and shellfish species in the marine ecosystem of the Colombian Pacific Coast. Our application of the portfolio selection approach also illustrates the use of constraints on the optimization problem to simulate potential policy options regarding resource sustainability and social equity.

This paper contributes to the growing literature on using portfolio selection theory to manage natural assets and optimize the flow of ecosystem services by providing a guide that researchers and practitioners can follow to construct ecosystem service portfolios. In addition, we demonstrate how constraints on the decision variables can be incorporated into portfolio selection analysis to simulate potential policy options.

2. Portfolios for natural resource management

Portfolio selection can be applied in situations where multiple management options are available, each with their own observable stream of potential payoffs. For our purposes, we refer to each of these options as an asset, and the payoff from each asset is referred to as the asset's return. In such situations, the decision-maker must choose which assets to invest in. The deciding agent, whom we refer to as the portfolio manager, is presumed to be seeking high returns at low levels of risk. Portfolio managers trading in financial markets can choose from among a myriad of assets such as bonds, stocks, derivatives, futures, options and swaps (Cvitanic and Zapatero, 2004). For each of these assets, the investor has expectations regarding returns and the variation in those returns. Observations of past returns, coupled with other information at the investor's disposal, are often useful in the formation of these expectations.

The starting point for portfolio selection is a vector of expected returns from the n available assets at time t, denoted $\mu(t)$, and a matrix of covariances in asset returns at time t, denoted $\Sigma(t)$[1]. In practice, portfolio developers generally rely on time series data of returns in past time periods to obtain the vector of expected returns and the covariance matrix. If historical observations on returns do not exist, returns can be simulated using computational methods (Ando and Mallory, 2012a; Mallory and Ando, 2014; Shah and Ando, 2015) or derived through non-stochastic methods (Knoke et al., 2015). If the asset's series is perceived to be stationary, a measure of central tendency can be used to obtain the expected returns. If the series is non-stationary or if recent time periods are expected to have a stronger influence on the value and covariance of expected returns, portfolio developers can use methods such as exponential smoothing, vector autoregression, or conditional heteroskedasticity (Sanchirico et al., 2008) to improve the performance of their selection models.

The portfolio manager then chooses a vector of weights for all assets, denoted $c(t)$, which dictates how much of the asset is purchased or held. In financial portfolios, the weights determine what portion of the total investment is allocated to purchasing each asset. The expected returns of the portfolio are given by

$$E(R_p) = c(t)'\mu(t) \tag{1}$$

which is essentially a weighted average of the returns of all assets included. Similarly, the variance of the portfolio, which is seen as a measure of the inherent risk, is given by

$$V_p = c(t)'\Sigma(t)c(t). \tag{2}$$

The efficient, or minimum risk set of portfolios can be found by choosing the $c(t)$ vectors that solve the programming problem

$$\begin{aligned} &\text{Minimize} \quad c(t)'\Sigma(t)c(t) \\ &\text{Subject to} \quad c(t)'\mu(t) ges M(t), \end{aligned} \tag{3}$$

where $M(t)$ is a minimum expected return target that can be iteratively changed to recover the set of $c(t)$ vectors that solve the problem for a wide range of expected portfolio returns. Additional constraints can be placed on the programming problem to obtain solutions that reflect the objectives and limitations of the portfolio manager. For instance, financial portfolio managers may include a constraint $c(t) \geq X(t)$ to require the investments to be larger than a pre-specified quantity $X(t)$, or $c(t) \leq X(t)$ to require these investments to be smaller than the same pre-specified quantity. Similarly, portfolio managers may wish to require investments to be non-negative to ensure that no short sales are allowed, and would impose $c(t) \geq 0$ as a constraint. Since the portfolio weights are interpreted as proportions of the total investment, the portfolio manager can also ensure that all investment resources are utilized by setting $\sum_i c_i(t) = 1$. a constraint.

There are some important elements in which the application of portfolio selection to natural resources diverges significantly from its use in finance. Natural resource managers may be acting on behalf of society rather than as private individuals, and their motives may not always be profit-related. Differences in the manager's objectives and physical limitations on managers and resources will dictate programming constraints of a very different nature. These differences hint at four essential questions that deal with (1) the nature and objectives of the portfolio manager, (2) the definition of an asset to be included in the portfolio, (3) the way in which returns and risks are measured and distributed, and 4) the definition of constraints in the programming problem. These four questions, whose answers are inter-related, are discussed in turn.

3. Four questions for portfolio development

3.1. Who is the portfolio manager?

Financial portfolio managers are generally investors acting on their own behalf or that of some other individual with the

[1] For the exposition of portfolio theory in this section we focus on the mean-variance portfolio framework most often encountered in the literature; however, as is discussed later in the article, variance is not the only measure of risk applicable to portfolio theory. In some instances, downside measures of uncertainty are more appropriate based on risk preferences and the distribution of asset returns.