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Payal Shah
Okinawa Institute of Science and Technology

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The Economics of Conservation and Finance: A Review of the Literature

Amy W. Ando[1] and Payal Shah[2]*

[1] *Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA and Resources for the Future, Washington, DC 20036, USA; amyando@illinois.edu*
[2] *Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan; payal.shah@oist.jp*

ABSTRACT

This article summarizes key insights into conservation that come from the intersections of economics and finance: public finance, conservation finance, and financial theory applied to problems of conservation. We discuss some of what has been learned from the study of conservation and finance that helps us to understand when, where, and even whether conservation activities should occur; portfolio theory has been harnessed to help guide conservation planning under uncertainty, and real options theory helps us understand whether to commit to conservation or to wait. We distill some of the extant research on how resources can be gathered to support conservation through local referenda, payment for environmental service programs, private donations, user fees, and value capture through property taxes. The article concludes with suggestions for promising future directions in this area of work.

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1 Introduction

Individual species, biodiversity, and natural habitats provide a wide range of values to humanity. People are often willing to pay to protect endangered species even when they gain no direct use value from them (Kotchen and Reiling, 2000). Biodiversity has intangible value (Gowdy, 1997) and benefits for society in increasing ecosystem services like natural control of agricultural pests (Letourneau *et al.*, 2015); ecosystems like wetlands (Woodward and Wui, 2001) and forests (Pearce, 2001) provide a wide range of provisioning, regulation, and recreational benefits.

Species and habitats are widely damaged and threatened by human activities. In some cases, like hunting, fishing, or logging, the direct goal of the activity is to kill animals or harvest trees. Unless carefully managed, such activities can drive species populations to inefficiently low levels and even lead to extinction. Other human actions claim species and habitats as inadvertent collateral damage — expansion of agricultural production converts areas of natural habitat to managed fields, urban development eats away at the natural areas that surround centers of human populations, and intensive water use drains groundwater supplies and reduces flow rates in rivers and streams. Much has already been lost and the loss continues. Humans are accelerating species extinction rates (Dirzo *et al.*, 2014; Pimm *et al.*, 2014) and ecologists worry that whole biomes are threatened as more than 20% of all land area on the globe has been converted away from its natural status (Hoekstra *et al.*, 2005).

Policies like the Endangered Species Act of 1973 and fishery regulations attempt to regulate some human activities that directly harm species populations. However, early work (Fisher and Krutilla, 1975; Fisher *et al.*, 1972; Krutilla, 1967; Scott, 1955) kindled recognition

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among economists that general preservation needed to be taken seriously as a problem for economists. Economics can help us to think about policies to encourage limits on actions that have negative externalities in the form of species and habitat destruction, and economics makes clear that the public good nature of habitat and species means that concerted effort is needed on part of government and nonprofit organization to promote protection of natural areas. But how much conservation do we need? And where? And how do we marshal the resources needed to accomplish sufficient conservation given the public choice problems present in public good provision?

Economists have contributed much to research on species and habitat conservation. Most of that work is grounded in mainstream economics or multi-disciplinary work with conservation biologists, with extensive (and extensively reviewed) strands of research on optimal reserve-site selection (Boyd *et al.*, 2015), estimating the values people derive from the things we preserve (Richardson and Loomis, 2009), and policy evaluation and design (Ferraro *et al.*, 2007; Langpap, 2006; Polasky and Doremus, 1998).

This article will summarize key insights into conservation that come instead from the intersections of economics and finance: public finance, conservation finance (as known by people in the nonacademic world who are working actually to make resources for conservation possible), and financial theory applied to problems of conservation. We discuss some of what has been learned from the study of conservation and finance that helps us to understand when, where, and even whether conservation activities should occur and how resources can be gathered to support conservation at efficient levels. We conclude with suggestions for promising future directions in this area of work.

2 How Can Conservation Be Financed?

Theory tells us that democratic processes may not yield efficient outcomes for environmental policy and public good provision (Cornes and Sandler, 1996; Samuelson, 1954). Certainly some conservation is accomplished for the public good through federal government purchase of either the titles to lands or conservation easements and agreements. In the United States, for example, great swaths of land are permanently protected by the government as national parks and yet more land is temporarily protected by government-funded programs such as the Conservation Reserve Program (CRP). However, Anderson and King (2004) show that conservation easement programs do not necessarily lead to optimal conservation outcomes. Albers *et al.* (2008) further illustrate scenarios in which public conservation spending can be welfare reducing if it crowds out private conservation efforts. Thus, it seems clear that the amount of conservation provided by large government agencies and programs does not satisfy public demand for protecting or restoring nature. But how, then, can sufficient resources be directed toward conservation to achieve efficient levels of protection?

Many mechanisms exist to accomplish conservation through means other than pure government purchase of lands. For example, Tallis *et al.* (2009) quantified characteristics (threats, goals, funding, and implementation mechanism) of over 100 conservation projects implemented by international organizations. While many of these projects use conventional government land acquisition to accomplish the conservation goals, the toolbox of mechanisms was diverse and included methods such as developing markets to encourage sustainable management practices (say, through certification programs) and making payments (either private or public) for provision of ecosystem services on private lands. Here we discuss a range of tools that could be used to accomplish conservation goals without government coercion (such as tradable development rights programs or zoning laws), beginning with methods that have attracted significant research attention and moving towards discussion of tools that might warrant more exploration by economists.

2.1 Local referenda

The public choice problem thwarting efficient provision of public goods is likely to be most severe at aggregated levels of government that serve heterogeneous populations. Tiebout (1956) posed the notion that people would "vote with their feet" and gravitate toward communities that provided levels of public goods consistent with their preferences, and that sorting would be associated with local provision of many public goods such as education and, as it turns out, conservation. A wave of local provision of open space conservation occurred in the years around the turn of the twenty-first century. Between the years 1989 and 2014, 2163 local referenda for conservation funding were held and 1856 of them passed, raising about $70 billion in funds (bonds and taxes) for conservation (TPL, 2015).

Several papers carried out econometric analyses of national data on this wave of local referenda to understand what features of a community make it more likely to have taxed itself to finance conservation of local open space (Banzhaf *et al.*, 2010; Kotchen and Powers, 2006; Nelson *et al.*, 2007). Heintzelman *et al.* (2013) provides a nice review of the early literature on this subject beginning with Deacon and Shapiro (1975), and adds spatial dependence and analysis of timing to the mix of methods in this area of research. While the results vary slightly with details of the analyses, the overwhelming message of this body of work is that such funding is most likely to emerge in places that are losing open space rapidly and where the residents are wealthy and well-educated.

The magnitude of resources directed by local referenda toward conservation has created much excitement in the conservation community, but this tool is not a silver bullet. Several of the papers point out that strategic conservation planning might not prioritize open-space protection so disproportionately in areas with those demographic features, though Banzhaf *et al.* (2010) do find that referenda appear preferentially in places with numerous endangered species and surface water resources. That paper goes further to suggest that a large-scale conservation group trying to target communities in which to encourage conservation referenda could benefit by focusing efforts less disproportionately on wealthy, white, Northeastern communities and more towards communities in the Southeast with significant minority populations. However, theoretical work by Warziniack (2010) finds that in the presence of spillovers of conservation benefits among communities, local provision of open space by majority voting is unlikely to achieve efficient provision of conservation — many conservation projects that would be welfare improving will fail to pass a majority vote. Local referenda alone will not be sufficient to finance efficient levels and patterns of conservation.

2.2 Payment for Environmental Service (PES) Programs

Many conservation activities can be categorized as PES programs. This conservation approach leaves resources in private hands, but pays land owners to change something about the way they manage their lands. Fee-simple purchase of land is expensive as one must compensate land owners for the indefinite flows of all the uses of the land they are relinquishing in order to buy it. PES strategies might help conservation funds go farther by allowing land owners to retain title and many uses of the lands.

Many papers have studied the efficient design and effectiveness of PES programs (see Pattanayak *et al.* (2010) and Ferraro (2011) for reviews). We focus here on other questions regarding the potential for PES programs to help solve the problem of adequate financing of conservation.

While PES programs may be more cost-effective than fee simple purchase and retirement of lands, someone still needs to pay for the payments. Some national PES policies, like the U.S. CRP, are paid for by federal tax revenues, and many others are funded by the largest environmental nonprofit groups like The Nature Conservancy and the World Wildlife Fund. However, one virtue of the PES mechanism is that it helps society to leverage funds from a wide array of sources rather than relying exclusively on government tax revenues or large NGOs. Kaplowitz *et al.* (2012) review research indicating that many small communities in developing countries have high willingness to pay (WTP) to improve watershed-based ecosystem services. That paper's own dichotomous-choice contingent value survey research in Costa Rica finds evidence that some small communities in developing countries are likely to be able to self-fund localized PES schemes to improve the quality of water resources on which they depend.

While benefits from watershed improvements may accrue largely to local people such that local funding is a viable option, other benefits of conservation (nonuse values of biodiversity, climate regulation values from carbon sequestration) accrue to all humanity. Thus, funding mechanisms are needed to capture at least some of the value that accrues to populations across the globe to compensate landowners in places like the Amazon and Indonesia for providing them. Farley and Costanza (2010) review the limited funding mechanisms that exist for global-scale international PES programs and explore potential alternatives. They suggest solving two environmental problems at once by using an international cap-and-auction system to limit global CO_2 emissions, and then using the auction revenues to fund a PES program to encourage biodiversity conservation and carbon sequestration on private lands.

For-profit firms in the private sector may be willing to invest in PES programs under two different conditions. For example, Koellner *et al.* (2010) surveys a wide range of companies, and finds that many would voluntarily be willing to invest (WTI) in PES programs in Costa Rica that conserve biodiversity, sequester carbon, protect scenic beauty, and safeguard watersheds but the magnitude of voluntary demand is low. In a less voluntary twist, point sources of environmental degradation can be convinced to provide payments to nonpoint sources if a market for offsets is established and it is cheaper for the point source companies to pay others to carry out required mitigation rather than doing it themselves (Ribaudo *et al.*, 2010).

Details of PES finance and payment design are critical determinants of how efficiently they function to provide conservation. On the finance side, Roumasset and Wada (2013) develop a dynamic theoretical model in which groundwater users are taxed to finance payments to people upstream to promote groundwater recharge. They find that joint welfare in the system is higher if users are charged a fixed tax that does not vary with the amount of the ecosystem service (i.e., groundwater) that they use so that their use behavior is not distorted. On the payment side, lower payments may be needed to induce landowners to re-enroll in fixed-term PES agreements if social norms can be harnessed such that each landowner feels pressured by the belief that their neighbors are likely to re-enroll (Chen *et al.*, 2009). And when the benefits produced by conservation actions depend on the spatial pattern of conservation activity in a landscape, total benefits can be higher if the payments of a PES service account for spatial dependence with agglomeration bonuses (e.g., Drechsler *et al.*, 2010) or an auction mechanism in which the payment a landowner receives is a function of the benefits actually produced by their conservation action (Polasky *et al.*, 2014).

One particular question surrounding PES programs remains an issue of dispute: when a single management or conservation actions produces multiple benefits, should landowners be permitted to receive payments for more than one of those benefits? The practice of giving multiple payments for a single action can be called "stacking," "bundling," or "double-dipping" depending on the rhetorical objectives of the writer, but it is always controversial because if a payment does not display "additionality" (e.g., it stimulates more conservation than would have been done in the absence of that payment) then one can argue the money would have produced more benefits if it were spent elsewhere. Woodward (2011) tackles the issue of stacking in a general theoretical framework with continuous marginal benefit and marginal cost functions, and finds that stacking of payments for pollution abatement leads to the best outcome for society if (but only if) all sources of the pollutants are covered by the programs and the pollutant caps are set optimally. Lentz *et al.* (2014) and Robertson *et al.* (2014) find in the case of payments for wetland services, stacking of payments for multiple services may or may not improve welfare depending on idiosyncratic details of the situation. It seems that no general prescription exists for whether social welfare is increased by letting PES programs stack payments.

One particular form of payment bundling raises a slightly different set of concerns. In the absence of large, stable funding for conservation efforts in developing countries, many conservation groups have turned to international payments from projects that protect or enhance sequestered carbon in forests and promote sustainable management (REDD+). Wendland *et al.* (2010) show potential value in bundling payments for biodiversity with payments for carbon sequestration in Madagascar. However, Phelps *et al.* (2011) warn that this strategy has risks, and argue that conservation projects should use diversified sources of funds rather than relying exclusively on REDD+ funding that has necessary long-run uncertainties.

2.3 Other Conservation Mechanisms

While PES programs have been heavily studied by economists and widely implemented in the field, analysis of flows of funds through such programs indicates that this funding mechanism in its current form and scale is unlikely to generate sufficient funds for efficient levels of biodiversity conservation worldwide (Hein *et al.*, 2013). Here we discuss research on other possible mechanisms for accomplishing conservation, all of which are good targets for further investigation. User fees and value capture through property taxes extract financial resources from people who gain direct value from the conservation, while private philanthropy and voluntary corporate action are forms of purely voluntary financing.

2.3.1 Value capture

A general principle in local public finance is that municipalities can sometimes finance investments in public goods such as subway lines and expanded roads through increased property tax revenues on lands that have increased values as a result of those investments. A similar principle could be harnessed to finance conservation, so we ask, how can communities or park owners capture the value of conservation and open space to provide the funds needed to create and maintain protected areas? Theoretical work by Ando and Shah (2010) indicates that the actual value to people of reserves (and thus the potential for protected area managers to gain financial support for those reserves) will be higher if reserves are located strategically in proximity to human populations when amenity values are subject to distance decay.

Empirical work helps us to understand whether the values created by conservation could be captured by taxes on increased land values and provide meaningful finance for conservation activities. Heintzelman (2010) and Geoghegan *et al.* (2003) use hedonic analysis of land values to identify explicitly how open space and preservation increase the values of properties nearby, and the latter paper finds that increased property tax revenues from additional land conservation could indeed fund much (though not quite all) of that conservation. Balsdon (2012) combines a theoretical model of municipal demand for conservation and rent-seeking land-supply restriction with an empirical analysis of conservation referenda in the Northeast. He finds evidence that demand for conservation is motivated both by WTP for environmental amenities and by land owners seeking to drive the values of their homes up by restricting supply. This reminds us that while tax revenues will increase on developed or developable lands in response to investment in conservation and that increase will be larger than the tax rates multiplied by the capitalized value of the conservation amenity, tax revenues may fall on the areas that have development restricted. However, in a Vermont case study, King and Anderson (2004) quantify the net effects of conservation easements on property tax rates over time and find that while conservation easements force property rates to rise initially, the long run effect of easements on property tax rates is negative or insignificant.

2.3.2 User fees

Some individuals benefit very directly from conservation in settings with recreational value as they make use of protected and improved resources for hiking, fishing, hunting, birdwatching, and scenic experience. Some conservation has always been funded through fees in the form of small entry fees for national parks and hunting and fishing licenses. However, extractive use of wildlife is in a long secular decline; the resulting loss of fee revenue poses a major challenge to state conservation and wildlife management agencies who have long relied on those funds (Bissell *et al.*, 1998). Could increasing or creating other kinds of user fees usefully increase revenues for creating and maintaining protected areas? Research suggests that user fees have potential as a tool for conservation finance, but with limitations. First, there are large transaction costs in levying relevant fees on some kinds of users of wildlife. Viewing areas for birdwatchers are highly dispersed and the equipment needed to engage in birdwatching is minimal, so collecting fees from such nonextractive users would be challenging; McFarlane and Boxall (1996) propose alternative mechanisms (volunteering, management information provision) to extract value from birdwatchers and contribute toward conservation support, but that source of conservation finance resources remains underutilized. Work by Johnston *et al.* (1999) highlights a concern that must be addressed if user fees are to be accepted as a conservation finance mechanism; citizens must have faith that funds raised through such fees will actually be used to support the resources for which they are ostensibly levied.

Second, scholars and managers have long been concerned about the equity characteristics of extensive user fees for public lands. Richer and Christensen (1999) use survey research to quantify the tradeoff between revenue and participation associated with the magnitude of park fees, presenting managers with a menu of options. The severity of that tradeoff is likely to vary from one case to another. While Thur (2010) and Baral *et al.* (2008) find that the visitor fees at Bonaire National Marine Park and at Annapurna conservation area in Nepal could be much increased without hurting visitation, More and Stevens (2000) find survey evidence that increased user fees would significantly crowd low-income families out of public recreational areas in New Hampshire and Vermont. The key to that heterogeneity may lie in the fact that simply traveling to Bonaire or Nepal is extremely expensive and the recreational activity there (scuba diving, mountain climbing) involves costly equipment; the populations that self-select into those recreational markets may be much less price sensitive than the average family who drives a few hours to go hiking in the woods of Vermont.

Note that user fees are not limited to public lands. Ribaudo *et al.* (2010) review research on demand for access to private agricultural lands for hunting, and observe that while any hunters use such lands and would be willing to pay for the access, few farmers charge fees. Widespread guidance to help farmers reap financial benefits from fostering wildlife populations on their lands could increase private provision of wildlife stewardship. However, the promise of fee revenue will not work to motivate private land owners to steward their land for recreational access unless legal issues are resolved such that charging fees does not trigger enhanced liability for the landowners (Mozumder *et al.*, 2007).

2.3.3 Private donations

Because of the public-good nature of conservation benefits, neoclassical economic theory suggests that private philanthropy will not be sufficient to fund efficient levels of conservation activity. Nonetheless, individuals do contribute to a wide range of environmental and conservation NGOs, some of which are able to translate those funds into significant shares of global conservation. Could policy makers and nonprofits themselves take steps to increase the role that private philanthropy plays in financing conservation? At least some research has explored the answer to that question, including extensive work from experimental economics. In his review of the literature on charitable giving in general, List (2011) suggests that contributions could be increased by enhancing the tax deductibility of donations, and that donation campaigns are more effective when tools like seed donations and matching grants are used. Poe *et al.* (2002) review and add to the literature on different mechanisms to elicit private contributions to public goods. Simple voluntary contribution mechanisms yield serious underprovision relative to true willingness to pay, while adding a provision point mechanism (a total contribution level — or provision point — below which the good is not provided at all) reduces free riding. Swallow *et al.* (2008) give a background on research into how to induce private actors to pay for the environmental services from which they benefit, including a discussion of results obtained from a field experiment regarding multiple market mechanisms to fund conservation of grassland birds. Yen *et al.* (1997) carry out econometric investigation of actual donations to environmental groups by households in parts of Canada, and find that donations to wildlife conservation would be negatively affected by declines in hunting activity and total expenditures on wildlife recreation; thus, cultivating outdoor activity may be an important factor in increasing donations to wildlife conservation. A more cautionary tale emerges from the work by Kits *et al.* (2014), who find experimental evidence that participation in a conservation auction — as one might find in a PES program — causes voluntary donations to decline.

2.3.4 Voluntary corporate action

The field of environmental economics has a large literature on voluntary corporate programs to be more environmentally friendly. However, most research has focused on programs to reduce toxic pollution, carbon emissions, and energy use rather than habitat and species loss (Kitzmueller and Shimshack, 2012). A few exceptions hint that more work could be done in this realm. Benabou (2014) reviews the emerging area of voluntary biodiversity offsets. Ruysschaert and Salles (2014) critique the effectiveness of voluntary habitat conservation standards in the palm oil industry. Moles (2003) reviews the potential for venture capital to be a bigger player in the world of conservation finance. Meissner (2013) uses a model of noncooperative game theory with coalitions to study whether an international market in protected area certificates could effectively stimulate private firms to reduce rates of ecosystem destruction through the twin incentives of cultivating a green image and reducing exposure to risk from actual environmental damage, and finds that credible product labels are critical for reducing free riding in this game.

3 Insights From Finance: Whether, When, and Where Should Conservation Happen?

As discussed in the introduction to this piece, much research in economics has explored questions of whether and where to carry out conservation activities. However, the standard paradigms of that research do not work well in the current state of the world in which massive uncertainty about the extent and nature of future climate change creates similarly great uncertainty about how ecosystems will function and where species' ranges will be. Theoretical and decision tools from finance are well suited for decision making under uncertainty. Scholars are beginning to translate some well learned lessons from financial theory into more efficient conservation management strategies that better address whether to take up a particular conservation initiative and if yes, when and where limited conservation resources should be targeted. Portfolio theory and option value theory are two particular financial tools that are being used increasingly to guide conservation planning in uncertain scenarios.

3.1 Portfolio Theory To Manage Uncertainty: Where and What to Protect?

Portfolio theory is traditionally used to manage investments in financial assets such as stocks or bonds in order to minimize risk (for a given level of desired returns) or maximize returns (for a given level of desired risk). Modern portfolio theory (MPT) uses information about the joint probability distributions of outcomes for all possible assets (including means, variances, and co-variances of returns) to select a portfolio that efficiently manages risk (Markowitz, 1952). Uncertainties in ecological and conservation outcomes result from a wide range of environmental (e.g., species survivor possibility, climate change uncertainty) and/or economic (e.g., future price of land, possibility of conversion) factors. To manage the chances of large unanticipated losses, conservation planning needs to account explicitly for these uncertainties. Studies show that explicit treatments of uncertainty in model parameters lead to different management and conservation decisions (Doyen and Béné, 2003; Grafton and Kompas, 2005; Lande *et al.*, 2003; McCarthy and Possingham, 2007; Regan *et al.*, 2005). In recent work, portfolio theory has been adapted from finance to ecological and ecosystem conservation settings for choosing management strategies that allow decision makers to reduce the tradeoffs between risk and returns.

3.1.1 Portfolio theory in ecological settings

Management of ecological assets and ecosystem services is in many ways similar to financial portfolio management. They both target high returns while minimizing risk under uncertainty. While in finance, assets represent stocks, bonds or commodities, in environmental settings, one can think of "assets" as genes, populations, species, or landscapes that have some inherent risks and returns. MPT has been applied to several ecological and conservation biology contexts including species and gene conservation (Figge, 2004; Koellner and Schmitz, 2006), fisheries management (Griffiths *et al.*, 2014; Moore *et al.*, 2010; Schindler *et al.*, 2010), and forest conservation (Crowe and Parker, 2008; Moloney *et al.*, 2011). Figge (2004) recognizes the need for diversification of genes, species, and ecosystems and uses portfolio theory to construct a "bio-folio" of species as a way to manage risks to biodiversity. Koellner and Schmitz (2006) use grasslands as an example to analyze the bio-folio concept of treating species as assets in an ecosystem portfolio. Crowe and Parker (2008) use MPT to design a planned adaption strategy using a case study of regenerating white spruce forests based on modeled seed performance and adaptation data under several different climate change scenarios. Moloney *et al.* (2011) use portfolio selection to evaluate whether including kangaroo harvesting into a mixed-grazing strategy is beneficial for Australian pastoralists. Griffiths *et al.* (2014) use portfolio theory to evaluate the most efficient salmon fishery portfolio based on long-term data of variability of salmon returns across and within individual salmon populations. Schindler *et al.* (2010) use portfolio theory to show the importance of population diversity in maintaining a healthy ecosystem and accommodating for the larger needs of the dependent economies using data for the sockeye salmon. Akter *et al.* (2015) apply portfolio theory to decisions regarding biosecurity (or pest control) and uses a choice experiment to monetize different benefits; however, the analysis does not shed light on WTP to reduce uncertainty, and thus cannot be used to help decision makers choose among multiple efficient portfolios that differ in the balance they strike between risk and return.

3.1.2 Spatial conservation portfolios

Uncertainty in key economic and environmental factors, such as climate change, also poses a major challenge in the identification and selection of priority conservation regions for achieving target ecological outcomes. Recent work uses MPT to characterize optimal spatial targeting of conservation and restoration policies and investments Ando and Mallory (2012). This work exploits information about expected return, variance, and co-variances associated with ecological outcomes on different parcels of land (for a range of climate change scenarios) in the Prairie Pothole Region to design an efficient portfolio of land parcels for wetland habitat protection and restoration. They find that using MPT instead of simple diversification in the Prairie Pothole Region can achieve a much higher value of the conservation objective for the same level of risk, or reduce outcome risk for only a small reduction in the expected level of conservation benefits.

MPT-guided diversification can help manage climate-change induced uncertainty of future ecosystem-service outcomes for a broad range of land policy and investment initiatives; however, work on using MPT for conservation and land policy planning is only in its infancy. One of the biggest challenges of MPT analyses is that given a probability distribution over n discrete outcomes, the maximum number of assets that can be considered in an MPT framework is $n - 1$. Allowing for n or more assets in the portfolio optimization framework would lead to an elimination of the uncertainty from the theoretical set-up (see Ando and Mallory, 2012 for more details). Thus, one must restrict the number of assets in the portfolio to be one less than the number of outcomes available for each asset. This is generally not a problem in finance because the n for such cases is very large. However, information about the probability distribution of ecological conditions associated with climate uncertainty is difficult to gain; this can be a limiting factor in situations where the number of sub-regions in a planning horizon are greater than the number of ecological forecasts available. Knoke *et al.* (2015) try to address this problem with a type of portfolio optimization that does not use information about the probability distribution of possible future outcomes. However, that retreat from information about probabilities is not necessary; Shah *et al.* (2015) develop algorithms to achieve more efficient portfolios for fine-scale conservation planning even when information is limited.

While traditional MPT has many benefits to offer to conservationists, it is important to carefully consider some of the underlying assumptions of MPT and what it means for ecosystem and biodiversity conservation. Portfolio allocations based on MPT use a mean–variance framework and are valid for settings in which returns are normally distributed and quadratic utility function is a good approximation of investor risk preferences. However, when conservation agents are loss averse or when ecological outcomes are not normally distributed, replacing variance with appropriate downside risk measures can result in significant differences in portfolio allocations and tradeoffs between risk and expected return. Shah and Ando (2015) replace variance with a downside measure of uncertainty and illustrate the differences in efficient portfolios and risk-return tradeoffs when return distributions for sub-regions of a broader landscape exhibit skewed distribution patterns in future conservation outcomes. Portfolio theory in finance has evolved to incorporate a variety of downside risk measures (Artzner *et al.*, 1999); conservation planners should consider their choice of risk carefully when using portfolio optimization.

3.1.3 Preferences over risk and returns

MPT yields an efficient frontier as its output. The frontier is comprised of the risk-return combinations associated with each of a set of efficient portfolios from which a manager could choose. However, MPT provides no guidance to the decision maker regarding which of those portfolios might be best. In recent work, Pindyck (2014) uses indifference curves to make normative evaluations regarding the tradeoffs between reduction in expected risk and expected returns associated with long-term environmental investments. In that paper, he argues that an important factor to consider when evaluating environmental policy is the tradeoffs between expected reduction of future environmental damages (which are uncertain) and the potential of the environmental policy to reduce the underlying uncertainty in future damages. He uses indifference curves to model consumer preferences for policies aimed at reducing expected risk (i.e., the extent to which the policy can reduce the future uncertainty associated with climate change) versus expected returns (i.e., the expected value of future benefits from policy adoption). Such analyses can help conservation planners estimate the optimal risk-return tradeoffs of environmental policy and estimate the social surplus of different policy alternatives (provided we know the cost of such policy adoption).

3.2 Real Options Theory and Conservation Timing

Agents choose when to convert land or accept a PES payment, and the government needs to design conservation policy with accurate expectations about how agents will make choices in response to the options that are presented to them. Delay can be a valuable tool for people to use in coping with uncertainty. Real options is a tool that translates the lessons and tools of financial option theory to real-asset investments. This tool can be used to help us think about the best timing and duration of conservation activities. A key advantage of the real options approach is it accommodates the uncertain and often irreversible nature of long-term investment decisions. Thus, real options theory has growing relevance to conservation decision making in a world where climate change magnifies uncertainties of all kinds.

There have been a wide variety of applications of real options analysis in environmental and natural resource economics. The interactions between the uncertainties and irreversibility associated with environmental costs and benefits affect optimal policy timing and decision making (Pindyck, 2000). Real options can help explicitly account for the numerous uncertainties that exist in environmental benefits and costs as well as the often irreversible nature of environmental decisions. The real options approach recognizes that flexibility in decision making has value when new information affecting the investment or policy alternative arrives either periodically or at random intervals in the future. Traditional net present value analyses and capital budgeting techniques cannot account for such flexibility.

Real options were first used in environmental economics to understand optimal private decision making to preserve or develop wilderness or natural habitats when development is irreversible and the future value of development is uncertain (Abildtrup and Strange, 2000; Arrow and Fisher, 1974; Conrad, 1980, 1997; Henry, 1974). These studies find that the presence of uncertainty and irreversibility create significant value of delaying conversion and keeping one's options open, and highlight the importance to private landowners of waiting for more information before taking irreversible decisions to exploit or develop the natural wilderness.

Real options approaches have also provided useful insights for policy alternatives that motivate private conservation efforts such as conservation easements and reduced emissions from degradation and deforestation (REDD) programs. In previous studies, real options framework was used to evaluate the value of conservation easements when the value from the irreversible conversion alternative (e.g., agricultural use of the land) is stochastic (Fackler *et al.*, 2007; Tegene *et al.*, 1999) or to evaluate the effect of various carbon credit payment schemes on deforestation decisions when timber prices are uncertain (Guthrie and Kumareswaran, 2009). These studies estimate the level of policy instruments required to induce conservation assuming uncertain prices for the conversion option and find that conservation payments that do not consider either uncertainty are currently mispriced and that private landowners might be reluctant to engage in permanent conservation at the prices offered. Studies also show that optimal length of programs aimed at motivating private land conservation (e.g., conservation easement program) varies when uncertainty in ecological and economic conditions are explicitly accounted for (Ando and Chen, 2011; Lennox and Armsworth, 2011).

Real options are well suited to renewable and nonrenewable resource extraction problems concerned with the determination of irreversible decisions for optimal forest harvesting, mining, and fishing. Clarke and Reed (1990) derive optimal harvest rules when timber prices are assumed to follow geometric Brownian motion (GBM). Insley (2002) and Insley and Rollins (2005) consider both GBM and mean-reverting (MR) processes in timber price stochasticities for determining the optimal price of harvesting an even-aged stand of trees. Reed (1993) and Insley and Lei (2007) incorporate the risk of catastrophic events into optimal resource management models.

Various studies have also used real options analyses to study optimal species and invasive species management. Kassar and Lasserre (2004) evaluate a model in which a decision maker can choose to optimally continue with or abandon the preservation of a set of unproductive species with an option to substitute the unproductive species for more productive species. Leroux *et al.* (2009) use the real options model to evaluate trade-offs between land conversion (which results in uncertain agricultural value) and conservation (associated with biodiversity benefits) and find that including the option value of biodiversity results in a lower rate of conversion. Marten and Moore (2011) develop a stochastic optimal control framework in bio-economic control models to design optimal strategies for invasive species management in an environment of uncertainty and irreversibility. Sims *et al.* (2013) illustrate that waiting to gain more information on the extent of damages from invasive species along with the degree of irreversibilty associated with possible policy alternatives are important determinants of optimal management strategies.

Previous studies have also used real options analyses to evaluate a farm's decision to invest in efficient irrigation systems for water conservation (Carey and Zilberman, 2002; Seo *et al.*, 2008). Carey and Zilberman (2002) assume water prices follow a GBM process and find that higher uncertainty in water prices delays investment in water saving irrigation technology. Seo *et al.* (2008) explore the options to invest and disinvest in water saving irrigation technologies and find that considering a possible exit strategy or potential divestment alternative lowers the initial adoption time of water conservation systems.

Real options analyses have important implications for environmental policy to tackle climate change. Pindyck (2000, 2002) uses a real options framework to show that optimal investment in climate change mitigating technology occurs at a higher level of emissions when the uncertainty in the benefits of reduced emissions and in the accumulation of such emissions are both high. Kolstad (1996) and Fisher and Narain (2003) use the real options approach to incorporate two competing irreversibilities: the irreversibility associated with investment in climate change mitigating technology and the irreversibility of climate change itself, and uncertainty in environmental damages from climate change. Results show that investment irreversibility has a stronger effect than climate irreversibility. Indeed, incorporating more uncertainties in the conservation decision process can not only depict a more accurate picture of the problem at hand, but also result in substantially different policy recommendations than more simplistic models with fewer uncertainties (Shah and Ando, 2016; Song *et al.*, 2011).

3.3 Foundation of Financial Theory

While financial theory provides a wide variety of tools for developing better strategies for environmental conservation, the policy solutions based on these tools rely highly on the fundamental definitions of risk, discounting, and uncertainty. Weitzman (1998, 2001, 2007, 2009, 2011,

2012) challenges some of these fundamental definitions that are generally accepted in environmental policy design, especially as they are related to climate change. This work can critically inform analyses of whether we should engage in certain conservation and environmental policies. A key ingredient of climate change, and other environmental policies, is the use of an appropriate discount rate in the cost–benefit analysis of long-term investment projects. Weitzman (1998, 2001) argues in favor of a low discount rate for weighing long-term investments because this is the only limiting scenario as far as current conditions are concerned. All other scenarios with higher discount rates are relatively less important today because of their resulting lower net present value. In contrast, Gollier (2004) illustrate that the most efficient discount rate in an uncertain future is one that increases with time. These opposing views (what has come to be known as the Weitzman–Gollier puzzle) were finally resolved to show that indeed the appropriate long term discount rate over time decreases towards its lowest possible value (Gollier and Weitzman, 2010). Arrow *et al.* (2013) further investigate the sensitivity of cost–benefit analyses for long-term environmental projects to the discount rate and provide evidence for using a declining discount rate over time.

Weitzman (2007) explores how parameter uncertainty can drastically affect the shape of assumed distributions based on realized data to the extent that previously assumed normal distributions with relatively thin tails can transform into fat tailed distributions. Nordhaus (2011) points out that such tail events can have drastic effects on policy decisions, as it did following the financial crises of 2007–2008 after which banks shifted focus from containing individual bank specific risk to containing systemic risk. Weitzman (2009) proposes the possibility of tail events in climate change wherein for rare scenarios, the expected risk from climate change can be infinite. The existence of fat tails is further exacerbated when people are particularly risk averse. Under such conditions, using standard cost-benefit analyses is inappropriate.

In his review of the *Stern Review on the Economics of Climate Change*, Weitzman (2007) highlights the importance of further research that gathers information about thick tailed uncertainties associated with rare climate catastrophes and development of realistic emergency plans to manage such disasters. Pindyck (2007) also advocates the need for additional research on the causes and likelihoods of severe climate change outcomes. Climate change is just one of several environmental problems with the possibility of a low probability catastrophic event that results in extremely large and potentially irreversible damages. In such scenarios, one must move beyond the standard cost–benefit analyses and employ more drastic measures as indicated by Weitzman (2009, 2011, 2012, 2014), Nordhaus (2011), and Pindyck (2013).

3.4 Information Challenges

All conservation planning, both with traditional methods and the new tools we highlight here, is complicated by information limitations. Research has shown that serious problems can be caused by two particular kinds of limited information: incomplete knowledge of the monetized benefits of conservation, and incomplete or asymmetric information in conservation costs.

3.4.1 Measuring benefits

The benefits of conservation can be quantified most straightforwardly in physical terms — number of species present in an ecosystem, amount of carbon sequestered, and so forth. Economists define the values of positive changes of ecosystem goods and services to humanity as the maximum amount of money people would be willing to pay to have the ecological improvement. Many methods exist to estimate those values (Freeman III *et al.*, 2014). In practice, however, it can be challenging to develop robust estimates of some ecosystem service values and some scholars raise ethical objections to the practice (Hanley, 1992; Kareiva *et al.*, 2011). Thus, much research on ecosystem service provision and management is done without valuing some or all of the services; in one of many possible examples of this practice, Nelson *et al.* (2009) analyze tradeoffs among multiple (and possibly competing) ecosystem services in a landscape, where commodity production and carbon sequestration are monetized but biodiversity, soil conservation, storm peak management, and water quality are measured only in biophysical units or indexes.

Unfortunately, some research has begun to show how carrying out conservation planning without estimating the monetized social values of the benefits can yield decisions that are highly sub-optimal, and even welfare reducing. Vincent (2015) observes that widespread impact evaluation studies of deforestation only estimate the average treatment effect on the treated (ATT); for example, they quantify how much deforestation is avoided if a protected area is put in a particular place. He shows how if the benefits of avoided deforestation and the costs of protected areas are heterogeneous across space, then protected area prioritization motivated by ATT rankings can yield undesirable outcomes. Mallory and Ando (2014) carry out a portfolio analysis to guide allocation of conservation investment among several subregions with two different measures of the ecological benefits from conservation activity in a given subregion for a particular climate outcome: one measure is the actual social WTP for the conservation, and one measure is a stylized index which is a nonlinear but monotonically increasing function of that value. They find that portfolio recommendations are highly sensitive to how benefits are quantified; the analysis of the index measure yielded investment recommendations that were completely different from those that actually yielded the highest value to society for a given level of uncertainty. They show that portfolio recommendations are robust to using an index if, but only if, that index is a linear function of social WTP. For an index like "number of species protected," if marginal WTP for additional species is declining, then this condition will not be met.

3.4.2 Measuring costs

At least since Ando *et al.* (1998), economists have known that conservation networks will not be cost-effective if the planning process ignores cost heterogeneity across areas that could be included in the networks. Mallory and Ando (2014) show this is largely true of conservation actions guided by portfolio analysis as well as traditional conservation planning tools. However, they also find that if a planner is highly risk averse, risk diversification might be more effective if carried out over a measure of benefit alone rather than a benefit/cost ratio.

It is challenging, however, to account for the future social opportunity costs of protecting different lands because climate change can alter both the best use of the land in the future and what that use will be worth. Furthermore, wide disagreement exists amongst economists about even the qualitative nature of such changes in the future value of undeveloped land Mendelsohn and Dinar (2003) and Schlenker *et al.* (2005).

Mallory and Ando (2014) explore the implications of different patterns of correlation between the responses of future conservation benefits and conservation costs to climate change using the MPT framework of Ando and Mallory (2012) and find that efficient portfolio recommendations are completely different when changes in future costs are negatively correlated with changes in conservation values than when the correlation between those changes is positive. Understanding the effects of climate change on the costs of conservation is just as vital as predictions of the effects of a warmer globe on ecosystem values.

Another major challenge for conservation through PES and other such contractual mechanisms is information asymmetry and adverse selection in program participation, both of which can increase conservation costs and hamper successful adoption of conservation policy. Private participants in contract-based conservation programs can collect substantial information rents when conservation planners do not have access to full information regarding conservation costs. Ferraro (2008) argues that such information rents can be reduced through three approaches: gathering information on land characteristics that are correlated with conservation costs, offering screening contracts, and use of procurement auctions. Lack of full information can also lead to adverse selection where private participants can choose whether or not to opt into the program. Voluntary offset programs, such as REDD, are especially prone to adverse selection (Van Benthem and Kerr, 2013). However, Van Benthem and Kerr (2013) find that while offset programs can never lead to first-best outcomes, they can be efficiency improving when the offset program is implemented at a regional or national level where the entire political jurisdiction is assigned a single, aggregate baseline and must choose to participate as one entity. Polasky and Doremus (1998) show that in the absence of adequate compensation schemes, private landowners may hinder information collection regarding presence of endangered species on their land in order to prohibit land use regulations. They use an analytical model to illustrate how an efficient solution for preserving endangered species on private land is possible by combining elements of compensation for restricted use of land and permitting certain land uses that are proven not to harm endangered species.

4 Directions for Future Work

Much research has already shed light on how we can finance conservation, and how theory from finance can improve the way the conservation planning and policy design take uncertainty into account. However, the challenges and intellectual puzzles in this area of research are still significant. We suggest that future work could fruitfully expand knowledge in several particular areas.

First, finding adequate funds for conservation programs and policies remains a major challenge. While research to make the best possible use of a fixed conservation budget is important, it seems likely that our conservation budgets are still too small relative to the social optimum. Several strands of research could improve our understanding of how to expand those budgets. Little has been done yet to explore how to extract value from nonconsumptive wildlife users like birdwatchers. Much more could be done to extend the research in traditional public finance on charitable donations to understand how to stimulate more private donations to conservation funds. Little work has been done yet on the role voluntary corporate action could play in increasing resources devoted to conservation, despite extensive productivity on research in other realms of voluntary commercial environmental action. And through all this work, there is the overarching question about how individual projects and policies should source their funds. Are funding portfolios more resilient to economic shocks, or do mixtures of financial models lead to counter-productive crowding out? Kafle *et al.* (2016) explore whether the availability of public funding affects private WTP for an environmental good; more such work needs to be done.

Second, research applying portfolio theory to conservation planning is still in its infancy, with many advances still needed. For example, current research using MPT in environmental settings restricts an agent's decision making to one-period problems. However, real life environmental conditions are often dynamic in nature and need to allow for periodic review and updating of investments and policies (as do monetary financial portfolios). Thus, conservation planning over longer planning horizons would benefit from use of dynamic portfolio optimization techniques that enables a conservation agent to rebalance the portfolio of protected lands at multiple intervals over the planning horizon.

Third, applications of real options theory to conservation policy should be expanded. Ecologists have been thinking recently about the roles that could be played by temporary or spatially flexible conservation contracts in a conservation strategy under climate change uncertainty. Ando and Hannah (2011) suggested such contracts could have value, but more formal research is needed to identify exactly how such contracts could best be designed and deployed. Conservation planners should also consider the choice of underlying assumptions for modeling the stochastic processes assumed in applications of real options theory. For analytical and computational flexibility, GBM is popularly used to model uncertainties. However, studies are increasingly showing that assumptions about stochasticities, whether they follow GBM or mean reversion processes, are important and can substantially affect the optimal policy choice (Insley, 2002).

All these research efforts will do more to bring the strengths of finance and economics — theoretical rigor and experience with decision making under uncertainty — to bear on conservation planning and financing. Such efforts are needed at a time when conservation needs are great, and growing uncertainties make the solutions of traditional methods increasingly difficult to employ.

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