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A Portfolio Approach to Climate Change Adaptation

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1 Introduction

The mission of the U.S. Department of the Interior includes conserving and protecting wildlife, providing access to the nation's natural heritage, and offering recreation opportunities. These responsibilities have a large area of overlap in the Department's wildlife management duties: ensuring survival of endangered plants and animals, and maintaining populations of iconic species on our protected lands. A changing climate is affecting how the Department meets these responsibilities, as well as the ultimate level of success in fulfilling the mission.

This paper considers how a land manager charged with ensuring survival of a particular species might use a portfolio approach in choosing where to concentrate their efforts. We model species survival at multiple discrete sites, depending on the interactions among site characteristics, climate change, and the manager's restoration and maintenance activities. We then explore the site-selection problem from the perspective of modern portfolio theory and the tradeoff between risk and returns.

2 Literature Review

The issues discussed in this paper can generally be considered a variation of the site selection problem. The literature related to this class of problems has evolved since the 1990s to broadly consider algorithms to optimally select: the minimum number of "reserve sites" (or minimum cost) necessary to represent a given set of species (the "minimum reserve set" problem) or to evaluate the maximum number of species that can be preserved given a fixed budget. Extensions to the literature account for the uncertainty of land development and price effects on surrounding non protected lands.

In its simplest form, the reserve design problem is stated as selecting a minimum number of habitat sites that contain populations of a specified set of species, or maximizing the number of species that can be protected under a conservation budget constraint or area limitations. Both problems are formulated as linear integer programs (IP), being special cases of the prototype 'set covering' problem and the 'maximal covering' problem.

Because the habitat necessary to protect species is typically limited, the earliest literature focused on addressing the minimum reserve set problem (e.g., Kirkpatrick 1983, Pressey 2002). The methods employed to solve this type of problem were often based on tables that indicated whether or not a particular species or landscape feature was present within a particular site. In some methods, sites were scored and ranked based on species richness and other criteria, and those sites with the highest scores were chosen sequentially until all targets were met or until a budget had been exhausted. Other methods selected sites one at a time, using a "greedy" algorithm where the next site selected was the one that contained the largest number of remaining unprotected species.

Mathematical programming methods (linear programming, integer programming, and dynamic integer programming) have typically been employed to address reserve selection problems (Margules and Pressey 2000; Vane-Wright et al. 1991; Nicholls and Margules 1993; Pressey et al. 1993; Pressey et al.

1997). The development of GIS software facilitated the manipulation and visualization of data used in solving reserve site selection problems.

Early approaches to reserve site selection included Margules, Nicholls, and Pressey (1988) and Pressey et al. (1993). Extensions of the site-selection framework have included incorporating heterogeneity either in the land costs (Ando et al., 1998) or in the vulnerability to future land-use conversion (Abbitt, Scott, and Wilcove, 2000; Myers et al., 2000; Margules and Pressey, 2000). These approaches are essentially different approaches to targeting. Sites can be targeted based on conservation value and the possibility of conversion to other land uses; or sites can be targeted to achieve a least cost solution. The major advantage of the cost-constrained solution is that it avoids the high cost sites proximate to urban areas where land values are high.

Protection of existing environmental benefits requires a different targeting approach than restoration. Restoration increases the quality and quantity of ecosystem services flowing from a parcel of land. For example, Babcock et al. (1997) evaluated efforts to convert or restore cropland to land that provided improved wildlife habitat. Babcock found that un-enrolled cropland is unlikely to be voluntarily devoted to conservation uses and that restoration efforts are efficiently targeted for the highest ratio of net benefits achieved to opportunity costs for enrolled parcels.

Costello and Polasky (2004) develop a theoretical model for dynamic reserve site selection that incorporates the benefits, land costs, and vulnerability to future land-use conversion. Conservation decisions are framed in a dynamic setting since all available sites are neither immediately conserved nor developed. The authors compare targeting efficiency for several common heuristic algorithms and the optimal solution using stochastic dynamic integer programming. In all cases, they find that greater targeting efficiency can be achieved when conservation decisions are made prior to development, relying on the fact that the probability of development is nonnegative for any unprotected site. Their simulation and empirical examples consider only heterogeneous benefits and probability of development, while land costs are considered homogeneous. Hence, they do not consider whether and when to conserve more vulnerable, expensive sites versus less vulnerable, inexpensive sites.

3 Issue

We consider the case of a wildlife manager charged with maintaining a species population above a certain threshold level within a particular area. The basis of this objective may be biological (e.g., species preservation) or in support of some other management goal (e.g., to provide opportunities for hunting or wildlife viewing). The manager’s objective function is to choose sites and projects (restoration and maintenance) that maximize the probability of species survival, subject to a budget constraint.

The land manager has available a set of 1-acre sites as potential habitat areas, which may be selected to create a portfolio. These sites may be areas where the species is currently found, or areas to which the species might be relocated. These areas may also figure into a wider conservation strategy, as suggested by Lawler (2009): enlarging or connecting existing reserves, spanning gradients in climatic or other characteristics, or facilitating shifts in species population. Sites are located in roughly the same area, though we assume that they differ in terms of their current suitability, indicated by the state of several "suitability factors" such as availability of water, prey base, plant cover, proximity to humans, etc. These factors affect the ability of the site to support the species of interest. Suitability factors may change over time, and may be enhanced by undertaking various restoration projects. Suitable sites also may require some degree of ongoing maintenance to remain in a suitable condition. The value of a site as a portfolio asset is its contribution toward the manager's goal of species survival.

We assume that Interior already owns the sites under consideration, so no land purchase is required in choosing a site, and any projects undertaken are entirely within the boundaries of the site, so there are no coordination costs with other landowners. However, restoration and maintenance costs vary by factor. For example, enhancing local plant cover may be less costly than increasing local water supplies. In selecting a site the manager commits to any restoration and maintenance projects necessary for ensuring suitability of the site. These project costs represent asset costs.

4 The Model

We assume a two-period model. In the first period, the manager chooses a site (or sites) to include in the species management "portfolio." The characteristics of the selected sites determine which restoration projects must be undertaken, and which maintenance projects may be undertaken for these sites. The presence of a stressor in the first period requires the manager to perform a restoration projects to correct the problem. Even if a stressor is absent in the first period, climate change may allow it to become a problem in the second period. The manager may elect to do optional maintenance projects to address stressors that, while not presenting a problem in the first period may present a problem in the second period.

In the second period, the results of the projects and the effects of climate change determine the outcome for the species of concern. In the model, the primary difference between restoration and maintenance projects is that restoration projects are focused on addressing a specific problem related to the presence of one of the stressors identified below. We assume that appropriate monitoring and oversight occur to ensure the project is completed as envisioned. In contrast, a maintenance project entails a less concentrated effort devoted to maintaining current site conditions.

We assume that there are four stressors that affect species survival at a site:

- Fragmentation (Frag): roads, fences or other structures;
- Institutions (Inst): ownership patterns, rights-of-way, split estate mineral rights, or other agreements that might impair a manager's ability to manage the site;
- Geography (Geo): slope, elevation, orientation, surface water, ground water, land-cover, temperature, precipitation, pH, wildfire, etc.; and
- Invasives (Inv): invasive species are established on the site.

The manager has available a set of N sites. Information on the suitability factors for these sites is collected in a "stressor matrix," **S** ($4 \times N$). Table 1 presents an example stressor matrix for a set of three sites ($N = 3$). The jth column of **S** represents Site j, with 0s and 1s indicating site condition in terms of the four stressors. Specifically, 1 indicates the presence of a given stressor, making the site unsuitable for the species of interest. In contrast, 0 indicates the absence of a given stressor, that is, no impact on site suitability for the species.

Table 1. Stressor Matrix (S) [1 =stressor present; 0 = stressor absent]

Affected by Climate Change	**Factor**	**Abbreviation**	**Site A**	**Site B**	**Site C**
✓	Invasives	(Inv)	1	0	0
✓	Geography	(Geo)	0	1	0
	Fragmentation	(Frag)	1	0	1
	Institutions	(Inst)	0	1	1

As indicated by the check-marks in the leftmost column, the first two stressors (*Invasives* and *Geography*) are subject to changing along with shifts in the climate, while the last two (*Fragmentation* and *Institutions*) are unlikely to change with the climate (though we recognize that climate change might put pressure on existing land management institutions). Climate change is introduced in two ways:

- Stressors that are absent in the first period may become a problem in the second period, as the climate changes, as described in Section 4.a.ii; and
- Species resilience or susceptibility to climate change, such that with probability Pr($\mathit{Extinction}_j$) or Pr(E_j) the manager's plan turns out to be insufficient for species survival on Site j, perhaps because the species' habitat-needs change as the climate changes. This probability represents unknowns in species biological requirements given the manager's current understanding. Pr(E_j) also includes the exogenous risk of a population succumbing to disease or predation. Thus, resilience (or extinction risk) includes all stressors not covered those listed in Table 1.

Costs associated with restoration and maintenance projects may also be subject to uncertainty, though we assume that managers can either perfectly forecast project costs, or that estimated project costs include contingencies to cover cost changes.

4.a Restoration

For a stressor i presenting an impediment to survival on any site ($\mathbf{S}_{i,*} = 1$), the manager must undertake a restoration project to resolve the issue. This project has the potential to change the 1 to 0. Project outcomes are uncertain; these projects succeed with probability Pr($\mathit{Restoration}_i$), or Pr(R_i). In the portfolio management analogy, sites requiring projects with a low risk of failure (such as removing fencing or other barriers) are roughly analogous to "risk-free" investments like government bonds.[1] As shown in Table 2, we assume that projects to address the stressors *Fragmentation* and *Geography* are low-risk projects, while projects to address the stressors *Invasives* and *Institutions* are high-risk projects.

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[1] We note that there are several differences between this model and a portfolio of financial assets, including divisibility (to be addressed later) and liquidity. Further, the actions of the land manager in part determine the magnitude of returns, whereas this is uncommon with financial assets.

Table 2. Restoration Projects Arrayed by Risk and Return

		Low Return	High Return
Low Risk	e.g., Pr(Success) = 0.9	*Fragmentation*	*Geography*
High Risk	e.g., Pr(Success) = 0.3	*Invasives*	*Institutions*

In choosing a site, the manager commits to incurring the cost of the restoration projects required to address any stressors. For example, referring to Table 1, if the manager chooses Site A, they are required to complete two projects: one to address the invasive species and a second to address the fragmentation that currently makes Site A unsuitable for the species of concern.

4.b Maintenance

A site that is free of stressors in the first period may see this condition deteriorate (a change from 0 to 1 in **S**) under the effects of climate change in the second period. This occurs with probability Pr($Stressor_i$) or Pr(S_i). Maintenance projects allow the manager to prevent problems from arising, helping to ensure that 0s stay as 0s. These outcome of these maintenance projects is also uncertain, and these projects succeed with probability Pr($Maintenance_i$), or Pr(M_i). Again, sites where lower-risk projects are undertaken are analogous to risk-free portfolio investments. Table 3 illustrates our assumptions about the risks and returns associated with maintenance projects. Note that as only Invasives and Geography are susceptible to climate change, these are the only two types of maintenance project included in Table 3.

Table 3. Maintenance Projects Arrayed by Risk and Return

		Low Return	High Return
Low Risk	e.g., Pr(Success) = 0.9	*n/a*	*Geography*
High Risk	e.g., Pr(Success) = 0.3	*Invasives*	*n/a*

4.c The Manager's Objective

The manager's objective is to choose the sites and projects that maximize the probability of species survival, subject to a budget constraint. The manager's utility function depends on achieving the management goal, stated in terms of species survival, which for Site j depends on the state of the stressors vector $\mathbf{S}_{*,j}$. Any stressor presenting a problem ($\mathbf{S}_{i,j} = 1$) makes it impossible for the species to survive. We also use the complement $1 - \mathbf{S}_{i,j}$, which measures the lack of a stressor, where it is easier for the species to survive. We model the probability of survival on a site with a multiplicative model, and the objective function can be written:

$$\max \Pr\left(Survival_j\right) = \left[1 - \Pr\left(E_j\right)\right] \cdot \prod_{i=1}^{4}\left(1 - \mathbf{S}_{i,j}\right) \text{ subject to Total Project Costs} \leq \text{Budget},$$

where $\Pr(Survival_j)$ is the probability of species survival on Site j in sufficient numbers or densities to satisfy the management goal, and $\Pr(E_j)$ is the probability of species extinction on Site j due to factors other than those listed in Table 1 (for example, disease, predation, or needs that change as the climate changes). The manager may choose more than one site in order to create a diversified portfolio of sites, though survival at any one site is assumed to be sufficient to satisfy the objective. Choosing multiple sites also increases the costs of required projects.[2] In general, if the manager chooses n out of the possible N sites, the probability of the species surviving (anywhere) is given by the probability of the union of survival on the individual sites:

$$\Pr(Survival) = \Pr(Survival_1 \cup Survival_2 \cup \ldots \cup Survival_n)$$

The manager's task is to maximize expected survival by choosing:

- A set of sites (with their required restoration projects) from among lands already owned by the government, and
- Maintenance projects that will maximize the chances of species survival, subject to a budget constraint (see Section 4.d).

The manager's choices are represented by:

- $\mathbf{X}^{\mathbf{R}}$ ($4 \times N$), a 0-1 matrix where $x_{i,j} = 1$ indicates that the manager will undertake a **restoration** project to remove Stressor i from Site j.; and
- $\mathbf{X}^{\mathbf{M}}$ ($4 \times N$), a 0-1 matrix where $x_{i,j} = 1$ indicates that the manager will undertake a **maintenance** project to maintain suitability factor i on Site j.

For example, if the manager is presented with the set of sites shown in Table 1, and selects Site C (with required restoration projects for *Fragmentation* and *Institutions*), this choice is represented by

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[2] We assume that potential sites are already owned by the government, thus there are no land costs or transaction fees associated with choosing a site.

$$\mathrm{X}^{\mathrm{R}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

where the two columns of zeros indicate no commitment to projects for Site A or Site B, while the third column indicates that manager undertakes restoration projects only for two stressors: $\mathrm{x}_{3,3}^{\mathrm{R}} = 1$ indicates that the manager chooses to do a restoration project (R) to address Site C's Stressor$_3$ (*Fragmentation*); $\mathrm{x}_{4,3}^{R} = 1$ indicates a project for Stressor$_4$ (*Institutions*). If the manager further commits to undertake a maintenance project (M) to discourage invasive species (but no project to maintain *Geography*), this choice is represented by

$$\mathrm{X}^{\mathrm{M}} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where $\mathrm{x}_{1,3}^{\mathrm{M}} = 1$ indicates a maintenance project for Factor$_1$ (*Invasives*) on Site C.

It is also useful to define the complementary set of stressors and sites that are *not* selected for any projects; these are the sites and stressors that will be subject to the unmitigated effects of climate change. We define $\mathbf{X}^{\mathbf{NR,NM}} \equiv \mathrm{J}_{4,N} - (\mathrm{X}^{\mathrm{R}} + \mathrm{X}^{\mathrm{M}})$, where $\mathbf{J}_{\mathrm{i,j}}$ is an (*i,j*) matrix of ones. Note that the manger will not undertake *both* restoration and maintenance for any one factor in one period at a site, so $\mathbf{X}^{\mathbf{R}}$ and $\mathbf{X}^{\mathbf{M}}$ have no overlapping 1s. Subtracting their sum from the matrix of ones (**J**) gives the complement of $\mathbf{X}^{\mathbf{R}}$ plus $\mathbf{X}^{\mathbf{M}}$, turning 1s to 0s and 0s to 1s. For our example,

$$\mathrm{X}^{\mathrm{NR,NM}} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

indicates that the manager chooses to do no restoration or maintenance projects on Site A or Site B, and on Site C, chooses to do no project related to Factor$_2$.

4.a Evolution of Site Conditions over Time

The site conditions in **S** can evolve over time, via a three-part framework:

- Restoration projects can alleviate stressors, turning stressor-matrix entries from 1 to 0. These projects succeed with probability Pr(R*estoration$_i$*); in the case of failure the 1s stay as 1s.
- Meanwhile, climate change can raise new problems, turning 0s into 1s, with probability Pr(*Stressor$_i$*).
- Lastly, maintenance projects can forestall these new climate-change related problems, keeping 0s as 0s. These projects succeed with probability Pr(*Maintenance$_i$*); in the case of failure the 0s turn to 1s with probability Pr(*Stressor$_i$*), as above.

The sections below develop the model following this same three-part framework.

4.a.i The Effects of Restoration

Consider first only the effects of restoration projects, ignoring any effects related to climate change, or maintenance projects to forestall these effects. Continuing the previous example, the initial state of the set of potential sites in Table 1 at time t = 1 is represented by[3]

$$\mathrm{S}_{t=1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

If the manager chooses Site C, they *must* incur the cost for two projects: one to address *Fragmentation* ($\mathbf{S}_{t=1;3,3}$ = 1) and one to address *Institutions* ($\mathbf{S}_{t=1;4,3}$ = 1). If these projects are a success, they turn the 1s to 0s; if the projects fail the 1s stay 1s. If the manager knows something about the probability of success for these projects, they can forecast an expected value for these two suitability factors next period (t = 1). For example, considering the possible outcomes for the *Institutions* project:

- $\mathbf{S}_{t=2;4,3}$ = 1: the restoration project fails, and the *Institutions* stressor remains an issue. This occurs with probability [1 – Pr($Restoration_4$)]; and
- $\mathbf{S}_{t=2;4,3}$ = 0: the restoration project is a success. This occurs with probability Pr($Restoration_4$); so
- The expected value is given by (1) · [1 – Pr(R_4)] + (0) · [Pr(R_4)] = [1 – Pr(R_4)].

Thus, the manager's expectation for next period, based only the effects of the restoration projects is given by

$$\mathrm{E}[\mathrm{S}^{\mathrm{R}}_{t=2}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 - \Pr(\mathrm{R}_3) \\ 0 & 1 & 1 - \Pr(\mathrm{R}_4) \end{bmatrix}$$

4.a.ii Climate Change and Stressors

Considering next the effect of climate change, the manager knows that new problems can arise for certain factors. In the case of Site C, the 0 for *Invasives* becomes 1 with probability Pr($Stressor_1$), and the 0 for *Geography* becomes 1 with probability Pr($Stressor_2$). If the manager undertakes no maintenance activities for *Geography*, they can forecast the expected value in the next period (t = 2):

- $\mathbf{S}_{t=2;4,2}$ = 1: climate change causes *Geography* to become an issue. This occurs with probability Pr($Stressor_2$); and
- $\mathbf{S}_{t=2;4,2}$ = 0: climate change creates no *Geography*-related problems This occurs with probability [1 – Pr($Stressor_2$)]; so
- The expected value is given by (1) · [Pr(S_2)] + (0) · [1 – Pr(S_2)] = [Pr(S_2)].

The other sites (not in the portfolio, i.e., sites A and B) are also subject to the effects of climate change, so Site A's *Geography* and Site B's *Invasives* may develop problems in the next period. Recall that

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[3] This is one of many different possibilities for populating the initial conditions matrix. We selected this structure to help illustrate how the model works.

Fragmentation and *Institutions* are not subject to the effects of climate change. The manager's expectation for next period, including the effects of climate change (with no maintenance projects) is given by:[4]

$$\mathrm{E}[\mathrm{S}_{t=2}^{\mathrm{R,CC}}] = \begin{bmatrix} 1 & \Pr(\mathrm{S}_1) & \Pr(\mathrm{S}_1) \\ \Pr(\mathrm{S}_2) & 1 & \Pr(\mathrm{S}_2) \\ 0 & 1 & 1 - \Pr(\mathrm{R}_3) \\ 1 & 0 & 1 - \Pr(\mathrm{R}_4) \end{bmatrix}$$

4.a.iii The Effects of Maintenance

Lastly, the manager may undertake maintenance projects to reduce the likelihood of climate-change related problems arising. A maintenance project designed to keep problems at bay for *Invasives* ($\mathit{Stressor}_1$) succeeds with probability Pr($\mathit{Maintenance}_1$), or fails with probability 1- Pr($\mathit{Maintenance}_1$). Likewise for *Geography* ($\mathit{Stressor}_2$). Recall that only Invasives and Geography are subject to change with the climate; *Fragmentation* ($\mathit{Stressor}_3$) and *Institutions* ($\mathit{Stressor}_4$) are considered unchanging with respect to climate change.

Note that the effects of climate change are only seen if

1. The climate actually changes, and
2. A maintenance project fails.

This intersection occurs with a probability of Pr($\mathit{Stressor}_1$) · [1 – Pr($\mathit{Maintenance}_1$)]. With any other outcome, climate change is avoided, and a 0 in the stressor matrix for *Invasives* remains 0. The expected value next period is given by

$$(1)\cdot\{\Pr(S_1)\cdot[1-\Pr(M_1)]\} + (0)\cdot[1-\{\Pr(S_1)\cdot[1-\Pr(M_1)]\}] = \{\Pr(S_1)\cdot[1-\Pr(M_1)]\}$$

Thus the manager's expectation for next period, including the effects of restorations, climate change and maintenance projects *only to address invasives*[5] is given by:

$$\mathrm{E}[\mathrm{S}_{t=2}] = \mathrm{E}[\mathrm{S}_{t=2}^{\mathrm{R,CC,M}}] = \begin{bmatrix} 0 & \Pr(\mathrm{S}_1) & \{\Pr(\mathrm{S}_1)\cdot[1-\Pr(\mathrm{M}_1)]\} \\ \Pr(\mathrm{S}_2) & 0 & \Pr(\mathrm{S}_2) \\ 0 & 1 & 1 - \Pr(\mathrm{R}_3) \\ 1 & 0 & 1 - \Pr(\mathrm{R}_4) \end{bmatrix}$$

4.a.iv Matrix Form

This section again follows the three-part framework described in 4.a to develop a matrix representation for the evolution of site conditions over time. We collect the probabilities of restoration project success, Pr($\mathit{Restoration}_i$), along the main diagonal of 4×4 diagonal matrix $\mathbf{P}^{\mathbf{R}}$:

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[4] The superscript CC indicates the effect of climate change only. At this point the decision to do a maintenance project has not been modeled.

[5] Purely for illustrative purposes we illustrate the case of the manager choosing to do a maintenance project for invasives and not geography.

$$\mathrm{P}^{\mathrm{R}} \equiv \begin{bmatrix} \Pr(R_1) & 0 & 0 & 0 \\ 0 & \Pr(R_2) & 0 & 0 \\ 0 & 0 & \Pr(R_3) & 0 \\ 0 & 0 & 0 & \Pr(R_4) \end{bmatrix}$$

We also collect the probabilities of a site avoiding climate change-driven suitability problems under a do-nothing scenario, [1 – Pr(*Stressor$_i$*)], along the main diagonal of $\mathbf{P}^{\mathbf{No\ CC}}$. Note the zero probability of climate change for *Factor$_3$* (*Fragmentation*) and *Factor$_4$* (*Institutions*):

$$\mathrm{P}^{\mathrm{No\ CC}} \equiv \begin{bmatrix} 1-\Pr(S_1) & 0 & 0 & 0 \\ 0 & 1-\Pr(S_2) & 0 & 0 \\ 0 & 0 & 1-0 & 0 \\ 0 & 0 & 0 & 1-0 \end{bmatrix}$$

Setting aside the effects of maintenance projects for the moment, the evolution of conditions on the set of sites based on the effects of restoration projects and unmitigated climate change is given by:

$$\mathrm{S}_{t=2}^{\mathrm{R,CC}} = (1-\mathrm{P}^{\mathrm{R}}) \cdot [(\mathrm{S}_{t=1}) \circ (\mathrm{X}^{\mathrm{R}})] + \mathrm{P}^{\mathrm{No\ CC}} \cdot [(\mathrm{J}_{4,N} - \mathrm{S}_{t=1}) \circ (\mathrm{X}^{\mathrm{NR,NM}})]$$

where $\mathbf{J}_{i,j}$ is an (*i,j*) matrix of ones, and ○ indicates the entrywise product.[6] Subtracting $\mathbf{S}_{\mathbf{t=1}}$ from **J** converts 0s to 1s in $\mathbf{S}_{\mathbf{t=1},}$ indicating "at risk" areas, where stressors are currently not an issue, though they might be once climate change hits. As described in Section 4.c, $\mathbf{X}^{\mathbf{NR,NM}}$ is the complement of $\mathbf{X}^{\mathbf{R}}$ plus $\mathbf{X}^{\mathbf{M}}$, showing where the manager undertakes no projects. Multiplying the "no-project" matrix by the "at risk" matrix isolates stressors and sites that will be subject to the unmitigated effects of climate change. We assume that for factors on sites chosen for restoration, climate-change effects are captured in the risk of project failure (1-Pr(*R$_i$*)).

The first of the additive terms in $\mathrm{S}_{t=2}^{\mathrm{R,CC}}$ represents values for the sites and stressors the manager is attempting to address with restoration. Stressors will only be a problem in the second time period to the extent that restoration projects undertaken in the first period fail. The second term represents values for sites and factors receiving no restoration or maintenance effort.

Section 4.a.iii derived the probability that the manager undertakes a maintenance project and the site avoids the effects of climate change (either because the project is a success, or because no climate change occurs): $\Pr(\mathrm{S}_i) \cdot [1 - \Pr(\mathrm{M}_i)]$. We collect the probabilities of climate change-related effects being offset by successful maintenance projects along the main diagonal of 4×4 diagonal matrix $\mathbf{P}^{\mathbf{CC,M}}$:

$$\mathrm{P}^{\mathrm{CC,M}} \equiv \begin{bmatrix} \Pr(S_1) \cdot [1-\Pr(M_1)] & 0 & 0 & 0 \\ 0 & \Pr(S_2) \cdot [1-\Pr(M_2)] & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Now that we have developed matrices representing the probability of successful restoration projects ($\mathbf{P}^{\mathbf{R}}$), the probability of avoiding climate change with maintenance ($\mathbf{P}^{\mathbf{CC,M}}$), and the probability of avoiding

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[6] The entrywise (Hadamard) product A○B is a new matrix of the same dimension as A and B, in which each element *i,j* is the product of $A_{i,j}$ and $B_{i,j}$.

climate change under a do-nothing scenario ($\mathbf{P}^{\mathbf{NO\ CC}}$), we are able to describe the evolution of site conditions over time:

$$\mathrm{S}_{t=2} = \mathrm{S}^{\mathrm{R,CC,M}} \equiv \mathrm{P}^{\mathrm{R}} \cdot [\mathrm{S}_{t=1} \circ \mathrm{X}^{\mathrm{R}}] + \mathrm{P}^{\mathrm{CC,M}} \cdot \left[\left(\mathrm{J}_{4,\mathrm{N}} - \mathrm{S}_{t=1}\right)\circ \mathrm{X}^{\mathrm{M}}\right] + \mathrm{P}^{\mathrm{No\ CC}} \cdot \left[\left(\mathrm{J}_{4,\mathrm{N}} - \mathrm{S}_{t=1}\right)\circ \mathrm{X}^{\mathrm{NR,NM}}\right]$$

For the individual (*i,j*) elements of $\mathbf{S}_{\mathbf{t=2}}$, we can write

$$s_{t=2;i,j} = (1 - \Pr(R_i)) \cdot \left[s_{t=1;i,j} \cdot x_{i,j}^{R}\right] + [1 - \Pr(S_i)] \cdot [(1 - s_{t=1;i,j}) \cdot x_{i,j}^{NR,NM}]$$
$$+[\Pr(S_i) \cdot [1 - \Pr(M_i)] \cdot [(1 - s_{t=1;i,j}) \cdot x_{i,j}^{M}]$$

Revisiting the manager's objective function from Section 4.c, we recall the probability of species survival (and achievement of the manger's objective) on Site *j* is given by

$$\Pr\left(Survival_j\right) = \left[1 - \Pr\left(E_j\right)\right] \cdot \prod_{i=1}^{4}(1 - s_{t=2;i,j})$$

In general, if the manager chooses *n* out of the possible *N* sites, the probability of the species surviving (anywhere) is given by the union of the probability of survival on each site:

$$\Pr(Survival) = \Pr\left(\cup_{j=1}^{n} Survival_j\right)$$

This can be expressed for the general case using the inclusion-exclusion principal[7]:

$$\Pr(Survival) = \sum_{k=1}^{n}(-1)^{k-1} \cdot \sum_{\substack{J \subset \{1\ldots n\} \\ |J|=k}} \prod_{j \in J} \Pr(Survival_j)$$

4.b Restoration Project Costs

There is a vector of restoration project costs $\mathbf{c}^{\mathbf{R}}$ (4×1) listing the costs of the projects that will address issues for each suitability factor, i.e. changing 1 to 0 in **S**. Restoration costs are taken to be the present value of all project costs including items such as planning, construction, and monitoring. We assume that these costs remain constant over the period of analysis. For simplicity we consider the costs associated with each factor to be independent. In reality, costs may depend on site size, scale of the project; other projects being undertaken at the site; as well as site conditions in previous time periods and other problem factors present on the site. Table 4 provides a sample cost matrix.

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[7] The inclusion-exclusion principal relates to the depiction of probabilities as areas in Venn diagrams. For example, the union of two probabilities $A \cup B$ is given as the sum of the two areas $(A + B)$ minus the area in any overlap (equivalent to $A \cap B$).
Thus, for *n* = 2 above,

$$\Pr(Survival) = (-1)^0\,[\Pr(Survival_1) + \Pr(Survival_2)] + (-1)^1[\Pr(Survival_1) \cdot \Pr(Survival_2)]$$

$$= \Pr(Survival_1) + \Pr(Survival_2) - \Pr(Survival_1) \cdot \Pr(Survival_2)$$

Table 4. Restoration Project Cost Matrix (c^R)

Factor	Cost ($ per acre)	Example projects/activities to fix problems
(Inv)	2,800[8]	Remove tamarisk
(Geo)	2,500	Regrading? Drill gw well: $50/foot, 500 ft
(Frag)	1,000	Remove buildings, fences , roads
(Inst)	1,000[9]	Buying a Right-of-way; buy surface and mineral rights.

4.c Maintenance Costs

There is also a vector of maintenance costs $\mathbf{c}^M$ (4×1) that indicates the present value of the cost of maintaining a site in suitable condition during the current period, i.e. keeping the 0s as 0s in **S**. Maintenance costs may be incurred in each period that the manager wishes to try to offset the effects of climate change on a suitability factor. As climate change does not affect *Fragmentation* or *Institutions*, there are no maintenance costs for these factors. Table 5 provides an example maintenance cost matrix.

Table 5. Maintenance Cost Matrix (c^M)

Factor	
(Inv)	$500
(Geo)	$200
(Frag)	n/a
(Inst)	n/a

4.d Total Cost

The total cost of achieving the management goals depends on the state of the chosen site in terms of the restoration projects required to make the chosen site suitable, and any maintenance projects chosen to offset climate change-induced deterioration of site conditions. Returning to the previous example, the manager selected Site C committing to two projects: one to address *Fragmentation* for $1,000 and one to address *Institutions* for $5,000, and a maintenance project to control invasive species for $500 (though no project to maintain *Geography*). Under this scenario they will spend a total of $6,500.

In matrix notation, the total cost is given by

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[8] Zavaleta, E. 2000. The Economic Value of Controlling an Invasive Shrub. *Ambio*, Vol 29, No. 8, pp. 462-467.

[9] This rough estimate is based on BLM ROW annual rental values, converted to a permanent value by discounting at 10%. It may be impossible to generalize for mineral rights.

$$C = \{c^{R'} \cdot (S_{t=1} \circ X^{R}) + c^{M'} \cdot [(J_{4,N} - S_{t=1}) \circ X^{M}]\} \cdot J_{N,1}$$

where $\mathbf{J}_{i,j}$ is a matrix of ones, and ○ indicates the entrywise product. As noted in Section 4.a.iv, subtracting $\mathbf{S}_t$ from $\mathbf{J}$ indicates stressors currently posing no issues, but "at risk" of becoming a problem once climate change hits. In developing the costs, this is interpreted as the potential scale of a maintenance project. Multiplying by $\mathbf{J}_{N,1}$ reduces the expression to a scalar.

This allows us to write the manager's budget constraint as simply Total Costs ≤ B.

5 Model Results and Monte Carlo Simulation

We used the model developed above, coupled with a Monte Carlo analysis, to evaluate the probability of survival for three scenarios of a three-site portfolio.[10] In our simple model, each site can be thought of as a separate type of asset (e.g., a stock, a bond, and a machine). Each of these assets has different characteristics that respond differently to climate change and to maintenance and restoration projects (which all can be envisioned as conditions that affect all assets economy-wide). In concept, a portfolio of sites, if constructed properly, will provide a higher probability of survival than any single site could provide. The scenarios are summarized in the Table 4 and are described below:

- Scenario 1 - The mean probability of climate change creating problems associated with invasives and geography is 90%; maintenance projects have a mean probability of success of 90%; and restoration projects also have a mean probability of success of 90%. In this scenario, uncertainty is modeled as 10% of the mean.
- Scenario 2 - The mean probability of climate change creating problems associated with invasives and geography is 10%; maintenance projects have a mean probability of success of 10%; and restoration projects also have a mean probability of success of 10%. In this scenario, uncertainty is modeled as 10% of the mean.
- Scenario 3 - The mean probability of climate change creating problems associated with invasives and geography is 50%, with a level of uncertainty of 10%; maintenance projects also have a mean probability of success of 50% with a 10% level of uncertainty; a restoration project to address invasives has an average 10% probability of success, with a level of uncertainty equal to the mean; a restoration project to address geography has an average 90% probability of success, with a level of uncertainty equal to 90%; a restoration project to address fragmentation has an average probability of success of 90%, with a level of uncertainty of 5%; and a restoration project to address institutions has an average success rate of 10%, with a level of uncertainty of 1%.

To examine the combined effects of maintenance projects, restoration projects and climate change, we developed a Monte Carlo simulation of the transition from $\mathbf{S}_{t=1}$ to $\mathbf{S}_{t=2}$. The parameters required for the simulation are:

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[10] This implementation of the model does not explicitly include a budget constraint reflecting the costs associated with the various restoration and maintenance projects.

- Distributions of the probability of climate change for two factors (*Invasives* and *Geography*);
- Distributions of failure probabilities for the two types of maintenance project (*Invasives* and *Geography*);
- Distributions of failure probabilities for the four types of restoration project (*Invasives*, *Geography*, *Fragmentation* and *Institutions*);
- Costs for the two types of maintenance project (*Invasives* and *Geography*); and
- Costs for the four types of restoration project (*Invasives*, *Geography*, *Fragmentation* and *Institutions*).

The conceptual model developed above suggests that there may be a cheap way and an expensive way to manage climate change, and that the total cost is affected by the distribution of the costs (and likelihood of success). Land managers are faced with choices in their management strategy, and there may be interactions among those choices. Ideally, managers would account for marginal costs and benefits in their decision making. Another message is that investments in information may be useful. Better understanding of the probabilities associated with survival, success of restoration projects, success of maintenance projects, etc.

Table 6. Scenarios Modeled

	Avg Prob of CC affecting (Std dev)		Avg Prob of maintenance project success (Std dev)		Avg Prob of restoration project success; (Std dev)			
Scenario	Invasives	Geography	Invasives	Geography	Invasives	Geography	Fragmentation	Institutions
All High	90% (9%)	90% (9%)	90% (9%)	90% (9%)	90% (9%)	90% (9%)	90% (9%)	90% (9%)
All Low	10% (10%)	10% (10%)	10% (10%)	10% (10%)	10% (10%)	10% (10%)	10% (10%)	10% (10%)
Mixed	50% (10%)	50% (10%)	50% (10%)	50% (10%)	10% (10%)	90% (90%)	90% (5%)	10% (1%)

The results of the analysis are summarized in Table 5 and described below:

- The results from the All High scenario indicated that the probability of survival at the individual sites ranges from about 60-70%. However, when considered as a portfolio, the probability of survival increases to over 90%.
- The results from the All Low scenario indicated that the probability of survival at the individual sites is basically 0%. However, when considered as a portfolio, the probability of survival increases slightly to about 3%. In this scenario, because the probability of survival is quite low to begin with, having a portfolio does not increase the overall survival probability.
- The Mixed scenario perhaps best illustrates the advantages of the portfolio approach. The probability of survival at the individual sites ranges from about 2 -13%. However, when considered as a portfolio, the probability of survival increases to about 20%.

The Monte Carlo analysis, at least for this simple model, does not provide significantly more information beyond what is obtained from just the expected values. This follows from the fact that when all of the probabilities and levels of uncertainty are similar (homogeneous) the results of the Monte Carlo analysis are similar to the one-shot expected value. In contrast, when the probabilities (and levels of uncertainty) are heterogeneous, Monte Carlo analysis can reveal results very different from the expected values.

Table 7. Model Results

Probability of survival						
Scenario	Site A	Site B	Site C	Expected value - All Sites	Monte Carlo – all sites Mean	Std Dev
All High	0.71	0.66	0.62	0.96	0.96	0.03
All Low	0.00	0.01	0.01	0.03	0.03	0.02
All Mid	0.19	0.21	0.16	0.46	0.42	0.08
Mixed	0.13	0.02	0.07	0.20	0.16	0.06

6 Extensions

In this section we discuss possible extensions to the model, including additional time periods, allowing assets to be divisible (providing for more flexibility in assembling portfolios). We also continue an examination of the site-selection problem from the perspective of modern portfolio theory, and consider the impact of risk tolerance. We also discuss potential future directions for research to improve the model.

6.a Divisible Assets

The suitability factors in **S** can be graded more finely, allowing for fractional values between zero and one indicating the extent of the issue to be addressed by a potential project. For example, a value of *Invasives* = 0.25 could indicate that 25% percent of the site is affected by invasive species, or that invasives represent a problem with an index score of 25 on a scale from 0 to 100.

The manager could also choose the scale for restoration and maintenance projects. This would allow a finer trade-off between projects to address the various factors. Some distinction could be made among the sites for how they fit into a larger conservation strategy. Lawler (2009) suggested that managers might acquire new sites to expand or connect existing reserves, to span a range of climatic or other characteristics, or to facilitate species population shifts.

6.b Application to Modern Portfolio Theory

The site-selection model developed in this paper can be explored in terms of portfolio theory. In this extension, we consider the individual sites as potential assets. The return to an asset is defined as the change in the probability of species survival that occurs as a result of including the site in the portfolio.

6.b.i Theoretical Framework

In the simplest framework for portfolio choice (Markowitz, 1959), individuals select a portfolio in the first period that produces an uncertain return in the second period. The model assumes investors are risk averse and, when choosing among portfolios, they care only about the mean and variance of their one-period investment return. Different investors, with different risk preferences, can create portfolios with different risk profiles. If all of the possible portfolios available to investors are displayed in risk-return space, a frontier characterizing the efficient portfolios can be derived. This frontier represents the set of available portfolios that maximized the return for a given level of risk. Risk in this case is defined as the standard deviation of the returns to the portfolio.[11] Figure 1 shows the efficient frontier. Portfolios A and C have the same level of risk, but portfolio C has a higher return. Portfolios C and B have the same return, but different levels of risk. All else equal, an investor would portfolio C. The curvature of the frontier represents the benefits associated with diversification. A portfolio made up only assets X and Y (e.g., portfolio Z) would like along the dotted line between points X and Y. The risk and returns to portfolio Z would be a weighted average of the risks and returns to X and Y. However, for any point along the dotted line there is another portfolio with high returns and lower risk. For example, an investor could choose a portfolio with lower risk and higher returns by selecting portfolio C.

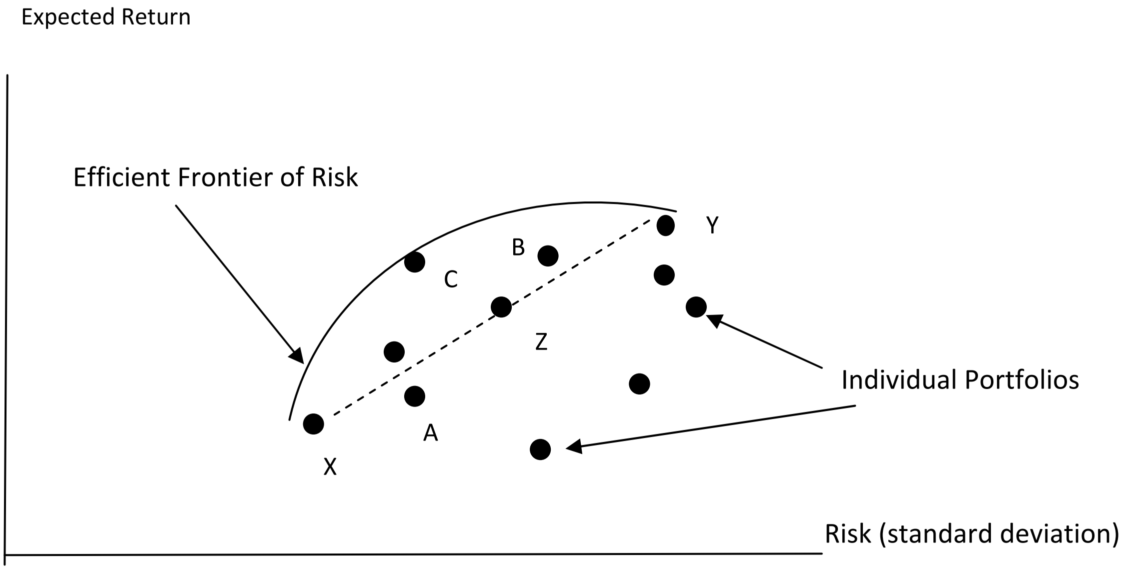

Figure 1. The Risk-Return Tradeoff

Investors also have the option of holding a risk free asset (e.g., cash, Treasury securities), or holding various combinations of the risk free asset, R_f, with risky assets. These combinations can be represented by the dotted lines in figure 2. The dotted line R_f and X represents combinations of the risk free asset and asset X. If the investor was willing to borrow, then more than 100% of the risky asset could be held, which would make portfolios A and beyond available. However, portfolio C is still p referred to A because it provides a higher return for the same level of risk. In fact, portfolio C is preferred to all of the combinations on the dotted line between R_f and X. Portfolio C is also preferred to portfolios along the line between R_f and Y. This establishes portfolio C as the optimal risky asset and the optimal portfolio for a chosen level of risk will be a combination of asset C and the risk free asset. The slope of the line –

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[11] The set of portfolios that define the frontier minimize the standard deviation of returns to the portfolio. The shape of the frontier depends on the degree of correlation between the risky assets, with the curve becoming flatter as the covariance between asset returns approaches +1.

known as the "Sharpe ratio" -- between R_f and C represents the optimal risk - return tradeoff. When comparing two assets each with the expected return E[R] against the same benchmark with return R_f, the asset with the higher Sharpe ratio gives more return for the same risk.[12] The slope can also be thought of as the price of risk reduction, in that it shows by how much the expected portfolio return rises if the standard deviation (chosen by the individual) increases by one unit.

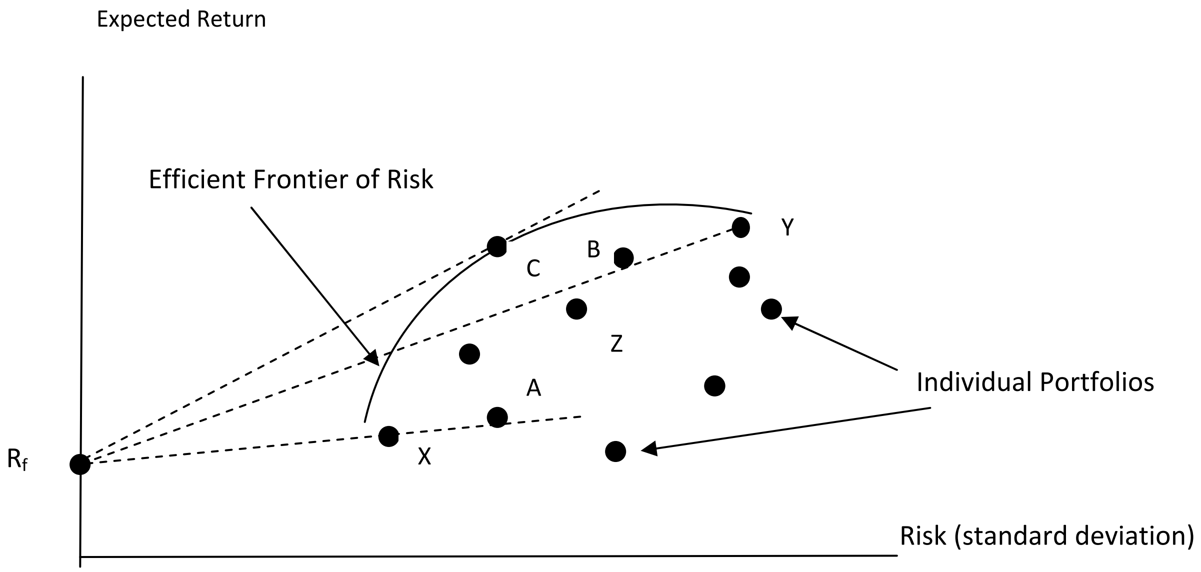

Figure 2. Risk-Return Tradeoffs with Risk Free and Risky Assets

There are two kinds of risk: risk that is diversifiable ("systemic risk"), that is it can be eliminated by combining the asset with other assets in a diversified portfolio; and risk that is nondiversifiable ("unsystemic risk"), that is it reflects the future is unknowable and cannot be eliminated by diversification. As assets are added to a portfolio, the diversifiable risk decreases and begins to approach zero -- the only risk left is nondiversifiable risk. Systematic risks are unanticipated economy wide events that affect almost all assets to some degree.

6.b.ii Site Selection Application

In concept, land managers can select from a large set of assets that could be used to compose a portfolio. Rather than financial assets, land managers select different parcels of land that have different characteristics. A set of portfolios along the Efficient Frontier of Risk as shown in Figure 2 could be identified. The Frontier would then allow land managers to explicitly visualize the risk-return tradeoffs when selecting portfolios of sites to help address climate change problems. Different sets of assets or parcels, when combined, will provide different risk-return combinations. A portfolio of parcels could be selected to match the land manager's tolerance for bearing risk. In the model discussed in this paper, the risk free rate of return can be defined by the returns associated with addressing the fragmentation stressor. The rationale for this is that fragmentation problems might have relatively low returns in

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[12] The Sharp ratio is defined as the difference between the risk free return and the return to the risky asset divided by the standard deviation of the return to the risky asset. This line is also known as the Capital Market Line in the Capital Asset Pricing Model.

terms of changing survival probabilities (especially for say a plant species), but these returns would not be anticipated to have a high variance.

In our model, we assume that the four stressors are what drive the risk-return profile of the various sites (the assets). The projects available to address these stressors contribute to species survival (the return), but they have different probabilities of success (the risk). Table 6 shows the restoration projects for the four stressors arrayed by risk and return, and Table 9 does the same for maintenance projects.

Table 8. Restoration Projects Arrayed by Risk and Return

		Low Return	**High Return**
Low Risk	e.g., Pr(Success) = 0.9	*Fragmentation*	*Geography*
High Risk	e.g., Pr(Success) = 0.3	*Invasives*	*Institutions*

Table 9. Maintenance Projects Arrayed by Risk and Return

		Low Return	**High Return**
Low Risk	e.g., Pr(Success) = 0.9	*n/a*	*Geography*
High Risk	e.g., Pr(Success) = 0.3	*Invasives*	*n/a*

In the context of our model, the assets are the available sites. Returns to these assets are measured by the impact of the probability of species survival by including the site in the portfolio, and undertaking any required restoration or maintenance projects. Returns, in terms of changes to the probability of survival depend on whether a maintenance project is undertaken.

The risk associated with a portfolio depends on the variation in returns of the underlying assets as well as the covariance among the assets:

$$\mathrm{Var}(\mathrm{A}+\mathrm{B}+\mathrm{C}) = \mathrm{Var}\,(\mathrm{A}) + \mathrm{Var}(\mathrm{B}) + \mathrm{Var}(\mathrm{C}) + 2[\mathrm{Cov}(\mathrm{A},\mathrm{B}) + \mathrm{Cov}(\mathrm{B},\mathrm{C}) + \mathrm{Cov}(\mathrm{A},\mathrm{C})]$$

The return for the portfolio can be defined as:

$$\Delta\Pr(Survival) = \mathit{\Delta}\sum_{k=1}^{n}(-1)^{k-1}\cdot\sum_{\substack{J\subset\{1\ldots n\}\\ |J|=k}}\prod_{j\in J}\Pr(Survival_j)$$

Using the inclusion-exclusion principal (as in Footnote 7), for three sites (n = 3), this expression becomes

$$\Delta\Pr(Survival) = \Delta\{\Pr(Survival_1) + \Pr(Survival_2) + \Pr(Survival_3)$$

$$-[\Pr(Survival_1)\cdot\Pr(Survival_2) + \Pr(Survival_2)\cdot\Pr(Survival_3) + \Pr(Survival_1)\cdot \Pr(Survival_3)]$$

$$+\Pr(Survival_1)\cdot\Pr(Survival_2\cdot\Pr(Survival_3)\}$$

Thus the impact of adding a site to the portfolio depends on the probability of survival on that site (the return), as well as the returns of other sites in the portfolio.

The return for site j can be defined as:

$$\Delta \Pr(Survival_j) = \Delta[1 - \Pr(E_j)] \cdot \prod_{i=1}^{4}(1 - s_{t+1;i,j})$$

$$\Delta \Pr(Survival_j) = [1 - \Pr(E_j)] \cdot \prod_{i=1}^{4}(\Pr(R_i) + \Pr(M_i)]$$

Recall that restoration projects must be undertaken if stressors are present. In contrast, maintenance projects are undertaken at the discretion of managers (and only where stressors are currently absent). In this situation, climate change can affect the extent to which the maintenance project changes the survival probability. For the case where a maintenance project is not undertaken, $M_i = 0$.

When assets are divisible and the manager may choose the level of effort to expend on a particular project, the probabilities of project success in the return are multiplied by terms indicating the level of the problem (i.e. the value of the stressor in the first period) and the level of effort the manager chooses (from zero up to a maximum level equal to the value of the stressor).

6.c Risk preference

Once the efficient portfolio frontier has been determined, and the optimal risky asset (or indexed basket) has been identified, the investor considers their risk preference to choose their preferred mix of risky and riskless assets, along the Sharpe ratio line. The site-selection equivalent is the manager choosing among more and less risky assets according to their risk preference.

Several things may influence the manager's risk preference. A national-scale land-management program would be able to spread risk spatially (across the landscape) as well as temporally (across generations). These abilities would be expected to increase risk tolerance. Conversely, the more doubtful a species' future, the less risk the manager would be willing to accept. Managers addressing populations with few remaining members, or increasingly scarce habitat or food sources would tend to have lower risk tolerance.

6.d Future Areas for Research

In future work, we could allow interaction among characteristics of neighboring sites, be they existing reserves, potential sites, or non-sites. For example, a serious issue with Invasives on one site could more easily affect a neighboring site. This extension raises the possibility of coordination costs among neighboring land owners.

Lastly, the analysis could run for multiple periods, rather than the two-period model assumed for this analysis. This would allow managers to undertake a restoration project in the first period, with follow-on maintenance projects in subsequent periods.

7 Potential Applications and Conclusions

Critical Habitat: Following listing under the Endangered Species Act (ESA), the Secretary of the Interior (Secretary) is required to designate critical habitat (CH) for the species, defined as habitat that is essential to the conservation of the species. The ESA allows the Secretary to exclude areas from the critical habitat designation if the economic benefit of doing so is sufficiently large and if the exclusion will not result in extinction. Economic analysis is typically undertaken in order to evaluate the economic impacts of proposed CH designations and to inform the Secretary's decision to exclude areas from the Designation. Essentially, a portfolio of sites is identified to form the Designation, with the expected survival probability representing the returns to the portfolio.

Analysis similar to that undertaken in this paper could be undertaken as part of the economic analysis associated with CH designations. Underlying a CH designation is an evaluation of the extent to which including or excluding certain areas in the designation affect species survival probabilities. Based on habitat characteristics (and how these characteristics might change in presence of climate change), Monte Carlo analysis could help to better understand how survival probabilities might change as different sets of parcels (with different habitat qualities) are included or excluded in the designation (i.e., how survival probabilities might change given different costs).

Habitat Conservation Banks: The U.S. Fish and Wildlife Service (FWS) describes conservation banks as permanently protected lands that contain natural resource values, which are conserved and permanently managed for species that are endangered, threatened, candidates for listing as endangered or threatened, or are otherwise species-at-risk (U.S. FWS 2012). Conservation banking is a market-based program that provides "credits," or units of trade related to habitat or species of interest at the bank site, to landowners that undertake conservation activities, which they may then sell to parties that need to mitigate unavoidable impacts to a species. At the Federal level, conservation banking is regulated by the USFWS (for terrestrial and freshwater species and some marine mammals) and the National Marine Fisheries Service (for marine and anadromous species). The USFWS began approving conservation banks in the early 1990s, and 105 banks have been approved as of March 2013.

The type of analysis used in this paper could be applied in the context of conservation banks. For any given set of species where banks have been established, the FWS has essentially created a portfolio of sites to promote species survival. Additions to the portfolio of existing banks would be expected to change the expected "returns" (i.e., survival probability of the species) to the portfolio. Additions to the portfolio could be evaluated using Monte Carlo analysis in order to estimate how the expected returns might change.

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