Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region

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Climate change is likely to alter the spatial distributions of species and habitat types but the nature of such change is uncertain. Thus, climate change makes it difficult to implement standard conservation planning paradigms. Previous work has suggested some approaches to cope with such uncertainty but has not harnessed all of the benefits of risk diversification. We adapt Modern Portfolio Theory (MPT) to optimal spatial targeting of conservation activity, using wetland habitat conservation in the Prairie Pothole Region (PPR) as an example. This approach finds the allocations of conservation activity among subregions of the planning area that maximize the expected conservation returns for a given level of uncertainty or minimize uncertainty for a given expected level of returns. We find that using MPT instead of simple diversification in the PPR can achieve a value of the conservation objective per dollar spent that is 15% higher for the same level of risk. MPT-based portfolios can also have 21% less uncertainty over benefits or 6% greater expected benefits than the current portfolio of PPR conservation. Total benefits from conservation investment are higher if returns are defined in terms of benefit–cost ratios rather than benefits alone. MPT-guided diversification can work to reduce the climate-change–induced uncertainty of future ecosystem-service benefits from many land policy and investment initiatives, especially when outcomes are negatively correlated between subregions of a planning area.

optimal reserve-site selection | efficient frontier | cost-effective

Climate change poses dire threats to species diversity and other ecosystem services and causes uncertain changes in future spatial patterns of conservation-related outcomes (1–4). To ensure future flows of ecosystem services and species diversity, much work has been done to build tools for cost-effective conservation planning that exploit information about the current spatial distributions of species and other targets of protection (5, 6). Such tools help society to obtain the most benefit possible out of conservation investments and have even partially addressed conservation uncertainty by proposing "minimax" algorithms that minimize the largest possible ecological loss from worst-case outcomes (7). However, unprecedented uncertainty stemming from climate change makes it difficult to implement existing conservation planning paradigms. Innovative new tools are needed to manage the risk that climate uncertainty attaches to the future outcomes of current conservation investments. This paper adapts a risk management tool from financial portfolio theory to exploit information about spatial covariances in future ecological conditions and applies that tool to spatial targeting of conservation and restoration investments.

Conservation scientists have suggested approaches to the problem of conservation planning in the face of climate change uncertainty (4, 8–12). These approaches include increasing connectivity of reserves (including corridor creation), increasing the number and size of reserves, using movable protected areas, and modifying reserve selection criteria to include information about the expected values and variances of future ecological values on areas in the planning landscape. Nonetheless, even strategies that sound like diversification (13–15) are not harnessing all of the benefits of efficient risk diversification. Those approaches choose lands for conservation that have diverse biophysical or climatic characteristics (either currently or in a single future climate scenario), but they do not use information about covariances between future ecological outcomes in different parts of the landscape. Therefore, the products of such conservation strategies have more uncertain overall outcomes than could be obtained with efficient diversification (16).

Modern Portfolio Theory (MPT) uses information about the joint probability distribution of outcomes on all possible assets in a portfolio (including means, variances, and covariances) to select a portfolio that efficiently manages risk. Although MPT has been applied to financial assets for risk management since the 1950s, it has been used very little by ecologists and conservation biologists and then largely to analyze optimal species and genetic diversity (17–21). In this paper we use MPT to characterize optimal spatial targeting of conservation and restoration policies and investments, translating MPT into the context of choosing protected lands in a landscape. We use a case study of wetland habitat protection and restoration in the Prairie Pothole Region (PPR), an area of conservation importance for ecosystem services such as waterfowl production.

In the nomenclature of finance, assets are things that are owned or controlled for the purpose of generating value (or a return) over time, a portfolio is simply a collection of assets held simultaneously, and the risk of a portfolio depends on the SDs of individual asset returns as well as their covariances. The idea of risk diversification is that one should spread around exposure to risk so that bad performance of a single asset will not wipe out one's entire investment. MPT formalizes implementation of this intuition. By correctly choosing portfolio weights (fractions of total investment) among assets one can find portfolios that are efficient in the sense that for a given level of return there is no portfolio with a lower level of risk and for a given level of risk there is no portfolio with a higher expected return (22). The collection of these portfolios forms what is called the efficient frontier.

Our case study for using MPT in spatial conservation planning is the PPR, which covers a swath of the North-Central United States and Canada. Fig. 1 shows the 64-million acre US portion of the PPR divided into three subregions (Western, Central, and Eastern). This mosaic of small shallow wetlands is a region of great conservation importance, serving as breeding grounds for almost 200 species of migratory birds. The US Fish and Wildlife Service (FWS) has already protected >3 million acres in the PPR through two types of actions: purchasing land outright or purchasing indefinite conservation easements. Lands are placed in protective status that precludes conversion away from natural

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Fig. 1. States and subregions in the US Prairie Pothole Region. The US part of the Prairie Pothole Region (PPR) extends through significant portions of Montana, North Dakota, South Dakota, Minnesota, and Iowa. It is shown here divided into three subregions.

conditions and sometimes allows steps to be taken to restore land to its natural state. The FWS seeks to quadruple the amount of habitat protected in the PPR (23).

Conservation goals in the PPR are often expressed in terms of acres of high-quality habitat protected or restored. The FWS uses historical data on the locations of breeding waterfowl to guide its conservation priority setting in the PPR (23). Another measure of wetland habitat quality is the cover-cycle index (CCI) (24). Historical CCI measures are spatially correlated with the indicator of conservation priority used by the FWS, but historic conditions may not continue to exist in the future PPR should climate change come to pass.

CCI outcomes have been modeled (25) for four different future regional climate scenarios including three plausible outcomes of climate change (26): historic conditions, warming of 2 °C, warming of 4 °C, and warming of 4 °C plus precipitation increased by 10%. Under historic conditions, modeling finds that the best wetland habitat is in the Central subregion, which is also the region that FWS analysis highlights as high-quality habitat that should be targeted for conservation. However, in a warmer PPR the best habitat (and highest values of CCI) shifts markedly to the East (25), as can be seen from the numbers in Table 1. This geographic shift induces a negative correlation between future CCIs in the Central and Eastern subregions; the expected returns and covariances implied by Table 1 and that serve as inputs to the portfolio analyses are presented in Table S1.

It is difficult to say how likely each of the four climate scenarios are; such probabilities depend, for example, on implementation of climate-change mitigation policy (27), which is itself uncertain. Thus, we consider two sample probability distributions to demonstrate the sensitivity of optimal portfolio analysis to assumptions about outcome probabilities: One distribution, denoted "no change likely," is weighted heavily toward historic conditions, whereas the other, denoted "uniform," assumes each climate scenario is equally likely to occur.

Table 1. Basic parameters for optimal portfolio analyses

	Like historic	+2 °C	+4 °C	+4 °C, wetter
Probabilities of climate outcomes				
"No change likely"	0.80	0.10	0.05	0.05
"Uniform"	0.25	0.25	0.25	0.25
Average wetland habitat quality (CCI)*				
Western	0.290	0.178	0.124	0.168
Central	0.718	0.587	0.251	0.503
Eastern	0.317	0.561	0.584	0.654
Average conservation cost†				
Western	$0.601	$0.631	$0.631	$0.536
Central	$0.697	$0.720	$0.720	$0.659
Eastern	$1.21	$1.23	$1.23	$1.20

*CCI values are taken from ref. 25; subregion variances and covariances are calculated by the authors.

†One thousand dollar value of land per acre. Data for historic values are from ref. 30; future values are estimated with regression results from ref. 30.

The literature on land conservation (5, 28, 29) has established that cost-effective conservation planning considers both benefits and costs. The cost of conservation in places like the PPR is determined in large part by the value of the lands that must be purchased or placed under easements, and land values in the PPR vary greatly across space. Thus, we carry out two types of portfolio analyses: We select portfolios of lands on the basis of information on benefits only, and we select portfolios on the basis of spatial information about the ratios of wetland habitat benefits to conservation costs.

Results

Benefit-Only Portfolio Analysis. We derive the efficient benefit-only frontiers for the two probability distributions by finding the composition of an acre of land-conservation investment that maximizes the expected value of the portfolio's CCI for a given degree of riskiness. These frontiers are shown in Fig. 2. Some portfolio points on these efficient frontiers are highlighted for discussion. Table 2 contains detailed information about each of these highlighted portfolios, with full detailed results in Dataset S1. Four general lessons about MPT-based conservation diversification are illustrated by these results.

First, portfolios with the highest expected values for habitat quality also have the most uncertainty associated with their outcomes. Thus, each efficient frontier in Fig. 2 displays a typical upward-sloping shape in risk/expected benefit space. Points A and D show the combinations of risk and expected benefits for

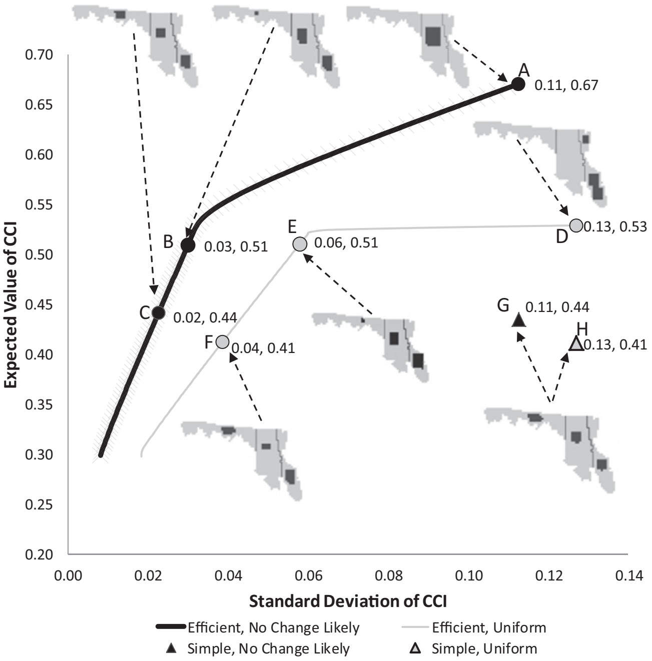

Fig. 2. Results of benefits-only portfolio selections for two sets of probabilities. The solid areas show how 6 million acres of protected or restored habitat are allocated between the three subregions in the indicated portfolios. Points A and D maximize the average expected value of CCI for the "no change likely" and "uniform" probabilities, respectively. Points G and H show the expected outcomes and SDs for simple diversification (i.e., splitting conservation evenly between the three subregions) for no change likely and uniform probabilities, respectively.

Table 2. Selected results of optimal portfolio analyses

	Portfolio weights			Portfolio outcomes	
Point on figure	Western	Central	Eastern	σ^R	$E[R]$
Fig. 2, R = CCI					
A	0.00	1.00	0.00	0.11	0.67
B	0.04	0.47	0.47	0.03	0.51
C	0.25	0.32	0.42	0.02	0.44
D	0.00	0.00	1.00	0.13	0.53
E	0.05	0.38	0.57	0.06	0.51
F	0.34	0.20	0.47	0.04	0.41
G	0.33	0.33	0.33	0.11	0.44
H	0.33	0.33	0.33	0.13	0.41
Fig. 3, R = CCI/cost					
A	0.00	1.00	0.00	0.17	0.96
B	0.00	0.57	0.43	0.08	0.68
C	0.18	0.36	0.45	0.05	0.57
D	0.00	1.00	0.00	0.24	0.74
E	0.00	0.85	0.15	0.19	0.69
F	0.00	0.71	0.29	0.15	0.65
G	0.08	0.26	0.66	0.04	0.50
H	0.14	0.76	0.10	0.13	0.82
I	0.14	0.76	0.10	0.19	0.65
J	0.33	0.33	0.33	0.06	0.57
K	0.33	0.33	0.33	0.09	0.50

the two probability distributions that result from a decision rule that allocates conservation between subregions just to maximize the expected value of the habitat quality of protected lands. To maximize expected benefits per acre, the decision maker would put all lands in the one subregion with the highest expected value of CCI. These portfolios are technically efficient. However, in both cases we could choose a different portfolio with much less outcome variation without sacrificing much in expected value. For example, when all climate scenarios are equally likely, portfolio E has >50% less risk than portfolio D, with only a 4% loss in expected benefit. This effect is present but less striking for the no change likely scenario.

Second, the best way to divide an investment depends on the balance the decision maker wants to strike between risk and expected benefits. Using the *Inset* maps in Fig. 2 to track the efficient allocation of conservation between the three subregions as we move from point A to point C along the efficient frontier for the no change likely distribution, we see that risk reduction is accomplished in this situation by shifting some investment out of the Central area, which has the highest CCI in the most likely outcome (historical conditions), and into the other areas. Many of the benefits of diversification come from investment in the Eastern subregion because habitat quality tends to be relatively good there when conditions cause habitat in the Central subregion to be relatively poor. The kink that appears right before point B exists because at that point, further risk reduction optimally entails shifting conservation into the Western subregion that has the lowest expected value of the CCI. Comparing portfolios D and E on the efficient frontier for the uniform distribution, massive risk reduction is accomplished by shifting much of the conservation investment from the Eastern subregion (which has the highest expected value of CCI under this probability distribution) into the Central area because outcomes in those two areas are negatively correlated. As in the no change likely case, further risk reduction entails more investment in the West where expected returns are relatively low, so the slope of the frontier is steeper when we move from E to F.

Third, the probabilities we place on the occurrence of the various climate scenarios influence several features of optimal diversification. (*i*) The probability distribution affects the position of an efficient portfolio frontier in risk/expected benefit space. In the case of the PPR, the efficient frontier lies higher (with as much as 34% higher expected values of habitat quality possible for a given level of uncertainty) when no change is likely than in the case when the four climate scenarios are equally likely because climate change is generally bad for waterfowl habitat in the PPR. (*ii*) The distribution influences choices about portfolio weights. For example, the portfolio that maximizes benefits per acre depends critically in the PPR on our assumed probabilities: Comparing points A and D, we see that when no change is likely, a benefit-maximizing portfolio has all lands in the Central subregion, whereas if all climate scenarios are equally likely, the Eastern subregion is best. (*iii*) The distribution affects the severity of the trade-off decision makers face between risk and expected benefits. In the PPR, if no change is likely, there is generally less uncertainty in conservation outcomes, so more expected value must be killed to reduce outcome variation. Fourth, science-based MPT analysis often yields much better results than simplistic diversification schemes. The results associated with points G and H show that simple diversification—splitting investment evenly between subregions—yields inefficient conservation portfolios in the PPR. Depending on which probabilities apply, using MPT identifies a portfolio with the same risk that has 29–52% higher expected benefits and a portfolio with the same expected benefits that has 30–18% lower risk.

Benefit–Cost Portfolio Analysis. We derive another set of efficient frontiers for the two probability distributions by finding the composition of an acre of land-conservation investment that maximizes the expected value of the portfolio's benefit–cost ratio for a given degree of uncertainty in that ratio. The efficient frontiers are given in Fig. 3, details of the highlighted points are in Table 2, and full results are detailed in Dataset S1.

Comparing Figs. 2 and 3 shows that one can carry out portfolio analysis in terms of benefit–cost ratios, and some features of the results are the same as if one just diversifies in terms of benefits. The efficient frontiers are still upward sloping. The frontier is still higher if no change is likely than if all climate scenarios are equally likely (with returns as much as 43% greater for the same risk). Simple diversification is still inefficient, especially for the case with uniform probabilities; point G has the same expected return as point K with 44% less risk, and a point directly above K has 15% greater benefits per unit cost for the same risk. Finally, the probabilities over climate outcomes still affect diversification advice. To see this, consider the current portfolio of lands held by the FWS in the PPR. If no change is likely, the current portfolio (point H) is very close to the efficient frontier. However, that portfolio is inefficient in the case of uniform probabilities (point I). If all scenarios are equally likely, decision makers could make changes in the portfolio to bring it up to the frontier. Expected benefits per dollar spent can be increased 6% (from point I to E) with actions that disinvest in the West and shift the ratio of lands in the Central to the Eastern subregions to 85:15; to reduce benefit uncertainty per unit cost by 21% (move from I to F), that ratio should be 71:29.

Despite these many similarities, the results shown in Figs. 2 and 3 differ in two critical ways. First, portfolio choices change if we consider benefit–cost ratios rather than benefits alone. To maximize cost effectiveness, one should invest in all lands in the Central subregion even when probabilities are uniform because land in the Eastern subregion is very expensive (point D, Fig. 3). The benefits-only MPT analysis put all conservation lands in the Eastern subregion to maximize benefits with uniform probabilities (point D, Fig. 2) because it neglected cost variation. When costs vary across space and climate outcomes, portfolio analysis should take them into account.

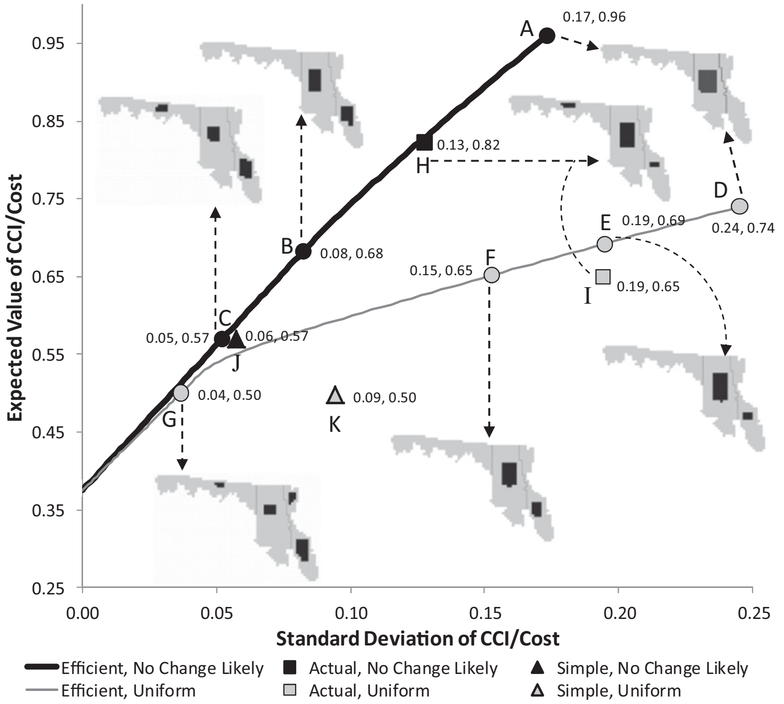

Fig. 3. Results of benefit–cost portfolio selections for two sets of probabilities. The solid areas show how 6 million acres of protected or restored habitat are allocated between the three subregions in the indicated portfolios. Points A and D maximize the average expected value of B/C for the "no change likely" and "uniform" probabilities, respectively. Points H and I show actual current Fish and Wildlife Service conservation weights in the PPR for no change likely and uniform probabilities, respectively.

Second, if an investment is constrained not to exceed some total cost, planners may gain more benefits from that investment using portfolios from the benefit–cost results. To illustrate, we assume uniform probabilities and calculate what total wetland habitat benefits would be gained from $1 billion worth of lands purchased in the PPR according to the weights prescribed by the return-maximizing points on the efficient frontiers of the benefit-only analysis and the benefit-cost analysis (point D in Figs. 2 and 3). The resulting total expected benefits are almost three times greater with the portfolio recommendation from the benefit–cost analysis than from the analysis of benefits alone because the benefits-only portfolio is heavily weighted toward the expensive Eastern subregion so few acres of land can be purchased under the cost constraint.

Discussion

The results of this paper show conservation groups and Federal agencies how to cost-effectively divide conservation effort between subregions of the PPR to reduce conservation-outcome uncertainty; if climate change is likely, actions to shift to an efficient portfolio would reduce holdings in the West and increase holdings more in the Eastern than the Central subregion (especially if one is risk averse). There is a trade-off between uncertainty and the expected value of habitat quality; planners can choose the portfolio on the efficient frontier that best satisfies their preferences over risk given their beliefs about the likelihood of climate change.

Our analysis yielded several unexpected findings. We found that the current FWS holdings are remarkably close to the efficient frontier if no climate change is likely (although whereas federal conservation choices may inadvertently have been diversifying appropriately for a world in which historical conditions are likely to prevail, this portfolio is far from efficient if a warmer climate is likely). We also found that whereas simple diversification schemes may be intuitively appealing, they can perform very poorly, with more risk or lower returns than can be gained from an efficient portfolio.

Analysts must have access to several critical types of information to carry out MPT-based portfolio analysis: the probabilities of different climate scenario outcomes, the spatial distribution of climatic and ecological conditions under each of those scenarios, and the spatial distribution of conservation costs under each of those scenarios. With these data, the analyst can calculate the spatial outcome covariances that are necessary inputs to risk-managing MPT. Diversification can be carried out at a finer spatial scale than we present here, but only if planners have information about ecological outcome forecasts over a relatively fine spatial grid and for a large number of possible climate outcomes. These data needs highlight three research priorities. First, more research needs to be done to resolve the current debate about how climate change is likely to affect land values (30, 31). Second, more work is needed to understand the probability distribution over all possible climate outcomes rather than just which climate outcome is most likely for a given path of greenhouse gas emissions. Third, spatial modeling is needed to learn how values of conservation objectives change over space for various climate-change outcomes.

MPT can be a useful planning tool in a wide range of contexts that have the following four characteristics. First, climate change poses significant uncertainty regarding the future spatial distribution of the costs and ecological benefits of the conservation activity being targeted. Second, action to adapt to climate change or mitigate its effects must be taken long before that uncertainty is resolved. Third, there must be a spatial region over which the outcome of interest is somewhat fungible. Fourth, although one can carry out portfolio analysis under other circumstances, the greatest benefits can be had if the spatial distribution of the conservation outcome covaries negatively across locations. For the large number of problems that have these basic features, MPT can help planners make strategic conservation investments that manage risk more effectively than simple diversification schemes, diversifying strategically across space to reduce future outcome variation for a given expected level of conservation success.

Methods

Portfolio Analyses. In financial theory, an unlimited quantity of each asset can be bought or sold to construct the portfolio—i.e., “short selling” is permitted—but in a conservation setting where the assets are parcels of land, short selling is not possible. A conservation project might also need a minimum number of contiguous acres for an ecological benefit to be realized. To account for these special considerations, we can require assets that enter the conservation portfolio to be larger than a minimum threshold. The assets in our PPR example are large tracts of land, so even a small optimal portfolio weight corresponds to a substantial allocation of land. Thus, we do not impose a minimum constraint on portfolio weights except to require them to be nonnegative.

Our specific numerical implementation of MPT solves for the efficient fractions of total land to invest in each of the PPR subregions (also known as portfolio weights). The objective is to minimize the variance of the return, R, for a specific level of expected R of the portfolio’s land holdings. Formally,

$$\min_{w} w^T \Sigma w, \text{ subject to } \sum_i w_i = 1, w_i > 0 \text{ for all } i, \text{ and } E[R]^T w = \mu, \qquad [1]$$

where the w_i are the weights of the portfolio of land holdings, T is the transpose operator, Σ is the covariance matrix of R, $E[R]$ is the expected return of each asset region, and μ is the target expected return. We trace out the shape of the efficient frontiers in Figs. 2 and 3 by solving the problem in Eq. **1** for each μ within the discretized interval, $\mu \in [\mu_{\min}, \ldots, \mu_{\max}]$. For example, we set $\mu_{\min} = 0.2975$ and $\mu_{\max} = 0.5291$ and used 100 evenly spaced values between the minimum and the maximum to construct the efficient frontier in the uniform-probability benefits-only analysis. We perform the calculations above using the *frontcon* routine in the Financial Toolbox of the Matlab R2011a release (32).

Benefits. We translate CCI forecasts from the maps in ref. 25 into values on a gridded map of the PPR such that each grid square covers 200 km^2 and calculate the average CCIs of the grid squares in each subregion of the PPR for each climate scenario. Note that for each region the future CCI varies widely depending on the climate change outcome such that the calculated future CCI values are negatively correlated between the Central and Eastern subregions and between the West and the East but positively correlated between the Center and the West. The assumed probabilities for our two probability-distribution scenarios are in Table 1 along with the expected values and covariances of CCI outcomes across subregions for each of the two scenarios.

In the benefits-only analyses, we define the return as R = CCI. Using the probability-distribution assumptions from Table 1, the expected CCI in each region is defined as

$$E[\mathrm{CCI}_i] = \sum_j p_j \mathrm{CCI}_{ij} \text{ for all climate scenarios } j. \qquad [2]$$

That is, the expected CCI in region i is the sum of the probabilities of each climate scenario times the realized CCI in region i for climate scenario j. Entries in the covariance matrix, Σ, are defined by Eq. **3** for two regions, m and k:

$$\Sigma_{m,k} = \mathrm{Cov}[\mathrm{CCI}_m, \mathrm{CCI}_k] = E[(\mathrm{CCI}_m - E[\mathrm{CCI}_m])(\mathrm{CCI}_k - E[\mathrm{CCI}_k])]. \qquad [3]$$

Costs. Conservation costs in the PPR are largely equal to the price of land. A land trust with a fixed budget that is interested only in conservation benefits may use current land values to define costs because current values determine budget outlays (land is purchased or placed under easement now to yield future benefits). However, a government agency may define costs as the value of the land that obtains under the long-term climate-change scenario that comes to pass, because those numbers reflect the foregone use values of the lands that are locked up in conservation status for years to come. We use the latter approach, although the difference is small in the PPR context because land values are not predicted to change much there as a result of climate change. To estimate the frontier of efficient conservation that takes both conservation benefits and cost into consideration, we need estimates of future land price outcomes in the PPR under the climate scenarios we consider. We use the estimates found in ref. 30 to construct predicted land values in each of our climate change scenarios to use in our benefit–cost portfolio analysis. After replicating Table 2 in ref. 30 we use the coefficient estimates to predict land values associated with our climate outcomes (that is, warming of 2 °C, warming of 4 °C, and warming of 4 °C plus precipitation increased by 10%). Then we define the benefit–cost ratio as B/C = CCI/Cost, and

$$E[\mathrm{CCI}_i/\mathrm{Cost}_i] = \sum_j p_j \mathrm{CCI}_{ij}/\mathrm{Cost}_{ij} \text{ for all climate scenarios } j. \qquad [4]$$

That is, the expected benefit–cost ratio in region i is the sum of the probabilities of each climate scenario times the realized benefit–cost ratio in region i for climate scenario j. Entries in the covariance matrix, Σ, are defined by Eq. **3** for two regions, m and k:

$$\begin{aligned}\Sigma_{m,k} &= \mathrm{Cov}[\mathrm{CCI}_m/\mathrm{Cost}_m, \mathrm{CCI}_k/\mathrm{Cost}_k] \\ &= E[(\mathrm{CCI}_m/\mathrm{Cost}_m - E[\mathrm{CCI}_m/\mathrm{Cost}_m])(\mathrm{CCI}_k/\mathrm{Cost}_k - E[\mathrm{CCI}_k/\mathrm{Cost}_k])].\end{aligned} \qquad [5]$$

Total CCI Given Budget Constraint. Using predicted land values and the portfolio weights that underlie the efficient frontiers in Figs. 2 and 3, we calculate the total CCI that can be purchased given a conservation budget of \$1 billion for the portfolios that underlie points D in Figs. 2 and 3. If we denote the expected value of the CCI of 1 acre of an efficient portfolio as CCI^1, the cost of 1 acre unit of conservation in each subregion as C_i^1, the subregion weights in the efficient portfolio as w_i, and the cost constraint as M, the expected value of the total CCI is calculated by $E[\text{Total CCI}] = (M/\sum_i w_i \times C_i^1) \times \mathrm{CCI}^1$. In Fig. 2 that total is 357,442 CCI units; in Fig. 3 it is 1,057,183 CCI units.

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