

Will Ecosystem Services Attract Investors?

Charles Sims Associate Professor, Baker School of Public Policy and Public Affairs, University of Tennessee, Knoxville; Department of Economics, University of Tennessee, Knoxville; cbsims@utk.edu

Ben Blachly Researcher, Baker School of Public Policy and Public Affairs, University of Tennessee, Knoxville; benblachly@gmail.com

Travis Warziniack Research Economist, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado; travis.w.warziniack@usda.gov

ABSTRACT *An unanswered question in conservation economics is how to leverage impact investing for the provision of ecosystem services. We develop and apply a general conceptual model of a diversified ecosystem service portfolio to highlight two key insights about which ecosystem services will attract impact investing. First, generating a positive expected return via markets or payments for ecosystem services is a necessary but insufficient condition to elicit impact investment in ecosystem services. Second, ecosystem services can show a new diversification value that increases the value of the ecosystem service asset to an institutional investor. (JEL Q57)*

1. Introduction

Impact investing, now estimated to be worth around \$500 billion (Hand et al. 2020), is experiencing rapid growth. Impact investing is the use of institutional investors (endowment funds, commercial banks, mutual funds, hedge funds, pension funds, and insurance companies) to generate a measurable, beneficial social or environmental impact alongside a financial return for their clients or members. Impact investing with an environmental focus has largely been channeled toward renewable energy projects and negative emissions technologies (Gibon et al. 2020). However, impact investing is increasingly being used to fund ecosystem service provision. Since 2017, more than \$129 billion in green bonds

have been issued with more than one-quarter targeted to raise funds to conserve land, water, and air.¹ To date, the Nature Conservancy's NatureVest program has raised \$1.3 billion to fund "investments that seek to achieve specific conservation outcomes while providing competitive, risk-adjusted financial returns to investors" (Nature Conservancy 2020). Impact investment is expected to increase as opportunities to invest expand.² This article advances our understanding of how to leverage private impact investments for providing ecosystem services by considering the portfolio of other assets institutional investors are likely to hold.

Like any asset, investment in ecosystem services is driven by financial return. Market forces dictate the return from investments in companies, organizations, and funds that enhance many provisioning services, such as timber and water yield. These markets are often regulated and in many areas are subject to influence from large swaths of public lands. For many regulating services, such as carbon sequestration or water filtration services, markets have not traditionally existed and have instead relied on payment for ecosystem service (PES) programs. Techniques to value ecosystem services have been fundamental in establishing the returns for ecosystem services whose markets are heavily regulated or where markets would not exist without PES programs.

Risk is another consideration that often emerges from surveys of asset managers. Investors can invest in a variety of assets in different sectors of the economy to diversify

¹Information retrieved April 12, 2022, from Bloomberg terminal.

²For example, the New York Stock Exchange recently filed listing standards for corporations that hold the rights to ecosystem services produced by natural or working landscapes (i.e., natural asset companies).



(reduce) the unsystematic risk exposure of holding one particular asset. Emerging markets for ecosystem services provide a new asset class that can help diversify risk from holding assets elsewhere in the economy. For example, individual and institutional investors have long viewed timber investments as a way of diversifying risk and hedging inflation (Redmond and Cabbage 1988; Washburn and Binkley 1993; Sun and Zhang 2001; La and Mei 2015; Matthies et al. 2015). However, ecosystem services also introduce new sources of risk from natural disasters (e.g., storms, fires, insect outbreaks) and climatic variation. For example, valuable resources may be devoted to preserving a forested watershed to sequester and store carbon or provide drinking water only to have these benefits reduced through forest fire, pest outbreak, or climate change. Investors can diversify this risk by investing in other ecosystem services or shifting investments to other geographic areas less exposed to those risks. Thus, impact investors must consider risk-return trade-offs in the portfolio of ecosystem service assets they hold and how the portfolio of ecosystem service assets diversifies risk of the broader portfolio of assets.³

A major unanswered question in conservation economics is how these risk-return trade-offs influence which ecosystem services will attract institutional investors. To address this, we use modern portfolio theory (MPT) to identify an institutional investor's optimal allocation of funds across ecosystem services. The optimal investment portfolio balances the financial return for clients or members with the financial risk that ecosystem service flows will be eliminated by natural, randomly occurring disturbance events, such as fire, insect outbreak, or storm. We use a general conceptual model and an application to ecosystem service investments in the western United States to highlight two key insights about

which ecosystem services will attract impact investing.

First, generating a positive expected return via markets or payments for ecosystem services is a necessary but not sufficient condition to elicit impact investment in ecosystem services. Certain ecosystem service assets appear consistently in optimal portfolios despite offering relatively low expected returns. Others offer high returns but fail to attract significant investment. The ability of ecosystem services to attract investment depends on expected return and risk and on the covariance of that asset's returns with others. Optimal allocations depend on which ecosystem services are available to the investor, which could be determined either by the availability of viable markets or by the investor's preferences (e.g., some investors may favor a particular ecosystem service or a particular region). Thus, while impact investing is often seen to leverage financial markets for ecosystem service provision, not all ecosystem services will receive this injection of funds because institutional investors view these services as part of a larger portfolio instead of as individual assets.

Second, ecosystem services can have a new diversification value that increases the value of the asset to an institutional investor. We define diversification value as the return an investor is willing to forgo to reduce risk. We attribute diversification value to individual ecosystem service assets by measuring the forgone portfolio return associated with adding a single asset to the portfolio. The presence of diversification value is not guaranteed. The service's expected return could be high enough to induce investors to increase (rather than decrease) their overall portfolio risk. We find that diversification value exists in more than half of the cases we studied. It ranges in size from virtually nothing up to 58% of the investor's ecosystem service investment budget. Our results suggest that individual asset diversification values may decline in the future from increasing environmental risk (e.g., from climate change) and the availability of an increasing number of investable ecosystem service assets.

MPT has been applied in the context of a conservation organization (i.e., nature

³This distinction is often referred to as diversification versus asset allocation in the finance literature. Diversification focuses on investing in different ways using the same asset class (here, ecosystem service assets), whereas asset allocation focuses on investing across a wide range of asset classes to lower the risk.

conservancies, land trusts, government agencies) that holds a collection of assets (the conservation portfolio) with each asset representing, for example, a species population (Figge 2004; Koellner and Schmitz 2006; Sanchirico, Smith, and Lipton 2008; Moore et al. 2010; Schindler et al. 2010; Alvarez, Larkin, and Ropicki 2017) or candidate sites for protection (Halpern et al. 2011; Ando and Mallory 2012; Mallory and Ando 2014). Crowe and Parker (2008) use MPT to identify an efficient portfolio of seed sources used to restore impacted forestlands. Halpern et al. (2011) and Ando and Mallory (2012) were the first to use MPT for spatial targeting of conservation investment allocation decisions. More recently, Vinent et al. (2019) use MPT to show how conserving lands with diverse characteristics can reduce the risk of losing wetland ecosystem services from rising sea levels. Unlike the conservation organizations considered in much of this previous work, institutional investors often consider multiple ecosystem services at the same time, do not directly use the ecosystem service, or currently own the land that is generating the ecosystem service.⁴ This characteristic of institutional investors differentiates our work from existing MPT studies in two ways.

First, we use portfolio theory to inform questions about ecosystem service valuation instead of land management. Portfolio theory originates from finance, where analysts estimate the value of securities and portfolio managers decide how much and which securities are included in a portfolio. To date, most economic research on ecosystem service valuation takes the analyst's perspective in that they value a single ecosystem service in isolation. However, investors recognize that value originates from the valuation of individual

assets and from the composition of the portfolio. Likewise, value can originate from an accurate estimate of the economic value of an ecosystem service and from the composition of ecosystem services that attract capital investment. In other words, diversification implies that, when held in a portfolio with other assets, certain ecosystem services provide a risk-reduction benefit that is overlooked when those ecosystem services are valued in isolation. This diversification value is separate and in addition to the return from the ecosystem service itself and thus represents a new source of value.

Second, we consider a unique source of uncertainty that originates from differences in the spatial variation or patchiness of ecosystem supply. Spatial variation in ecosystem service supplies can make it difficult to predict losses from natural disturbance events like fires, insect outbreaks, and droughts because these events occur randomly in space. Ecosystem services whose supplies are spatially patchy will look relatively riskier than one whose supplies are relatively uniform over the management jurisdiction.⁵ If the ecosystem services are equally as valuable, a risk-averse investor will choose assets with less spatial variation. If there are other ecosystem services that are negatively correlated (i.e., occur in areas where other ecosystem services do not), the investor can reduce their risk by investing in a portfolio of these services. In previous applications of portfolio theory to conservation, spatial risk arises because of variation in the expected effects of future climate change scenarios on land types (Vinent et al. 2019) or regions (Ando and Mallory 2012). In those examples, diversification occurs only across space. Institutional investors can diversify across ecosystem service and space simultaneously. Thus, the spatial variation of ecosystem service supply can create risk and new avenues to diversify risks.

⁴For example, an institutional investor would invest in the company that owns the rights to the ecosystem service, such as a real estate investment trust or a carbon capture company. This differs from payments for ecosystem service programs that are typically bilateral transactions between the owners of land that generates ecosystem services and the benefactors of ecosystem services that previously enjoyed those services for free. For example, conservation organizations like Ducks Unlimited and the Nature Conservancy have long compensated landowners for activities that encourage wildlife habitat.

⁵Spatial variation in ecosystem service supply can also create measurement error. Investors must base decisions on coarse-resolution measures of ecosystem service supply. Coarse-resolution data on ecosystem service supplies will generate large errors when those supplies are spatially patchy. Depending on where investments are made, realized supplies will differ from the expected measures.

2. Impact Investing for Ecosystem Services

Consider the case where an institutional investor chooses how much to invest in ecosystem services supplied by a landscape. The landscape is composed of $k = 1, \dots, K$ spatial subunits grouped into J regional units such that $k \in j$ indicates the set of subunits making up region j . Each region provides $i = 1, \dots, I$ ecosystem services that are traded in well-defined markets. Institutional investors choose which region(s) and ecosystem service(s) to invest in. Each region–service pair is considered an asset, so there are $i \times j$ potential assets. For example, an institutional investor may choose to invest in grazing services in California and Nevada and water filtration services in Arizona and New Mexico. Investment in an asset generates an unknown economic return R_{ij} . The return is unknown because disturbance events (e.g., fires and insect outbreaks) reduce the value of the ecosystem service and occur randomly at different points in the landscape. Investors may know the expected return from each ecosystem service in each region but cannot predict financial losses from disturbance events because they cannot predict where these events will occur. Much like purchasing many shares in a stock expected to perform exceptionally well, an institutional investor may choose large investments in ecosystem services in regions expected to provide a large economic benefit. Likewise, an investor may choose to avoid investments in converse cases.

A portfolio of ecosystem services is a combination of at least two distinct region–service pairs (i.e., assets, a). The expected return on a portfolio of ecosystem services is $R_P = \sum_a \omega_a R_a$. A portfolio with $\omega_a = 0$ does not include asset a . However, any given portfolio is risky in that an investor cannot be certain where in the landscape a disturbance may occur. For example, an investor may invest in a timber company only to have a fire destroy the value of the company's forestlands.

Risk Diversification

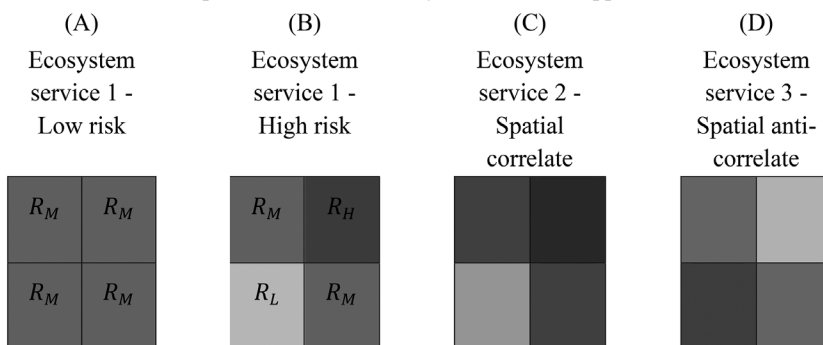
Applying MPT in environmental and resource economics typically focuses on risk that

originates from temporal variability, such as the inability to predict future populations of an endangered species or the effect of future climate change on a landscape. However, providing ecosystem services through impact investing is subject to a unique form of risk that arises because of the spatial variation in ecosystem service supplies. Ecosystem services whose supplies vary substantially at different points in the landscape will look relatively riskier than an ecosystem service whose supplies are relatively uniform due to the random location of disturbance events.

Figure 1 illustrates a hypothetical landscape composed of four cells. The shading in the cells represents the economic return from an ecosystem service in each cell, with darker shades representing higher returns. For the exposition, R_H is the annual return in the darkest cells. It is R_L in the lightest cells and $R_H > R_M > R_L$ in the intermediate cells. The ecosystem service is uniformly spaced in landscape (A) and is patchy and varied in landscape (B). Assume a disturbance occurs every year in one cell and eliminates the return in that cell. After one year, vegetation regenerates, and the ecosystem service returns to its previous level. These disturbances occur randomly in space, with equal probabilities. The annual return from the ecosystem service in landscape (B) is unknown, with an expected value of $2R_M + R_H + R_L - \frac{1}{2}R_M - \frac{1}{4}R_H - \frac{1}{4}R_L$. The annual return from landscape (A) is known with certainty and is $4R_M - R_M$. Landscape (B) will provide a larger expected return when $R_H > 2R_M - R_L$. However, investing in the ecosystem service in (B) looks riskier than investing in (A).⁶ A risk-averse investor may still choose to invest in (A) because it provides a certain payoff. An institutional investor may be able to reduce the risk created by the spatial variation in ecosystem service supplies by simultaneously investing in other ecosystem services that are not spatially correlated with (B).

⁶It could also be the case that the homogeneous landscape on the left is less risky due to measurement error. For example, the spatial resolution of economic valuation studies may suggest that economic values look like the landscape on the left when the real economic values look like the landscape on the right.

Figure 1
Spatial Variation in Ecosystem Service Supplies



Note: The variation creates risk that can be correlated or anticorrelated with other ecosystem services. Darker shades indicate larger economic returns.

Landscapes (C) and (D) in Figure 1 show the two other ecosystem services. That shown in (C) occurs in many of the same locations as (B); that is, (B) and (C) are spatial correlates. Thus, investing in the ecosystem service in (C) would increase the risk facing the investor. Landscape (D) mostly occurs in areas where ecosystem service (B) does not occur; that is, (B) and (D) are spatial anticorrelates. Thus, diverting some of the funds invested in (B) to (D) could reduce the overall ecosystem service risk that the investor faces, even if (D) offers a lower expected return. For example, investing in grazing may offer a higher expected return than investing in water filtration services. But if water filtration services are more valuable in areas where the value of grazing is low, investors would lower their risk by diverting some of the funds invested in grazing toward water filtration.

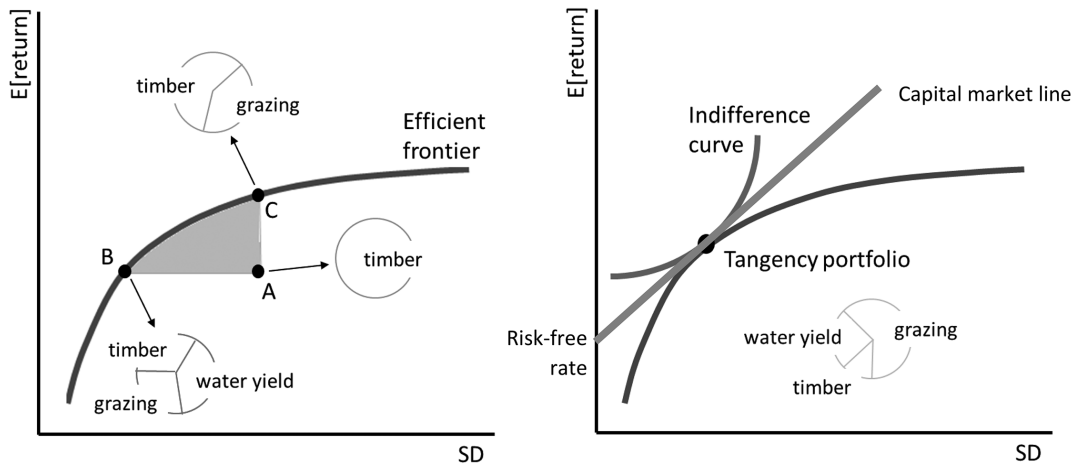
While these concepts of spatial correlates and anticorrelates have been used to describe the trade-offs facing conservation planners (Ando, Howlader, and Mallory 2018), we use these concepts to introduce a new form of risk that originates from the randomness of natural disturbance processes. The spatial correlation between ecosystem service objectives determines the asset correlation facing the institutional investor giving rise to what Ando, Howlader, and Mallory (2018) call multi-objective scenario correlation. A key result when considering this type of risk is that portfolios composed of ecosystem services

that tend to coexist in the same locations will be riskier than portfolios of ecosystem services that do not coexist. This runs counter to conventional wisdom in the conservation planning literature, which recommends protecting in “win-win” areas where two or more valuable species coexist. While this strategy will increase the expected return from the individual investment in species protection, it will also increase the riskiness of the portfolio of protected areas.

The reason these win-win strategies are more risky is that a portfolio of ecosystem service assets has a lower collective variance when compared with the average of variances of all individual assets because the variance of the portfolio of ecosystem services (a measure of the risk of a portfolio) is the sum of all individual variances plus all covariances $\sigma_P^2 = \sum_a (\omega_a \sigma_a)^2 + \sum_a \sum_b (\omega_a \omega_b COV_{ab})$, where $COV_{ab} = \sigma_a \sigma_b \rho_{ab}$ is the covariance of ecosystem service assets a and b , σ_a is the standard deviation (SD) of the return on ecosystem service asset a , and ρ_{ab} is the correlation between ecosystem service assets a and b . Thus, an ecosystem service portfolio may be composed of investments with relatively small SDs (i.e., the returns from these ecosystem services are relatively certain). However, if the correlation among the returns in these ecosystem services is large, the risk of investing in the portfolio of ecosystem services may be high. In other words, a strong relationship among returns across ecosystem services is

Figure 2

Ecosystem Service Assets (Portfolios): *left*, Three Hypothetical Portfolios; *right*, Hypothetical Tangency Portfolio



Note: The points along the efficient frontier in the left graph define combinations of portfolios that maximize expected return for a given level of risk ($= SD$). The graph at right shows the optimal (tangency) portfolio for an individual investor that depends on risk preferences (represented by an indifference curve) or the ability to invest in an alternative risk-free asset (represented by the capital market line).

akin to putting all your eggs in one basket, which increases the risk of the overall strategy. Efficient portfolios are those combinations of ω_a that achieve a required rate of return at the lowest risk or minimum acceptable risk with the highest return. By varying these required rates of return and minimum acceptable risk levels, one can trace an efficient portfolio frontier that summarizes the risk-reward trade-off across ecosystem service portfolios (Markowitz 1952).

Figure 2 (left) illustrates the concept using three hypothetical portfolios. For simplicity, assets are defined as ecosystem services rather than region-service pairs. Portfolio A allocates investments for managing timber harvesting. In contrast, portfolio B shifts some of the investment to enhance forage for grazing. Portfolio C splits investment between timber, grazing, and water yield. Portfolio A is inefficient because portfolios exist with the same expected return but less risk (point B) and portfolios with the same risk but higher expected return (point C) as well as portfolios with a combination of higher return and less risk (shaded area). The efficient frontier illustrates the implicit trade-off between expected return and risk that underlies decisions about

how to invest in ecosystem services. However, the frontier provides no guidance regarding which of those portfolios might be best.

Optimal Portfolio Selection and Diversification Value

We assume that the utility an investor receives from their investment is a function only of R_p and σ_p , the expected portfolio return and risk (SD). They do not care which services make up the portfolio, either because ecosystem services do not enter their utility function or because they assume the impact of their investment on the overall ecosystem service provision will be virtually zero. Finally, assume investors prefer higher returns ($dU/dR_p > 0$) and lower risk ($dU/d\sigma_p < 0$), suggesting that indifference curves will be upward sloping (Figure 2, right). Utility is maximized by choosing the "tangency portfolio" where the price (i.e., forgone expected return) of a marginal risk reduction equals the investor's willingness to trade off expected return against risk. In Figure 2 (right), the hypothetical tangency portfolio is composed of grazing, water yield, and timber investments. Indifference curves for a more risk-averse

investor would be steeper (i.e., they would be willing to forgo greater returns for a marginal risk reduction), resulting in an optimal portfolio with lower expected return and lower risk. Conversely, investors who are less risk-averse select a portfolio along the higher portion of the efficient frontier.

Many investors will be willing and able to shift investment from ecosystem services to risk-free assets, such as a U.S. Treasury bond or investments in well-diversified portfolios of assets other than ecosystem services. For these investors, it is possible to identify a single optimal portfolio along the frontier without knowing the underlying utility function and risk preferences (Sharpe 1964). Consider any portfolio defined by the frontier as a risky asset that can be combined with the risk-free asset to form a new portfolio. If the investor allocates 100% of their budget to the risk-free asset, the expected return equals the risk-free rate, and the expected SD is zero. Conversely, if the investor allocates 100% of their budget to the risky asset, the expected return and SD are a point along the frontier. For all other allocations, the expected return and SD of the new portfolio are linear functions of the weight assigned to the risk-free asset, so it is possible to expand the efficient frontier by drawing a ray originating at the risk-free rate on the y -axis and extending through any point on the frontier—the capital market line. The point that dominates all others is the point of tangency between the capital market line and the efficient frontier (Figure 2, right).

The capital market line is a practical concept for our application to institutional investors, since the same portfolio is chosen by all investors, regardless of risk preference. Investors who show a high degree of risk aversion will select a low-risk, low-return point on the capital market line, and those who are less risk-averse will opt for a point higher along the capital market line. Points on the capital market line below the tangency are achieved by splitting investment dollars between the tangency portfolio and the risk-free asset, while points above the tangency are achieved by borrowing at the risk-free rate and investing the proceeds in the tangency portfolio. Regardless, only the ecosystem service assets

that appear in the tangency portfolio (timber, grazing, and water yield in the hypothetical example) attract investment.

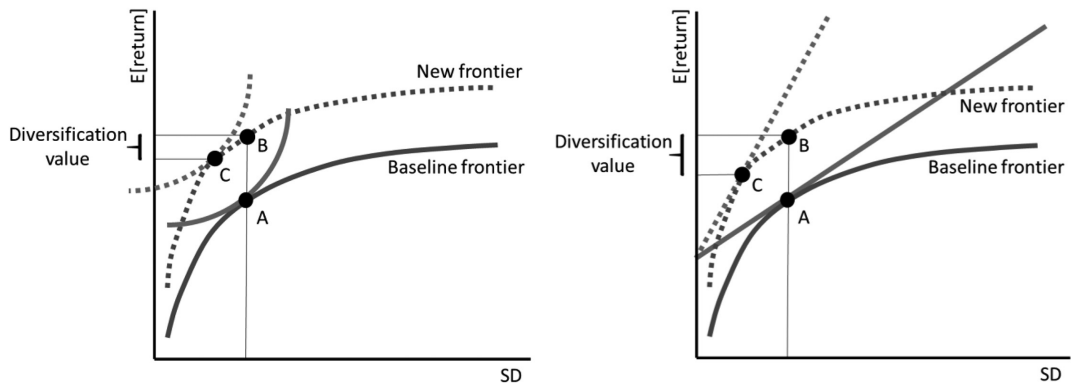
The ability of ecosystem services to reduce financial risk implies that impact investing could unlock a new source of value from ecosystem services: diversification value. Environmental economists have identified, and often quantified, several sources of value from ecosystem services: direct use value, existence value, option value, and cultural value, for example. Diversification value is different from these other sources of value because its existence and size depend on how an ecosystem service fits in a broader portfolio. For example, timber may hold little diversification value when held alongside carbon sequestration, since the two services tend to be colocated. The diversification value of timber could be significant when held alongside a service like grazing, with which it tends to have negative spatial correlation.

There are several preconditions for the existence of diversification value. First, the ecosystem service must be an investable asset generating a monetary return. Second, there must be other investable ecosystem service assets available to construct a portfolio. Third, the ecosystem service asset must appear in the investor's optimal portfolio. A low-return, low-risk asset, for example, is likely to appear only in portfolios to the left of the efficient frontier. An investor showing low-risk aversion will not hold the asset (or derive any diversification value from it) because they choose a high-return, high-risk portfolio toward the right of the frontier. These conditions are necessary but do not guarantee the diversification value as we define it next.

The diversification value of ecosystem service i is the expected return an investor is willing to forgo to enjoy lower risk when ecosystem service i is added to their portfolio. The concept is illustrated in Figure 3. Before the addition of ecosystem service i , the investor chooses the baseline portfolio A. Assuming the three conditions outlined in the prior paragraph are met, the additional ecosystem service expands the frontier to allow the investor to improve the expected return without incurring additional risk (portfolio B). However,

Figure 3

Diversification Value of an Ecosystem Service Asset Based On: *left*, Investor Risk Preferences; *right*, Investment in Risk-Free Asset



Note: Diversification value of an ecosystem service asset arises when the introduction of the asset shifts the efficient frontier out such that the investor chooses a new portfolio of ecosystem services (C) that has lower return and risk compared to portfolio B, the newly available portfolio offering the same level of risk but higher return than the baseline portfolio (A). Diversification value will depend on investor risk preferences (i.e., indifference curves shown at left) if all investment must be directed to ecosystem services. If the investor can shift investment to a risk-free asset, diversification value can be calculated without knowledge of investor preferences (right).

the investor can improve utility further by forgoing some portion of that higher return to secure lower risk (portfolio C). Conceptually, diversification value can be interpreted as the investor's willingness to pay for the risk reduction associated with moving from portfolio A to portfolio C. There is no guarantee, however, that the new portfolio will have a lower risk than the baseline portfolio. The new ecosystem service i may have an expected return so high that its addition to the portfolio induces the investor to take on more risk. In this case, ecosystem service i does not show diversification value. This constitutes the fourth requirement for diversification value: the newly chosen portfolio must have lower risk compared with the baseline portfolio. It follows from the four requirements that the existence and size of an ecosystem service's diversification value depends on the baseline portfolio to which it is added.

Our effort to define and quantify the diversification value of ecosystem services builds on the work of Ando (2018), who propose three metrics for evaluating the effectiveness of risk diversification. The two most similar to our work are elasticities along the efficient frontier, which measures the trade-off between risk and return. Lower elasticity indicates that

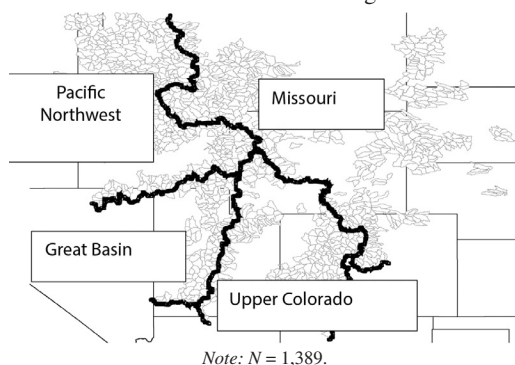
less return must be sacrificed to obtain a marginal risk reduction. Our concept of diversification value differs in two main ways. First, we incorporate decision-making, allowing the focus to be placed only on portfolios that are likely to be selected. The risk-return trade-off (i.e., elasticity) at the high end of the efficient frontier, for example, would only be relevant to individuals with extremely low-risk aversion. Second, we isolate the diversification value of individual ecosystem service assets rather than the overall usefulness of diversification for a set of assets. Attributing diversification values to individual assets represents a new source of value from ecosystem services.

3. Illustrative Example: Wildfire Risk in the Northern Rockies

Our empirical analysis considers an institutional investor interested in supporting ecosystem services in and around public lands in the northern Rockies (Figure 4). In this area, we identified all HUC 10 watersheds that include public land ($N = 1,389$). The watersheds fall within four distinct HUC 2 basins, or regions: Missouri (10), Upper Colorado (14), Great Basin (16), and Pacific Northwest (17).

Figure 4

Study Area of HUC10-Level Watersheds Divided into Four HUC2-Level Regions



We consider a hypothetical future where robust markets for five ecosystem services have developed: (1) provision of timber, (2) provision of forage for grazing, (3) provision of water for municipal and agricultural uses, (4) removal of sediment and pollutants in drinking water, and (5) carbon sequestration. We relax this assumption later. Four regions and five ecosystem services yield a total of 20 service–region combinations that we treat as potentially investable assets. The investor constructs a portfolio from these assets based on expected returns, risk, and covariance. Risk in our application is in the form of unpredictable losses to ecosystem services from intense wildfires.

Simulating Returns to Ecosystem Service Assets with Wildfire Risk

We start by calculating v_{ik} , the annual value of each ecosystem service i in each HUC 10 watershed k . Then we sum to the HUC 2 basin levels, indexed by j , so that $\sum_{k \in j} v_{ik}$ represents the total monetary value of ecosystem service i in region j absent any fire-induced losses. Next we introduce a time subscript, t , and a binary variable, a_{kt} , taking a value of one if watershed k experiences devastating wildfire in period t , zero otherwise. To obtain the monetary value of ecosystem service i in region j , $V_{ijt} = \sum_{k \in j} (1 - a_{kt}) v_{ik}$, we simulate values for a_{kt} using a two-step process designed to replicate each watershed's fire risk

based on historic data.⁷ In step 1, we define total acres burned, S_t , as a random variable and take random draws from a distribution of annual acres lost to large fires based on data from 1992–2015. In step 2, we simulate the location of fires (α_{kt}) by randomly drawing watersheds without replacement using probabilities derived from U.S. Forest Service Fire Simulation (FSim) results (Thompson et al. 2016) until burned watersheds sum to S_t . We repeat this process 1,000 times to simulate the severity and location of 1,000 fire seasons. The average asset returns, variation (risk) in asset returns, and the covariances between asset returns, therefore, are driven by the spatial distribution and colocation of ecosystem services along with wildfire risk within and across regions.

Finally, we convert to a benefit-cost ratio (or comparably, return on investment) by dividing by C_{ij} , the estimated annual cost of conserving the land in region j associated with producing ecosystem service i . To summarize, we construct a $20 (I \times J)$ by T matrix of returns with simulated fire-induced losses as follows:

$$R_{ijt} = V_{ijt} / C_{ij}. \quad [1]$$

Details on the data and calculations underlying each component of equation [1] are in the [Appendix](#). From the matrix of returns, we obtain the necessary components to construct an efficient frontier: the expected (mean) return, SD (risk), and covariance of the ecosystem service assets.

The expected return and SD (risk) for all 20 assets, in benefit-cost units, are in Table 1. Benefit-cost ratios greater than one indicate that investors can expect a positive return. The mean expected return across all assets is 3.42, but there is considerable variation. Grazing in the Missouri basin offers the highest expected return (8.08), and water yield in the Great Basin offers the lowest (1.03). Averaging returns by ecosystem service (i.e., column) indicates that water filtration tends to offer the highest returns, followed by timber, grazing, carbon sequestration, and water yield, respectively.

⁷ See the [Appendix](#) for details of our fire simulation process.

Table 1
Expected Return for Each Asset in Ecosystem Service–Region Pair

	Timber	Grazing	Water Yield	Water Filtration	Carbon Sequestration
Missouri	3.30 (0.02)	8.08 (0.05)	2.87 (0.01)	5.80 (0.09)	3.58 (0.02)
Upper Colorado	3.03 (0.02)	2.02 (0.01)	1.75 (0.01)	3.74 (0.04)	2.22 (0.01)
Great Basin	2.29 (0.05)	1.70 (0.04)	1.03 (0.02)	2.83 (0.07)	1.73 (0.03)
Pacific Northwest	5.62 (0.08)	2.17 (0.05)	2.76 (0.02)	7.37 (0.11)	4.45 (0.04)

Note: Standard deviations are shown in parentheses.

Averaging by region (i.e., row) suggests that returns are highest in the Pacific Northwest, followed closely by the Missouri, then Upper Colorado, and finally the Great Basin. Private investors must weigh expected return against risk. In absolute terms, water filtration in the Pacific Northwest region is the riskiest asset (0.11 SD), while grazing, water yield, and carbon sequestration in the Upper Colorado, along with water yield in the Missouri are the least risky (0.01 SD).⁸

Consistent with expectations, the riskiness of ecosystem service assets is directly related to the patchiness of their provision. The distribution of each ecosystem service across each region is shown in Figure 5. To quantify patchiness, we use the watershed-level mean and standard deviation of each ecosystem service value in a region to calculate coefficients of variation. Higher values indicate greater patchiness. Consider the Missouri (upper right) region. The patchiness is highest for grazing (3.811), reflecting the prevalence of extreme values across the region (Figure 5b). In contrast, the lowest patchiness coefficient in that region is for water yield (0.499), indicating a more uniform distribution (Figure 5c). There is also variation in the degree of wildfire risk (Figure 5f). On average, watersheds in the Great Basin face the highest probability of devastating wildfire, followed by the Pacific Northwest, Upper Colorado, and the Missouri, respectively. The correlation

coefficients between the patchiness of ecosystem services and the return risk in each region range from 0.58 to 0.88, indicating that patchiness magnifies fire risk.⁹

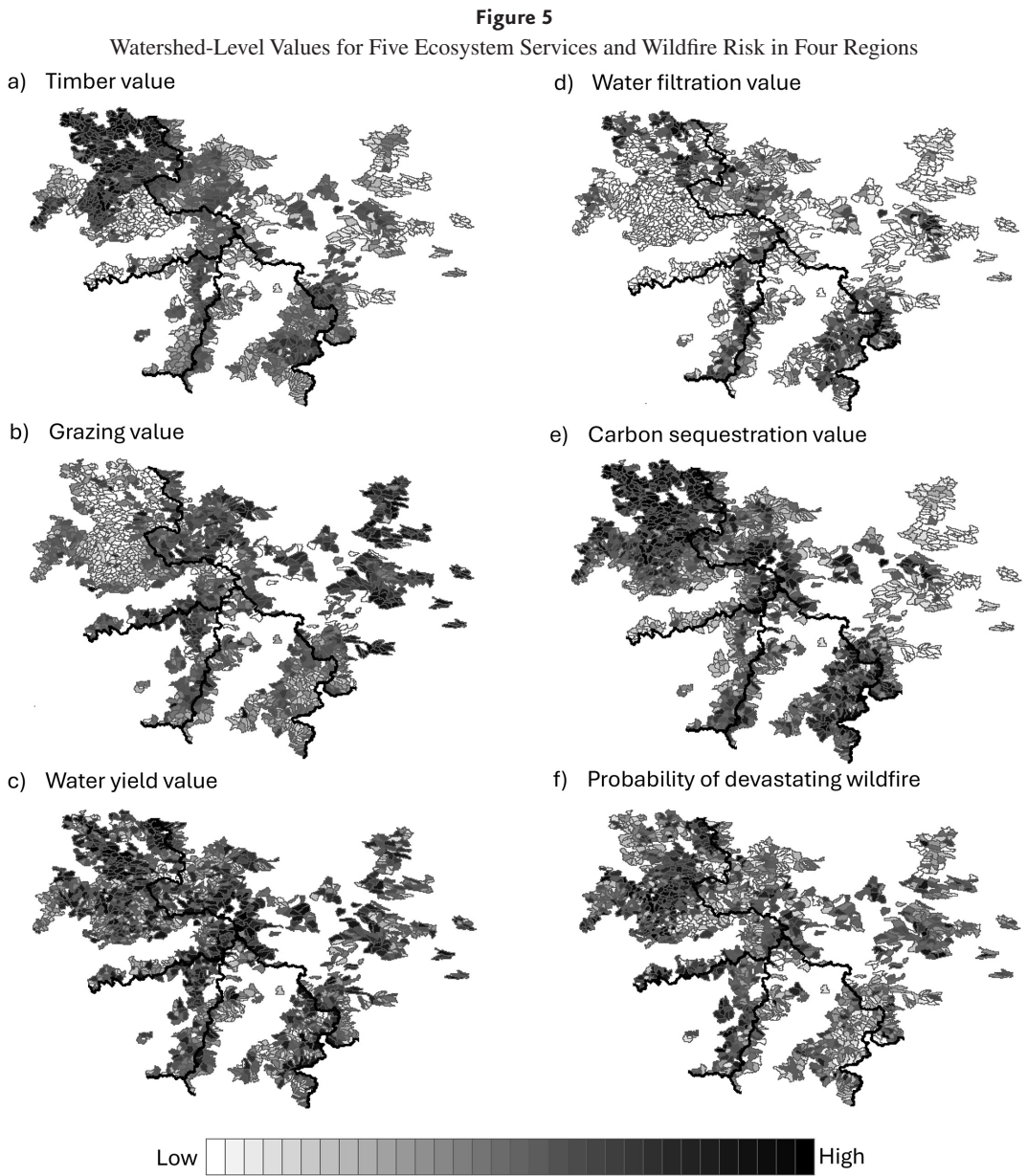
Efficient Frontier, Tangency Portfolio, and Diversification Value

The concave shape of the efficient frontier (see [Appendix Figure A2](#)) indicates that investors can reduce their exposure to wildfire risk through diversification. Ecosystem service assets are sufficiently uncorrelated to generate diversification benefits. At the leftmost point on the frontier is a low-return, low-risk portfolio investing in water yield across each of the four regions. At the rightmost point is a high-return, high-risk portfolio that is 100% allocated to grazing in the Missouri region. Between those extremes are various weighting schemes that maximize the expected return for each level of risk.

Investors can split their budget between ecosystem services and a risk-free asset that allows derivation of the capital market line and tangency portfolio. Following the conceptual approach in Figure 3 (right), we specify a risk-free rate (2%)—a reasonable value based on 10-year U.S. Treasury yields over the past decade—and use the capital market line and tangency portfolio to empirically estimate diversification values. The composition of the tangency portfolio and the diversification value of assets in the tangency portfolio are shown in Table 2. The expected benefit-cost ratio of the tangency portfolio is 3.03: every

⁸As an alternative to standard deviation, coefficient of variation can be used to compare the riskiness of assets relative to their expected return. According to that metric, the most and least risky assets are water filtration in the Great Basin and water yield in Missouri, respectively.

⁹See [Appendix Figure A1](#) for details.



\$1 invested in the tangency portfolio generates \$3.03. The Missouri region receives over 70% of the impact investment, with the large majority (67.9% overall) being allocated to water yield in that region. This is not the asset with the highest return. Seven of the 20 assets receive zero investment, and five others receive less than 1% of the budget. As a region,

the Great Basin receives just over 2% of the impact investment.

Diversification value is the return that investors are willing to forgo to reduce risk when a new asset becomes available (i.e., the vertical distance between portfolio B and C in Figure 3). This raw measure of diversification value represents forgone return independently

Table 2
Tangency Portfolio Composition and Diversification Value of Individual Ecosystem Service Assets

Region	Service	Tangency Portfolio Weight	Diversification Value (%)
Missouri	Timber	0	
	Grazing	0.0381	0
	Water yield	0.6794	0.50
	Water filtration	0	
	Carbon sequestration	0	
Upper Colorado	Timber	0.0901	0
	Grazing	0.0194	0.68
	Water yield	0	
	Water filtration	0.0142	0
	Carbon sequestration	0.0805	0
Great Basin	Timber	0.0016	0
	Grazing	0	
	Water yield	0	
	Water filtration	0.0057	0
	Carbon sequestration	0.0149	0.66
Pacific Northwest	Timber	0.0002	0
	Grazing	0	
	Water yield	0.0488	0.65
	Water filtration	0.0046	0
	Carbon sequestration	0.0025	0

from the size of the resulting risk reduction, making comparisons of diversification values across assets and portfolios awkward. To address this shortcoming, we transform the raw diversification value into a more intuitive elasticity that reflects the percentage of the tangency portfolio's return investors are willing to forgo to reduce risk by 1% (i.e., the arc elasticity between portfolio B and C in Figure 3):

$$\text{Diversification value} = \frac{\% \Delta E[\text{return}]}{\% \Delta SD}, \quad [2]$$

where $\% \Delta SD$ is the percentage decrease in risk. Table 2 includes estimates for the diversification value of assets held in the tangency portfolio. Of the 13 assets with nonzero weights, just four show a diversification value. The diversification value ranges from 0.5% (water yield in the Missouri) to 0.68% (grazing in the Upper Colorado). These diversification values represent the value of the risk diversification made possible by adding water yield in the Missouri or grazing in the Upper Colorado to the group of available assets. For example, if the institutional investor's budget for ecosystem services was \$1 billion, roughly equivalent to the Nature Conservancy's NatureVest

program, the value of the risk diversification made possible by these ecosystem services would be \$15.2 million and \$20.6 million.¹⁰

Role of Market Development and Investor Preferences

The benchmark results presented thus far assume that markets have developed for all five ecosystem services in the four regions and that investors hold no preference over which services or regions receive their investment. As outlined in the conceptual section, diversification value is unique among ecosystem service values in that it derives from the asset's relationship in a portfolio rather than from attributes of the ecosystem service. The diversification value of timber in the Missouri basin, for example, likely differs if only markets for timber and grazing exist or if investors are focused on a single region. Our results are also based on historic wildfire data. However, wildfire risk is expected to increase in

¹⁰These diversification values are found by multiplying the investor budget by the expected return for the tangency portfolio times the diversification value: \$1 billion $\times$ 3.03 $\times$ 0.005 = \$15,150,000 and \$1 billion $\times$ 3.03 $\times$ 0.0068 = \$20,604,000.

the future, potentially changing which assets attract investment and generate diversification values.

To explore the implications of relaxing those assumptions, we define six alternative scenarios by varying the ecosystem services available for investment. Scenarios 1–4 involve the elimination of ecosystem service markets in all regions, culminating in scenario 4, where only markets for timber and grazing exist. Scenario 5 considers the case where all ecosystem services are available to the investor, but the investor has chosen to focus investment in one of the four regions. For example, a nature or land conservancy may choose to restrict their attention to certain states or regions. Scenario 6 considers the case where all regions are available, but the investor has chosen to direct investment to one of the five ecosystem services. For example, a climate fund may focus exclusively on carbon sequestration instead of timber and grazing. For each scenario, we create an efficient frontier and use the capital market line to identify tangency portfolios and the assets that will attract institutional investors. Weights associated with the tangency portfolios are summarized by the size of the bubbles in Figure 6. Figure 6a shows results from scenarios 1–4, Figure 6b shows results from scenario 5, and Figure 6c shows results from scenario 6. The first column in each part shows the weights associated with our benchmark scenario in Table 2 (all 20 assets are available for investment).

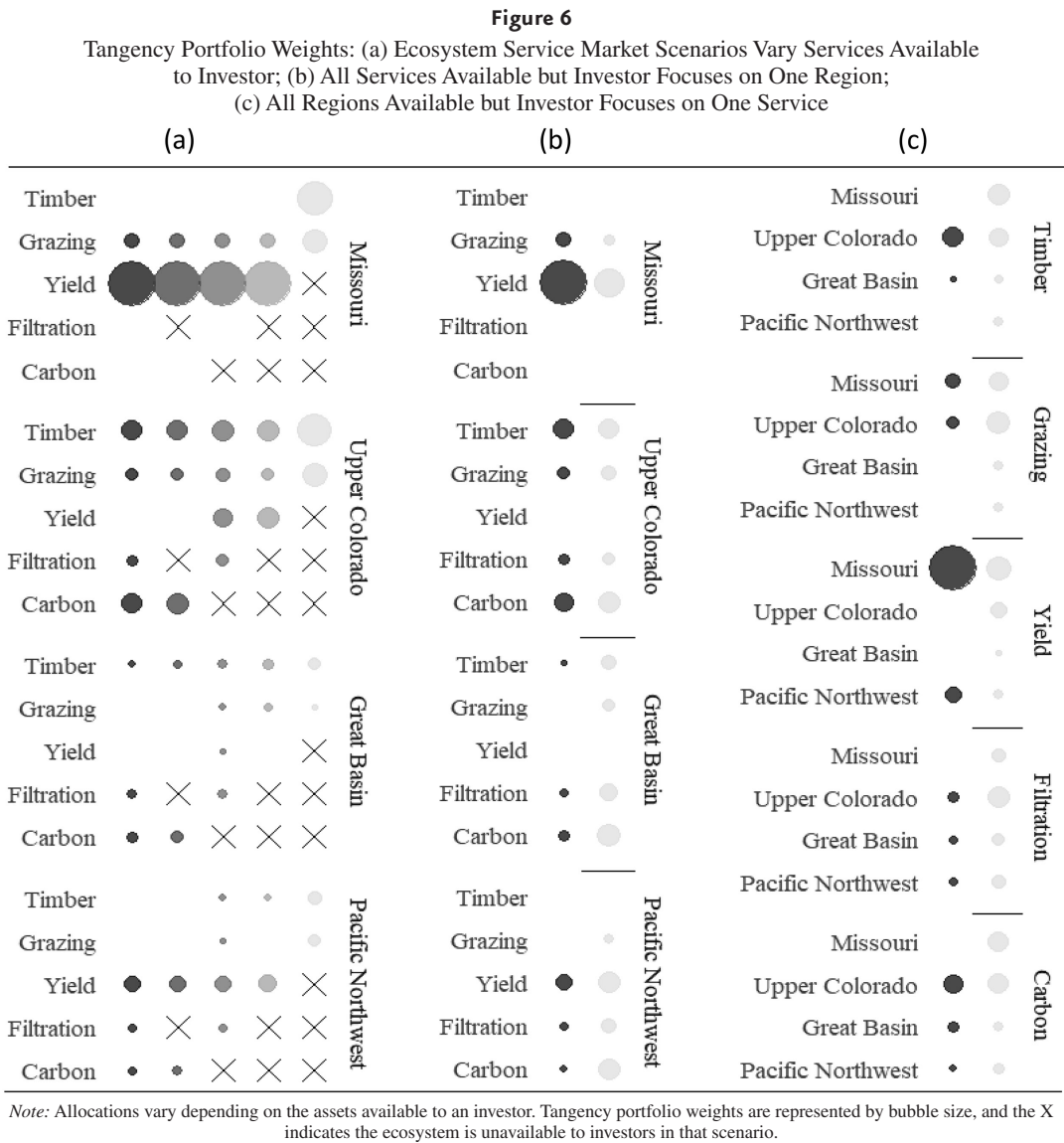
Restricting the availability of filtration and carbon markets (scenarios 1–3) in the Missouri basin does not affect the allocation of investment since the benchmark scenario's tangency portfolio did not include these assets. However, eliminating carbon markets in the other three basins shifts investment into water yield (Upper Colorado and Great Basin) and grazing and timber (Great Basin and Pacific Northwest). Restricting markets does little to shift investment across the basins. Overall, the Great Basin and Pacific Northwest basins attract a small portion of investment in scenarios 1–4.

The interpretation of results from the remaining scenarios (5 and 6) is slightly different, since these scenarios represent optimized

investment within-region and within-service, respectively. In scenario 5 (Figure 6b), investors choose a region and then optimize investment across ecosystem services. The allocations in the Missouri and Upper Colorado regional portfolios closely resemble the benchmark allocation where all service–region asset pairs are available to the investor. However, a regional focus on the Great Basin or Pacific Northwest basins increases the allocation to filtration and carbon sequestration and adds grazing to the portfolio. A regional focus, which is common among investors, usually reflects the investor's preferences. For example, land trusts often have a regional focus. The diversification value these investors give up with a regional focus ranges from 0.49% in the Upper Colorado to 0.58% in the Great Basin and Pacific Northwest basins (see [Appendix](#)). For example, if the budget for a land trust focused on the Pacific Northwest was \$1 million, the value of the risk diversification given up with a focus on that region is \$17,671. The forgone diversification value in the Great Basin and Pacific Northwest basins are higher because these basins make up a smaller share of the benchmark portfolio.

In scenario 6 (Figure 6c), that regional focus is relaxed, and investment skews heavily back toward the Missouri and Upper Colorado basins. In these scenarios, investors choose an ecosystem service, then optimize investment across regions. Investors have historically been focused on specific ecosystem services. For example, many real estate investment trusts have historically focused on timber. Of the scenarios we explored, this is the only instance where all 20 assets receive at least some investment.

To further investigate diversification values, we created a database by calculating the diversification value of each asset that draws investment across the benchmark scenario and each alternative scenario (i.e., each bubble in Figure 6). We expanded the database of returns from equation [1] by increasing the fire season size in step 1 of the fire simulation process to reflect expectations that wildfire will become more severe in the future because of climate change. Specifically, we repeated the fire simulation process with a moderate



and severe increase in the mean annual acres burned. We repeated the process of finding tangency portfolios and calculating diversification values for each scenario using the new return series. The final database consists of 448 ecosystem service investment opportunities, of which 362 opportunities attract impact investing.¹¹

¹¹Timber and grazing are available in all 7 investment scenarios (see Figure 6a) at 4 different fire risk levels for a

In our dataset, 208 of the 362 (58%) ecosystem service assets attracting impact investment exhibit diversification value (Table 3). For the 42% of cases where diversification value does not exist, the asset's return is so

total of $7 \times 4 = 28$ investment opportunities in each region. Water yield is available $6 \times 4 = 24$ times in each region. Water quality and carbon sequestration are available $4 \times 4 = 16$ times in each region. Summing over all assets and all regions yields 448 investment opportunities.

Table 3
Sensitivity of Diversification Values to the Services and Regions Available to an Investor

Region	Service	Proportion Scenarios Asset Attracting Investment	Proportion Scenarios Asset Exhibiting Diversification Value	Diversification Value (%)		
				Min.	Mean	Max.
Missouri	Timber	0.29	0.29	0.25	0.45	0.67
	Grazing	1.00	0.00			
	Water yield	1.00	0.96	0.39	0.53	0.59
	Water filtration	0.25	0.25	0.65	0.67	0.70
	Carbon sequestration	0.25	0.25	0.47	0.50	0.53
Upper Colorado	Timber	1.00	0.29	0.29	0.51	0.73
	Grazing	1.00	0.43	0.59	0.69	0.75
	Water yield	0.79	0.83	0.42	0.60	0.74
	Water filtration	1.00	0.38	0.49	0.55	0.69
	Carbon sequestration	1.00	0.25	0.44	0.46	0.48
Great Basin	Timber	0.75	0.36	0.47	0.62	0.75
	Grazing	0.93	0.64	0.47	0.66	0.79
	Water yield	0.42	0.50	0.47	0.66	1.12
	Water filtration	0.81	0.25	0.63	0.65	0.67
	Carbon sequestration	1.00	0.88	0.46	0.57	0.67
Pacific Northwest	Timber	0.75	0.36	0.47	0.65	0.76
	Grazing	0.86	0.50	0.63	0.72	0.81
	Water yield	1.00	1.00	0.43	0.63	0.75
	Water filtration	1.00	0.63	0.62	0.71	0.76
	Carbon sequestration	1.00	0.19	0.49	0.54	0.60

large that its addition increases the risk associated with the tangency portfolio. Grazing in the Missouri, for example, draws private investment 28 times in the dataset. However, as an asset it never shows diversification value. With an expected benefit-cost ratio of 8.08, it offers a large enough increase in return that investors are willing to accept the increase in risk. Water yield in the Pacific Northwest, on the other hand, shows positive diversification value all 24 times it is made available as an investable asset. Since the investor is willing to forgo return to achieve lower risk, the asset holds diversification value each time it attracts investment. Overall, diversification values are most common among water yield services and in the Great Basin and Pacific Northwest basins. The diversification values range from 0.25 for timber in the Missouri to 1.12 for water yield in the Great Basin. Mean diversification values are largest in the Pacific Northwest and for water quality.

Modeling the Determinants of Diversification Value

Using our database of 362 diversification values, we estimate the following left-censored

tobit model to uncover determinants of the presence and size of diversification value:¹²

$$\begin{aligned} \text{Diversification value} = & \beta_1 \text{Sharpe} + \beta_2 \text{patchiness} \\ & + \beta_3 \text{burnacres} + \beta_4 \text{assets} \\ & + \beta_5 \text{elasticity} + \epsilon. \end{aligned} \quad [3]$$

As noted, the diversification value is unique among ecosystem service values because it depends on the portfolio of assets to which the ecosystem service is added, in addition to the service itself. The first two explanatory variables therefore describe characteristics of the ecosystem service asset, while the third and fourth describe the investment scenario. In equation [3], *Sharpe* is the return-risk ratio of the ecosystem service asset (i.e., Sharpe ratio) which is a common way to generally characterize financial assets. Asset risk is decomposed into its two underlying environmental sources: spatial patchiness of the ecosystem

¹²When the asset causes investors to choose a new portfolio with higher risk than the baseline, the raw diversification value is negative. However, since our concept of diversification value requires a risk reduction, we assign cases of increased risk a value of zero resulting in a left-censored dependent variable necessitating a tobit model.

service asset (*patchiness*) and wildfire magnitude (*burnacres*). Since a risk reduction is necessary to achieve a diversification value (see Figure 3), we expect *patchiness* and *burnacres* to be negatively correlated with diversification value.

To quantify the overall portfolio, we use the total number of assets available for investment (*assets*) and the difference in the arc elasticity of the old frontier without the asset and the new frontier with the asset (*elasticity*).¹³ Since diversification opportunities generally improve when more (nonperfectly correlated) assets are available to an investor, we expect *assets* to be negatively correlated with diversification value. In general, lower arc elasticity (a flatter frontier) indicates that better opportunities exist for reducing conservation risk through diversification, since the investor can lower risk without sacrificing as much expected return (Ando et al. 2018). A larger value for *elasticity* means the additional asset has flattened the frontier, improving the prospects for diversification overall. Thus, we might expect β_5 to be positive.

Table 4 presents results of regressions used to explore the determinants of diversification value. The coefficient on the Sharpe ratio is negative as expected but insignificant. The patchiness risk measure has a significant negative relationship with diversification value. Unit increases to patchiness (i.e., coefficient of variation describing spatial distribution) decrease the diversification value. These results are intuitive. Assets with high expected returns entice investors to take on additional risk, whereas assets with high risk are unable to reduce portfolio risk. The final two variables describe the overall portfolio, rather than the individual asset. Each additional asset in the portfolio decreases the diversification value. When more assets are available to an investor, more opportunities to diversify exist, so the diversification value of any single asset is lower. Finally, the difference between arc elasticities without and with the asset is positively correlated with diversification values. This is as expected, because the addition

Table 4
Tobit Results for Determinants of Diversification Value

Variable	Coefficient (SE)
Sharpe	-0.03 (0.44)
Patchiness	-0.13*** (0.03)
Burnacres	0.01 (0.01)
Assets	-0.03*** (0.01)
Elasticity	0.73** (0.34)
Pseudo R-squared	0.09
N	362

* $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

of the asset has lowered the return an investor must forgo to achieve a risk reduction.

4. Conclusion

In response to growing evidence that ecosystem services provide real value, there has been a push for impact investing that would leverage financial markets to direct private investment to the supply of previously undervalued ecosystem services. Despite the substantial amount of impact investment directed toward natural assets to date, how investors value these assets is poorly understood. This knowledge gap has limited our ability to predict which ecosystem services will attract institutional investors and to design markets that fully leverage private impact investments for the provision of ecosystem services. We provide two results that partially fill this knowledge gap.

First, a positive expected return on ecosystem services is a necessary but not sufficient condition for attracting impact investment from institutional investors. In many cases, ecosystem service assets with relatively low expected returns attract significant investment owing to their ability to reduce portfolio risk. Conversely, assets with relatively high expected returns may fail to attract investment because they force the investor to accept excessive risk. Ultimately, determinations about whether to invest in a particular asset depend on how the asset relates to the overall

¹³ Arc elasticity is calculated as the elasticity between the high-risk, high-return portfolio and the efficient portfolio with median risk (Ando et al. 2018).

portfolio. Given the focus of institutional investors on risk and return of the portfolio of environmental assets, it is unlikely that impact investing will deliver socially optimal levels of all ecosystem services.

Second, an institutional investor will hold a unique value for ecosystem services as a risk-reducing tool. In 208 out of the 362 cases where an ecosystem service appears as an asset in an optimal portfolio, the asset induces investors to accept lower portfolio return in exchange for lower portfolio risk. As an elasticity, this diversification value ranges in size from 0.25 to 1.12, depending on the asset and the portfolio to which it is added. Diversification values are not static, however, and they could face upward and downward pressures in the future. For example, our tobit results indicate a negative relationship between diversification value and patchiness, suggesting that diversification values will be sensitive to shifting land use patterns. In addition, the expansion of markets for ecosystem services is likely to increase the diversification value of ecosystem services generally. However, the diversification value of any single ecosystem service asset is lower when more services become available to investors. Finally, we note the relationship between diversification value and the effectiveness of diversification identified by Ando et al. (2018).

While our numerical analysis is focused on a specific geographic location (northern Rocky Mountains) and a specific source of risk (wildfires), the method we demonstrate can be used to identify likely targets for impact investing and the diversification value of those assets in a variety of ecosystem service markets. However, this study has a few limitations that would be fruitful areas for future work. First, it is based on a partial equilibrium analysis. It is reasonable to expect prices of individual ecosystem service assets will adjust in response to demand from private investors, which will affect allocations and diversification values in ways that we are unable to capture. Second, we simplified the risks facing ecosystem service assets to focus on the spatial aspects of environmental risk. Realistically, returns from ecosystem services will also be subject to more traditional risks, such as price risk. The market price of carbon

credits, for example, fluctuates wildly, which directly impacts returns from carbon sequestration. We also simplify to a single source of environmental risk. More data on the spatial allocation of natural disturbance events will allow us to capture a broader array of environmental risks associated with investing in ecosystem services (e.g., insects or disease). Despite limitations, this study provides a foundation for a better understanding of how environmental risks will drive participation and the flow of dollars in impact investing for ecosystem services.

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