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Return on investments in restoration and fuel treatments in frequent-fire forests of the American west: A meta-analysis

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ABSTRACT

Arid forests in the American West contend with overly dense stands and a need to reduce fuels and restore more natural fire regimes. Forest restoration efforts include fuel treatments, such as thinning and prescribed burning, that can reduce ground and ladder fuels. Restoration and fuel treatments have emerged as leading wildfire risk-reduction strategies in the American West, yet little is known about the cost-effectiveness of such programs. To evaluate forest restoration and fuel treatment benefits and costs, we conducted a meta-analysis of benefit-cost ratios for restoration benefit types documented in the literature for Western U.S. dry mixed conifer forests at risk of uncharacteristic wildfires. A total of 120 observations were collated from 16 studies conducted over the last two decades, with benefits ranging from enhanced ecosystem services to extensively avoided wildfire costs. Significant variation in the value of restoration and fuel treatment benefit types was found, indicating that restoration benefits differ in value based on societal importance. Overall, 17 individual benefit types were aggregated to show that in the most valuable and at-risk watersheds, every dollar invested in forest restoration can provide up to seven dollars of return in the form of benefits and provide a return-on-investment of 600%.

1. Introduction

Escalating wildfire size and intensity across forests of the American West are well-documented and linked to warming temperatures and changes in precipitation from global climate change (Abatzoglou et al., 2019; Wasserman and Mueller, 2023). All forests that evolved with fire are today experiencing wildfire sizes and intensities outside their evolutionary envelope (Hessburg et al., 2021). Historically, western frequent-fire forests, such as ponderosa pine and dry mixed-conifer forests, burned every 3–35 years with little overstory loss; today, these forests are burning with stand-replacing events at increasing patch sizes, due to a combination of past management practices and today's climate (Hagmann et al., 2021). Western fires are resulting in unprecedented damage to the quality of life for many rural communities, inflicting severe consequences on human health and property (Thomas et al., 2017; Wang et al., 2021). Wildland-urban interface (WUI) areas across the entire U.S. have rapidly expanded, largely due to new housing, resulting in increased wildfires for many communities (Radeloff et al., 2018).

The rapidly increasing wildfire risk for communities in the Western U.S. has created urgency for developing solutions to lessen wildfire risk, minimize the overall costs to society caused by catastrophic wildfires, and restore forest health. For example, the U.S. Department of Agriculture Forest Service annual funding for wildfire management (inclusive of suppression, fuels reductions, research and development, rehabilitation, etc.) has continued to balloon over the last decade, up 60% from 2010 to 2020; it is now pushing $5 billion annually and consuming 60% of the entire Forest Service budget (Aldrich and Hjerpe, 2022). Billions more annually are being spent by other federal, state, and private land management agencies and organizations on wildfire management. Much of this increased risk of fire size and severity in the West can be found on public lands, but there is a need to understand and prioritize work to meet the shared risk across all land ownerships (Dunn et al., 2020).

To address increasing uncharacteristic wildfire in dry pine and dry mixed conifer forests of the western U.S. (estimated at 25.5 million hectares of forested area by Baker, 2018), numerous resources are being applied by various jurisdictions (e.g., federal, state, county, city, private, and tribal lands) to help reduce wildfire threats. In frequent-fire forests, forest restoration includes both mechanical thinning and prescribed fire fuel treatments; this management has emerged as the most comprehensive and effective proactive treatment for reducing wildfire risk in overly dense frequent-fire forests (Reinhardt et al., 2008; Prichard et al.,

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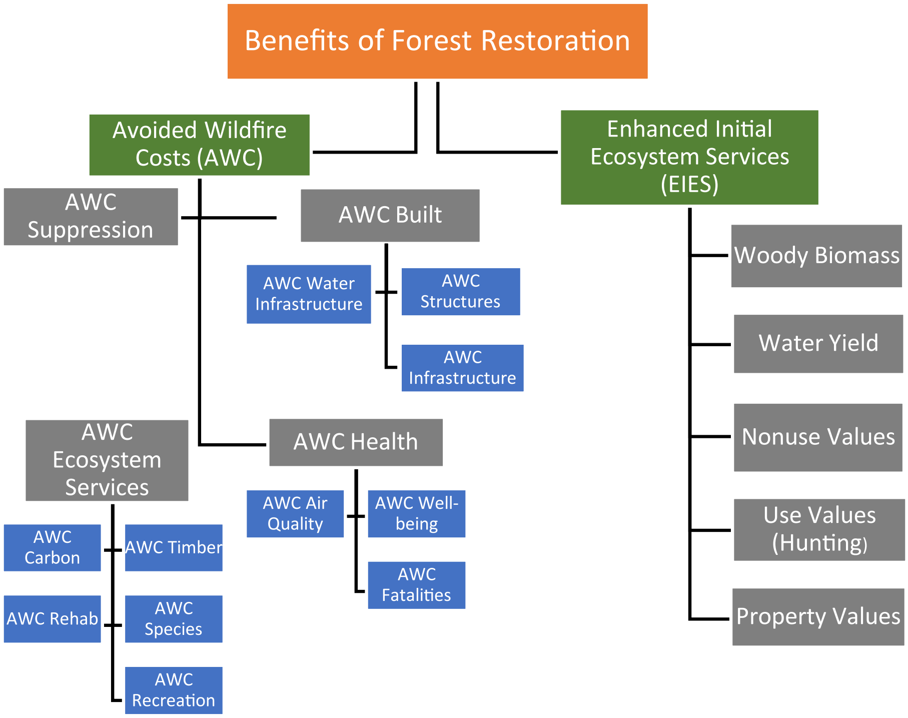

Fig. 1. Types of Forest Restoration Benefits Quantified in the Literature (Gray boxes are broad benefit types; blue boxes are individual benefit types that compose broad AWC categories). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of studies and benefit types included in meta-analysis.

Primary study (year of publication)	N_i	Forest Restoration Benefit Type								
		AWC Built	AWC ES	AWC Health	AWC Suppress	Hunting	Property Values	Nonuse Values	Water Yield	Woody Biomass
Buckley et al. (2014)	*8*	3	3		1					1
Gannon et al. (2019)	*1*	1								
Guo et al. (2023)	*8*								8	
Huang et al. (2013)	*12*	4	4	2	2					
Jones et al. (2017)	*2*	2								
Jones et al. (2022)	*24*	8	12		4					
Kim and Wells (2005)	*1*						1			
Loomis et al. (2002)	*4*					4				
Loomis and González-Cabán (2009)*	*1*							1		
Lynch (2001)	*5*									5
Lynch et al. (2000)	*1*									1
Lynch and Mackes (2003)	*3*									3
Mason et al. (2006)	*12*	2	4	4	2					
Podolak et al. (2015)	*22*								22	
Skog and Barbour (2006)	*8*									8
Wildish et al. (2020)	*8*	3	3	1	1					
Total	***120***	***21***	***26***	***7***	***10***	***4***	***1***	***1***	***30***	***18***

Notes: AWC = Avoided Wildfire Cost; N_i = Number of observations taken from primary study *j*. *Loomis and González-Cabán (2009) provided only the net forest restoration benefit per acre for California for willingness to pay, composed primarily of nonuse values. To derive a conservative benefit-cost ratio, we used a per acre restoration cost of $2000, or a doubling of the average per acre cost recorded in all other studies.

2010 & Prichard et al., 2021; Fulé et al., 2012). However, insufficient funding and lack of accounting for all economic benefits are the primary socioeconomic barriers to widespread forest restoration implementation (Hjerpe et al., 2009). Additionally, the geographic and financial scope of the wildfire crisis is too large to treat every acre, meaning that it would be prudent to prioritize forests where restoration yields the greatest amount of benefits and the greatest benefit to cost ratios. Understanding the economic returns on investment of various wildfire risk reduction strategies is paramount to crafting the most economically efficient forest treatment (Wu et al., 2011). Better quantification of the economic outcomes of forest restoration may also help expand the discussion about the importance of this work and shift the focus from narrow measures, such as timber targets on federal land, for explaining treatment outcomes to decision-makers.

At this nascent stage, an economic model is needed to compare various forest restoration benefits and costs within a single analytical framework (Holland et al., 2022). Return on investments can be distilled from forest restoration's benefit-cost analysis (BCA). The evolution of forestry and accompanying economic efficiency analysis means that BCA of forest restoration must incorporate a multitude of restoration benefits, including both market and non-market types of benefits, as compared to traditional forestry BCA and its myopic focus on one management benefit—revenue from timber stumpage. Ultimately, BCA can incorporate any benefits and costs of forest management that can be monetized. With the rapid advancement of forest restoration practices, some of the benefits of forest restoration have now been monetized and are available for benefits transfer.

To develop our economic model, we conducted a meta-analysis of benefit-cost ratios for forest restoration and fuel treatments found in the literature for dry mixed conifer forests of the American West. We focus on measuring the economic efficiency of pre-wildfire ignition strategies related to preventive activities associated with fuel reductions, including thinning and burning. Benefit-cost ratios, and BCA, can be used to measure the economic efficiency of projects, which can then be used to highlight the environmental returns on investment (e.g., for each dollar invested in forest restoration, how much and how many benefits are returned to the investors) (Jones et al., 2017). While the costs of forest treatments are generally well-known, the range of market and non-market benefits of forest restoration requires a comprehensive collection and evaluation of documented forest restoration benefits (Kline, 2004).

With little quantified knowledge of forest restoration benefits, we conducted an extensive literature review on all potential benefits of restoring frequent-fire forests. Because forest restoration effects are manifested in society in various fashions (e.g., reduced wildfire risk, avoided wildfire costs, avoided adverse human health effects, increased native biodiversity, and water supply protection), we assessed benefits and costs stemming from evidenced-based primary research and modeled effects of forest restoration as a wildfire fuel treatment and as a generator of beneficial biophysical changes. The following sections provide a literature review, detail the methodological approach of the meta-analysis, show the results, and conclude with a discussion of the returns on investment in forest restoration in arid forests of the American West. While it is important to note that other forest restoration activities besides thinning and prescribed burning also yield numerous environmental benefits (Eriksson et al., 2022), they are beyond the focus of this meta-analysis.[1]

1.1. Literature review

In contrast to forest restoration efforts in many tropical and international locations where the focus is on reforestation and repairing damage to forests that have been slashed and burned for development (Chazdon, 2008), restoration of arid forests in the American West contend with overly dense forests and a need to reduce fuels and restore more natural fire regimes (Covington, 2003), primarily through thinning and prescribed burning of forests to reduce ground and ladder fuels and to open up canopies. Forest restoration of frequent-fire forests typically starts with mechanical and hand thinning, as forest density is now generally too great across the West to start with prescribed burning. After fuels have been reduced via mechanical and hand thinning, multiple forms of prescribed burning (broadcast, jackpot, and pile burns) are appropriate to further reduce fuels (Harris et al., 2021). Even when merchantable material is removed for processing, thinning in arid Western forests results in a short-term increase in surface fuels from an increase in brush, chips, and needles (Johnston et al., 2021), indicating that the combination of both thinning and burning provides the greatest impact on reducing fuels and overall wildfire risk and can typically be effective for at least ten years (Martinson and Omi, 2013; Prichard et al., 2021).

While the ecological science appears to be largely in agreement on the biophysical effectiveness of forest restoration and its ability to reduce wildfire severity (e.g., Martinson and Omi, 2013; Waltz et al., 2014; Kalies and Kent, 2016; Lydersen et al., 2017; Hagmann et al., 2021), the questions of cost-effectiveness remain largely unanswered due to the complexity of quantifying the multitude of benefits of forest restoration (Ager et al., 2017; Hunter and Taylor, 2022). Forests provide myriad benefits, or ecosystem services, to society resulting in amenities for adjacent communities. Dubay et al. (2013) provide a detailed list of the various types of economic benefits afforded by arid forest restoration in the West, based on an examination of Western forest restoration conducted under the Collaborative Forest Landscape Restoration Program (CFLRP). Generally, these include avoided wildfire costs (in terms of both human health and property and suppression costs), enhanced ecosystem service production, enhanced property values, and the production of marketable woody byproducts. When qualitatively synthesized, most individual benefit types will not provide enough benefit, by themselves, to exceed the costs of the project (Hunter and Taylor, 2022).

Documented economic benefits of forest restoration in frequent-fire forests include enhanced use values for society such as enhanced property values (Kim and Wells, 2005), provision of woody biomass to be used for merchantable energy and wood products (Lynch et al., 2000; Prestemon et al., 2012; Hjerpe et al., 2021), increased water supply to be used for irrigation and hydropower (Mueller et al., 2013, Mueller, 2014, Podolak et al., 2015, Guo et al., 2023), and greater demand and willingness to pay for big game hunting (Loomis et al., 2002; Loomis et al., 2003).

Society also holds nonuse values for forest restoration, such as existence, bequest, and option values, as people generally value nature and would like to bestow (or bequeath) non-degraded forests to future generations (Loomis and González-Cabán, 2009). That is, society is willing to pay for forest restoration to allow for the protection of native species and to retain option values for potential future use (Loomis and González-Cabán, 1998; Loomis et al., 2005; Kaval et al., 2007). For example, Hjerpe et al. (2015) found an average willingness to pay of $60 per affected household (updated to 2023 $US using the Consumer Price Index) for forest restoration across numerous countries. While some of the willingness to pay is for personal use values, the majority was found to be for nonuse values.

Perhaps the greatest economic benefits of forest restoration in frequent-fire forests are avoided wildfire damages and costs (Simon et al., 2022). As uncharacteristic wildfire has increased in the Western U.S., so too has the documentation of how forest restoration can reduce and limit wildfire damages. By reducing forest fuels, wildfire intensity and spread can also be reduced (Cochrane et al., 2012). Thus, if a restored forest encounters a wildfire, the fire will likely cause less damage than if the forest were still in a degraded (overstocked) condition. Because we cannot experiment with wildfire in the landscape, and therefore, cannot develop a comparable counter factual, avoided wildfire costs from treatments typically need to be modeled in an *ex ante* form.

Researchers have estimated avoided wildfire costs in several categories, often focused on just one benefit type. A primary example is looking at avoided wildfire costs from protecting drinking water sources, where wildfire and sediment loading models are paired. Jones et al.

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[1] Comprehensive forest restoration also includes a focus on spatial and structural heterogeneity of forests and activities associated with returning forests to more historically natural conditions such as road decommissioning, removal of invasives, watershed re-channelization, and culvert placements (Stephens et al., 2021). Necessary access roads and equipment cause their own disturbance in stands slated for forest restoration requiring proper road decommissioning and clean up. Additionally, arid Western forests have myriad old logging and fire roads and an extensive history of livestock grazing that have left a legacy of forest degradation. The optimal time to conduct other forest restoration activities such as culvert replacements, stream restoration, invasive removals, and proper decommissioning of legacy roads is immediately after these forests are being restored with mechanical thinning, so that access roads and trails can be used for other restorative purposes before they are decommissioned. These other forest restoration activities can limit wildfire damages and costs, but also provide for the enhancement of a broad range of ecosystem services produced by the forest that are highly valued by the public (e.g., increased pollination, increased fish habitat, increased recreational value).

(2017) modeled the effectiveness of fuel treatments at reducing sediment loading from post-wildfire flooding in source watersheds outside of Denver, Colorado, finding a range of economic benefits depending on the scale of the storm event modeled (e.g., 10-year or 100-year storm event). The most effective scenario modeled showed thinning benefits to be 10 times greater than costs, due primarily to avoided dredging costs. Gannon et al. (2019) conducted a similar analysis for thinning and burning in forested source watersheds providing municipal water supply to the city of Ft. Collins, Colorado. While they found fuels reduction treatments to be effective at reducing wildfire risk and subsequent sediment loading, they found very low average avoided wildfire costs (and low benefit-cost ratios) for source water protection due to the low probability of both uncharacteristic wildfire and a subsequent large-scale storm event at any exact point in the watersheds.

Additionally, forest restoration can save future wildfire suppression costs (Snider et al., 2006; Fitch et al., 2018). This benefit is difficult to model due to the complexity of overlapping optimization and simulation models and accurately projecting changing climate and fire patterns (Thompson and Anderson, 2015). Thompson et al. (2013) provide a methodology for estimating potential reductions in wildfire suppression costs from fuel treatments, projecting sizeable reductions in wildfire size and suppression costs per fire in a central Oregon example. However, other advanced models of avoided wildfire suppression costs did not find significant effects due to fuel treatments (Sánchez et al., 2019).

Others have conducted broad valuations of forest restoration benefits, including those associated with wildfire damages. Mason et al. (2006) produced one of the first broad valuations of avoided wildfire costs from fuel treatments, quantifying benefit-cost ratios for avoided damages in the Inland West for fatalities, facilities, timber, rehabilitation, and suppression costs that ranged from 0.01 to 1.3. Huang et al. (2013) modeled similar benefits as Mason et al. (2006) for forest restoration in northern Arizona and included an inconclusive estimation of carbon storage benefits.

Buckley et al. (2014) provide perhaps the most collaborative and exhaustive research on all benefits of fuel treatments in frequent-fire forests, with extensive modeling for avoided wildfire costs (including carbon benefits) and woody biomass returns in California's Sierra Nevada. They found that benefits of fuel treatments exceeded costs by two times under the low-value scenario and by three times under the high-value scenario, suggesting that forest restoration and fuel treatments are very cost-effective in the Sierra Nevada. Buckley et al. (2014) also provide a clear picture of the various beneficiaries of restoration in forests at risk of high-severity wildfire, including landowners, public and private entities, taxpayers, and utility rate payers. A similar BCA of fuel treatments was undertaken on the Sante Fe National Forest in New Mexico, demonstrating a return-on-investment of $1.44–$1.67 of benefits for every dollar invested (Wildish et al., 2020). Most recently, Jones et al. (2022) conducted a BCA of fuel treatments and a payment for watershed services program outside of Denver, Colorado, finding generally positive, but wide ranging, benefit-cost ratios. Finally, syntheses of forest restoration benefits and costs are few. Hunter and Taylor (2022) provide a recent qualitative synthesis of fuel treatment benefits and costs, with most studies coming from the American West, and found various benefits with most not being able to fully cover the cost of treatments by themselves.

Documenting the costs of forest restoration is much more straightforward as compared to documenting the numerous restoration benefits. Despite the comparative ease, estimating and synthesizing the costs of restoration and fuel treatments is still complicated by the wide variety of equipment, operations, treatment methods, and stand conditions that may be involved (Rummer, 2008). Additionally, various cost types for restoration and fuel treatments, beyond those just associated with implementation, are often reported such as planning costs and net costs when timber and biomass revenue might be included in a restoration agreement.

Lynch and Mackes (2003) found average restoration treatment costs, from mechanical thinning, for four Colorado projects to be between $1118 and $1786 per acre. Calkin and Gebert (2006) found an average cost of $90 per acre for prescribed burns in the Western U.S., and an average cost of $321 per acre for mechanical thinning. Analyzing prescribed fire in the Pacific Northwest, Berry et al. (2006) found costs ranging from about $60 to $220 per acre. Importantly, they noted that prescribed burning costs were 139% higher, all things equal, when conducted in the WUI. Hartsough et al. (2008) reported prescribed burning costs from various Western forests ranging from $177 to $695 per acre and mechanical thinning costs ranging from $992 to $2995 per acre. All previous cost estimates have been updated from their base year to $2023 using the Consumer Price Index.

While forest restoration and fuel treatments are not exactly synonymous (Reinhardt et al., 2008), they have solid convergence in the arid dry-mixed conifer forests of the American West that are overly dense (Stephens et al., 2021). Ager et al. (2016) and Taylor et al. (2015) illustrate the economic tradeoffs, or range in benefits afforded by forest restoration in the Western U.S., are ultimately dependent on the specific restoration or fuel treatment prescriptions and the primary objective of projects (e.g., ecological objectives, financial optimization, etc.). With understanding that forest restoration and fuel treatments are well aligned in degraded frequent-fire forests, we include the primary fuels reduction components in frequent-fire forests, mechanical thinning and prescribed burning, as representative of forest restoration throughout the rest of this paper.

2. Meta-analysis methods

Benefits of forest restoration can be grouped into two categories: enhanced initial ecosystem services (use and nonuse values) and avoided wildfire costs. While all restoration benefits can be classified as ecosystem services (see for example Vukomanovic and Steelman's, 2019 classification of ecosystem services affected by wildfire), we separate avoided wildfire costs from enhanced initial ecosystem services that happen immediately upon restoration (e.g., increased woody biomass, water yield, use values, and nonuse values) that are not dependent on the restored forest experiencing wildfire. Fig. 1 illustrates the types of restoration benefits quantitatively documented in the literature for arid, dry mixed conifer forests in the western U.S. It should be noted that ecological improvements coming from the restoration of degraded forests are numerous and rarely economically valued, meaning that our presentation of documented benefits is only a sample of total benefits, and the total economic value of forest restoration is greater (potentially much greater) than illustrated in our model.

With 17 different types of individual restoration benefits identified in the literature, we aggregated the avoided wildfire costs in four total categories: avoided suppression costs (AWC Suppression), avoided structure costs—buildings and infrastructure (AWC Built), avoided health costs (AWC Health), and avoided ecosystem service costs (AWC Ecosystem Services). These four avoided wildfire cost categories are combined with the five enhanced initial ecosystem services (regardless of potential wildfire) to make nine total forest restoration benefit types assessed in our meta-analysis (gray boxes in Fig. 1).

We hypothesize that forest restoration benefit types provide different value based on their economic importance to society. Specifically, we test the null hypothesis that the benefit types are of equal value:

$$H_{01}: \beta_1 = \beta_2 = \beta_3 \ldots = \beta_9; \text{where } \beta_x = \text{coefficient for benefit} - \text{cost ratios for nine types of forest restoration benefits (AWC Built, AWC ES, AWC Health, AWC Suppress, Hunting, Nonuse Values, Property Values, Water Yield, and Woody Biomass)}.$$

2.1. Data selection

We conducted a detailed literature search to find estimated benefits and costs of forest restoration, utilizing Google Scholar, ScienceDirect, JSTOR, Treesearch, and web search engines including Yahoo and Google. Key words searched included: “forest restoration,” “fuel treatments,” “fuel reductions,” “benefits,” “costs,” “ecosystem services,” and “economic values” with the Boolean operator “and” used to aggregate key words and “or” to separately search forest restoration, fuel treatments, and fuel reductions. Both peer-reviewed and gray literature were identified, with a spatial limitation of forest restoration and fuel treatments conducted (or modeled) in dry mixed conifer forests of the Western U.S. The primary language for the search was English and our temporal search range was between the year 2000, as forest restoration implementation grew rapidly beginning in the 2000s, and the year 2023 (literature search ended on July 15th, 2023). We also used snowball techniques, using references from relevant studies. All authors participated in screening articles and reports, with the lead author conducting the data extraction. Inclusion in our meta-analysis was based on an overarching criterion that studies had to provide benefits (and costs) of forest restoration and fuel treatments on a per unit area (acre or hectare) basis in the American West.

Benefit estimates were primarily from modeled scenarios, with a couple of retrospective, evidenced-based benefits. Primary economic translations used in collated studies include avoided costs, replacement costs, and willingness to pay/avoid. Avoided wildfire costs studies typically combined vegetation, wildfire, sediment, and climate models with treatment effectiveness over time and space, using net present valuation to estimate present benefit-cost ratios. Table 1 lists all included studies and restoration benefit types.

Many of the studies selected provide ranges of benefit-cost ratios for restoration and fuel treatments based on various modeled scenarios (e.g., wildfire probability, wildfire intensity, size of post-wildfire rainstorm, etc.). Generally, we selected all relevant stand-alone ratios that met the above criteria, meaning that some restoration benefit types included multiple observations from the same study. In cases where studies’ sensitivity analyses included small incremental changes, we selected the mean observation. Data used from studies are available as supplementary information.

2.2. Model specification

We specify a model that allows for the dependent variable, the benefit-cost ratio for each benefit type, to be a function of independent variables such as the type of benefit being analyzed, how the study was conducted, and the location.

Specifically:

$$BCR_{ij} = F(RB, V, S) \tag{1}$$

In this equation, $\mathbf{BCR_{ij}}$ is the estimate (i) of the benefit-cost ratio for forest restoration reported in the j_{th} primary study included in the meta-analysis. **RB** represents the nine general types of forest restoration benefits shown in Fig. 1. **V** is a vector of study, or valuation characteristics including the publication outlet (peer-reviewed journal or gray literature), restoration treatment type (thin only, burn only, thin and burn), and benefit category (avoided wildfire cost or enhanced initial ecosystem service). Finally, **S** represents the various locations, or states, where the study was conducted. Table 2 details all variables used in the analysis.

Table 3 shows descriptive statistics for variables used in the analysis. For restoration benefit types, 25% of the observations were for increased water sales for hydropower and irrigation (Wateryield) coming from forest restoration, while about 20% of observations were for avoided wildfire costs for ecosystem services (ACWES—such as avoided wildfire costs associated with endangered species, carbon, timber, and recreation damages) and for avoided wildfire costs for built infrastructure (ACWBuilt) respectively. The average benefit-cost ratio for every restoration benefit examined was 0.478, ranging from almost zero to 1.7. About 70% of observations were from peer-reviewed sources, with gray literature accounting for the remaining 30% of observations. Most studies examined benefits and costs for thinning and prescribed burning restoration activities in the same landscape.

2.3. Meta-analysis estimation

Our 120 total data points selected for the meta-analysis came from a total of 16 individual studies. Because multiple observations from one study share common valuation techniques and authors, our dependent variable can be nested, or correlated, among each study. Research (e.g., Bateman and Jones, 2003) has illustrated that certain studies and authors can be associated with large residuals due to the hierarchical nature of nested data and that accounting for nested data, by incorporating multi-level regression models, can help overcome this bias.

Model diagnostics included tests for outliers, heteroskedasticity, skewness, and multicollinearity. Cook’s Distance tests and leverage plots were conducted for all observations. All observations were retained with no observations exhibiting a Cook’s Distance greater than one or excessive leverage. A Bruesch-Pagan test revealed a significant chi-squared statistic indicating the presence of heteroskedasticity. Normality plots (histogram, kernel density) and further tests (sktest, Shapiro-Wilk test) indicated a non-normal dependent variable with skewness (right-tailed) but not severe kurtosis. We transformed the benefit-cost ratios to natural log to adjust the distribution of the dependent variable residuals, resulting in a final semi-log regression. Fig. 2 illustrates the kernel and normal densities of observed and predicted dependent variables after log transformation.

Multicollinearity was evaluated in multiple manners including correlation tests, collinearity condition numbers, and variance inflation factors. Our overall benefit category (e.g., AWC or EIES) and the burn-only form of treatment type exhibited high levels of collinearity with other variables and were removed from our final estimates. We account for spatial association and dependencies among our data points by delineating which state the study was conducted in as dummy variables. Because the primary studies in our analysis lacked specific geo-referenced coordinates and were often focused on multiple forests, we could not test for spatial association among the dependent variables or conduct spatial regressions.

Table 2
Description of variables used in the analysis.

Variable	Description
Dependent Variable	Benefit-cost ratio (value of individual restoration benefit type divided by the cost of restoration)
Multi-level model grouping variable	Lead author of primary study
Explanatory Variables	
Restoration benefit type (RB)	
AWC Built	Dummy = 1 if the benefit is avoided wildfire cost for structures/infrastructure; else 0
AWC Ecosystem Services	Dummy = 1 if benefit is avoided wildfire cost for ecosystem services; else 0
AWC Health	Dummy = 1 if benefit is avoided wildfire cost for human health; else 0
AWC Suppress	Dummy = 1 if benefit is avoided wildfire cost for suppression; else 0
Hunting	Dummy = 1 if benefit is for increased hunting WTP; else 0
Nonuse values	Dummy = 1 if benefit is for increased nonuse values; else 0
Property values	Dummy = 1 if benefit is for increased property values WTP; else 0
Water yield	Dummy = 1 if benefit is for increased water yield; else 0
Woody biomass	Dummy = 1 if benefit is for woody biomass for wood products or power; else 0
Valuation characteristics (V)	
Peer-reviewed	Dummy = 1 if study was published in academic journal; 0 if published in gray lit
Restoration treatment type	
Burn only	Dummy = 1 if treatment type was burn only; else 0
Thin only	Dummy = 1 if treatment type was thin only; else 0
Thin and burn	Dummy = 1 if treatment type was thin and burn; else 0
Benefit category	
Avoided wildfire cost (AWC)	Dummy = 1 if benefit category was avoided wildfire cost; else 0
Enhanced initial ecosystem service (EIES)	Dummy = 1 if benefit category was enhanced initial ecosystem service; else 0
Year	Continuous variable of study publication year
States (S)	
Arizona	Dummy = 1 if study was for Arizona; else 0
California	Dummy = 1 if study was for California; else 0
Colorado	Dummy = 1 if study was for Colorado; else 0
Inland West	Dummy = 1 if study was for Inland West; else 0
New Mexico	Dummy = 1 if study was for New Mexico; else 0

Table 3
Descriptive statistics for variables (n = 120).

Variable	Mean	Std. Dev.	Min	Max
Dependent Variable				
ROI	0.478	0.496	0.001	1.696
lnROI	−1.724	1.804	−6.908	0.528
Explanatory Variables				
Restoration Benefit Type				
AWCBuilt	0.192	0.395	0	1
AWCES	0.217	0.414	0	1
AWCHealth	0.058	0.235	0	1
AWCSuppress	0.083	0.278	0	1
Hunting	0.033	0.18	0	1
Nonusevalues	0.008	0.091	0	1
Wateryield	0.25	0.435	0	1
Woodybiomass	0.15	0.359	0	1
Propertyvalues	0.008	0.091	0	1
Valuation Characteristics				
Peerreviewed	0.683	0.467	0	1
Burn	0.033	0.18	0	1
Thin	0.25	0.435	0	1
ThinandBurn	0.717	0.453	0	1
AWC	0.55	0.5	0	1
EIES	0.45	0.5	0	1
Year	2013.99	7.05	2000	2023
State				
Arizona	0.108	0.312	0	1
California	0.35	0.479	0	1
Colorado	0.3	0.46	0	1
InlandWest	0.167	0.374	0	1
NewMexico	0.067	0.25	0	1

3. Results

The following sections illustrate the results from the meta-analysis and the results from our return-on-investment research questions.

3.1. Meta-regression results

The preferred model was a semi-log, multi-level, mixed effects regression grouped by authors. The broad restoration benefit types were analyzed compared to one category—avoided wildfire costs for built infrastructure (AWCBuilt). Eight of the nine restoration benefit types exhibited significant differences in benefit-cost ratios, with Wateryield being the only benefit type having a p-value greater than 0.1 (though close). With clear separation between benefit-cost ratios of restoration benefit types, we reject our null hypothesis that there is no value difference between benefit types. The restoration benefit types with the highest positive coefficients were nonuse values, property value increases, and woody biomass—all benefit types that happen when restoration is completed regardless of future wildfires. Table 4 shows the final model estimates.

The nine broad restoration benefit types were modeled as dummy variables, and we used the benefit type AWCBuilt, inclusive of avoided costs for wildfire damage to all houses and structures, transportation and utility infrastructure, and drinking water infrastructure, as the broad benefit type omitted in the meta-regression to be the comparison for the remaining eight broad restoration benefit types. All broad restoration benefit types yielded benefit-cost ratios greater than zero, with avoided wildfire suppression costs (AWCSuppress), nonuse values, woody biomass, and property values all having a greater positive influence on modeled benefit-cost ratio than AWCBuilt–the omitted dummy variable. Avoided wildfire costs for ecosystem services (AWCES) and for health (AWCHealth), along with hunting and water yield benefits, had lesser influence (negative coefficients in Table 4) on modeled benefit-cost ratio when compared to AWCBuilt.

In terms of valuation characteristics, peer-reviewed observations were associated with higher benefit-cost ratios (mean = 0.53), exhibiting a mean benefit-cost ratio almost 50% greater than the mean for gray literature observations (mean = 0.36). Thin-only restoration treatments were associated with higher benefit-cost ratios (mean = 0.74) than the combination of both thinning and burning (mean = 0.41). This finding can be partially explained by the fact that many of the immediate restoration benefits, such as enhancement in initial ecosystem services including water yield, woody biomass for utilization, and use values result primarily from mechanical and hand thinning of overly dense stands. The treatment type "thin and burn" increased avoided wildfire costs (benefits) (e.g., Buckley et al., 2014) but did not greatly affect other benefit types. With a paucity of research focused on the economic benefits of prescribed and managed fire in isolation, and the fact that the "burn" treatment type in comprehensive forest restoration adds to the total treatment costs, "thin and burn" treatments have less of an influence on the documented benefit-cost ratio than "thin-only" treatments.

While the year of the study was ultimately not a significant explanatory variable for benefit-cost ratios of forest restoration, trend analysis (e.g., scatter plot with fitted line, simple regression) indicated a negative coefficient showing that benefit-cost ratios from the literature have been generally declining over the last two decades. This is likely indicative of a couple of factors at play. First, environmental economic valuation techniques experience refinement over time, often leading to a constriction in values as was the case with the contingent valuation

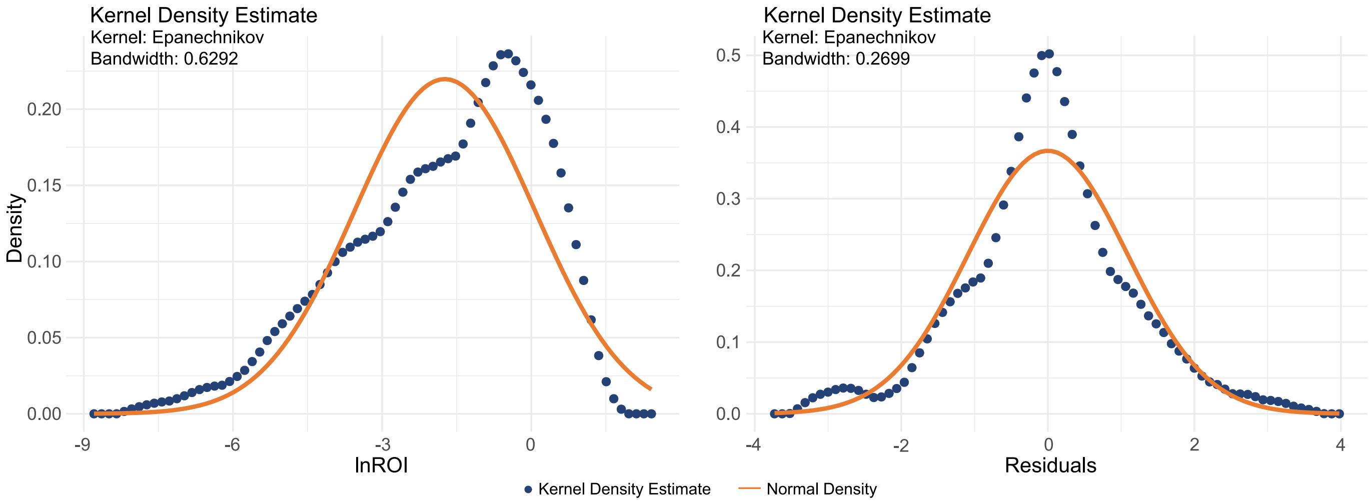

Fig. 2. Kernal desnity estimates for forest restoration return-on-investment (natural log transformed; left) and residuals (right).

method (Boyle, 2017).

Secondly, and probably more importantly, early studies quantifying forest restoration benefits started by researching the most immediate and tangible benefits, or the low hanging fruit from a research perspective, such as being able to make wood products from thinned material. The last decade has seen multiple large-scale avoided wildfire costs models and the development of quantified benefits associated with prescribed fire and mechanical thinning. As the field of restoration economics has matured, more and more restoration benefit types are being modeled and analyzed. For example, avoided wildfire cost modeling has greatly increased, bringing to light many more economic benefits of forest restoration. These newer, and typically more complex, restoration benefit types add to the total amount of forest restoration benefits but typically in an incrementally smaller manner over time.

In terms of study locations, California and New Mexico had the largest average benefit-cost ratios as compared to Colorado and Arizona. Typically, the areas with the greatest infrastructure and populations at risk of uncharacteristic wildfire (e.g., California) will experience the greatest economic benefit from forest restoration, especially in terms of avoided wildfire costs. Additionally, woody biomass revenue for thinned forests is ultimately dependent on accessible wood utilization infrastructure and markets, such as sawmills and biomass power plants. Prestemon et al. (2012), for example, show that wildfire thinning treatments conducted in more productive forests with greater wood utilization capacity, such as those in the Western coastal states of Washington, Oregon, and California, will yield the greatest timber sale benefits.

3.2. Return-on-investment results

Overall, 17 unique types of forest restoration benefits were identified and quantified in the literature. Importantly, these individual categories of restoration benefits are not mutually exclusive, nor overlapping, and can thus be aggregated in forests where values are applicable.[2] In some of the most valuable forested watersheds in the Western U.S., especially those associated with source drinking water, all 17 types of individual restoration benefit types may be prevalent, along with other benefits yet to be quantified. The total site-specific basket of benefits must be considered and prioritized when planning forest restoration activities, demonstrating the folly in focusing on only one benefit type when investigating the economic efficiency of forest restoration (e.g., requiring woody biomass revenue to cover the costs of forest restoration). Mean benefit-cost ratios of the various detailed forest restoration benefits, with sample sizes, are illustrated in Fig. 3.

The collective bundle of benefits can be used to illustrate return on investments in forest restoration. For example, aggregating the means of the individual 17 forest restoration benefit types, shows the total benefit-cost ratio to be 7.04 (see Fig. 4). That is, for every dollar invested in forest restoration in high risk, high-value forested watersheds, over seven dollars of benefit may be returned to investors. Applying a financial type of return-on-investment to forest restoration,[3] where only returns in excess (or below) of the initial investment are calculated, indicates the potential for a 600% return on investments in the most valuable at-risk forested watersheds.

Regarding total returns on investments in forest restoration, a cautious approach to calculating returns for specific forest stands should be incorporated as total values will depend on the location. The placement of forest restoration treatments will largely determine which benefit types will be present and how much benefit will be provided. For example, which values and infrastructure are at risk? Many of the studies represented in our meta-analysis represent high-value restoration benefit types. However, examples where certain restoration benefit types are not present, or not of much value, are less likely to be the focus of research and less likely to be published due to publication bias. Many restoration treatments will be conducted where some identified and quantified benefit types may not be present.

From our collated primary studies, Buckley et al. (2014) provided perhaps the most comprehensive assessment of which values and infrastructure are at risk due to wildfire for a particular watershed. They quantified eight types of individual forest restoration benefits in the Mokelumne watershed in California, including seven individual avoided wildfire cost types (benefits) related to at risk houses, water infrastructure, energy infrastructure, suppression costs, timber costs, carbon costs, and rehabilitation costs. All these value sets are at high risk of uncharacteristic wildfire in the Mokelumne watershed and Buckley et al.'s (2014) analysis showed that the benefits of fuel treatments would

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[2] We have taken efforts to make sure that detailed benefit types are unique and to eliminate possibilities of double counting. One benefit type, nonuse values and its associated willingness to pay estimates, includes potential overlap with some of the use value categories such as hunting and recreation. However, research (e.g., Hjerpe et al., 2015) has demonstrated that the majority of stated preference values held for forest restoration are composed of nonuse values.

[3] The typical financial return-on-investment formula is: (gain from investment − cost of investment)/(cost of investment) and is often expressed as a rate or percentage.

Table 4
Multilevel model estimates (Semi-log).

lnROI	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
Restoration Benefit Type							
AWCES	−1.378	0.768	−1.79	0.073	−2.884	0.128	*
AWCHealth	−2.336	0.606	−3.85	0.000	−3.523	−1.148	***
AWCSuppress	0.695	0.241	2.88	0.004	0.222	1.168	***
Hunting	−6.033	0.798	−7.56	0.000	−7.596	−4.47	***
Nonusevalues	2.329	0.645	3.61	0.000	1.065	3.594	***
Wateryield	−0.523	0.347	−1.51	0.132	−1.203	0.158	
Woodybiomass	0.797	0.403	1.98	0.048	0.007	1.587	**
Propertyvalues	1.861	0.497	3.75	0.000	0.887	2.835	***
Valuation Characteristics							
Year	−0.04	0.03	−1.32	0.186	−0.1	0.019	
Peerreviewed	2.023	0.243	8.31	0.000	1.546	2.5	***
Thin	1.035	0.606	1.71	0.087	−0.152	2.222	*
State							
Arizona	0.226	0.296	0.76	0.445	−0.354	0.805	
California	3.43	0.056	60.98	0.000	3.32	3.54	***
InlandWest	0.244	0.199	1.23	0.220	−0.146	0.634	
NewMexico	3.332	0.193	17.23	0.000	2.953	3.711	***
Constant	76.697	61.402	1.25	0.212	−43.648	197.043	
Mean dependent var	−1.724		SD dependent var.		1.804		
Number of obs	120		Chi-square		.		
Prob > chi2			Akaike crit. (AIC)		394.986		

*** $p < .01$, ** $p < .05$, * $p < .1$

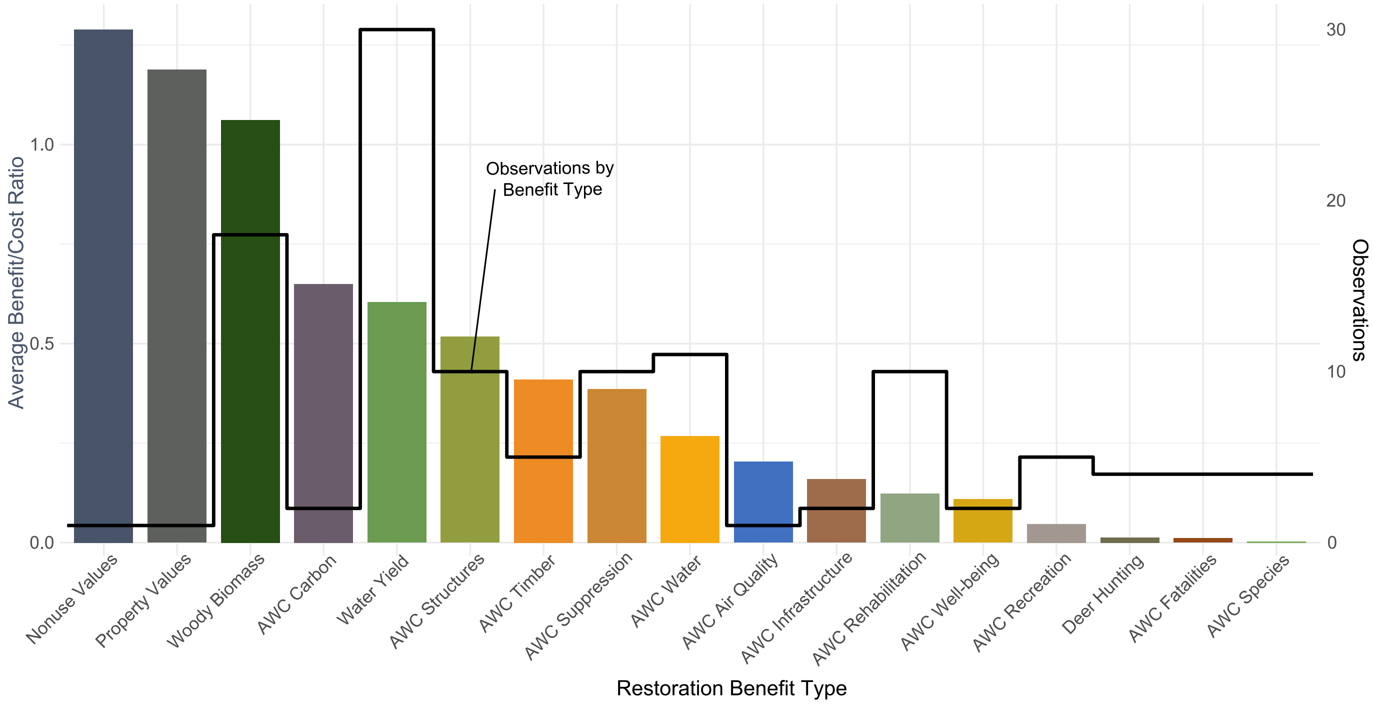

Fig. 3. Average Benefit-Cost Ratios by Detailed Benefit Type (Mean for all B/C Ratios = 0.478).

range from 1.9 to 3.3 times greater than the costs. Many other restoration benefit types were not quantified, meaning that their findings are a conservative estimate of total benefits and overall benefit-cost ratios.

Many restoration benefits have not been documented or quantified, rendering our aggregate returns on investment incomplete and certainly understated. Forest restoration can be used to protect cultural and archaeological resources from uncharacteristic wildfire (Tarancón et al., 2021) and has great potential to lessen indirect wildfire damages such as post-wildfire flood damages (Hjerpe et al., 2023). Restoration treatments also provide “leverage,” or multiplier effects, in adjacent unrestored stands that reduce future wildfire intensity and associated damages (Cochrane et al., 2012), while reducing future wildfire suppression costs and providing greater fire suppression leverage (Thompson et al., 2017). Few of the avoided wildfire costs from fuel treatment models include the concept of leverage in adjacent unrestored stands. The avoided wildfire costs from forest restoration are likely to be far greater and much more widely prevalent (i.e., many more individual restoration benefit types) than currently documented in the literature. For example, greater understanding of the economic values associated with avoided wildfire damages to native flora and fauna is needed. Likewise, mental health impacts associated with smoke and dangers of uncharacteristic wildfire (Eisenman and Galway, 2022) may be reduced or avoided with forest restoration, but there has been little economic valuation research to date.

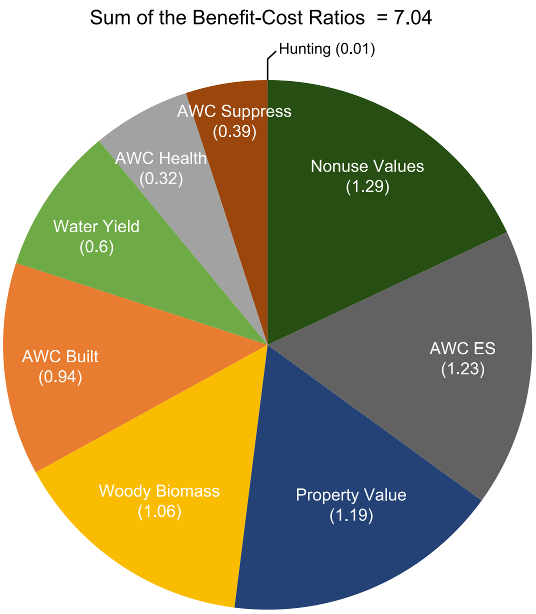

Fig. 4. Aggregated Total Potential Returns on Forest Restoration Investments*. *Mean benefit-cost ratios for nine broad types of forest restoration benefits are in parentheses. Three broad benefit types include the sum of means for multiple individual restoration benefit types: 1) AWC Built includes AWC Structure, AWC Infrastructure, and AWC Water; 2) AWC ES includes AWC Carbon, AWC Timber, AWC Rehab, AWC Recreation, and AWC Species; and 3) AWC Health includes AWC Air Quality, AWC Well-Being, and AWC Fatalities.

4. Discussion and conclusion

Our analysis is the first quantitative synthesis of the return on investments in forest restoration for the American West. Given the relatively recent development of forest restoration as a primary wildland fire management strategy, the applicability of our meta-analysis is constrained by limited observations in the literature. A total of 17 unique forest restoration benefits in the Western U.S. were identified, with a few benefit types being represented by only one observation. Our calculations of the return-on-investments in forest restoration using the 17 benefit types provided a benefit-cost ratio of 7.04, which means that over seven dollars of benefit may be returned to investors for every dollar invested in forest restoration in high risk, high-value watersheds.

The data constraints limit the precision with which our meta-regression can be used for benefits transfer purposes. Despite the limitations, our model can be incorporated into forest restoration planning by matching regional values within watersheds planned for restoration to our quantified benefit types. This identification process of benefit types (both presence and amount) can help demonstrate the economic efficiency of planned forest restoration treatments on multi-jurisdictional lands and can help identify potential beneficiaries who may be willing to pay for restoration services. Stakeholders and managers can also utilize our meta-analysis to help prioritize and identify forest stands that might yield the greatest benefits and returns on investments based on the proximity of populations and infrastructure to forests at high risk of uncharacteristic wildfire.

Future research is needed to quantify other restoration benefit types that still need to be documented in the literature. Notable missing quantified benefit types include protecting archaeological resources and cultural ecosystem services from wildfire (Wildish et al., 2020; Tarancón et al., 2021) and many other avoided wildfire costs. Thomas et al. (2017) identified 22 categories of direct and indirect wildfire damages and losses, all of which could be lessened with forest restoration; our analysis identified only 12 categories of quantified avoided wildfire costs from restoration for the American West. Finally, improved native species habitat from forest restoration is another large topical area for future research. For example, Colorado forest restoration showed improved avian communities, but the researchers did not assign a monetary value to this ecological effect (Latif et al., 2020).

Likewise, future research is needed on monetizing forest restoration benefits, where appropriate, in the form of payments for ecosystem services. With limited federal funding for forest restoration, tapping into funding from direct beneficiaries is necessary, such as water utilities and rate payers (Jones et al., 2023) and potential investors of green bonds (Clavet et al., 2021). Research has demonstrated actual and theoretical willingness to pay for forest restoration ecosystem services from landowners, governments, utilities, businesses, and the general public located near forests at high risk of uncharacteristic wildfire. Beyond stumpage fees paid for woody biomass from forest restoration, other payments for forest restoration ecosystem services are being manifested as community bonds (e.g., the $10 million, taxpayer approved bond that initiated the Flagstaff Watershed Protection Program), public utility funding (e.g., Pacific Gas and Electric Company Nature Grants in California), and utility rate increases (e.g., Santa Fe Watershed Program).[4] Formal programs through federal and regional agencies, such as Payments for Watershed Services, Forests to Faucets (e.g., Denver, Colorado), and Wood for Life (e.g., Northern Arizona), also provide and leverage payments and goods for forest restoration ecosystem services. A critical research need is learning how to bundle the many enhanced ecosystem services forest restoration provides for package deals (Deal et al., 2012). Engaging with forest restoration beneficiaries upfront in planning can help realize ecosystem service payments.

Our model could also be used to develop a measure for the value of a restored acre, including improved ecological conditions and greater resilience to wildfire. On federal lands, for example, current valuations used by federal agencies are tied to the products (i.e., trees and biomass) removed during restoration work or timber harvesting using measures of volume and wood value according to a transaction evidence appraisal approach. However, as this work has demonstrated, the byproducts of forest restoration work are only one part of the larger context, and numerous other values are tied to forest restoration. Furthermore, in many Western forests, the byproducts of forest restoration are largely small diameter, poor quality trees and large quantities of biomass that do not have high economic values in the current market and will rarely offset the full costs of restoration (Hjerpe et al., 2021).

Developing a measure for the economic value of the restored acre would help shift the focus around forest restoration to the social and ecological outcomes and benefits, as well as help in developing performance measures and outcome metrics that are not just tied to timber volume and acres treated. This would represent a paradigm shift in how decision-makers and the general public think about public investments like wildfire avoidance and restoration. Social science has consistently demonstrated that there is broad, public support for comprehensive forest management (e.g., Edgeley and Colavito, 2022; Toman et al., 2014), though this can vary depending on the context (Paveglio and Edgeley, 2023), but an approach to restoration that focuses on both ecological *and* social outcomes would be supported by research on social perceptions of landscape treatments (Edgeley, 2023).

We recommend that researchers conducting economic efficiency research on land management activities, such as forest restoration, should make efforts to summarize their findings (modeled or evidenced-based) in a quantitative manner conducive for BCA per land unit (e.g., acre, hectare, river mile, road mile, etc.). Numerous economic studies on forest restoration and fuel treatments in the American West were not included in our quantitative synthesis because a benefit-cost ratio could not be determined. Often, this is due to a need for more implicitly incorporating quantitative parameters most important for economic

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[4] See Swezy et al. (2020) for a review of payments for ecosystem services related to forest restoration.

efficiency analysis such as the total size of the modeled restoration efforts, the total costs, or the total benefits.

As this is a first attempt at quantitatively aligning various forest restoration benefits with associated costs, our model should be considered as coarse estimates for the return on restoration investments. As this field of research grows and ripens, our template for measuring returns on investments in forest restoration can be expanded to incorporate new measurements to provide for greater sample sizes among and within restoration benefit types. While more research in this arena is needed, we found that the restoration of degraded frequent-fire forests in the American West provides significant return-on-investments and can be cost-effective in many watersheds.

CRediT authorship contribution statement

Evan E. Hjerpe: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Melanie M. Colavito:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Amy E. M. Waltz:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Andrew Sánchez Meador:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108244.

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