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Measuring the long-term costs of uncharacteristic wildfire: a case study of the 2010 Schultz Fire in Northern Arizona

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ABSTRACT

Background. Wildfires often have long-lasting costs that are difficult to document and are rarely captured in full. **Aims.** We provide an example for measuring the full costs of a single wildfire over time, using a case study from the 2010 Schultz Fire near Flagstaff, Arizona, to enhance our understanding of the long-term costs of uncharacteristic wildfire. **Methods.** We conducted a partial remeasurement of a 2013 study on the costs of the Schultz Fire by updating government and utility expenditures, conducting a survey of affected homeowners, estimating costs to ecosystem services and updating costs to real 2021 US dollars. **Key results.** Costs associated with the Schultz Fire continued to accrue over 10 years, particularly those associated with post-wildfire flooding, totalling between US$109 and US$114 million. Suppression costs represented only 10% of total costs. **Conclusions.** This study is the first of its kind to include a remeasurement of wildfire costs and to provide a long-term assessment of the same wildfire over a 10-year period. **Implications.** Our results and lessons learned can help standardise approaches for full cost accounting of wildfire and illuminate the breadth of typically latent and indirect economic costs of wildfire such as post-wildfire flooding.

Keywords: community wellbeing, ecosystem services, forest restoration, full cost of wildfire, net value change, post-wildfire flooding, risk mitigation, Schultz Fire, uncharacteristic wildfire.

Introduction

Wildfires often have long-lasting social and ecological effects that are difficult to document and are not fully captured. Thus, an increasing area of research is concerned with documenting the full financial costs of wildfire, both in terms of suppression while the fire is burning, as well as the costs that continue to accrue long after the fire has been contained (Dale 2010; Troy *et al.* 2022). Full cost accounting after wildfires is critical for adequate government budgeting, post-wildfire resource allocation such as disaster recovery assistance and understanding the full scope of wildfire to help communities learn to better live with fire (Schoennagel *et al.* 2017). Given the scant literature on this topic, exploring potential approaches to economic assessment presents an opportunity to initiate conversations around consistent documentation after wildfires with varied outcomes and impacts. Furthermore, research suggests that the economic impacts of fire can last for years to decades; many of these costs have gone undocumented owing to the longevity of these impacts and challenges associated with accessing accurate economic data. As policy at the federal level in the USA increasingly demands the facilitation of resilient landscapes and fire-adapted communities, full cost accounting efforts after wildfire offer unique insights into the post-wildfire conditions that can support their development.

The Western Forestry Leadership Coalition produced two major reports (Dale 2010; Troy *et al.* 2022) that describe and categorise the types of costs associated with wildfire, as well as present a framework to more systematically document wildfire costs. A recent Pew report also examines the effect of wildfire on state budgets (Foard *et al.* 2022). Other research has explored the costs of wildfire at different geographic and temporal scales.

For example, Thomas *et al.* (2017) examined various types of wildfire costs across the US, Headwaters Economics (2018) explored the costs of wildfire across communities, Wang *et al.* (2021) looked at wildfire costs within the state of California, and Baylis and Boomhower (2023) explored how home value is tied to fire suppression costs. However, we are not aware of published research that has comprehensively tracked a broad range of costs over time for a single wildfire. Elevating economic examinations of fire to include this level of complexity is critical to advance more accurate understandings of post-wildfire costs. To that end, we provide an example for measuring the full costs of a single wildfire over time, using a case study from the 2010 Schultz Fire near Flagstaff, Arizona, to enhance our understanding of the long-term costs of uncharacteristic wildfire.

In 2013, following the Schultz Fire, an initial cost assessment was conducted by Combrink *et al.* (2013), resulting in a technical report detailing a number of costs. With the benefit of this initial cost accounting and hindsight, we built on the previous study and documented the long-term economic costs of the fire and post-wildfire flooding over 10 years that culminated in preliminary cost estimates in a recent white paper (Colavito *et al.* 2021). Our remeasurement incorporated some of the methods and costs from the original study (Combrink *et al.* 2013) but offers updated costs based on a rearview mirror perspective.

Literature review

Tracking the costs of wildfires is critical for understanding the extent of damages and for compiling multiple data points to average wildfire costs across forest and community types. Furthermore, wildfire cost accounting can serve as a measure of economic efficiency when comparing costs of preventive treatments (e.g. forest restoration) with the costs of wildfire. Economic efficiency analysis of wildfire management started with 'cost plus loss' (C + L) models developed by Sparhawk (1925). Modern efficiency analysis of wildfire management has evolved to encompass 'cost plus net value change' (C + NVC), where 'cost' is a measure of wildfire suppression and pre-suppression expenditures and 'net value change' is a measure of monetary loss (or gain) resulting from wildfire damages such as the loss of structures or adverse human health effects (Gorte and Gorte 1979; Rideout and Omi 1990; Donovan and Rideout 2003). Although the goal of C + NVC models is to minimise wildfire management spending and losses, understanding that suppression expenditures can affect the extent of damages, the model is a helpful way to conceptualise wildfire costs and damages.

Wildfire suppression cost data are mostly straightforward to collect as they are widely reported. However, the 'net value change' component of wildfire cost minimisation includes a broad array of direct and indirect wildfire damages that are rarely tracked with consistency. Additionally, 'net value change' implicitly allows for a loss *or* gain in monetised damages or benefits and does not assume that all change resulting from wildfire is 'economically bad' (e.g. Althaus and Mills 1982; Baumgartner and Simard 1982). Characteristic wildfires of low and medium severity (depending on the natural fire regime) are historically natural and provide several ecosystem service benefits (e.g. tree regeneration, understorey enhancement, nutrient cycling). Wildfire can also reduce fuels, which can potentially save future suppression expenditures (Houtman *et al.* 2013), though some high-severity wildfires can lead to greater frequency of wildfire. Financially quantifying ecosystem service benefits from wildfire is complex, leading most wildfire cost accounting research to focus on uncharacteristic wildfire, where fire severity is greater than traditional and more natural wildfire regimes, and ecosystem benefits are few.

Thomas *et al.* (2017) provide a list of the 'net value change' categories associated with wildfire damages, or net losses from wildfire. They list eight 'direct' wildfire loss categories, or net losses directly related to wildfire such as deaths, loss of structures and loss of timber. For 'indirect' wildfire losses, 14 categories are listed that represent net losses resulting from subsequent activities indirectly related to fire, such as post-wildfire flooding, housing market losses, utility disruptions and business impacts. In general, net wildfire loss and damage categories detailed in Thomas *et al.* (2017) are related to adverse impacts to human health, property (including infrastructure), businesses and ecosystem services.

Wildfire cost categories

Aside from suppression and pre-suppression fire management costs, there are many direct and indirect wildfire costs. These wildfire costs have been estimated for a number of individual cost categories, especially for human health effects from wildfire smoke (e.g. Kochi *et al.* 2010; Jones 2018). Human health impacts from wildfire range from injuries to sickness to mortality, due to exposure to fire, smoke, or post-wildfire flooding. Adverse psychological effects due to increased fear of wildfire, evacuations and post-wildfire flooding also have economic costs on overall wellbeing and are typically translated using non-market valuation techniques (O'Donnell *et al.* 2014; Ambrey *et al.* 2016).

In terms of structure losses, Thomas and Butry (2012) estimated that from 2002 to 2006, approximately 1250 US structures were annually damaged by wildfire, with an estimated loss of US$160 million. These numbers have skyrocketed in the last decade; reported incidents from the National Fire and Aviation Management Web indicate that since 2005, almost 100 000 homes, businesses and other structures in the USA have been destroyed by wildfire (as reported by Headwaters Economics at https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/). In 2017 and 2018 alone, California wildfires caused billions of dollars in structure damages (Buechi *et al.* 2021).

Less understood are the damages to infrastructure and structures due to post-wildfire flood events that often occur well after the wildfire has been contained, such as damages to drinking water infrastructure (Jones *et al.* 2022). Risk assessments have shown that arid forested regions such as those near Flagstaff, Arizona, can have elevated post-wildfire flooding risk for a third of all structures and a quarter of all county facilities (Youberg *et al.* 2019). West-wide, this represents billions of dollars of structure and infrastructure at risk of post-wildfire flood damage.

Market costs due to wildfire include disruptions to tourism and outdoor recreation destinations (Otrachshenko and Nunes 2022), interruptions in general commercial activities due to damaged infrastructure and losses in real estate value due to perceived natural hazard risk and loss of aesthetics (Donovan *et al.* 2007). For example, Loomis (2004) and Mueller *et al.* (2009) employed hedonic property analyses and found that unburned communities adjacent to wildfires experienced house price declines ranging from 10 to 23%.

Finally, ecosystem service damages from wildfire can range from losses in regulating services, such as reduced carbon sequestration and flood protection, to losses in provisioning services such as timber production (Butry *et al.* 2001). Vukomanovic and Steelman (2019) looked at how ecosystem services were affected by uncharacteristic wildfires and found largely negative effects. Environmental damage caused by uncharacteristic wildfire, such as vegetation loss and soil damages, represents losses in supporting ecosystem services but also has indirect consequences on services like flood protection and the production of drinking water. Loss of associated wildlife habitat from wildfire, especially for threatened and endangered species, also results in substantial decreases in societal welfare as non-market values such as existence and bequest values for wildlife are extensive. For example, Loomis *et al.* (1994) and Loomis and González-Cabán (1997) illustrated societal willingness to pay up to US$8 billion ($US 2021) for protecting spotted owls from uncharacteristic wildfire. Other cultural ecosystem services, such as heritage, spiritual and recreational values, can also be adversely affected by wildfire. In terms of recreation, research has demonstrated reduced economic demand and lost consumer surplus for recreationists in and near wildfire scars (Englin *et al.* 1996; Hesseln *et al.* 2004; Duffield *et al.* 2013).

Total wildfire costs

Although research on individual categories of wildfire damages is plentiful, there have been few published studies looking at *total* wildfire costs. Butry *et al.* (2001) examined the economic losses related to 'catastrophic' wildfires in northeastern Florida during the summer of 1998. Their wildfire cost accounting included damage estimates for suppression costs, disaster relief expenditures, timber losses, property damages, tourism-related losses and human health effects. Butry *et al.* (2001) found damages of at least US $600 million (over US$1 billion in 2021 $US), on par with damage estimates from level-2 hurricanes.

Lynch (2004) estimated the total costs from two 'catastrophic' Colorado wildfires (Hayman and Bobcat Gulch Fires) in the early 2000s, finding broad costs beyond just those associated with suppression, property and human health effects, such as substantial habitat destruction to the threatened Pawnee Montane Skipper butterfly. However, Lynch (2004) notes that in the arid American West, long-term damage to forest watershed resources (such as damaged water supply infrastructure and post-wildfire flooding) may represent the largest, and least documented, costs of uncharacteristic wildfire over time.

Recently, Wang *et al.* (2021) looked at the total wildfire costs in the state of California as a result of the 2018 wildfires. They estimated US$148.5 billion in economic costs for that single year, which included capital losses (19%), health costs (22%) and other indirect costs (59%). Meanwhile, Thomas *et al.* (2017) estimated the costs of wildfire across the entire US in 2016 to range from US$71.1 to US$347.8 billion.

The literature on the costs of wildfires illustrates the breadth of cost types and the complexity in full-cost accounting of wildfire damages. It also highlights that the long-term and indirect damages of wildfire typically constitute the majority of costs, yet the most-reported costs are the immediate suppression costs. It is important to note that costs of wildfires, or the economic burden (Thomas *et al.* 2017), are incurred by various constituents ranging from individuals to industries to the taxpaying public at large.

Methods

We conducted a partial remeasurement of the Combrink *et al.* (2013) study on the costs of the 2010 Schultz Fire by: (1) remeasuring government and utility expenditures from 2010 to 2019; (2) conducting another survey of affected households to understand long-term experiences and costs; (3) estimating costs to ecosystem services by conducting an economic valuation of Mexican Spotted Owl (MSO) (*Strix occidentalis lucida*) habitat impacts as a proxy; and (4) updating costs that were not remeasured from the original 2013 study to account for inflation to 2021 dollars. Although we do not investigate general disruptions to businesses, such as the effect of the Schultz Fire on tourism and outdoor recreation,[1] we acknowledge additional market impacts not included in this study. We used costs for: (1) structural damage; (2) clean-up; (3) unpaid labour; (4) home contents; and (5) fire evacuation costs that were captured in Combrink *et al.* (2013) and updated to account for inflation to 2021 dollars. For loss of life, we followed the Environmental Protection Agency's recommendation of using US$9.76 million for the value of a statistical life in real 2021 dollars (EPA guidance on mortality risk valuation available at https://www.epa.gov/environmental-economics/mortality-risk-valuation).

Study site

The 2010 Schultz Fire was ignited by an abandoned campfire on 20 June 2010, northeast of Flagstaff, Arizona, in Coconino County, and burned 6100 hectares. The Schultz Fire burned with uncharacteristic severity, resulting in substantial damage within the fire perimeter (USDA Forest Service 2010). Unlike wildfires that garner sustained media attention, the Schultz Fire did not burn any structures, nor did it result in immediate loss of life. Instead, the greatest damages and loss of life were a result of subsequent post-wildfire flood events that happened months and years after the fire and led to subsequent heavy flooding that impacted neighbourhoods downstream from the fire. One life was lost during the flooding events. Monsoonal storms continued to impact the area and produced flooding, though to a lesser degree, in subsequent years as flood mitigation projects were implemented in and around the burn scar.

Flood mitigation projects began immediately in 2011 and were implemented every year thereafter through 2015, and again in 2019 as a result of damage from a 2018 monsoon storm that impacted post-wildfire infrastructure but was not tied to burn scar flooding. Because of the time lag that often occurs between wildfires and subsequent fire-related flooding, many of the costs associated with wildfire's full effect are not included in initial cost assessments, leading to latent economic damages from wildfires that are rarely documented.

The original 2013 study area included the neighbourhoods downstream from the Schultz Fire burn scar and an estimated flood path. This provided coverage for all parcels that were affected at the time. In the remeasurement, the study area was expanded to include the entire projected 100-year flood risk area associated with the burn scar (Fig. 1).

Data collection for government and utility costs

The original Combrink *et al.* (2013) study provided a detailed accounting of government and utility costs, including fire suppression and flood response costs in 2010, flood mitigation costs from 2011 to 2012, and projected flood mitigation costs from 2012 to 2014. Engineering studies and flood mitigation projects began immediately following the fire and many were jointly funded by entities like the Coconino County Flood Control District and partners like the US Department of Agriculture (USDA) Forest Service, Federal Emergency Management Agency, the US Geological Survey, the Arizona Department of Emergency and Military Affairs, the Natural Resource Conservation Service and the Federal Highway Administration.

To collect updated government and utility costs, appropriate agency personnel from the City of Flagstaff, Coconino County, USDA Forest Service and others were asked to report all Schultz Fire and post-wildfire flood-related response and mitigation costs for specific calendar years. We compiled both the original costs from Combrink *et al.* (2013) and all subsequent costs as documented by government and utility entities through 2019. We replaced the projected costs with reported costs and adjusted costs to account for inflation to 2021 dollars to calculate a total. We also reported the costs for individual flood mitigation projects across the study area, some of which took place on USDA Forest Service lands and others that took place in and around impacted neighbourhoods. Flood mitigation projects ranged from emergency watershed protection (EWP) projects such as check dams and sediment retention basins to box culverts and roadway realignments in neighbourhoods.

Household costs and survey methods

The Schultz Fire resulted in numerous household costs including payments for residential flood mitigation, structural repair costs and decreases in home values due to diminished aesthetics and perceived hazard risk. Both short- and long-term financial consequences to residents in areas affected by post-wildfire flooding have gone largely undocumented. This is of particular concern because these costs can be high, ranging from out-of-pocket temporary relocation costs to structural repair. These costs can also vary depending on flood insurance coverage, level of flood risk to the property and proximity to burn scar and mitigation infrastructure.

The majority of household costs can be ascertained by directly surveying affected residents (the primary exception being decreases in house sale prices). The original 2011 survey of Schultz area households conducted by Combrink *et al.* (2013) received 321 responses out of a possible 1339 for a 24% response rate. We expanded this effort by sampling households in the projected 100-year flood event area in the fall (autumn) of 2020. That expansion represented an

[1]Market impacts to industries from the Schultz Fire, such as tourism disruptions, are considered distributional economic impacts, where tourist expenditures are temporarily displaced from the Flagstaff region and are re-distributed to other comparable mountain towns. Research has shown that although some industries suffer during wildfires, total regional economic impacts can be positive owing to an influx of wildfire response teams and infrastructure services required to suppress fires (Davis *et al.* 2014). Distributional economic impacts are typically not included in efficiency, or cost–benefit, analyses and are a separate category of costs as compared with our reported government, utility, household and ecosystem costs.

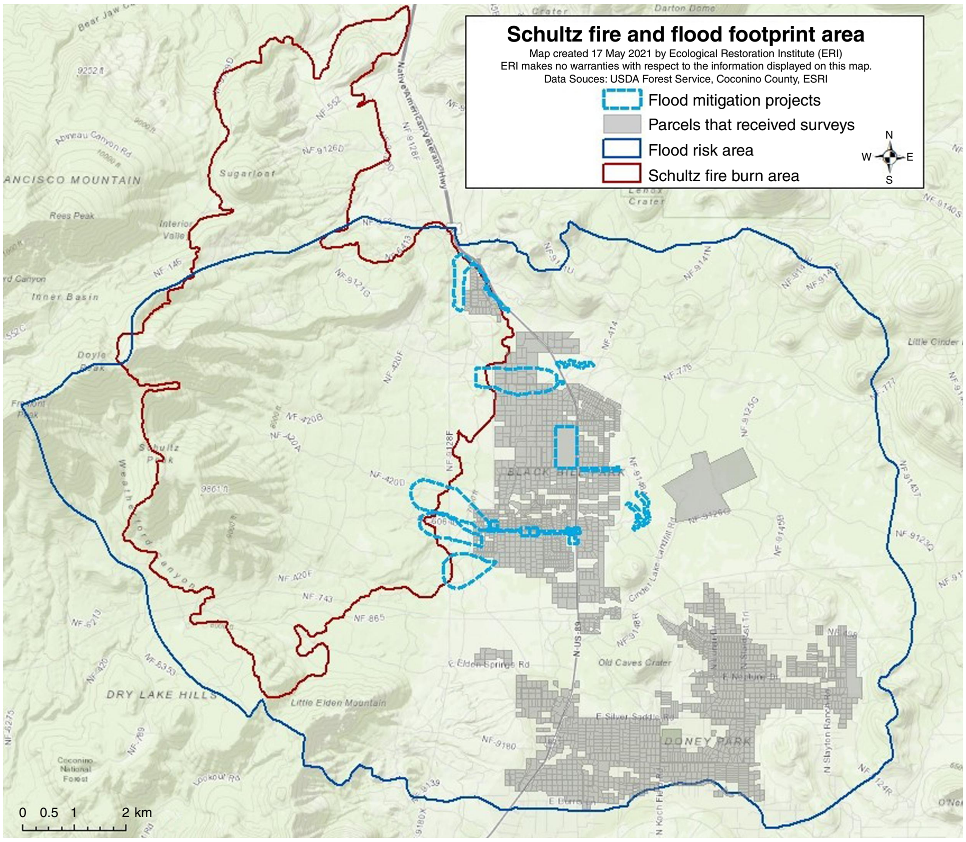

Fig. 1. Map of 2010 Schultz Fire perimeter (red), the projected 100-year flood risk area (blue), and flood mitigation projects (hashed blue). From Colavito *et al.* (2021).

improvement in model characterisation of potential flood risk for affected neighbourhoods. Our mixed-mode survey was administered to 1802 households, resulting in 407 completed questionnaires for a 22.6% response rate.

We replicated numerous economic questions from the 2011 survey instrument and expanded them further to investigate long-term household costs for this fire to better understand how these expenses and experiences have evolved over the past decade. Our survey instrument included questions on several cost-related topics including property impacts associated with flooding, insurance claims, mitigation actions and upkeep, and other out-of-pocket costs, as well as the effects of the Schultz Fire on respondent wellbeing.

Survey materials were mailed to households beginning in October 2020 and provided opportunities for both mail and online participation. Each household received materials in three phases following guidance from Dillman *et al.* (2014): (1) an introductory letter with information about the study, a questionnaire booklet and a pre-paid return envelope; (2) a postcard reminder 1 week later; and (3) a final reminder letter after an additional 2 weeks to incentivise responses from those yet to participate. For the full cost calculation, we extrapolated the reported survey responses for estimated costs to the entire study area. Using demographic information and non-response bias testing, we determined that the survey respondents were representative of the entire study area, so we extrapolated costs for: (1) flood insurance costs; (2) insurance claims; (3) damages not covered by insurance; (4) preventative measure costs; and (5) upkeep of preventative measures.

Some household costs, such as decreases in house sale prices due to the Schultz Fire, are difficult to determine with survey methods. The original cost assessment (Combrink *et al.* 2013) estimated that the Schultz Fire led to assessed house value decreases of US$59 million, or 44% of total estimated costs, based on County Assessor values by affected neighbourhood for 2 years following the fire. However, a few years later, a spatially delineated, hedonic property analysis that examined the Schultz Fire effect on housing sale prices was conducted by a team of researchers (Mueller *et al.* 2018). Estimating house value changes based on market price sales is more accurate than using assessed values. Likewise, hedonic models are the best way to assess important non-market attributes associated with housing sale prices (Taylor 2003), such as proximity to wildfire or post-wildfire floods, leading us to incorporate the more conservative Mueller *et al.* (2018) estimates into our total cost accounting.

Estimating ecosystem service proxy cost – damages to Mexican spotted owls

Ecosystem services, or nature's benefits to humans, can be adversely affected by uncharacteristic wildfire, resulting in economic losses to society. Ecosystem service damages from wildfire are vast but are typically only documented if they result in losses for marketed commodities (e.g. timber losses) or require direct expenditures for mitigation (e.g. suppression and infrastructure costs). Lost commodities are generally easy to calculate because they have market prices associated with them. Tracking damages from wildfires that are related to non-market goods and services is more difficult and thus represents more latent wildfire economic losses.

Given the difficulty of calculating all potential non-market ecosystem service damages from wildfire (e.g. carbon losses, vegetation loss, water quality loss), we provide an in-depth examination of one primary service adversely affected by the Schultz Fire – forest habitat. Specifically, we investigated the economic damages associated with reduced habitat for the threatened and endangered MSO as a proxy for collective ecosystem service damages, understanding that this approach vastly underestimates total ecosystem service damages. We used a benefit transfer approach to apply spotted owl valuations from the literature to estimate the costs associated with the loss of 424.92 hectares of Protected Activity Center (PAC) area burned at high severity in the Schultz Fire.

The Schultz Fire burned uncharacteristically, resulting in crown fires burning across three MSO PACs. Ecological monitoring over the last decade indicated that the Schultz Fire displaced existing owls but likely did not result in the immediate loss of owls (Shaula Hedwall, US Fish and Wildlife Service, pers. comm., 3 May 2021). Because we did not want to model the entire loss of MSOs or all their habitat, we needed to estimate the marginal cost of losing 424.92 hectares of MSO PACs. Thus, total willingness to pay (WTP) estimates in the literature for protecting spotted owls from uncharacteristic wildfire were whittled down to be applicable to our study site (Montgomery and Adams 1994). To estimate this cost, we employed benefits transfer methods where primary estimates from previous spotted owl valuations are transferred to the Schultz Fire and its MSO habitat reduction. Per-area WTP estimates were derived, and three types of benefit transfer were conducted: value unit, measure of central tendency and function transfer. Conservative choices were made when choosing between model alternatives, leading to a likely underestimate of the true WTP to protect MSOs from uncharacteristic wildfire.

Results

Government and utility costs

We calculate an updated cost of US$72 392 991 over 10 years for government and utility entities (Table 1). This represented an additional US$27 871 037 in expenses to government and utility entities from 2013 to 2019 that was not captured in the initial study (Combrink *et al.* 2013). The suppression costs for the Schultz Fire amounted to over US$11 million in 2021 dollars, are captured in the first column of Table 1, and account for almost 16% of the total government and utility costs.

Household costs

In this section, we present the findings of the 2020 household survey, with the intent to provide a temporal comparison of economic implications for residents and capture undocumented long-term consequences to Coconino County households. Responses from both the 2011 and 2020 surveys are compared wherever they are available. Respondents were demographically representative based on the most recent census data for this area.

Flood insurance

A total of 126 respondents (39%) self-reported that they had purchased flood insurance for their property in the 2011 survey, contrasted with 69 respondents (17%) who reported that they still renewed flood insurance annually in 2020. A subset of 2020 survey respondents reported the annual cost to renew that insurance coverage; Table 2 shows that the cost of flood insurance among respondents has almost doubled in the past decade.

Approximately one-third of 2020 survey respondents (n = 131) reported damage related to post-wildfire flooding since the Schultz Fire, a decline from the 45% (146 respondents) who reported damage in the 2011 survey. This shift is likely related in part to resident turnover in the area. Only 14 respondents to the 2020 survey made an insurance claim associated with flood damage or loss. Almost all respondents were underinsured; the average estimated cost of damage was ~US$23 285, but average compensation received was US$13 025.

Approximately one-fifth (22.5%, n = 90) of respondents reported flood damage to their property at some point between 2010 and 2020 for which they did not file an insurance claim. These reported losses included debris or mud removal, landscaping, lost rental income, loss of pasture for livestock, flooding in living areas of house and landscaping or fencing losses. The average cost of damages for which an insurance claim was not made was US$12 111, with a range of US$100 to US$75 000 (n = 76 respondents).

Flood risk mitigation and costs on private property

The cost of hazard mitigation on private property after fire is scarcely documented but represents significant out of pocket expenses for many affected households. Table 3 reviews household costs for preventative measures across both the 2011 and 2020 surveys. The average cost of preventative measures on private property has increased

Table 1. Government and utility expenses from the Schultz Fire 2010–2019 (real 2021 US dollars).

Funding agency	Fire response 2010	Flood response 2010	Flood mitigation 2011–2012	Flood mitigation 2013–2019	Total
City of Flagstaff	$39 494	$900 632	$5 365 628		$6 305 755
Coconino County		$6 360 584	$2 136 033	$11 580 316	$20 076 933
Coconino County Resource Advisory Council			$170 985		$170 985
Arizona Department of Emergency and Military Affairs		$1 006 892	$184 599	$246 416	$1 437 908
US Geological Survey		$60 006	$57 943		$117 949
Arizona Department of Transportation (ADOT)			$3 520 727		$3 520 727
Summit Fire Department	$33 603	$61 326		$49 388	$144 316
Unisource Energy Systems		$219 140			$219 140
Arizona Public Service		$138 013		$152 300	$290 312
Doney Park Water		$107 331			$107 331
Federal Emergency Management Agency (FEMA)		$4 792 040	$1 082 795	$807 476	$6 682 310
US Forest Service	$11 281 035	$4 980 457	$376 632	$603 626	$17 241 750
Natural Resources Conservation Service (NRCS)			$255 419	$9 225 920	$9 481 339
Federal Highway Administration (FWHA)			$1 390 642	$5 205 596	$6 596 237
Total	$11 354 133	$18 626 419	$14 541 402	$27 871 037	$72 392 991

From Colavito *et al.* (2021).

Table 2. Overview of flood insurance costs among respondents who still renew their coverage annually in nominal US dollars.

Survey year	Mean	Median	s.d.	Minimum	Maximum	No. respondents
2011	$357	$350	$357	$140	$900	113
2020	$613	$500	$353	$185	$2000	55

From Colavito *et al.* (2021).

significantly since 2011. Additionally, the cost of upkeep for these preventative measures over the past 10 years has been substantial, with a mean cost of US$3620 ($n = 37$ respondents).

Effects of the Schultz Fire on wellbeing

Although we do not attempt to monetise the impacts of the Schultz Fire on resident wellbeing, these costs have been quantified in other studies (e.g. Ambrey *et al.* 2016), and it is important to acknowledge that decreases in wellbeing associated with wildfire and post-wildfire flooding represent real and significant costs that may range from medical bills to unemployment. Negative outcomes for respondent wellbeing were predominantly documented among those who lived in the area during the Schultz Fire. We found that 18.9% of respondents moderately or strongly agreed that their mental health suffered as a result of the fire, with 25.3% reporting experiencing significant levels of stress; 12% moderately or strongly agreed that their physical health had suffered too. Approximately 8.3% of respondents reported that they had pre-existing health conditions that they reported were worsened by impacts associated with the Schultz Fire.

Housing sale price decreases

To estimate the effect of the Schultz Fire on housing sale prices, we incorporated detailed estimates from Mueller *et al.* (2018). They found a US$9.4 million aggregate loss for 528 houses that were sold after the Schultz Fire and located within 20 km of the fire perimeter. Additionally, they found a US$6.5 million aggregate loss for 351 houses that were sold after the Schultz Fire and located within 2 km

Table 3. Total estimated cost of preventative measures on respondent's property in nominal US dollars.

Survey year	Mean	Median	Minimum	Maximum	No. respondents
2011	$3089	$600	$30	$50 000	88
2020	$7227	$2500	$20	$100 000	118

From Colavito *et al.* (2021).

of post-wildfire flooding. Owing to separate methods and overlapping houses in the fire and flood perimeters, we cannot aggregate the two totals, but we do know that housing sale prices decreased at least US$9.4 million owing to the Schultz Fire.

Ecosystem service costs

Ecosystem service damages from the Schultz Fire manifest in a number of ways and are also included in other cost categories. In this section, we focus on a primary ecosystem service, economic costs of Schultz Fire damages to a threatened species – the MSO – that can be used as a proxy and a minimum estimate of broader ecosystem service damages. Three types of benefit transfer were conducted to estimate Schultz Fire damages to MSO habitat.

Unit value transfer

Starting with the unit value transfer approach, we transfer estimates from the one source study focused on MSO habitat protection. Loomis and Ekstrand (1997) found an annual mean WTP of US$66 per household (updated to real 2021 US dollars) to protect MSO habitat and found a total annual WTP of US$3.3 billion when extrapolated to all US households. To realise marginal costs of the Schultz Fire impact, we calculated a WTP of US$1770 per hectare (Loomis and Ekstrand 1997) and applied this to the 425 hectare MSO PAC loss, resulting in a societal welfare reduction of US$752 000.

Measure of central tendency value transfer

Synthesising multiple applicable source studies is another type of unit value transfer known as 'measure of central tendency value transfer' (Rosenberger and Loomis 2003). Without a specific valuation of WTP for MSO habitat and wildfire prevention programs, we synthesised four studies estimating WTP for protecting Northern and California Spotted Owl (NSO and CSO) habitat from intense wildfire (see Table 4). Per-hectare WTP values to protect spotted owls from wildfire were derived by dividing reported total WTP by the number of fire prevention hectares studied. Using the mean WTP of these four studies as the central tendency value, we found an average WTP of US$3798/hectare to protect spotted owls from wildfires. Applied to the Schultz Fire, we find a total loss of US$1.614 million (US$3798/hectare ~ 425 MSO PAC hectares).

Benefit function transfer

For the benefit function transfer, we applied the WTP function from Loomis and González-Cabán's (1998) study valuing fire protection for spotted owl habitat that illustrated how coefficients for explanatory variables (e.g. loss of area, importance of environmental quality) compose overall WTP. As their study was conducted in California, we adapted the WTP function to our study site, attaining equivalent metrics for Arizona for two of six explanatory variables (mean income and age). After adjusting to 2021 dollars, we found a median WTP of US$82 per household, slightly lower than estimated in California. We conservatively extrapolated median WTP to the Schultz Fire and found a WTP of US$1284/hectare with a corresponding total loss of US$546 000. Extrapolation of median Arizona WTP (US$82) accounted for a number of factors. We conservatively apply WTP to only 50% of households (Arizona and rest of the US), matching Loomis and González-Cabán's (1998) response rate. We remove households below the poverty line and then extrapolate to remaining US households at 50% of our Arizona estimated WTP.

Total costs

Costs associated with the Schultz Fire continued to accrue over 10 years, although at a slower rate than during the first analysis. The total costs for the 10-year assessment period were conservatively estimated to be between US$109 and US$114 million in 2021 dollars (Table 5). Although not quantified, adverse effects to resident wellbeing also accrued over time and represent additional economic costs. When excluding property value reductions estimated in the original and final studies, and accounting for inflation, there was a 29–35% real increase in the respective range of other costs from 2013.

Government and utility entities bore the largest costs in the amount of US$73.4 million over 10 years. Coconino County and the USDA Forest Service experienced the largest costs. Most government and utility costs were incurred in the first 5 years following the fire, between 2010 and 2015, highlighting the decreasing costs over time as mitigation projects are completed. For the study area, we calculated individual costs from the household survey in the range of US$4.6–$6.6 million for insurance-related costs, which includes insurance premiums, claims and damages. We also calculated a range of US$3.4–$5.3 million for prevention and mitigation measures, which includes initial costs

Table 4. Willingness to pay (WTP) for wildfire prevention for spotted owls.

Spotted owl protection policy being valued	Documenting research	Sampling frame	Policy area (million hectares)	Extrapolated total WTP (2021 US$billion)	Per-hectare WTP (2021 US$)
Fire reduction policy for protecting NSOs in Oregon	Loomis and González-Cabán (1994), Loomis *et al.* (1994)	Oregon	1.2	$1.52	$1252
Fire reduction policy for protecting CSOs in California	Loomis and González-Cabán (1996, 1997)	California; New England states	2	$8.07	$3987
Fire reduction policy for protecting NSOs in Oregon	Loomis and González-Cabán (1996, 1997)	California; New England states	1.2	$7.48	$6158

From Colavito *et al.* (2021).

Table 5. Costs of the 2010 Schultz Fire (in real 2021 US dollars).

Cost types	Total costs
Government and utility expenses 2010–2019	$72 392 991
Mexican Spotted Owl habitat displacement	$1 080 500 (range $546 000–$1 615 000)
House sale price losses	$9 920 000
Insurance	$5 611 193 (range $4 613 866–$6 608 520)
Prevention and mitigation measures	$4 368 748 (range $3 437 271–$5 300 225)
Loss of life	$9 760 000
Structural damage	$3 470 499
Clean-up	$2 044 592
Unpaid labour	$1 698 409
Home contents	$614 158
Fire evacuation costs	$250 456
Total	$111 211 546 (range $108 748 242–$113 674 850)

Adapted from Colavito *et al.* (2021).

and upkeep. We used the means to calculate the total costs for the study area (Table 5).

Discussion

Our calculations of the costs associated with the 2010 Schultz Fire highlight the longevity of wildfire and post-wildfire flooding costs. In our study, the costs for the Schultz Fire continued to accumulate over 10 years, although the costs incurred during and shortly after the fire due to flooding were larger than those in the subsequent years. It is important to note that our estimate is a conservative one, as we were not able to account for every potential direct and indirect 'net value change' category outlined by Thomas *et al.* (2017). We do capture both direct and indirect costs over time for which we have robust data, but our total cost figure surely underestimates the full cost of the 2010 Schultz Fire and post-wildfire flooding. Indeed, recent wildfires that burned over the Schultz Fire footprint, including the 2022 Tunnel and Pipeline Fires, further demonstrate the ongoing, and now compounding, impacts of a single uncharacteristic wildfire. Our research provides one blueprint for measuring costs associated with a single wildfire over time, as well as propositions for future research and monitoring to better estimate full wildfire costs moving forward.

This study is unique and innovative for several reasons. First, this study is the first of its kind to include a remeasurement of wildfire costs, which provides the opportunity to reevaluate approaches and learn from past work. Second, this study provides a long-term assessment of the same wildfire over a 10-year period, which was only possible given that the first study provided a baseline of initial costs after a 3-year period. The longer time span for measurement of costs also led to refinements, and in some cases reductions, in estimated costs such as affected house values and MSO habitat losses. Third, this study documents costs in multiple cost categories, whereas many other studies have focused on a single cost category, and provides costs for both social and ecological impacts related to the 2010 Schultz Fire.

Regarding considerations for documenting wildfire costs, we feel that valuable insights can be gleaned from our case study particularly related to the long-term nature of indirect wildfire costs. Thomas *et al.* (2017, table 1.3) classified direct and indirect wildfire costs, where direct costs include damages to human health, property and habitat directly occurring from the wildfire and indirect costs are all other costs that typically happen after the wildfire has been contained. Using this dichotomy of wildfire costs, indirect costs of the Schultz Fire accounted for approximately 89% of all costs, as the majority of government mitigation efforts, loss of life and structural damages occurred from post-wildfire flooding as opposed to the initial wildfire. However, suppression costs were estimated at 10% of total fire costs and lost MSO habitat (a direct cost) was estimated to be 1% of all costs.

Fig. 2 illustrates the approximate timing of the indirect costs of the Schultz Fire, showing an exponential decay rate of approximately 14% over 9 years.[2] If the Schultz Fire total costs had been reported after only 2 years, approximately half of all costs would have yet to occur. Thus, for any wildfires that may cause subsequent post-wildfire flooding, utility disruptions, or general community economic decline, indirect costs will persist for years following the fire and documentation of costs will need to be ongoing for some time. Uncharacteristic wildfire in communities with higher rates of population, structures and timber present than were affected by the Schultz Fire, and with less risk of post-wildfire flooding, will see greater direct costs that will be realised more immediately.

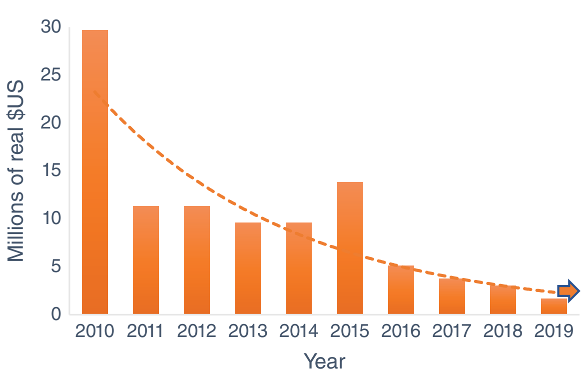

Fig. 2. Schultz Fire indirect costs 2010–2019 with exponential trendline.

In terms of minimising C + NVC, we hypothesise that fuel reductions and forest restoration (an increase in cost) would greatly reduce wildfire damages (NVC) as has been modelled as avoided wildfire costs in Colorado (Jones *et al.* 2017; Jones *et al.* 2022), California (Buckley *et al.* 2014), New Mexico (Wildish *et al.* 2020) and Arizona (Huang *et al.* 2013). A recent literature review by Hunter and Taylor (2022) documents a wide range of variability in benefits and costs of fuel treatments depending on location and project context. Forest restoration was planned within significant portions of the Schultz Fire footprint but was not implemented prior to the fire. Treatment costs were estimated to average US$3175/hectare for mechanical thinning and US$741.3/hectare for prescribed fire (Taylor *et al.* 2015), for a total average cost of US$12.5 million. Based on our study of the Schultz Fire, we estimate a wildfire cost of $18224/hectare, or four-and-a-half times the proposed restoration costs. If restoration treatments were even moderately effective at reducing the Schultz Fire intensity, millions of dollars in wildfire damages could have been avoided.

Conclusion

This study documents the ongoing and long-lasting, yet also conservative, costs of a single wildfire. Given the trends of increasing wildfire severity and duration of fire seasons (Hessburg *et al.* 2021), combined with studies that have explored costs of wildfire across the nation (Thomas *et al.* 2017) or looked at myriad costs of wildfire (Dale 2010; Troy *et al.* 2022), it is safe to assume the full costs of wildfire are vastly underrepresented and enormous. Additionally, as the Schultz Fire example demonstrates, a single fire often has many costs that are difficult to quantify and are temporally dispersed, such as costs to ecosystem services or community well-being. This further emphasises the importance of proactive fuel treatments and forest restoration work to reduce the risk of uncharacteristic fire and restore ecosystem health (Prichard *et al.* 2021).

Several lessons emerged over the course of this remeasurement. First, post-wildfire flooding, and the need for flood mitigation infrastructure, can occur for years after a wildfire. Our remeasurement captured an additional US $27 871 037 of government and utility costs that occurred for years after the Schultz Fire and after the initial study. In fact, the most expensive flood mitigation projects occurred 5 years after the fire. Thus, there is a benefit to waiting for

[2]The equation for exponential decay rate used is $y = a(1 - b)^x$, where y is the total amount of indirect costs, a is the first year of indirect costs, b is the decay factor, and x is the number of years passed.

3–5 years after a fire to understand the full costs of a single event. Additionally, by surveying affected residents a second time and after a decade, it was clear that household costs associated with the Schultz Fire continued to occur; additional analysis of survey data indicates that those engaged in collective action to address flood risk might have higher expenditures (Burnett and Edgeley 2023). Costs associated with household repairs and fire preparation continued to accumulate a decade later, though at a decreasing rate. Costs to wellbeing also continued for many years following wildfire. With respect to our ecosystem service calculation, the longer timeframe and ecological monitoring that occurred during that time afforded a more realistic picture of damage to MSO habitat, and thus, a more informative valuation of ecological damages due to the Schultz Fire.

There are limitations from our example of the 2010 Schultz Fire. We had to be opportunistic in using the costs that were available and quantifiable, so our example provides a broad-brush approach using the best available information from our specific case. Furthermore, we could not collect cost information in all of the 'net value change' cost categories (Thomas *et al.* 2017), so our study provides a range of costs rather than a full accounting of all possible costs. Finally, wildfires can also result in ecological benefits, and we did not measure any potential benefits that may have resulted from the Schultz Fire, especially in the areas that did not burn at high severity and were long overdue for fire.

There are many opportunities for future research on the full costs of wildfire. With limited research in this arena, additional studies documenting the full costs of a single wildfire over time are needed to provide enough information to create a standardised approach for calculating the full costs of wildfire. Additionally, some categories of wildfire costs, such as reductions in resident wellbeing, are routinely overlooked and additional research is needed to advance techniques for measuring these types of social costs. Lastly, future research should investigate the benefits, or the amount of wildfire damages that could be avoided, associated with preventive treatments. A simple extrapolation, as done under C + NVC modelling, illustrates that millions of dollars may have been saved by forest restoration treatments in key parts of the Schultz Fire perimeter before the fire. Research has clearly shown that forest restoration treatments in ponderosa pine forests result in overall lower-severity fires (Fulé *et al.* 2012), which lessens the intensity of subsequent post-wildfire flooding.

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Data availability. The data that support this study will be shared on reasonable request to the corresponding author.

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