Abstract
Climate change is intensifying fire regimes across boreal regions, and thus both burned area and carbon emissions from combustion are expected to increase significantly over the next several decades. Fire management through initial suppression of fires is effective at reducing burned area, but limited work has addressed the role that fire management can play in reducing wildfire carbon emissions and their impacts on climate change. In this work, we draw on historical data covering fire and fire management in Alaska to project burned area and management outcomes to 2100. We allow management to both respond to and impact variations in annual burned area and carbon emissions, while keeping decadal-average burned area at or above historical levels. The total cost of a fire is calculated as the combination of management expenditures and the social cost of carbon (SCC) emissions during combustion, using the SCC framework. Incorporating the tradeoff between management expenditures and burned area, we project that by 2100, increasing management effort by 5–10 times relative to current expenditures would minimize combined management and emissions costs. This is driven by the finding that the social costs of carbon emissions greatly exceed management costs unless burned area is constrained to near the average historical level. Our analysis does not include the many health, economic, and non-CO₂ climate impacts from fires, so we likely underestimate the benefits of increased fire suppression and thus the optimal management level. As fire regimes continue to intensify, our work suggests increased management expenditures will be necessary to counteract increasing carbon combustion and lower overall climate impact.

1. Introduction
As climate change alters temperature and weather patterns globally, the frequency of warm and dry conditions is increasing in the boreal region, intensifying boreal fire regimes in Alaska (Kasischke et al 2010, Turetsky et al 2011), Canada (Gillett et al 2004, Hanes et al 2019), and Siberia (Ponomarev et al 2016, Shvetsov et al 2021, Talucci et al 2022). Burned area in Alaska is projected to at least double by the end of the century, barring dramatic changes in emissions trajectories (Bachelet et al 2005, Balshi et al 2009, Euskirchen et al 2009, Rupp et al 2016, Pastick et al 2017, Genet et al 2018, Schultz et al 2019), suggesting Alaska’s boreal forests may soon become a net source of carbon to the atmosphere (Genet et al 2013), if they are not already (Zhu and McGuire 2016, Virkkala et al 2021). These trends pose a serious problem as nations seek to limit global average temperature increase to 1.5 °C above preindustrial levels (Secretariat, UNFCCC 2015). If unmitigated, wildfire carbon emissions through 2050 from Alaskan and Canadian wildfires alone have the potential to reduce the world’s remaining 1.5 °C global carbon budget by
roughly 4% (Phillips et al 2022). Active fire management is a potentially important tool to mitigate the effects of climate change on boreal fire regimes, but the costs, benefits, and trade-offs of fire management have yet to be quantified.

While fire management is effective at containing fires and reducing burned area, it can be resource-intensive. The vast aerial coverage and remoteness of most boreal forests in North America render fuels treatments impractical for managing burned area (Amiro et al 2001), but post-ignition management is effective at reducing burned area (Phillips et al 2022), particularly when fires are attacked early (Cumming 2005, Arienti et al 2006, Podur and Wotton 2010). Fighting wildland fires requires significant resources, including aircraft, ground vehicles, firefighting crews, and teams handling management and operations (AICC 2020). The cost of managing an individual fire in Alaska can extend into the hundreds of thousands or even millions of US dollars (AICC 2021).

While fire management can be costly, the emissions from combustion of vegetation and soil organic matter also generate large economic damages by contributing to climate change. The social cost of carbon (SCC) is typically used to quantify such damages (Nordhaus 1993, Stern 2007, IWG 2010, Arrow et al 2013, National Academies of Sciences 2017). To calculate the SCC, a small pulse of carbon or CO2 is ‘emitted’ in an Integrated Assessment Model, leading to a change in global average temperatures and subsequent economic damages. The discounted sum of these damages represents the social cost of the emissions pulse. SCC is commonly used in benefit-cost analyses for policy to value the cost imposed by emissions (IWG 2010, 2021, Metcalf and Stock 2017, Nordhaus 2017, Anthoff and Emmerling 2019, Tol 2019, Greenstone et al 2020, Russell et al 2022). In the Alaskan context, applying the SCC to wildfire emissions allows us to compare the operational costs of fire management to the climate costs of intensifying fire regimes.

To date, the role of boreal fire management as a potentially cost-effective tool to limit future carbon emissions has barely been explored. A limited number of papers attempt to project management costs based on burned area projections, but do not incorporate any effect of increased expenditures on burned area (Melvin et al 2017, Schultz et al 2019). As a result, we lack an understanding of (1) how changes in fire management may alter climate-driven increases in burned area, and (2) the economic costs and benefits of adjusting management regimes in response to climate-driven pressures.

Here, we apply the SCC to wildfire emissions in Alaska to compare the operational costs of fire management to the economic costs of carbon emissions from intensifying fire regimes. Carbon emissions and sequestration are already recognized as a potentially important component of wildfire and land management policy (Mills et al 2015, Haight et al 2020, Sánchez et al 2021), although wildfire emissions exacerbated by climate change are not included in SCC estimates. We present a modeling framework that combines projections of burned area from the fire science literature with fire management that is both responsive to changing fire regimes and capable of reducing burned area. We then use this framework to project burned area in Alaska through the end of the century under various management scenarios. The model integrates the direct financial cost of management efforts with the SCC emissions during combustion to project optimal fire management levels through 2100. This provides an economic framework to assess how changes in wildfire management can be used as a climate mitigation tool.

2. Methods

To estimate the management costs and carbon benefits of fire management in Alaska, we first developed a stochastic model, based on models presented in Rogers et al (2013) and Veraverbeke et al (2017), that simulates historical burned area patterns in Alaska based on ignition and fire size probabilities (section 2.1). We then integrated estimates of the effectiveness of fire suppression on limiting fire size based on agency cost data from Alaska (Phillips et al 2022), and used this model to simulate the impacts of climate change and altered management regimes on burned area, management costs, and social costs from fire carbon emissions (section 2.2). The overall study design is illustrated in figure 1.

2.1. Parameter selection model

We first divided Alaska into 191 grid cells (100 × 100 km) and assigned fires from the historical record into cells based on their ignition location (figure 2). The historical record includes fires from 1970–2019 published by the Alaska Interagency Coordination Center (AWFCG 2020). Each fire is represented by a point at the ignition site, and the observation includes the size of the fire. We excluded fires from before 1970 because the existing data include only an estimated 43% of true burned area (Kasischke et al 2002). Grid cells with no burnable area (containing only categories of ‘barren’ or water) were excluded from further analysis using the Landfire land cover mask (LANDFIRE 2008). We then generated a cumulative distribution function (CDF; figure 3) of the sizes of all fires across the state, which included over 25 000 observations. 90% of fires were under 200 ha, but there were a small number of very large fires (>200 000 ha), including 29 fires of over 1 million ha.

Our parameter selection model operates by randomly choosing the number of annual ignition events
Figure 1. Summary of methods. CDF stands for cumulative density function.

Figure 2. Ignition points and analysis grid.
and matching fire sizes for each grid cell in each simulated year for 10,000 years, yielding a simulated annual burned area. Ignitions are drawn randomly with replacement from a grid cell’s record of annual ignitions. For each ignition we generate a random number between 0 and 1, and then match it to the nearest fire size in the CDF for the entire state of Alaska, yielding a simulated size. The goal of the parameter selection runs is to derive a scaling factor specific to each grid cell such that the resulting long-term annual burned area closely resembles that of the historical record.

To derive this scaling factor, we compared the average annual burned area to the observed historical average for each grid cell after each simulation. For most grid cells, the average fire size is not equal to the state’s average, so the initial simulation did not match the observed historical average. We then assigned an exponent to modify the random number that selects fire sizes from the CDF. A large exponent parameter decreases the random number toward 0, whereas an exponent between 0 and 1 increases the random number toward 1. We iteratively increased or decreased this parameter until the simulated annual average was within 5% of the observed historical average burned area for each grid cell. Exponents ranged from 0.025 to 215, with a median of 2.8375. This approach allowed us to match the historical record without being confined to the available historical variation in fire sizes within a particular grid cell.

### 2.2. Projection model

After parameters were optimized for each grid cell, we used the model to project fires across Alaska from 2020 to 2100 by increasing burned area due to climate change and incorporating different fire management approaches, as discussed below. Although our parameter selection approach resulted in long-term burned area patterns that matched the historical mean, there are also temporal trends in the historical record (e.g. Veraverbeke et al. 2017). To address this in our projection model, we first divided the data into two periods: 1970–1989 (‘pre-climate regime’), and 1990–2019 (‘climate change-influenced’) (following Kasischke et al. 2010), and estimated the temporal trends in the historical data using a simple linear regression of time on fire size (table S2). In the first period, there was no significant temporal trend in either ignitions or fire size. In the second period, average fire size increased by an additional 3.37% for each year after 1990, significant at the 0.001 level, with no significant trend in ignitions. We therefore multiplied all the fire sizes generated for the projection model by $1.0337 \times (2019–1996)$, a factor of 1.76, beginning in 1996, the ignition-weighted mean year. While this scaling factor results in a slight upward trend in historical burned area, our pre-management burned area at the beginning of the projection period remains consistent with the historical trend. We also adjusted for the dampening effect of recent fires within a particular grid cell on fire size, following the results in Rogers et al. (2013); details are provided in the supplement.

To account for the influence of climate change on Alaska’s burned area during the 21st century, we conducted a literature survey, with methods detailed in the supplement. We ultimately included five peer reviewed papers (Bachelet et al. 2005, Balshi et al. 2009, Euskirchen et al. 2009, Pastick et al. 2017, Genet et al. 2018) and two government reports (Rupp et al. 2016, Schultz et al. 2019), containing a total of 23 projection scenarios using three fire models (table S3). While the magnitude of the increase in burned area varied, all the papers estimated that climate change will increase burned area in Alaska.

Giving each paper equal weight, the mean percent increase in burned area from 2020 to 2100 was 113% (table S4). Assuming a linear trend as in Phillips
et al (2022), we increased the number of ignitions by adding 1.4% of the historical ignition frequency each year, which then matched the total increase in burned area from the literature by 2100. This approach recognizes the role of increased lightning in changing fire regimes, since lightning strikes are the primary source of wildland ignitions and are projected to more than double by the end of the century (Veraverbeke et al 2017, Bieniek et al 2020, Chen et al 2021). After drawing the number of ignitions from a grid cell’s historical record, we scaled it by a factor of \((1 + 0.014 \times (\text{year} - 2019))\), rounded to the nearest whole number, to derive the climate-adjusted number of ignitions.

Once ignitions and fire sizes were calculated for all grid cells for a given year, we chose the amount of fire management (suppression) to implement across the state. On average, a 1% increase in Alaskan management expenditure from current levels corresponds to a 0.2063% decrease in average fire size (from Phillips et al 2022, summarized in the supplement). All Alaskan land is divided into one of four Fire Management Zones, or FMZs (figure 4(a)), each of which has its own standard response to fire. In land designated Critical, fires threaten human life, inhabited property, or infrastructure, and thus receive highest priority for management resources (AWFCG 2019). The management goal is complete suppression. In the Full zone, fires threaten uninhabited structures or areas that are used for resource extraction or valued for their cultural significance (DOF 2015). Fires in areas designated Full receive full suppression effort if the resources are not needed for fires in Critical zones. Limited areas are remote, and at most include points (like seasonal hunting cabins) that require protection. The standard response is to monitor fires and perform point protection. Finally, fires in Modified areas are treated like fires in Full areas until early to
mid-July, after which they receive the same minimal protection as other Limited areas, since late-season fires are less likely to spread enough to threaten priority sites (AWFCG 2019). The more actively managed FMZs receive both more dollars per designated acre and more dollars per acre burned compared to the less actively managed FMZs.

Since more actively managed zones receive more dollars per acre, grid cells with a large proportion of highly managed acres should receive a greater share of any increases in statewide management spending.

We therefore calculated weights to apply to each FMZ using two data sources: the management costs from Phillips et al (2022), which are extrapolated from spending reported by the Bureau of Land Management, and the costs from Melvin et al (2017), which include only spending by federal agencies. We calculated a spending ratio for each FMZ defined by the fraction of dollars spent per FMZ to the fraction of total land in that FMZ. We then applied these spending ratios to each grid cell in proportion to its relative coverage by each FMZ. The results from the two datasets are broadly similar (table 1). We used the results from Melvin et al because the year range is larger and ends closer to the present, and we assumed 2020 FMZ boundaries for future projections (BLM Alaska 2021). Based on these FMZ weights and the proportion of land in each FMZ designation by grid cell, we estimated the expected percent increase in management spending in each grid cell from a 1% increase in total spending.

The main specification of our projection model is the selection of state-wide management effort each year to minimize combined management and the SCC, while constraining the ten-year moving average of burned area at or above historical levels, as defined below, to avoid the ecological consequences of reduced or eliminated fire regimes.

### Table 1. Fire management spending by FMZ.

| FMZ       | Area (Square km) | Cost, millions 2015$ | Dollars per square km | Fraction of dollars spent | Fraction of area | Weight |
|-----------|------------------|----------------------|-----------------------|--------------------------|------------------|--------|
| Critical  | 116 158          | 29                   | 250.36                | 0.09                     | 0.01             | 6.53   |
| Full      | 1 109 243        | 157                  | 141.88                | 0.48                     | 0.13             | 3.70   |
| Modified  | 800 358          | 39                   | 48.32                 | 0.12                     | 0.09             | 1.26   |
| Limited   | 6 505 341        | 102                  | 15.68                 | 0.31                     | 0.76             | 0.41   |

Total reported federal response costs, 2002–2013

| FMZ       | Area (square km) | Cost, millions 2015$ | Dollars per square km | Fraction of dollars spent | Fraction of area | Weight |
|-----------|------------------|----------------------|-----------------------|--------------------------|------------------|--------|
| Critical  | 45 837           | 9                    | 200.84                | 0.06                     | 0.01             | 8.23   |
| Full      | 798 667          | 89                   | 111.44                | 0.57                     | 0.12             | 4.57   |
| Modified  | 567 135          | 29                   | 50.84                 | 0.18                     | 0.09             | 2.08   |
| Limited   | 4 986 704        | 29                   | 5.84                  | 0.19                     | 0.78             | 0.24   |

Estimated total response costs, 2007–2015

### Objective

\[
\begin{align*}
\text{Objective} = \min \left\{ \sum_{\text{grid cell}=i} \left( \frac{\text{Spending weight}}{\sum \text{Spending weight}} \cdot C \cdot M, \right. \right. \\
& \quad \left. \left. + \left( BA_{\text{year}} \cdot CO_2 \cdot SCC_{\text{year}} \right) \right\} \right. \\
\text{s.t.} \quad \left( \frac{\sum_{\text{year}=Y-9}^{Y} BA_{\text{year}}}{10} \geq BA_{h} \right)
\end{align*}
\]

### Spending weight

is change in grid cell spending relative to state spending; \(C\) is the baseline cost of management; \(M\) is the level of statewide management, with 1 representing no change from baseline; \(S\) is the grid cell management saturation point; \(BA_{\text{year}}\) is the statewide burned area in the year under consideration; \(CO_2\) is an estimate of carbon emissions per ha burned; \(SCC_{\text{year}}\) is the SCC in the year under consideration; and \(BA_{h}\) is the average historical level of burned area. The total costs from a fire season are the sum of management costs across all grid cells, which vary based on FMZ distribution and are defined according to the grid cell spending weight described above and summarized in figure 4(b), and the societal harm caused by carbon emissions during combustion, quantified using the SCC. The baseline cost of management is the average annual combined federal and state management cost from 2009–2015, or $99 386 015 in 2015 dollars (Jandt, personal communication). The social cost is positive when annual burned area exceeds the historical average, and negative when annual burned area is less than the historical average, implying a social benefit from fewer than average emissions. In historical fire regimes, this approach yields costs averaging close to zero over time, but under intensifying fire regimes this will result in positive and growing social costs in the...
In the primary specification of our model, management was chosen to minimize total annual costs. The BAU specification kept management at its current level, while including the impact of climate through the simulation period. In addition, we ran several alternate specifications to test the robustness of our modeling framework (table 2). We included a scenario that halved management effectiveness (Halved Effectiveness), since management is less effective when resources are stretched thin such as during large fire years and when fire weather is more intense. Another scenario halved the SCC applied to fire emissions (Halved SCC) to adjust for the fact that post-fire forest regrowth makes combustion emissions less persistent and thus may decrease the cumulative economic damages relative to GHG emissions from fossil fuel combustion. We also included scenarios where management was chosen to approximate a prespecified burned area level, either historical levels (approximately 0.2 Mha per year, 1970–89, Historical BA Target) or recent levels (approximately 0.51 Mha per year, 2010–2019, Modern BA Target) using the 10 year average burned area. Finally, we modeled cost-minimizing management under a range of climate scenarios: minimum, median, maximum, and 25th and 75th percentile burned area projections from the literature survey rather than the mean.

### Table 2. Projection scenarios.

| Category                  | Specification name | Description                                                                                                                                 |
|---------------------------|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Primary Specification     | Cost Minimizing Mgmt | Optimize management annually to minimize total costs, while keeping 10 year average burned area at or above historical levels. Full SCC, full management effectiveness, mean climate impact on fire regimes |
| BAU Burned Area Target    | BAU Mgmt.          | Maintain management at current levels, with mean climate impacts                                                                        |
| Modern BA Target          | Choose management annually so that 10 year burned area average matches the average from 2010–2019, 0.51 Mha     |
| Historical BA Target      | Choose management annually so that 10 year burned area average matches the average from 1970–1989, 0.2 Mha  |
| Cost Sensitivity          | Halved SCC         | As in Primary, optimize management annually to minimize costs, with halved SCC value. Accounts for the fact that post-fire forest regrowth makes combustion emissions less persistent and thus may decrease the cumulative economic damages |
|                           | Halved Effectiveness| As in Primary, optimize management annually to minimize costs, with halved management effectiveness. Accounts for the fact that management may be less effective when resources are stretched thin, and when fire weather is more intense, in large fire years |
| Climate Sensitivity       | Min Climate        | As in Primary, but with minimum climate impacts from the literature survey (9% increase in burned area 2020–2100)                          |
|                           | 25 Pct Climate     | As in Primary, but with 25th percentile climate impacts from the literature survey (37% increase in burned area 2020–2100)                 |
|                           | Median Climate     | As in Primary, but with median climate impacts from the literature survey (67% increase in burned area 2020–2100)                           |
|                           | 75 Pct Climate     | As in Primary, but with 75th percentile climate impacts from the literature survey (114% increase in burned area 2020–2100). Note this is very similar to mean, 113% |
|                           | Max Climate        | As in Primary, but with maximum climate impacts from the literature survey (530% increase in burned area 2020–2100)                         |

absence of increased management. For the amount of CO₂ emitted per square kilometer burned, we use the average from Alaskan sites included in the ABoVE combustion database (Walker et al. 2020). The average carbon emissions from Alaskan fires in the database, which covers the period 1983–2016, are 3.325 kgC m⁻² or 102.4 metric tons CO₂/ha (CO₂). after accounting for the fraction of carbon that does not convert to CO₂ (Akagi et al. 2011, Phillips et al. 2022). We used SCC values from the Dynamic Integrated Climate-Economy model (Nordhaus 2020) run under a Business As Usual (BAU) climate and policy pathway with a 3.9 °C temperature increase relative to preindustrial levels, to model costs through 2100. Further explanation of our SCC choice can be found in the supplement. This temperature increase is within the likely range for the most recent IPCC estimates for ‘high’ and ‘very high’ emissions scenarios, and is between the best-estimate values for the two scenarios (IPCC 2021).

Management in each grid cell is bound above by a saturation level, which is based on the management intensity from that grid cell’s mix of FMZs. At the saturation level of management, burned area is reduced to near-zero (5% of pre-intervention level) in the grid cell, and further state-wide management increases cannot decrease burned area or increase cost in that grid cell.
3. Results

In our primary, cost minimizing specification under mean climate influence (a 3.3 °C increase from preindustrial temperatures, leading to a 113% increase in burned area 2020–2100; figure 5), a major increase in management spending constrained burned area to near-historical levels throughout the projection period. Combined social and management costs rose throughout the 21st century, driven primarily by the social costs of emissions (figure 6), despite burned area remaining near historical levels. Rising social costs were driven by both a slight increase in burned area over the period, and SCC growth from $35/ton in 2020 to $225/ton by 2100, a standard feature of SCC estimates driven by both increasing marginal damages and closer future damages. In contrast, under BAU management, burned area doubled from its current level to over 1 Mha per year. Total costs, driven almost exclusively by the social cost of emissions, exceeded $20B annually by the end of the period, nearly ten times the costs associated with an optimal management regime.

When we compared these results to our alternate specifications (figure 7), we found our conclusions are robust to model formulation and assumptions. Changing the SCC or management effectiveness had a relatively small effect on optimal burned area and costs, although management increased significantly to compensate for lower effectiveness. Most alternate climate scenarios showed similar results, although the model struggled to contain burned area under the maximum climate influence scenario. Non-cost-minimizing scenarios generally resulted in lower management levels and substantially higher burned area and total costs.

4. Discussion

As fire regimes intensify, fire management spending, and by implication the resources available for fire management, will need to increase significantly if wildfires and their associated emissions are to be constrained. To limit the climate damages from wildfire carbon emissions, management spending may need to increase roughly tenfold by the end of the century under a high global emissions scenario. Even under the minimum climate impact scenario where burned area increases by only 9% from 2020, optimal management may need to increase more than fivefold to return burned area to historical levels. While this represents a large investment relative to historical spending, particularly under more pessimistic climate-fire scenarios, Alaska receives on average only 4% of U.S.
There are federal resources for wildfire management despite representing a fifth of US land area and over half the nation’s carbon emissions from wildfires (Phillips et al. 2022). The cost per ton of CO$_2$ emissions avoided by additional management is also low relative to other climate mitigation measures (Phillips et al. 2022). As described below, our analysis likely underestimates the harms from fires in several ways. Taken together, these suggest that our estimate of optimal management may in fact be more accurately regarded as a lower bound.

### 4.1. Additional social benefits of increased fire management

This analysis does not attempt to include every dimension along which fire and fire management can affect human welfare, and nearly all the effects of increased management and reduced burned area that are excluded from our model are benefits to society. During large fire events in the North American Arctic, air quality can exceed the EPA’s highest danger rating due to smoke (Trainor et al. 2009), with exposure extended across Canada, the conterminous US, and even to Europe (Le et al. 2014, Brey et al. 2018), although Indigenous communities in the Arctic are often disproportionately affected. Smoke exposure can lead to elevated rates of asthma, chronic obstructive pulmonary disease, bronchitis, pneumonia, respiratory infection, cardiovascular morbidity, and all-cause mortality (Liu et al. 2015, Reid et al. 2016, Cascio 2018).

In addition to their health impacts, wildﬁres often involve direct infrastructure losses, as well as impacts on forage and denning habitat for many animal species that afﬂict subsistence resources for Indigenous communities (Nelson et al. 2008, Kuuluvainen and Gauthier 2018). Wildﬁres can also cause direct deaths and injuries, disrupt transportation networks and supply chains, reduce water quality and erosion control, depress housing markets, and decrease revenue from recreation and tourism (Thomas et al. 2017). Since most of this literature takes a total damages approach rather than estimating damages from marginal increases in burned area, a reasonable approach since many of these damages are highly locationally dependent, we were not able to incorporate these costs into our model framework. However, to provide a sense of scale, total damages from wildfire in the US were recently estimated at $64B–$285B per year. This is roughly 0.3%–1.5% of US GDP and an order of magnitude more than what is spent on ﬁre prevention and preparedness, fuels management, and active suppression (Thomas et al. 2017).

We also likely underestimate the beneﬁts of additional management due to reductions in other climate impacts from wildﬁre. We use only estimates of the CO$_2$ released during combustion, but there are numerous other GHGs released that contribute to climate forcing (Randerson et al. 2006, Ward et al. 2012), including CH$_4$, N$_2$O, O$_3$, and O$_3$ precursors including NOx, non-methanogenic volatile organic carbons, and CO (Akagi et al. 2011, Ward et al. 2012, Huang et al. 2016, Wiggins et al. 2016). These collectively can more than double the radiative forcing from boreal fires compared to CO$_2$ alone (Huang et al. 2016). Fires also release organic and black carbon aerosols, which can impact the atmospheric radiative budget and generate large positive surface forcings when deposited on snow and ice (Flanner et al. 2007, Kostrykin et al. 2021). Moreover, by removing insulating organic layers, combustion can initiate permafrost degradation, leading to subsequent GHG emissions (Genet et al. 2013, Jafarov et al. 2013, Holloway et al. 2020, Treharne et al. 2022). Each of these wildﬁre impacts increases

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Figure 6. Total costs broken into social and management costs for primary cost-minimizing specification. All values display the 11 year moving average, centered on the year displayed, with shorter moving averages at the beginning and end of the time series.
Figure 7. Comparison of primary specification results averaged over the final decade of projection (red dashed line) to alternate specifications, including average management levels in the period 2090–2100 across specifications (a), average burned area (Mha) (b), and total costs (billions of 2015 dollars) (c). Management level gives the amount of management expenditure relative to baseline; for example, a management level of 2 means doubled expenditure relative to baseline. Alternate specifications are described in table 2.

the benefits of management, further suggesting that our cost-minimizing specifications may considerably underestimate the optimal level of management.

Finally, we quantify emissions costs using the SCC, which has faced criticism for underestimating the likelihood of or altogether excluding potential large feedbacks like permafrost thaw (Weitzman 2014, 2020) or intensifying fire regimes and their attendant emissions, and relying on outdated estimates of economic damages (Carleton and Greenstone 2021). Hence, the social cost of the combustion emissions we include could itself be an underestimate. Other critiques of SCC, like disagreements over the appropriate discount rate (Dasgupta 2008, Arrow et al 2013), failure to incorporate intersectoral and inter-regional feedbacks (National Academies of Sciences 2017), and objections to the basic modeling approach (Pindyck 2017), add uncertainty to our estimation of the social cost of fire emissions but do not clearly bias our estimate up or down. Moreover, while SCC has been applied to forest carbon sinks and fire emissions in previous literature (e.g. Mills et al 2015, Haight et al 2020), forest regrowth adds a novel challenge to its application. While we attempt to address this by
including a halved SCC scenario, this issue merits further study.

4.2. Evolving fire regimes and other caveats

To make our model tractable, we relied on several simplifying assumptions. We limited the influence of climate to the number of ignition events, and the influence of fire management to post-ignition suppression, although climate is predicted to impact ignitions, fire size, and intensity. We also selected pre-climate fire sizes solely to match historical burned area, although in reality fire size is determined by regional climate, fire weather, vegetation, topography, spatial patterns of land cover, and human influence. Our model also relies heavily on a single estimate of management’s effectiveness at reducing fire size, although management’s effectiveness is also dependent on many of the factors above. Finally, we optimized annually, rather than across the entire projection period (see supplement for further discussion). We adopted these simplifications because the goal of this work is to model the effects of climate and management on burned area, not to accurately reproduce every facet of the ecological system.

Despite these caveats, our model can replicate both historical burned area trends and projections from the literature while integrating responsive and effective management. Under more optimistic climate trajectories, for example those closely aligned with the 1.5 °C target established in the Paris Climate Agreement, such a drastic shift in management policy may not be required.

Although our model accounts for lower flammability in younger boreal forests, it may not account for the interacting ways in which shorter-interval fires limit subsequent burning and emissions (Higuera et al 2009, Parks et al 2015, Bernier et al 2016). Because of these effects, a ‘let it burn’ approach may result in higher deciduous cover (Rogers et al 2013), decreased flammability (Foster et al 2022), and increased carbon storage (Mack et al 2021). However, some studies and fire management reports (e.g. Walker et al 2019, Dieleman et al 2020) indicate that fuel feedbacks are limited during late season severe fire seasons, and may not be as effective under intensified climate change. Furthermore, any increase in carbon storage from conifer to deciduous forests, even neglecting the associated degradation of permafrost, will take many decades, whereas global climate goals emphasize the importance of lowering emissions over the next few decades (Masson-Delmotte et al 2018). Hence, a ‘let it burn’ approach is unlikely to result in net benefits by mid- or even late 21st century.

4.3. Implications for management policy

Our model framework does not address the implementation of increased management spending. It is widely documented that once fires become large, especially when combined with intense fire weather, they are difficult if not impossible to contain and control (Podur and Martell 2007, de Groot et al 2013). We therefore suggest a focus on expanding initial attack efforts. The majority of fires in boreal North America targeted for suppression are contained after initial attack (80%–99%) (Cumming 2005, Arienti et al 2006, Podur and Wotton 2010), and the remaining untargeted or escaped fires are responsible for over 95% of the burned area (Kasischke et al 2002, Stocks et al 2002). Analysis also shows that most initial attack failures are due to slow initial responses, as opposed to ‘containment’ failures (Arienti et al 2006). Moreover, the majority of ignitions in Alaska occur in June, whereas the majority of burned area occurs in July (Veraverbeke et al 2017); implying that most burned area occurs as a result of fires that remain small for several days or even weeks before spreading rapidly (Sedano and Randerson 2014). These facts suggest that increased resources for suppressing recently ignited fires would be an effective way to combat intensifying fire regimes.

Current Alaskan fire management is largely aimed at protecting human life and assets. Thus, fires in populated areas almost always stay very small, while there are large areas in the state where suppression is not the first response or primary goal. With additional resources, it could be possible to expand the areas where suppression is a management goal. One possibility is to increase the area covered under Full protection using a simple buffer around the existing areas as in Schultz et al (2019); another possibility is to expand protection to include areas that are particularly carbon dense in order to more efficiently target emissions reductions. The best approach would likely be informed by the management community, which has intimate knowledge of conditions and constraints on the ground. However, any discussion of which areas to target for expanded protection will remain purely theoretical until the resources available for fire management in Alaska are increased through state and/or federal budgetary appropriations. More broadly, our results show that the social costs of emissions are several orders of magnitude larger than management costs. This general result is relevant for fire management policy both inside and outside Alaska. While it is becoming more common for states to quantify wildfire carbon emissions (e.g. CARB 2020), assigning a price to these emissions is only beginning to be explored in the academic literature, and is not standard in policy. Our results illustrate how substantial this oversight could be.

5. Concluding thoughts

Overall, we find that the social cost of fire emissions greatly outweighs the cost of management when burned area exceeds historical levels, such that a large
increase in management resources is justified. While our study focuses on Alaska, this conclusion likely translates to many boreal regions in Canada that contain similar forest characteristics, fire dynamics, carbon stocks, and fire management frameworks. Our results are less applicable to systems with different fire and management characteristics, particularly ecosystems adapted to high-frequency and low-severity fire regimes where continued suppression results in high fuel loads and flammability, for example in the western United States. However, we urge researchers and policymakers across regions to consider the SCC emissions when creating and evaluating fire management policy. When the alternative is skyrocketing carbon emissions with a social cost of billions of dollars per year, increased fire management may be a prudent and essential investment in the years to come.

Data availability statement

The code that supports the findings of this study is openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.6395301.

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Author contributions

Research design: M E, C P, P F, B R
Analysis: M E, S P, B R
Writing—manuscript: M E, B R
Writing—reviewing and editing: M E, C P, S P, P F, B R.

Conflict of interest

Authors declare they have no competing interests.

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