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Quantifying the smoke-related public health trade-offs of forest management

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Prescribed burning can mitigate extreme wildfire risk and reduce total smoke emissions. Yet prescribed burns' emissions may also contribute to smoke exposures in nearby communities. Incorporating public health considerations into forest management planning efforts may help reduce prescribed burn-related exposure impacts. We present a methodological framework linking landscape ecology, air-quality modelling and health impact assessment to quantify the air-quality and health impacts of specific management strategies. We apply this framework to six forest management scenarios proposed for a landscape in the Central Sierra, California. We find that moderate amounts of prescribed burning can decrease wildfire-specific $PM_{2.5}$ exposures and reduce asthma-related health impacts in the surrounding region; however, the magnitude of that benefit levels off under scenarios with additional prescribed burning because of the added treatment-related smoke burdens. This framework can be applied to other fire-prone landscapes to incorporate public health considerations into forest management planning.

Wildfires are becoming more frequent and severe due to climate change and post-colonial fire management practices such as fire exclusion[1–8]. In addition to the direct economic damages and physical dangers to human life and property, wildfires produce substantial quantities of smoke, which can degrade air quality and public health[9,10]. Forest management activities, including prescribed burning, will probably play a important role in efforts to mitigate future extreme wildfire risk[11], yet little is known about how those efforts may impact public health. We develop an approach for quantifying public health impacts of forest and fire management planning actively under consideration and demonstrate its utility via an analysis of real-world management scenarios.

Epidemiological studies have identified significant associations between smoke exposure and increases in all-cause and respiratory-related mortality and morbidities, including exacerbation of asthma[9,10], and cardiovascular outcomes, including mortality, hospitalization, and acute coronary syndrome[9,10,12,13]. In response to our

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growing understanding of the population impacts associated with wildfire smoke exposures, there is widespread interest in strategies to decrease health-related damages from wildfire events[14–16]. Current public health responses have focused largely on minimizing downstream risks primarily through risk communication and individual- and community-level interventions (for example, at-home air filtration systems, clean-air centres and workplace regulations)[9,13,17–21]. Upstream actions—such as forest management, which may reduce emissions at the source—have the potential to decrease exposure and health risks for populations living near to and well beyond the jurisdiction where wildfires occur[15,22].

There is growing consensus within the forest and fire management community that achieving long-term forest health requires restoring natural fire regimes, especially in the western United States.[1,23]. Across the western United States, forest management plans have shifted away from full-blown fire suppression towards fuel reduction, forest restoration and maintenance efforts[1,24]. The goals of these strategies are to re-introduce smaller and more frequent fires (for example, via mechanical thinning and prescribed burning) to help reduce the occurrence of large and high-intensity fires[25–28]. The use of fire as an ecological management tool is not new: it has been used by Indigenous communities for millennia to accomplish a variety of land management goals[29,30]. In the United States, federal and state-level funding and strategic plans targeting increased fuel treatments reflect this shift in management priorities[16,31,32]; however, barriers to prescribed burning, such as concerns around air-quality and health impacts, limit its application, particularly across the western United States.[33–35].

Multiple studies have acknowledged the benefits of fuel reduction via prescribed burning in mitigating wildfire risk but have also highlighted the dangers of introducing additional treatment-related smoke[15,36–41]. Such studies have called for increased quantification of air-quality and health trade-offs in forest and fire management decision-making[39–41]. Despite these calls, to date, few studies have examined whether forest management—in the form of prescribed burning and mechanical thinning—can reduce overall population exposure to wildfire smoke and whether such actions are associated with reduced adverse human health risks. This gap reflects that the two fields (fire and forest ecology versus public health[9,10]) have so far generally progressed independently of each other. Previous evaluations of the air-quality and health impacts of increased forest management have relied on high-level representations of management increases (for example, hypothetically increasing prescribed burns by a defined percentage uniformly across a geographic area), which are not designed around specific landscapes or real-world management scenarios[42–44]. To address this gap in the literature, an integrated framework is necessary to conceptually link disparate but related analyses from these disciplines. Such a framework will allow for the evaluation not only of ecological factors, but also of the human exposure and health implications of forest management scenarios that are actively under consideration for real-world landscapes[15,45].

This paper presents a methodological framework that can be used to quantitatively integrate public health impacts into forest and fire management planning by reconciling data input requirements and spatiotemporal scales that differ across ecology, atmospheric science and public health methodologies. We apply this framework in a case study that evaluates the smoke exposure and health impacts of six forest management scenarios under consideration for a 970,000 ha landscape in the Tahoe–Central Sierra Initiative (TCSI) area in Central Sierra, California. The scenarios were developed by a consortium of land managers to investigate how increasing the area treated and the amount of prescribed burning would improve forest resilience to stressors such as wildfire, forest pests and drought[46]. Two management scenarios include mechanical and hand-thinning treatments only in locations close to developed areas or on private lands: Minimal Management scenario (9,300 ha yr^{-1}) and Business as Usual (BAU) scenario (16,600 ha yr^{-1}). Four management scenarios include increasing amounts of prescribed burning and thinning, ranging from Fire$^{\text{Lite}}$ (32,780 ha yr^{-1}) to Fire++ (51,400 ha yr^{-1}), in locations extending away from developed areas[47] (Fig. 1).

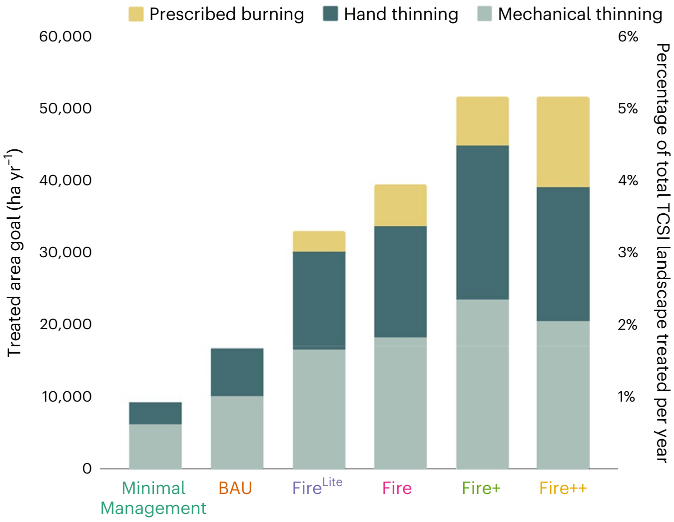

Fig. 1 | Overview of management scenarios. Treated area goals by treatment type across the six scenarios considered, with total hectares treated per year on the left *y* axis and percentage of total TCSI landscape treated on the right *y* axis.

We generate estimates of wildfire and prescribed burn-specific ambient smoke levels for the six proposed management scenarios (Fig. 2). We then use population smoke exposure to estimate health impacts. Our results indicate that forest restoration practices can be associated with reduced health risks and adverse exposure impacts; however, there are diminishing public health returns based on the intensity and scale of such practices. Our study advances these methods and evidence on whether sustainable forest management practices meant to return forests to natural fire regimes can result in broader societal benefits through reduced risks and impacts on human health.

Results

Forest management impacts on PM$_{2.5}$ exposure

We find the magnitude and spatial distribution of total smoke fine particulate matter (PM$_{2.5}$) concentrations (from wildfire and prescribed burns) are greatest under the Minimal Management and BAU scenarios, which involve no prescribed burning (Fig. 3a). Population-weighted 40 yr average total smoke concentrations under those two scenarios are 2.2 μg m^{-3} and 1.8 μg m^{-3}, respectively. Population-weighted total smoke under scenarios that include prescribed burning are lower: 0.71–0.96 μg m^{-3}. Of that, the portion from wildfires ranges from 0.28 μg m^{-3} (Fire++) to 0.41 μg m^{-3} (Fire$^{\text{Lite}}$), while the portion from prescribed burns ranges from 0.30 μg m^{-3} (Fire$^{\text{Lite}}$) to 0.68 μg m^{-3} (Fire++). Differences in the magnitude and spatial distribution of wildfire and prescribed burn-specific average dispersion patterns can be found in Supplementary Table 1 and Supplementary Fig. 2. We also see seasonal wildfire smoke concentration differences across scenarios, with the wildfire smoke season ending earlier in the year, tapering off in October on average, under all scenarios that include prescribed burning, relative to the longer wildfire season that extends into November under the Minimal Management and BAU scenarios (Fig. 3b).

Whether they stem from wildfire or prescribed burns, smoke events are often episodic and last on the order of hours to weeks. We examine how management scenarios impact the magnitude and frequency of these 'smoke-wave days' (short-term smoke events; see Fig. 4). The highest smoke-wave frequency (0.3 smoke-wave days per grid cell

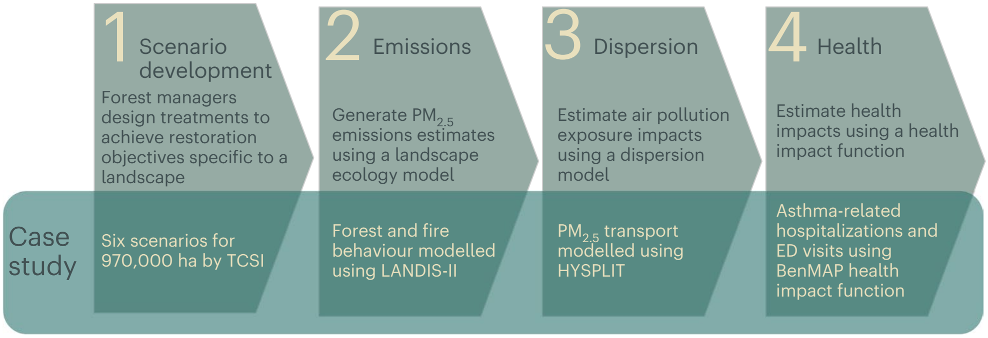

Fig. 2 | Modelling framework. Methodological framework for linking forest and fire modelling, air-quality modelling and health impact estimation efforts.

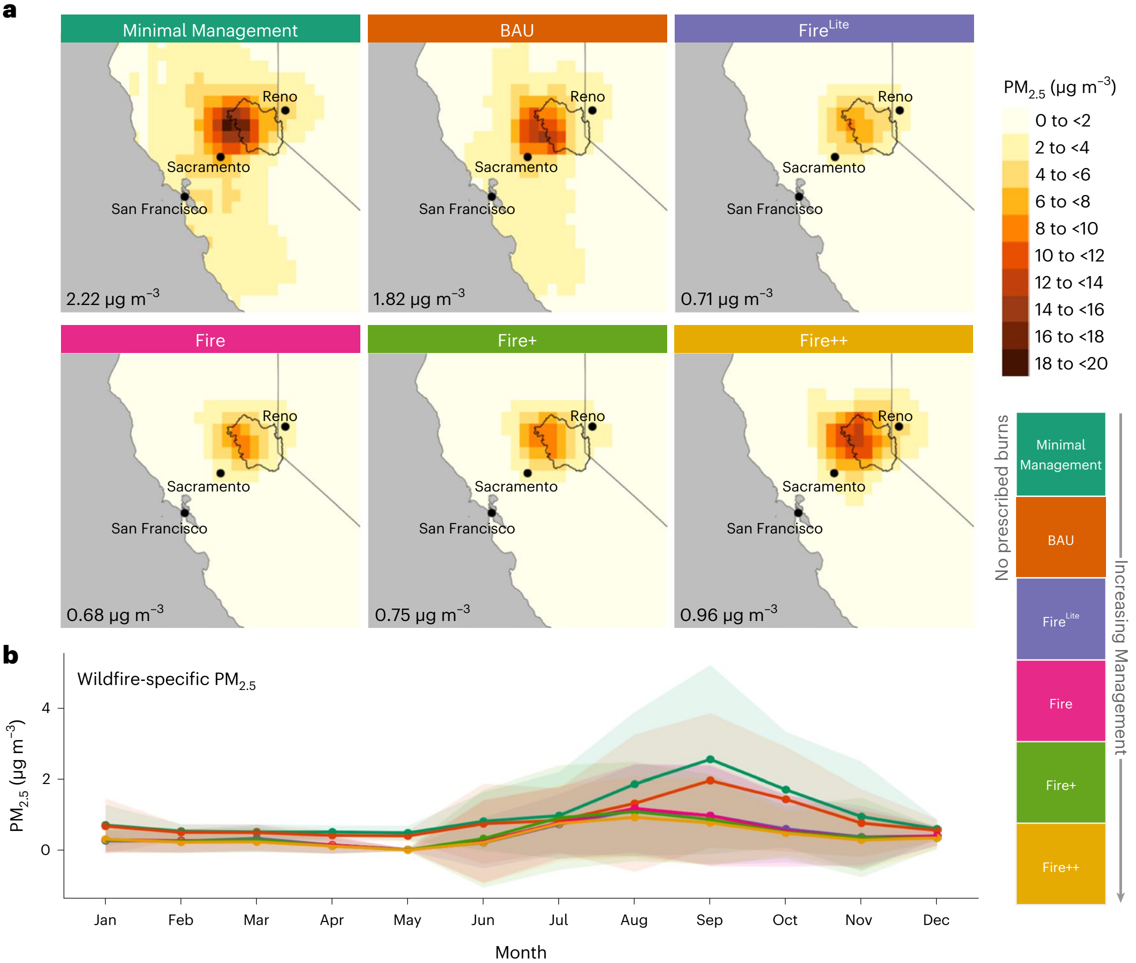

Fig. 3 | Total fire $PM_{2.5}$ concentration distributions. a, The 40 yr average total smoke $PM_{2.5}$ dispersion patterns for each scenario. Population-weighted 40 yr average total smoke $PM_{2.5}$ concentrations are at the bottom left of each map panel. The TCSI is the polygon outlined in black on the California–Nevada border. **b**, Average monthly wildfire smoke-specific $PM_{2.5}$ concentrations. Shading represents the standard deviation of the monthly estimates.

per year) occurs under the Fire++ scenario with the greatest amount of prescribed burning (12,408 ha yr^{-1}); however, the average magnitude of those smoke events (48.2 μg m^{-3}), stemming primarily from prescribed burning, is lower than that of smoke-wave days experienced under the Minimal Management (66.3 μg m^{-3}) and BAU (66.5 μg m^{-3}) scenarios, where smoke-wave days stem entirely from wildfire smoke events (Supplementary Tables 1 and 2). We find an inflection point of the lowest frequency (0.15 and 0.16 days) of smoke-wave days under Fire^{Lite} and Fire scenarios, under which 2,883 and 5,655 ha yr^{-1}, respectively, are treated with prescribed burns. This suggests that the rate and extent of prescribed burns under these scenarios may be optimal (among scenarios considered here) in terms of mitigating wildfire smoke exposure risk while also minimizing smoke impacts stemming from prescribed burns. This finding is consistent with our finding for average concentration (Fig. 3a) that the Fire scenario is optimal among scenarios considered.

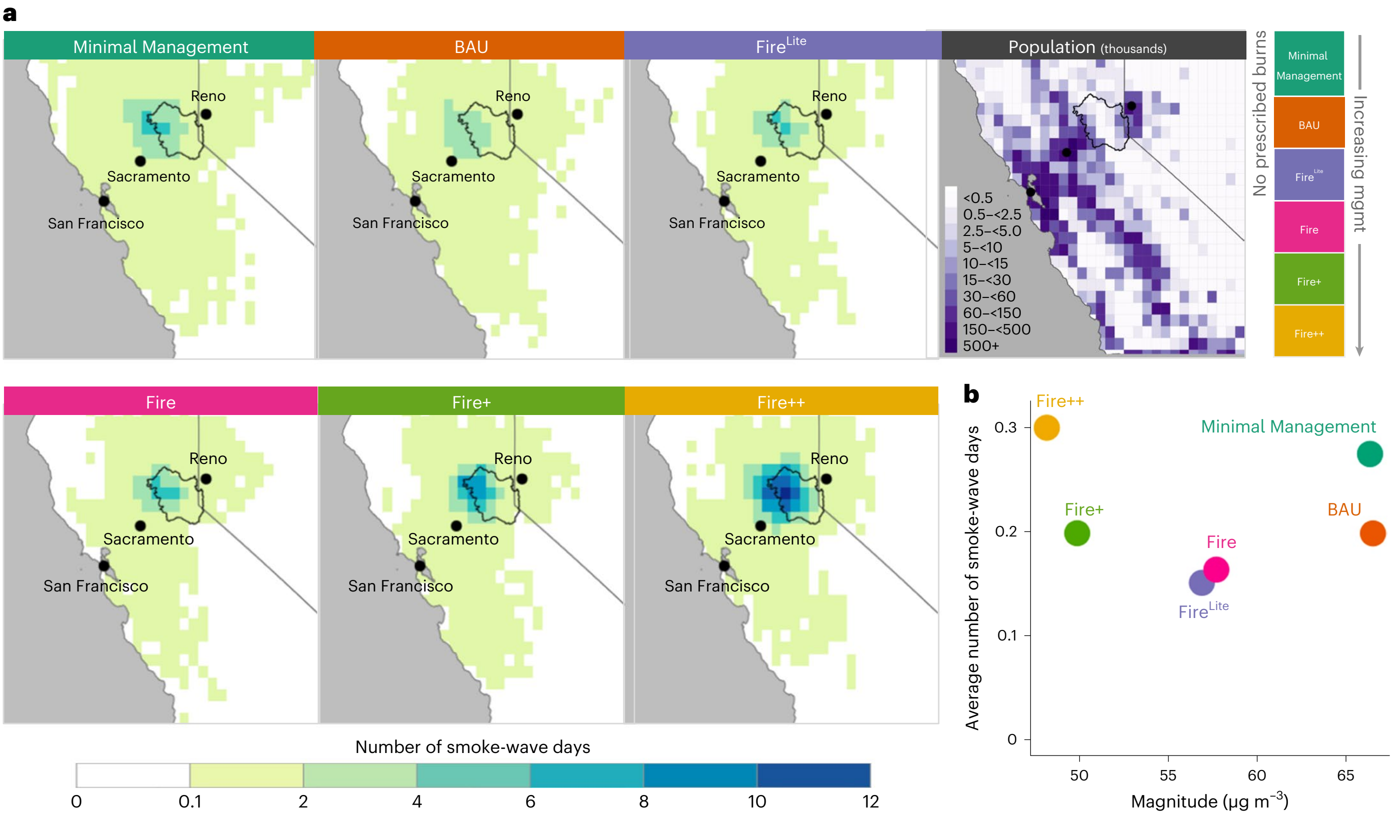

Fig. 4 | Smoke wave impacts. a, Average number of smoke-wave days stemming from total smoke per year per grid cell in California and Nevada. Grid-cell-level population count estimates in thousands of people are provided in the top right map panel. The TCSI is the polygon outlined in black on the California–Nevada border. **b**, Average number and magnitude of smoke-wave days per year per grid cell stemming from total fire smoke (smoke from wildfire and prescribed burns).

Forest management and public health benefits

Compared with the BAU scenario, estimated asthma-related hospitalizations and emergency department (ED) visits were lower under all scenarios with increased management (Fig. 5). Relative to BAU, the greatest health impact reduction for both outcomes occurs under the Fire^{Lite} and Fire scenarios, in which modest levels of prescribed burning are applied to the landscape. For both asthma-related hospitalizations and ED visits, the magnitude of the health benefits levels off as more smoke is emitted through prescribed burning. This trend is similar to that observed in our analysis of smoke-wave days, indicating a favourable scenario in regard to health co-benefits where enough prescribed burning is applied to the landscape to mitigate wildfire smoke exposure risk but not enough to substantially increase prescribed burn-specific smoke exposure risks and subsequent asthma-related health impacts.

Figure 6 shows the spatial distribution of the relative difference from BAU in health impacts under each management scenario at the county level, normalized by population. While reductions in asthma-related health outcomes are minimal in most counties under scenarios with increased management, we find notable benefits in counties closer to the TCSI and with higher pre-existing rates of these asthma-related outcomes. For example, we estimate that in Sacramento County, which sees an average baseline rate of 64.5 asthma-related ED visits and 6.4 asthma-related hospitalizations per 10,000 residents per year, we would expect a reduction of 0.6 hospitalizations and 0.05 ED visits per 10,000 residents per year under the Fire scenario versus BAU. Importantly, as prescribed burns increase to the amount called for under the Fire++ scenario, asthma-related hospitalizations increase by 0.02 and ED visits increase by 0.18 per 10,000 residents relative to BAU in Butte County, which lies directly northwest of the TCSI boundary (Fig. 6).

Discussion

There is growing interest in addressing the human health and well-being impacts from wildfire smoke. The public health sector has traditionally relied on risk communication and individual-level exposure reduction interventions to mitigate adverse health impacts from wildfire smoke. Those interventions focus on downstream behaviour change instead of addressing the source of exposure. Discussions regarding the merits and risks of forest restoration practices, such as prescribed burning and mechanical thinning, have emerged in recent years[1,23]. Yet little work has quantified to what extent such practices could benefit public health goals. We provide an integrated framework for evaluating how forest restoration practices can impact air pollution exposures and human health outcomes, such as asthma, using a case study from Central Sierra, California. We find that forest management activities can reduce overall exposure to smoke-related air pollution and associated health impacts in nearby communities. We chose to focus on the Central Sierra, California, because it is an area that is under active management where stakeholders are interested in managing the landscape for improving forest and fire ecology and human health and well-being goals. The scenarios themselves were previously developed with stakeholder input and represent actual management options under consideration rather than hypothetical scenarios with no basis in existing policy or practice.

Our results indicate that of the six scenarios under consideration, the Fire^{Lite} and Fire scenarios, which introduce moderate amounts of prescribed burn treatments, provide the largest benefit of mitigating future wildfire smoke exposure (0.41 μg m^{-3} population-weighted 40 yr average under Fire^{Lite} compared with 1.8 μg m^{-3} under BAU) while minimizing the contributions of prescribed burns to ambient smoke exposures (0.31 μg m^{-3} population-weighted 40 yr average under Fire^{Lite} compared with 0.68 μg m^{-3} under Fire++). We found that increasing

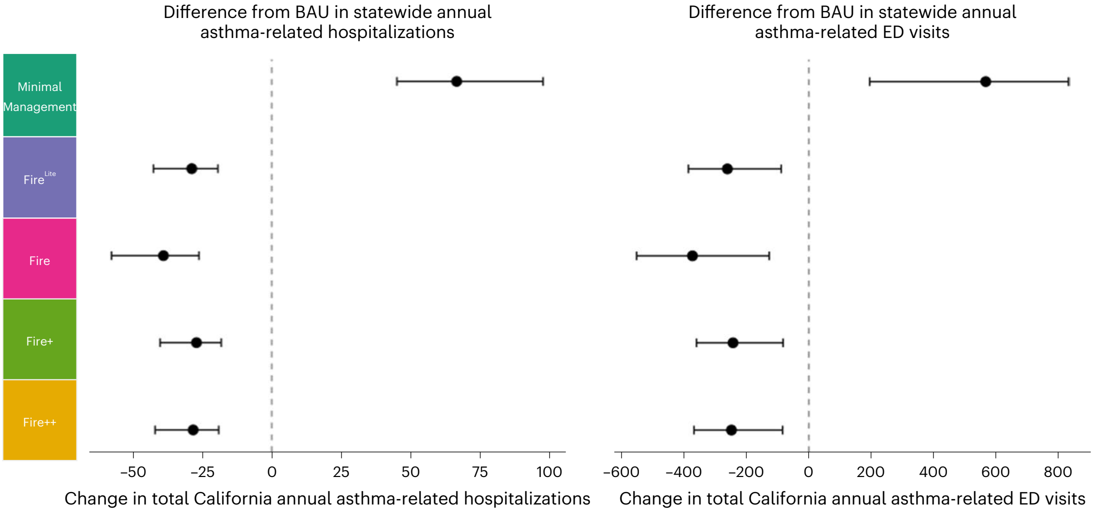

Fig. 5 | Statewide health impacts. Average change in annual state-wide asthma-related hospitalizations and asthma-related ED visits relative to BAU. The error bars represent the change in annual asthma-related hospitalizations and ED visits relative to BAU calculated using the 95% confidence interval of the relative risk reported in ref. 54.

management above BAU results in approximately a month shorter wildfire smoke season, which could help combat rising resource demands within the forest management sector linked to lengthening wildfire seasons in California[48]. Differences in the total magnitude and duration of smoke exposures may be particularly important in California's Central Valley, the state's most productive agricultural region, in which harvest of many crops intersects with peak wildfire season. Not only could lower wildfire smoke levels reduce the dose of $PM_{2.5}$ experienced by workers, which is often already higher than the general population due to time spent outside and higher respiration rates due to exertion, but the shortened wildfire smoke season could also reduce the duration of worker exposures, particularly for those who work later into the fall (Fig. 3a). We found that as the amount of prescribed burning increases to the amounts called for under the Fire+ (6,681 ha yr^{-1}) and Fire++ scenarios (12,408 ha yr^{-1}), smoke from the fuel treatments may have diminishing returns on the assessed health outcomes relative to the BAU scenario (Figs. 5 and 6). Importantly, under all metrics evaluated, the Minimal Management scenario, which calls for less management than is currently implemented, resulted in worse smoke exposure levels and associated health impacts (70 additional asthma-related hospitalizations and 582 additional asthma-related ED visits per year) (Figs. 5 and 6). This highlights the importance of some degree of baseline fuels treatment in mitigating wildfire and smoke impacts. While we found the middle-tier scenarios (Fire$^{\text{Lite}}$ and Fire) can reduce exposure and provide health co-benefits (261–371 fewer asthma-related hospitalizations and 29–38 fewer ED visits across California per year), decision-makers must also evaluate which scenarios can achieve forest management objectives, climate mitigation goals, conservation objectives and other priority considerations. Multiobjective evaluation is a clear next step in evaluating forest management scenarios, as other scenarios may look more favourable when examining these other outcomes[49–53].

Our integrated framework provides a roadmap that could be applied to other fire-prone landscapes where efforts to revive natural fire regimes are under consideration. While other management planning efforts have relied primarily on metrics related to wildfire risk, wildlife management, wildland–urban interface (WUI) protections, water quality management and other considerations to evaluate the efficacy of proposed management strategies, our framework presents an opportunity to add an additional metric of evaluation: the public health impacts of proposed forest and fire management activities[16,32]. To achieve this, we developed methods to link outputs from ecological and air-quality models with population and epidemiological data, which all rely on different sets of assumptions and are presented at varying spatiotemporal scales. This approach allows for the examination of not only prescribed burn impacts on air quality and health, but also the impacts of those fuel treatments on future wildfire occurrence and behaviour and downwind smoke impacts. This incorporation of smoke-related public health considerations into planning efforts opens the door to the development of more equitable and effective forest management interventions that restore natural fire regimes while simultaneously improving the air quality and health of surrounding communities.

Like all model-based studies, our methodological framework and analysis are constrained by existing data and models, including the assumptions and associated uncertainties of those models. For example, our approach considers only primary $PM_{2.5}$ and does not consider other pollutants or the role of atmospheric chemistry in the formation of secondary $PM_{2.5}$. Acknowledging the weaknesses of each individual model component, we present a framework that integrates methods from multiple disciplines and establishes a blueprint for future applications that could incorporate improvements to the specific models used here or the use of more complex models, which may provide, for example, more-accurate representations of chemistry and transport.

We evaluated the impacts of these scenarios under historical conditions; however, recent studies have shown that extensive management alone will not be sufficient to achieve sustainable forest management objectives given the projected impact of climate change on future forest and fire conditions[53]. Future work should examine the combined effects of future climate and forest management activities to holistically evaluate potential impacts on air quality and public health. Use of effect estimates from the current epidemiological literature, in this case relative risk estimates from a meta-analysis by ref. 54, applies the assumption that the characteristics of the exposed population and landscape are the same as those from the studies from which the effect estimates were derived. Our analysis focused on asthma-related health outcomes because the wildfire smoke impact on these outcomes has been relatively consistent across geographies[55,56]. Our results may be sensitive to our selection of health outcomes, and future health impact assessments of forest management plans may consider evaluating additional outcomes. Our analysis does not consider the impacts of co-exposures, such as anthropogenic sources of air pollution, smoke

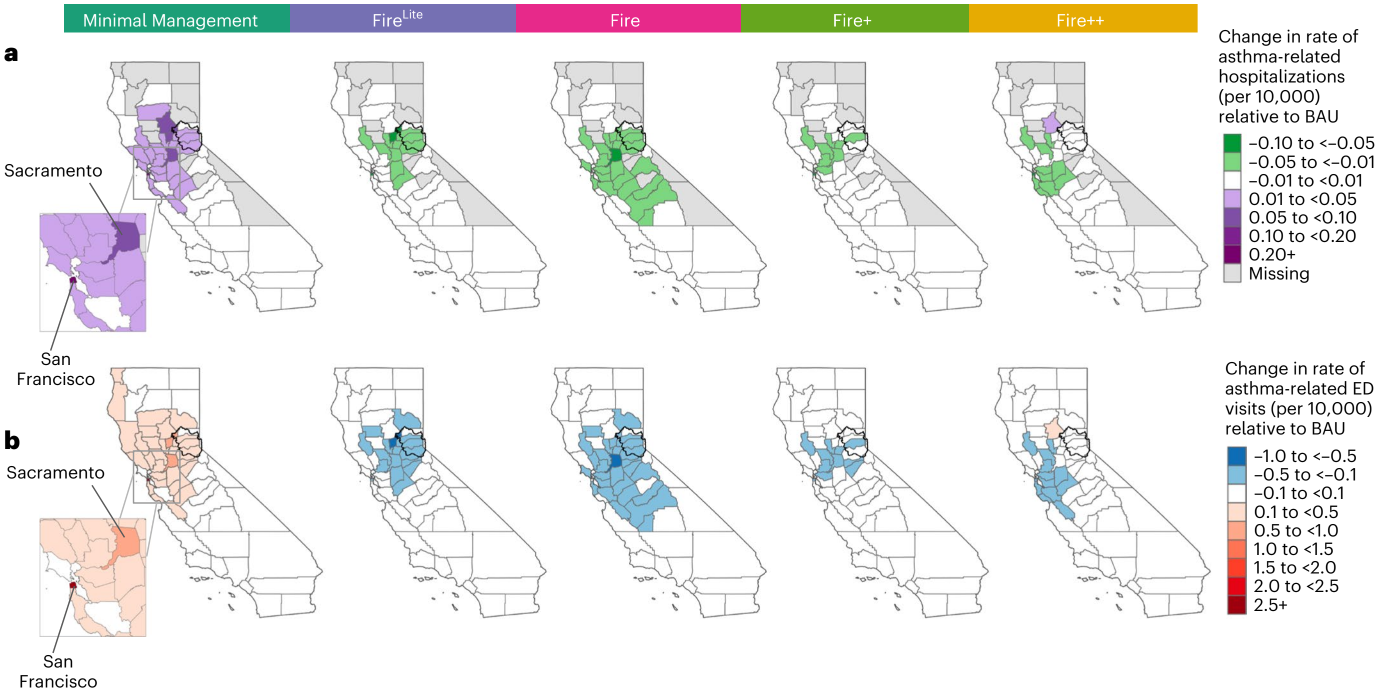

Fig. 6 | County-level health impacts. a, Change in county-level asthma-related hospitalizations per 10,000 residents relative to BAU. Missing values indicate suppressed baseline incidence data in accordance with California Health and Human Services Data De-identification Guidelines. **b**, Change in county-level asthma-related ED visits per 10,000 residents relative to BAU. The TCSI is the polygon outlined in black.

from fires outside the TCSI and extreme heat exposure, on the health of impacted populations. These co-exposures may contribute to uncertainties in our total exposure estimates and/or modify the concentration–response relationships used to estimate health impacts in this study.

Given recent policy shifts, it is likely that more attention and resources will be allocated towards ramping up fuel treatments across the western United States[14–16]. As forest managers start to develop more aggressive and longer-term management strategies at the local, state, and regional levels, it will be critical to integrate public health considerations into planning efforts. D'Evelyn et al.[15] initiated an important communication channel between researchers and practitioners across the public health and forest and fire management sectors to begin to establish common goals and collaboration strategies[15]. Following that effort, our methodological framework and case study provide a grounded approach to further bridge the public health and forest management sectors within actual management planning discussions. Through its application in the Central Sierra, we found the greatest smoke exposure reduction and health co-benefits under management scenarios with moderate amounts of prescribed burning. For the specific scenarios evaluated, the exposure and health benefits tapered off as more prescribed burning was applied to the landscape. While these results are not necessarily generalizable to other geographies due to specific ecosystem characteristics, our modelling framework is flexible and agnostic to the needed advances in models outlined in the preceding and can be adapted to other landscapes and other existing models to estimate smoke emissions and dispersion patterns. Accelerating our understanding of whether and how ecological and public health objectives can be achieved through active forest management is urgently needed to realize a resilient and sustainable future in fire-prone landscapes.

Methods

Overview

We employ an interdisciplinary, multi-step modelling framework (Fig. 2) that links forest management scenario development, emissions estimates generated by a landscape forecasting model, air pollution modelling and health impact estimation to evaluate the exposure and health impacts of the proposed management strategies. We simulate the exposure and health impacts of each scenario from 1981 to 2020. We chose a historical period instead of simulating scenario implementation into the future because of limitations and large uncertainties in future meteorological data availability, specifically future wind conditions required by both models used in this analysis.

Study area

Management scenarios were developed for 978,381 ha in the Sierra Nevada ecoregion around Lake Tahoe called the TCSI. Forest types range from low-elevation oak woodlands (*Quercus* spp.) to high-elevation montane conifers (*Abies* spp. and *Pinus* spp.). The region was largely spared from the megafires from the 2020 and 2021 fire seasons and from the insect outbreaks and drought that contributed to the mass mortality event across the Sierra Nevada between 2012 and 2017. Most of the land area (~68%) is within the National Forest system, of which 41% is within 2.4 km of houses or other buildings (the WUI). Privately owned production forests cover about 14% of the land, of which 11% is within the WUI.

Management impacts on emissions were tracked within the TCSI; however, because emissions can be transported substantial distances downwind, plumes were tracked across California and Nevada. Plume patterns impacted primarily regions to the west of the treatment landscape. Therefore, exposure levels were calculated only for impacted areas of western Nevada and California for the purposes of this case study. Supplementary Fig. 4 shows the domain for which population-weighted $PM_{2.5}$ concentrations and smoke-wave metrics were estimated on the basis of the maximum extent of smoke plumes stemming from the TSCI under all scenarios and state boundaries.

Scenarios

A consortium of land managers from various agencies and researchers co-developed six forest management scenarios[53]. The TCSI is made up of seven management zones, including private industrial and non-industrial land, WUI defence zones (400 m from structures and evacuation routes), WUI threat zones (2,000 m out from defence zone), general forest (forests within the National Forest system that are potentially treatable), roadless areas (forests within the National Forest system that can be treated but cannot have roads in them) and wilderness areas (reserve areas that are legislatively protected)[57]. Each management scenario varies in the extent and pace of thinning and prescribed burning applied to each zone. In the lowest-level management scenarios (Minimal Management and BAU), only private lands and WUI defence zones are treated using only mechanical thinning. In the BAU scenario, treatments include everything from the Minimal Management scenario plus mechanical treatments in the WUI threat zone. Prescribed burning is introduced in the middle-tier scenarios (Fire$^{\mathrm{Lite}}$, Fire and Fire+), applied modestly in general forest zones (5% prescribed burning, 95% thinning) and roadless zones (20% prescribed burning, 80% thinning). In the Fire, Fire+ and Fire++ scenarios, prescribed burning is introduced in threat zones (20% prescribed burning, 80% thinning) and is increased in the general forest and roadless zones under the Fire++ scenario (30% prescribed burning, 70% thinning). Figure 1 provides an overview of the rate and amount of each treatment type applied to the landscape each year under each scenario.

Landscape forecast modelling

Forest change in the region was simulated using the LANDIS-II landscape change model[58], which simulates forests as individual species-age cohorts within a grid of interacting cells, allowing spatial interactions among processes (for example, management, growth and succession, and disturbance) through time over large areas. Individual species-age cohorts compete for resources (for example, soil moisture, nitrogen and growing space) within each cell. Forest succession was simulated, as well as landscape carbon dynamics, using the Net Ecosystem Carbon and Nitrogen (NECN) succession extension (v.6.6)[59]. NECN simulates above- and below-ground processes, such as tree growth (as a function of age, climate and competition for available water and N) and decomposition (which is based on the CENTURY soil model)[59,60]. Model inputs and parameters were based on a suite of forest inventory, satellite data and literature sources. Soil data were from a gridded SSURGO product of California[61], with duff, litter and deadwood layers derived from interpolated Forest Inventory and Analysis data[62]. Initial communities were derived from Forest Inventory and Analysis plots that were interpolated using a k-nearest neighbours algorithm and updated to the year 2019 using remote sensing. We simulated 36 tree species and 3 shrub functional groups that were derived from literature sources[63–65].

The climate data fed to the LANDIS-II model were a combination of gridMET 2 m temperature, precipitation and relative humidity values and wind speed and direction values from the Weather Research and Forecasting (WRF) Advanced Research Weather and Forecasting (ARW) archived 27 km dataset that were resampled to the ecoregions used in the model[66]. The model was run for 1981–2020 with ten replicates of each management scenario to capture stochastic variation in disturbances and management. We divided the landscape into a 180 m (3.24 ha) grid. Wildfire was simulated within the model using the SCRPPLE extension on the basis of human- or lightning-caused ignition events, fuels derived from the NECN extension, topography and fire-weather conditions[67]. The number of prescribed burns called for under each scenario are carried out on selected burn days determined by meteorological constraints intended to reflect burn-day conditions used in the practice settings (constraints pertaining to wind speed, Canadian Fire Weather Index, temperature and humidity conditions). A more detailed description of the LANDIS-II component of this analysis, including the simulation of wildfire and fuel treatments within the model, can be found in ref. 46. Daily $PM_{2.5}$ emissions were estimated for each simulated wildfire and prescribed burn using burn area and fuel consumption estimates during the flaming and smouldering phases derived from the LANDIS-II output. Fuel consumption in the model is a function of fire severity, which depends on species, age and cell-level fire intensity. We utilize wildfire and prescribed burn-specific emissions factors in ref. 68. For the purposes of this analysis, we do not consider emissions stemming from machinery operations during mechanical fuel treatments. All model parameters, and the model and extension versions used, are available on GitHub[69].

Dispersion modelling

We modelled dispersion patterns of the gridded emissions estimates using the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)[70]. We used 27 km meteorological data from the WRF-ARW archived dataset as the meteorological inputs for the model. Emissions estimates from LANDIS-II were inputted into HYSPLIT as 4 ha area sources, with total emissions estimates distributed equally across the area. Emission releases for both wildfires and prescribed burns began at 6:00 LT, with wildfires burning for 11 h and prescribed fires burning for 6 h, based on release durations used in previous work[71,72]. Emissions were released uniformly throughout the release duration, with hourly emissions rates calculated as the LANDIS-produced emissions rate divided by the total burn duration for each fire type. Plume rise was calculated within HYSPLIT on the basis of estimates of fire heat release derived from flaming and smouldering fuel consumption estimates from LANDIS-II, using the Briggs equation, which is commonly used in HYSPLIT-based modelling frameworks such as BlueSky[73–75]. While plume rise can play an important role in plume dispersion patterns, previous work comparing surface $PM_{2.5}$ concentrations under different plume rise schemes (Briggs, Freitas and Sofiev) identified good agreement across schemes, with greater near-source differences in $PM_{2.5}$ relative to downwind and some variability across fire types and sizes[71,72,76]. Thus, given the coarse 27 km resolution of our HYSPLIT modelling domain, we elected to use the default Briggs plume rise scheme. Given the limited ability of HYSPLIT to accurately characterize the complex evaporation and oxidation properties that contribute to secondary aerosol formation within smoke plumes, we assume all $PM_{2.5}$ in the model is primary. In addition, previous work has documented that as smoke plumes age and more secondary aerosols are formed, change in total organic aerosol approaches zero[77,78].

The top of the HYSPLIT model domain (upper limit of meteorological grid) was set to the default height of 10,000 m. The concentration output grid was set to 27 km to match the WRF meteorological input grid. The total spatial extent spanned the 11 western states. Smoke concentrations were averaged at each grid point over 24 h. The number of particles released per emissions cycle was set to 2,500, with the maximum particle lifetime set to 15 days after release. Each management scenario was simulated in LANDIS-II ten times, producing ten replicates, which were all inputted into HYSPLIT. Ensemble mean dispersion distributions were generated for each scenario and used to calculate exposures.

Calculating particle dispersion across six management scenarios, each with ten replicates over 40 yr, requires numerous HYSPLIT simulations with different input and parameter set-ups. To reduce computation time and the need to re-parameterize the model by hand for each simulation, we developed a batch processing script, which allows the user to automate the generation of the HYSPLIT input files and run multiple simulations in parallel[79]. All analyses were carried out in Rstudio version 4.1.2.

Calculating exposure

Population-weighted smoke concentrations at the HYSPLIT grid-cell level were calculated using the following equation:

$$(\text{Population} - \text{weighted exposure level})_{\text{PM2.5}} = \frac{\sum(P_i \times C_i)}{\sum P_i}$$

where P_i is the population of a given grid cell, obtained from 2010 NASA Socioeconomic Data and Applications Center 1 km gridded population dataset[80], aggregated to our HYSPLIT output grid, and C_i is the concentration. For the county-level health impact analysis, we generated an area average weighted concentration of $PM_{2.5}$ for each county by calculating the ratio of the total county area to the area of each grid cell that falls within the county. We then calculated the concentrations for each county by taking the sum of the concentration of each grid cell multiplied by the area ratio[81].

Smoke-wave definition

We define a smoke wave as at least two consecutive days of total smoke $PM_{2.5}$ ($PM_{2.5}$ from both wildfires and prescribed burns) greater than 12 µg m^{-3}, which is the threshold between 'good' and 'moderate' air quality under the Environmental Protection Agency's (EPA';s) Air Quality Index. We chose this threshold because air pollution concentrations within the moderate range may pose a risk to those who are particularly susceptible to air pollution exposures, according to the EPA[82]. It is important to note that $PM_{2.5}$ concentrations reported in this study do not include contributions from sources outside of biomass burning within the TCSI such as anthropogenic sources and smoke from fires that may occur outside of the TCSI landscape. Therefore, these concentrations are probably underestimates of total $PM_{2.5}$ exposure.

Calculating health impacts

Changes in county-level asthma-related hospitalization and ED visits (ΔY) resulting from each of the scenarios were calculated using EPA's Environmental Benefits Mapping and Analysis Program health impact equation:

$$\Delta Y = Y_0 \times (1 - e^{-\beta \Delta \mathrm{PM}}) \times \mathrm{Pop}$$

where Y_0 is the baseline incidence, β is the effect estimate derived from the existing literature, ΔPM is the change in $PM_{2.5}$ concentration and Pop is the total exposed population. Effect estimates were derived from the meta-analysis of wildfire smoke-specific asthma-related health outcomes in ref. 54. Asthma-related outcomes were chosen because the effect estimates are most robust across the wildfire smoke epidemiological literature (including across geographies) relative to other outcomes[54,56]. Health outcomes are calculated for California only and not surrounding states due to lack of data availability for the specific outcomes of interest. Baseline asthma-related hospitalization and ED visit rates for California counties from 2015 to 2019 were acquired from the California Department of Health and Human Services. County-level rates were averaged across the five years of available data. The 2020 county-level population data were acquired from the US Census Bureau. Although our simulated smoke-specific $PM_{2.5}$ data go back to 1981, population data from 2020 were used because these scenarios are under consideration on the current landscape, potentially impacting the current population now and into the future. To capture uncertainties in the meta-analysis effect estimates, we also calculated the change in health outcomes using the confidence intervals of the effective estimates derived from ref. 54.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The HYSPLIT output data that support the findings of this study are available at https://doi.org/10.5061/dryad.sqv9s4n9d. Publicly available population data in gridded format were accessed via the Socioeconomic Data Applications Center (SEDAC) (https://doi.org/10.7927/H4JW8BX5) and at the county level via the US Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2020.html#list-tab-790442341). Asthma-related baseline health data were accessed via the California Department of Health and Human Services (hospitalization data: https://data.chhs.ca.gov/dataset/asthma-hospitalization-rates-by-county; emergency department visits: https://data.chhs.ca.gov/dataset/asthma-hospitalization-rates-by-county).

Code availability

The HYSPLIT parallel processing code can be found via https://doi.org/10.5281/zenodo.10064195.

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Author contributions

C.M. carried out the LANDIS-II modelling. C.L.S. carried out the HYSPLIT modelling, exposure and health impact analysis. C.L.S. wrote the paper. C.L.S., J.J., J.W., E.A., J. Baumgartner, J. Brun, T.B.I., J.M.L., M.E.M., J.D.M., Y.J.M., C.M., C.W.T., K.N.W., N.H.W. and J.T.S. contributed to the development of the paper through methodological advice, guidance on analysis, comments and edits to the text and figures.

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Competing interests

The authors declare no competing interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	Emissions data were generated using the LANDIS-II (v7) landscape forecasting model with the SCRPPLE fire extension (v3.3). Dispersion modeling was carried out using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model version 5.0.0. HYSPLIT batch processing script can be found via DOI 10.5281/zenodo.10064195.
Data analysis	Data analysis was carried out in RStudio version 4.1.2

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The data that support the findings of this study are available here: https://doi.org/10.5061/dryad.sqv9s4n9d. Publicly available population data in gridded format were accessed via the Socioeconomic Data Applications Center (SEDAC) (https://doi.org/10.7927/H4JW8BX5) and at the county level via U.S. Census Bureau (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2020.html#list-tab-790442341). Asthma-related baseline health data were accessed via the California Department of Health and Human Services (hospitalization data: https://data.chhs.ca.gov/dataset/asthma-hospitalization-rates-by-county; Emergency department visits: https://data.chhs.ca.gov/dataset/asthma-hospitalization-rates-by-county).

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Reporting on sex and gender	This information has not been collected
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Study description	We employ an interdisciplinary, multi-step modeling framework that links forest management scenario development, emissions estimates generated by a landscape forecasting model, air pollution modeling, and health impact estimated to evaluation the exposure and health impacts of the six forest management strategies proposed for 2.4 million acres in the Central Sierra region of California. We simulated the PM2.5 exposure and health impacts of each management scenario from 1981-2020 using HYSPLIT and the health impact function derived from EPA's BenMAP tool.
Research sample	Smoke exposure were estimated for the general population of California and western Nevada using gridded population data from SEDAC.
Sampling strategy	Daily smoke concentrations were estimated for a 40 year period (1981-2020), based on existing emissions input data provided by a collaborating landscape ecology modeling team.
Data collection	Smoke data were modeled using HYSPLIT
Timing and spatial scale	Emissions estimates from LANDIS-II were inputted into HYSPLIT as 4 ha area sources, with total emission estimates distributed equally across the area. Particle dispersion was estimated across a 27k km grid. Emission releases for both wildfire and prescribed burns began at 6:00AM, with wildfires burning for 11 hours and prescribed fires burning for 6 hours. Hourly emissions rates were calculated as the LANDIS-produced emissions rate divided by the total burn duration for each fire type. The top of the HYSPLIT model domain (upper limit of the meteorological grid) was set to the default height of 10,000m. The total spatial extent spanned the 11 western states. Smoke concentrations were averaged at each grid point over 24 hours. The number of particles release per emissions cycle was set to 2500, with ten maximum particle lifetime set to 15 days after release. Each management scenario was simulated in LANDIS-II 10 times, producing 10 replicates, which were all inputted into HYSPLIT. Ensemble mean dispersion distributions were generated for each scenario and used to calculate exposures.
Data exclusions	No data was excluded from the analysis.
Reproducibility	Emissions estimates were generated within LANDIS-II for 10 replicates of each scenario. Dispersion patterns for those 10 replicates were then modeled in HYSPLIT.
Randomization	Randomization is not relevant to out study because it is a descriptive ecological study design.
Blinding	Blinding is not relevant to our study because data were statistically modeled and note experimentally collected in the field or in a clinical setting.

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