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Climate change greatly escalates forest disturbance risks to US property values

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Abstract

Anthropogenic climate change is projected to drive increases in climate extremes and climate-sensitive ecosystem disturbances such as wildfire with enormous economic impacts. Understanding spatial and temporal patterns of risk to property values from climate-sensitive disturbances at national and regional scales and from multiple disturbances is urgently needed to inform risk management and policy efforts. Here, we combine models for three major climate-sensitive disturbances (i.e., wildfire, climate stress-driven tree mortality, and insect-driven tree mortality), future climate projections of these disturbances, and high-resolution property values data to quantify the spatiotemporal exposure of property values to disturbance across the contiguous United States (US). We find that property values exposed to these climate-sensitive disturbances increase sharply in future climate scenarios, particularly in existing high-risk regions of the western US, and that novel exposure risks emerge in some currently lower-risk regions such as the southeast and Great Lakes regions. Climate policy that drives emissions towards low-to-moderate climate futures avoids large increases in disturbance risk exposure compared to high emissions scenarios. Our results provide an important large-scale assessment of climate-sensitive disturbance risk to property values to help inform land management and climate adaptation efforts.

1. Introduction

Climate hazards are already having enormous economic impacts around the world and are expected to grow more frequent and severe in the 21st century due to climate change [1–3]. Hazards fueled by climate change such as droughts, floods, and wildfires can damage a wide range of physical infrastructure and its associated worth, including property values [2, 4, 5]. A broad body of literature has quantified the risks of some climate hazards, notably heatwaves, hurricanes, and floods, to the economy and infrastructure, typically at small spatial scales such as individual cities or regions [6]. Large-scale, systematic assessment of multiple categories of climate hazards and the property value exposed to these hazards is lacking. Understanding economic risks posed by climate hazards and how they vary in space and time in the 21st century is crucial for risk management, climate adaptation, and policy.

Climate change is a major driver of forest disturbances, particularly wildfire, severe drought- or climate stress-driven tree mortality, and insect-driven tree mortality [7–9], which can have large human and economic impacts [5, 10–13]. For example, the severe 2018 wildfire season in California triggered an estimated $150 billion (USD) in impacts, equivalent to 1.5% of California's annual gross domestic product, through a range of both direct and indirect pathways [10]. Capital losses from wildfire contributed around

20% of the total damages [10]. Non-fire, climate-sensitive forest disturbances can also impact property values. For example, the severe mountain pine beetle outbreak in Colorado had substantial impacts on property values both where trees died on given properties and, crucially, also when trees died within buffer zones around given properties [14].

Climate-sensitive forest disturbances of wildfire and tree mortality in the United States (US) are very likely to increase in the 21st century [8, 9, 15, 16]. Wildfire studies estimate increases of 50% to >400% of average area burned in the western US in the 21st century depending on climate scenario, climate model, and fire model [15, 17, 18]. Climate stress-driven tree mortality (e.g. drought-induced mortality) and insect-driven tree mortality are also widely expected to increase in US forests [18–20], although these disturbances are often more challenging to model than wildfire [21]. These predicted increases in climate-sensitive forest disturbances make quantifying exposure risks of projected wildfire and tree mortality on current property values important to inform risk management and policy, including climate policy, forest management, land use planning and fire risk mitigation at the wildland–urban interface.

Climate impacts studies quantify the exposure to given hazards and sometimes the direct economic damages, although these damage functions are currently highly uncertain [5]. While numerous case studies have documented impacts of individual events (e.g. fires, insect outbreaks) by region and/or year (e.g [10, 11, 14]), a systematic risk analysis across all contiguous US property values and multiple climate-sensitive forest disturbances is a critical gap. Here, we leverage high-resolution current maps and future projections of key climate-sensitive forest disturbances—wildfire, climate stress-driven tree mortality, and insect-driven tree mortality—and high-resolution property value maps to conduct a risk analysis for property value at risk from (i.e. exposed to) climate-driven forest disturbances. We ask: (1) what are current (i.e. 2000–2018) spatial patterns of exposure of US property values to fire and tree mortality? (2) How much do future climate scenarios increase risk and exposure of current property values in 2020–2049 and 2070–2099? (3) What are the projected spatial patterns of exposure of these disturbances in future climate scenarios? (4) How much exposure of current property values to disturbance risk can be avoided by following a low-to-moderate climate change scenario compared to a high climate change scenario?

2. Methods

2.1. Climate-sensitive disturbance models

We used recently-published contiguous US-wide estimates of the climate-sensitive disturbances of wildfire, climate stress-driven tree mortality, and insect-driven tree mortality [18]. We describe these datasets and models briefly here (full descriptions available in [18].). The wildfire model was constructed using historical satellite data from the Monitoring Trends in Burn Severity (MTBS [22];) dataset, which provides 30 m-resolution burn area for the contiguous US from 1984-present. This fire model used data from 1984 to 2018 and only included 'moderate' and 'high' severity wildfires in the MTBS dataset. Burn area was modeled at 16 km resolution using a two-part 'hurdle' model that estimated jointly: (i) the presence/absence of a fire in a given grid cell and (ii) the area burned in that grid cell. A hurdle model combines a binomial model to first predict 'did a fire occur' (0 or 1) in a given grid cell for a given month and second, where fires occurred, a more traditional regression model (e.g. linear Gaussian ordinary least squares model) to predict 'how much area was burned' in that grid cell. Predictor variables included monthly temperature, precipitation, and climatic water deficit from the TerraClimate dataset [23] and an intercept (i.e. dummy variable) for each 'forest group'. The fire model was then fit (predicted) at a 4 × 4 km resolution in all analyses.

The climate stress-driven and insect-driven tree mortality models were constructed using historical US Forest Service Forest Inventory and Analysis (FIA) data from long-term inventory plots from 2000–2018. Fire and human/management disturbances were excluded and tree mortality was modeled as a similar hurdle model from a set of six climate predictors, two plant physiological functional trait estimates [24], and stand age as a metric of stand structure [18]. We note that 'climate stress-driven mortality' appears to generally be drought-driven tree mortality, which has been widely documented in the western US (e.g [25–27]), but can include other climate stresses such as severe heat. We also note that 'climate stress-driven mortality' does include insects as a cause of mortality because insect attack frequently co-occurs and is considered a proximal driver of stress-driven mortality in many forest types (see [18] for discussion) and thus these two estimates are partially overlapping and not independent. We do not sum these exposures (i.e. dollar values of property exposed) at any point and thus this non-independence is not an issue in our risk analysis.

All three disturbance models have been extensively cross-validated and compared to independent datasets [18]. The fire model exhibited a cross-validated performance AUC of 0.89 across the entire record (where AUC values of 0.5 are random chance, 1 is perfect prediction, and >0.7 is generally considered strong performance). Historical climate stress-driven tree mortality had a cross-validated R^2 of 0.18 and insect-driven tree mortality had a cross-validated R^2 of 0.31 (where R^2 is the fraction variance explained by the model, thus an R^2 of 0.31 means that 31% of the variance is explained) [18]. We used the averaged modeled burn area and fractional basal area mortality from climate stress and insects over the 2000–2018 period for all analyses (figure 1). We used modeled values rather than raw observations because gaps in the FIA mortality data would preclude assessment of risk in some US states, notably Wyoming where substantial insect-driven tree mortality has occurred since 2000 [28].

These published disturbance models also contained projections in future climate scenarios using downscaled output from six Earth system models from the Coupled Model Intercomparison Project Phase 6 archive that span a range of precipitation and temperature climate space for the contiguous US. Downscaling to 4 km was performed using quantile mapping. We used the projected disturbance from Shared Socioeconomic Pathways (SSPs) 2–4.5 and 3–7.0 to capture a range of future climates. SSP2-4.5 is considered a low-to-moderate climate change scenario and SSP3-7.0 a high climate change scenario [29].

We note a few important limitations of these disturbance projections. First, these disturbance models do not include feedbacks between disturbance and vegetation properties (e.g. combustion of fuels leading to lower fire risk), although these feedbacks have been found to be substantially less important than the climate impacts in other analyses [30], or dynamic changes in vegetation (e.g. shifts in species composition). Second, these projections do not include effects of CO_2 on vegetation stress (e.g. improvements in water use efficiency). These two limitations could lead to overestimates of disturbance prevalence in the 21st century, although we also note there are other missing factors that could lead to underestimates of disturbance prevalence including non-linear impacts of insects and drought stress that are not characterized in the current models, interactions among disturbances, and novel pests and pathogens (see [18] for a full discussion).

2.2. Property value dataset

Our estimates of property values were based on a published, cross-sectional, rasterized (480 m × 480 m resolution) dataset of property-level estimates of fair market value (land + structures) [31]. These estimates were derived from a dataset of approximately 6 million land sales larger than 1 acre occurring between 2000 and 2019 in the contiguous US. The outcome variable—the natural log of 2010 per-hectare sales prices, in real 2017 dollars—is regressed on 29 predictors using spatio-temporal machine learning models (extremely randomized trees). 3108 county-level models were fitted, incorporating data from surrounding counties, as well as more distant counties if data of large vacant sales is locally rare. Fitted models were then deployed to make (out-of-bag) predictions of sales prices in 2010 (the temporal center of the sampling period) for all properties within each county, based on the same 29 predictors. Previous validation with an external dataset of 4029 publicly funded land acquisitions suggests that the resulting estimates capture a large percentage of the variation in the outcome variable ($R^2 = 0.72$) [31].

2.3. Risk and exposure analysis

To analyze spatial patterns in exposure to climate-sensitive disturbances, we first calculated the average disturbance risk, either burn area per year for fire or tree mortality in basal area per year, over the chosen time period (2000–2018 for historical; 2020–2049 and 2070–2099 for future climate SSPs). Burn area was already provided at a 4 × 4 km resolution raster and we rasterized the point data for climate stress-driven tree mortality and insect-driven tree mortality to a $0.25^\circ \times 0.25^\circ$ grid that weighted each forest type's contribution in each grid cell by the sum of its current biomass following previous analyses [18]. We then multiplied the 2010 property value for each grid cell by the disturbance risk maps to derive a continuous estimate of property value exposed that identifies and quantifies spatial patterns in relative risk in the current period (figure 1) and future climates (figure 3). In this calculation, both higher property values and higher disturbance probability/severity increase the visualized 'exposure' metric. The raw units are not important in this particular analysis, as our goal was to calculate relative risks across space. Because data were log-normally distributed, we $\log_{10}$ transformed the exposure metric for visualization.

To estimate the absolute value of property exposed in different climate scenarios and time periods, we chose specific thresholds for 'exposure' for each disturbance (figure 2) and then tested a range of thresholds to estimate the sensitivity (figures S1 and S2). Figure S3 provides regional boundaries for regional calculations. Climate-sensitive disturbances are inherently probabilistic and stochastic, and thus calculation of exposure requires some arbitrary decision of a given severity or probability level over a given period. For fire, our default calculation quantified the exposure of a >5% burn probability over a 30 year period (0.001 667 annual probability) for a moderate or severe wildfire. This threshold was chosen because a 30 year period is a typical time-period for a mortgage and a 5% probability broadly aligned with 'high risk' fire areas in previous analyses [15, 32]. We tested alternate thresholds of >2% and >10% over a 30 year period (figures S1 and S2). For climate stress-driven and insect-driven tree mortality, we chose a severity threshold of 4% basal area killed per year in our default calculation and explored alternate thresholds of 3% and 8% per year (figures S1 and S2). This threshold was chosen because spatial

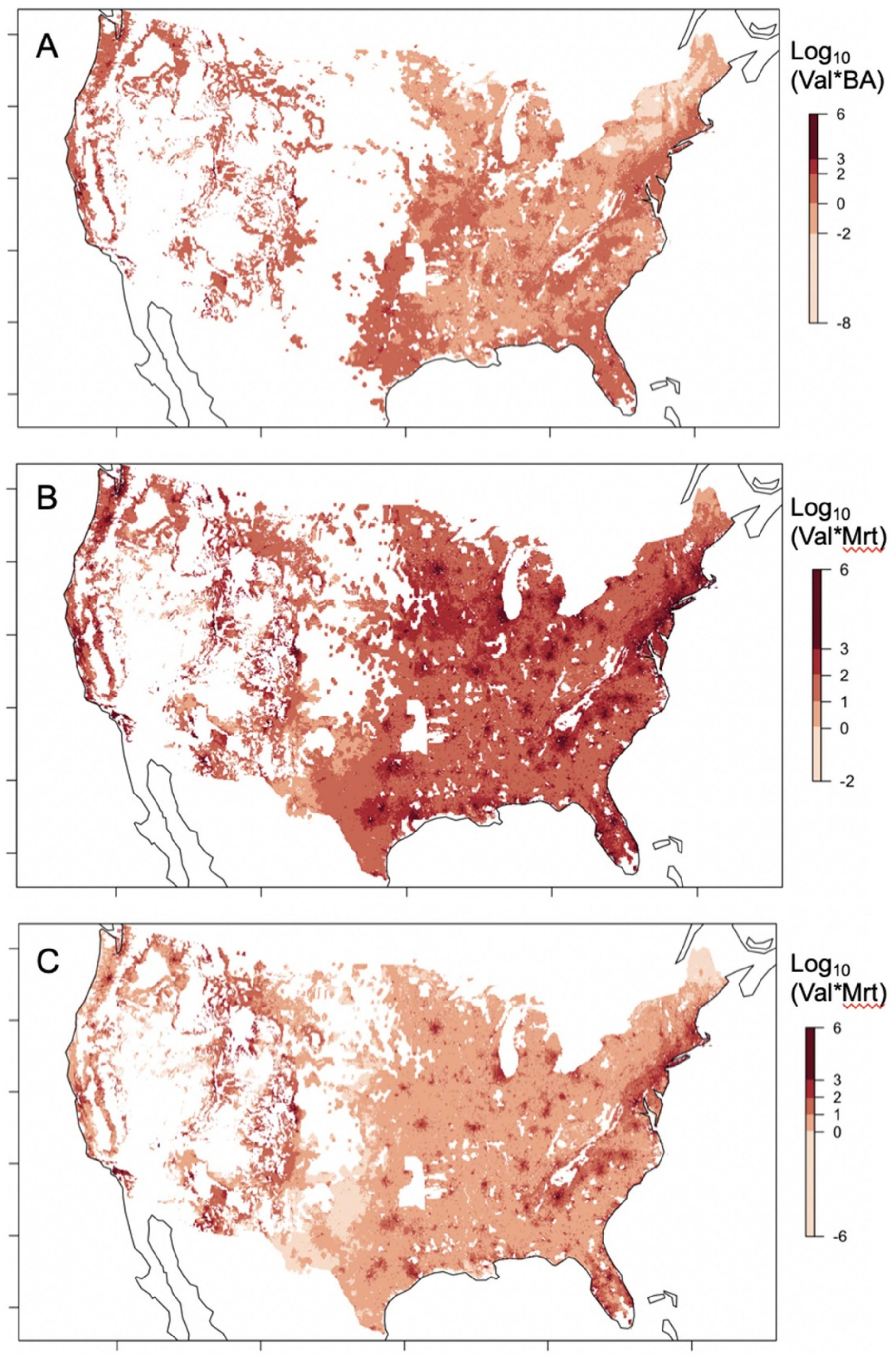

Figure 1. Current property value exposure to fire, climate stress-driven tree mortality, and insect-driven tree mortality. Exposure risk is displayed as the logged product of 2010 property values ('Val'; 2017USD$) multiplied by the average 2000–2018 burn area (BA) by moderate and severe wildfires (A) or the 2000–2018 average fractional basal area tree mortality (Mrt) from climate stress (B) or insects (C). Federal and tribal lands and non-forests are masked out (white).

patterns of mortality at this severity level broadly agreed with other analyses of severe, widespread mortality from other approaches [32, 33]. Because the climate stress-driven and insect-driven mortality projections occur at FIA plots and are thus point-based, we calculated the exposure in a 5 km radius around each point above the given severity threshold. This threshold was based on two lines of reasoning: (i) the spatial autocorrelation for mortality is relatively high across the US (typically 20–50 km in previous analyses [18]) and thus severe stress-driven mortality at a given point is likely indicative of regional mortality that occurs extending around individual points and (ii) the hedonic pricing literature has found substantial impacts on property values up to 10–15 km from severe mortality [5]. Thus, we believe this represents a conservative threshold for calculation of exposure to this disturbance.

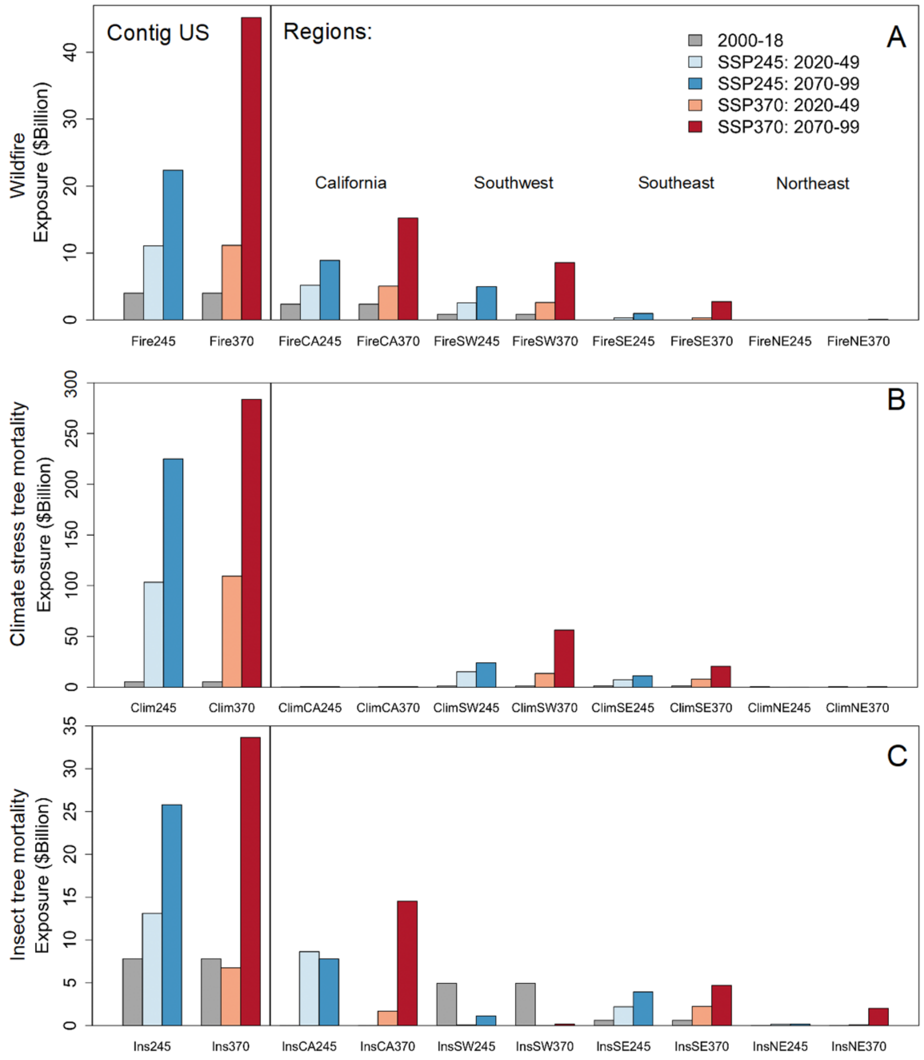

Figure 2. Climate change greatly increases property exposure risk to forest disturbances. Current exposure (gray) and future projected exposure (blue—low-to-moderate emissions SSP 2–4.5; red—high emissions SSP3-7.0) in billion 2017 $ USD for a given disturbance probability or severity threshold. For fire (A), probability threshold is >5% burn probability in a 30 year period. For climate stress-driven (B) or insect-driven (C) tree mortality, severity threshold is 4% annual basal area mortality averaged over a 30 year period. Regions on the right include California (CA), southwestern US (SW), southeastern US (SE), and northeastern US (NE). Note that regional breakouts do not cover the full contiguous US; see figure S3 for regional boundary definitions.

We performed an additional sensitivity analysis to provide a first-order exploration of feedbacks between high disturbance risk and subsequent property values. For SSP3-7.0, we calculated grid cells that exceeded our baseline exposure threshold for each disturbance during the 2020–2049 window. We assumed a 25% decline in property values in these grid cells due to high disturbance exposure, which is on the high end of the hedonic pricing literature [5]. We then calculated the property value exposed in the 2070–2099 period when including this feedback between high exposure and property values compared to the base case without including the feedback (figure S4).

To calculate the reduction in exposure risk between SSP3-7.0 and SSP2-4.5, we calculated the same continuous exposure metric in figure 3 for each climate scenario. We then estimated the percent change in risk for each grid cell of adjusting risk from SSP3-7.0 to that of SSP2-4.5 in the 2070–2099 period, compared to the SSP3-7.0 risk levels as a baseline. For all analyses except figure 3(A) (which does not include property values), we excluded all federal and tribal lands using data from the US Census Bureau's TIGER dataset and US Geological Survey [34]. This assumption leads to an underestimate of the true value exposed to climate risks, but was chosen to provide a conservative analysis and because precise values of non-private land are challenging to estimate. We used the 1 km U.S. Census Grids product to estimate 2010 households exposed in different scenarios [35].

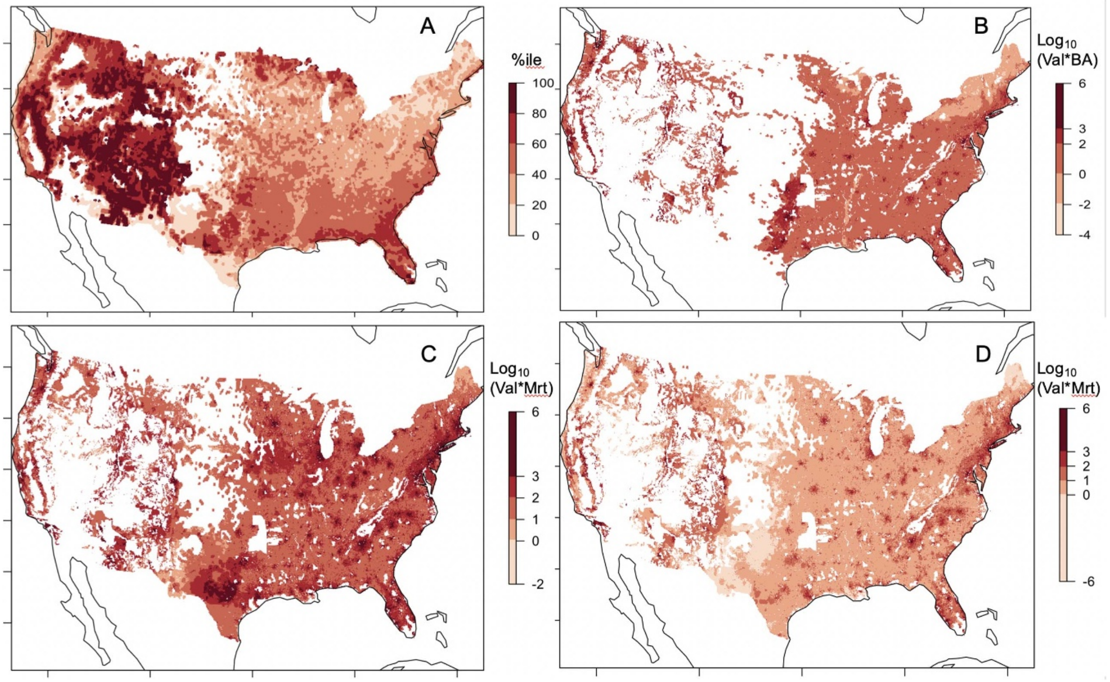

Figure 3. Spatial patterns of climate-sensitive disturbances and property values exposed to climate-sensitive disturbances. (A) Average percentile for wildfire, climate stress-driven tree mortality, and insect-driven tree mortality projected for 2070–2099 in a high climate change scenario (SSP 3–7.0) averaged across six Earth system models. (B) Projected property value exposure risk from wildfire, estimated as 2017 property value (Val) times projected burn area (BA), for the same 2070–2099 window and climate scenario. Projected property value exposure risk from (C) climate stress-driven tree mortality (Mrt) and (D) insect-driven tree mortality, estimated as 2010 property value times projected basal area mortality, for the same 2070–2099 window and climate scenario. Federal and tribal lands and non-forests are masked out (white) in panels (B)–(D).

2.4. Data analyses and code

We used the following packages for analyses: rworldmap [36], raster [37], RColorBrewer [38], and rgdal [39]. All analyses were conducted in the R statistical software [40]. All code used to conduct these analyses can be found at <https://figshare.com/s/a569841df12d71371f19> and all underlying disturbance data at <10.5281/zenodo.4741333> and property value data <https://datadryad.org/stash/dataset/doi:10.5061/dryad.np5hqbzq9>.

3. Results and discussion

We first mapped the current exposure patterns of property values (i.e. fair market value including land and structures; see methods) to the three climate-sensitive disturbances over the 2000–2018 period in the contiguous US by multiplying the modeled burn area for fire or the modeled tree basal area killed by non-fire climate stress or insects by 2010 property values [31]. This provides a continuous metric that captures both the severity of the disturbance and the value of property exposed to the disturbance. California exhibited high current exposure to all three climate-sensitive disturbances (figure 1), which is broadly consistent with extensive damages from wildfire, drought, and insect-driven mortality in the past two decades [10, 25]. Climate stress-driven tree mortality exhibited widely distributed exposure risks to property value across much of the contiguous US (figure 1(B)). Insect-driven tree mortality risks were most prominent throughout the Rocky Mountains and in southern California (figure 1(C)), also widely documented for individual disturbance events in those areas [14, 41].

Leveraging high-resolution downscaled climate projections from six Earth system models that span a range of future temperature and precipitation changes and statistical projections of these three disturbances [18], the 2010 property values exposed to disturbances were projected to escalate dramatically in the 21st century due to climate change (figure 2). For wildfire, property values exposed to a >5% chance of fire within a 30 year (e.g. mortgage-relevant) time period were projected to more than double in 2020–2049 to >\$11 B exposed per year (∼3.3 M households) as compared to the 2000–2018 baseline period (∼\$4 B exposed per year; ∼1.1 M households) in both a low-to-moderate (SSP2-4.5) and a high (SSP3-7.0) climate change scenario. This is likely because large divergences among climate scenarios tend to materialize in the second half of the 21st century [2]. By 2070–2099, the property value exposed was projected to increase ∼5-fold in SSP2-4.5 to >\$22 B/year and ∼10-fold in

SSP3.70 to >$45 B/year (figure 2(A)). Regional patterns showed particularly high levels of property value exposed to future fire risks in California, consistent with one earlier study based on two climate models and a simple fire weather model [16], and the emergence of fire exposure risks to property values in new regions of the US such as the southeastern US (figures 2(A) and 3(B)). Property value exposed to climate stress-driven and insect-driven tree mortality also was projected to rise dramatically in future climates, particularly high emissions scenarios, with highest regional risks projected in the southwestern US (figure 2(B)) and California (figure 2(C)) respectively. For example, property value exposed to climate stress-driven tree mortality rose from ∼1 M households with a combined value of ∼$5 B/year in the current period to ∼29 M households with a combined value of >100 $B/year in the 2020–2049 period for the contiguous US. The absolute amount of property value exposed naturally depends on the disturbance frequency and severity thresholds used, and thus we provide a sensitivity analysis of these values in figures S1 and S2.

To compare spatial patterns of relative risks in future climates, we normalized each projected disturbance into percentiles and calculated the average percentile for risks in the 2070–2099 period in SSP3-7.0. Spatial patterns of these combined climate-driven exposure risks were strikingly similar across the three disturbances (figure 3(A)). California, the southwestern US, and the intermountain (e.g. Rocky Mountain) West were projected to have consistently high risk (figure 3(A)). The eastern US, Texas, parts of the southeast, and the Great Lakes states were projected at consistently relatively higher risk, whereas the Northeast was projected to be at consistently lower risk (figure 3(A)). This percentile map provides one of the first multi-disturbance syntheses at large scales across a range of forest types and disturbances.

We finally estimated the percent reduction in exposure achieved by more ambitious climate policy by comparing the exposure in 2070–2099 in SSP3-7.0 to that of SSP2-4.5 for each climate-sensitive disturbance (figure 4). Risk reduction was most prevalent and strongest for wildfire, although with surprising spatial patterns in the relative reduction (figure 4(A)). All areas of the contiguous US experienced less property value exposed in the low-to-moderate climate scenario, but the highest proportional gains were in fact in northern latitudes, particularly in the Great Lakes states and the Northeast (figure 4(A)). For climate stress-driven and insect-driven tree mortality, much of the US did not exhibit large percent changes in exposure—either slight increases or slight decreases—though there were concentrated decreases in exposure in some key regions (figures 4(B) and (C)). The southwestern US, Texas, and parts of the southeast showed the strongest benefits of reduced exposure to climate stress-driven tree mortality (figure 4(B)). California, the southwestern US, parts of Texas, and parts of the northeast showed the greatest benefits of reduced exposure to insect-driven tree mortality (figure 4(C)).

We estimated here the current contiguous US property values exposed to current and a range of future climate-driven disturbances of fire and tree mortality. While the hedonic pricing literature is not yet able to provide specific continental damage functions of these disturbances, a body of literature highlights that the impacts of these disturbances on property values are often substantial [5]. Reported declines in property values from widespread tree mortality can range from 1% to 15% and fire-driven damages can be higher (3%–23%) depending on a range of factors [11, 12, 14, 42, 43]. We note, however, that our estimates capture only one component of risk (exposure) and the projections calculated here assume constant property values (fixed at 2010 values), and thus do not account for dynamic changes in migration and economics (e.g. population levels and property values at the wildland-urban interface [44]), nor risk mitigation in forests or communities. In a first-order sensitivity analysis testing property value declines following high disturbance exposure levels, we nevertheless observed large increases in property value exposed in future climate scenarios, though 19.6%, 9.6%, and 4.7% less than the base case without any temporal shifts in property values (figures 2 and S4). Future work is urgently needed to examine in more detail the sensitivity and adaptive capacity dimensions of the vulnerability of property values to climate change. Given current trends of increasing property values, this estimate of constant property values provides a conservative projection of exposure to disturbance. The disturbance projections used here also have inherent limitations, as with any model, including lack of dynamic vegetation and fuel feedbacks to fire risk [18]. Nevertheless, our estimates provide useful information for risk management, land management, and policy revolving around risks of climate extremes to US communities.

A broad body of recent literature has aimed to quantify the economic impacts of climate change in the US from a variety of factors [4, 45], but a systematic assessment of the exposure of property values to climate extremes such as fire is an urgent gap. In particular, large-scale assessments across a range of climate scenarios can inform regional and local risk management, for example providing information for insurance estimates or

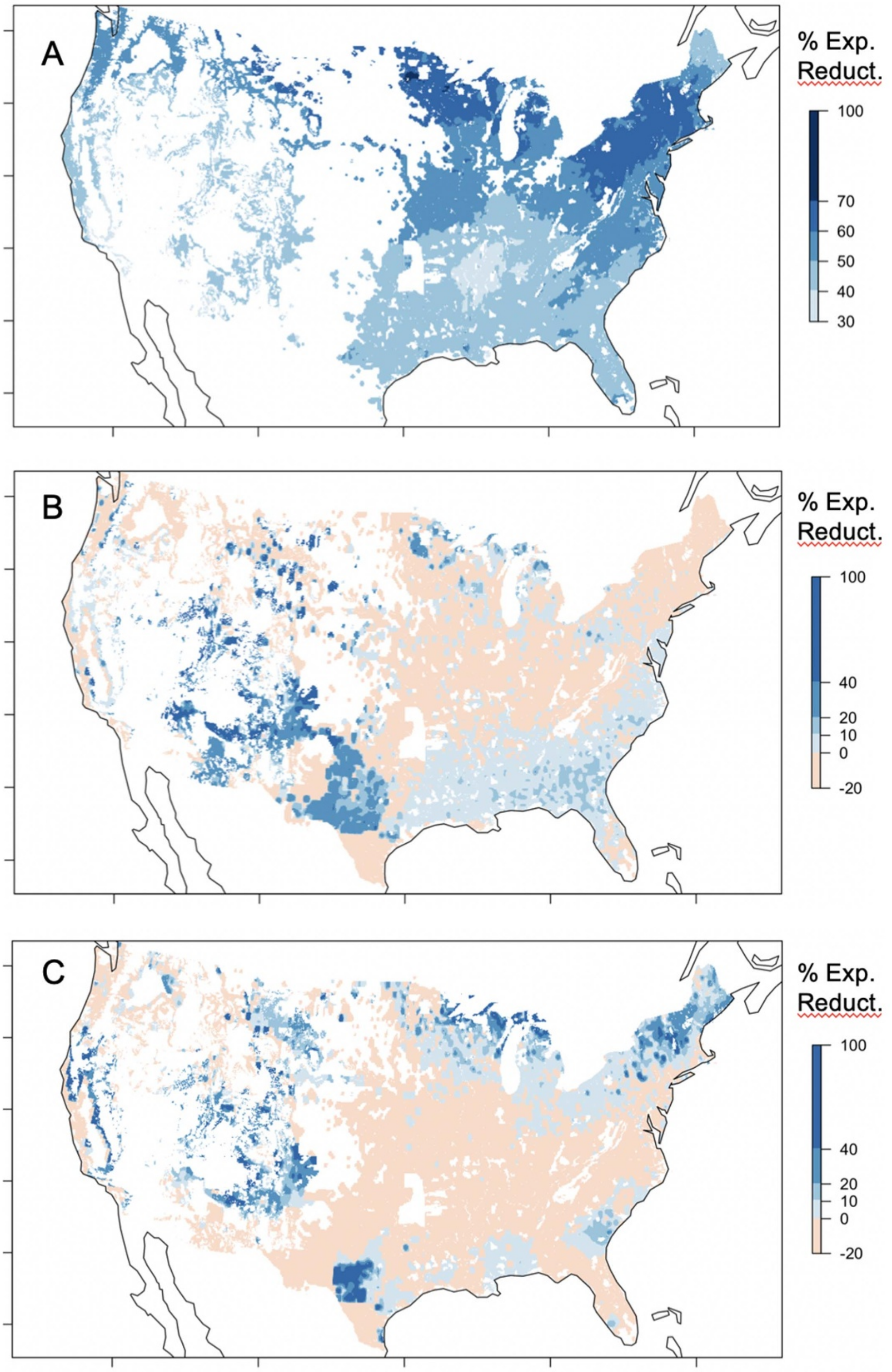

Figure 4. Avoided disturbance exposure risk to US property values between high and low climate scenarios. The percent change/reduction in exposure of 2010 property values of following the low-to-moderate climate scenario (SSP2-4.5) versus the high climate scenario (SSP3-7.0), compared to the high climate scenario baseline for wildfire (A), climate stress-driven tree mortality (B), and insect-driven tree mortality (C). Federal and tribal lands and non-forests are masked out (white).

land management activities such as 'fire hardening', and help governments at all scales prepare for future climate hazards. As evidenced by recent megafires with devastating economic impacts [10], these risks are already large in some regions. We find here systematic and substantial increases in the property value exposed to climate-sensitive disturbances that highlights enormous benefits of ambitious climate policy to follow lower emissions scenarios.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.4741333.

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