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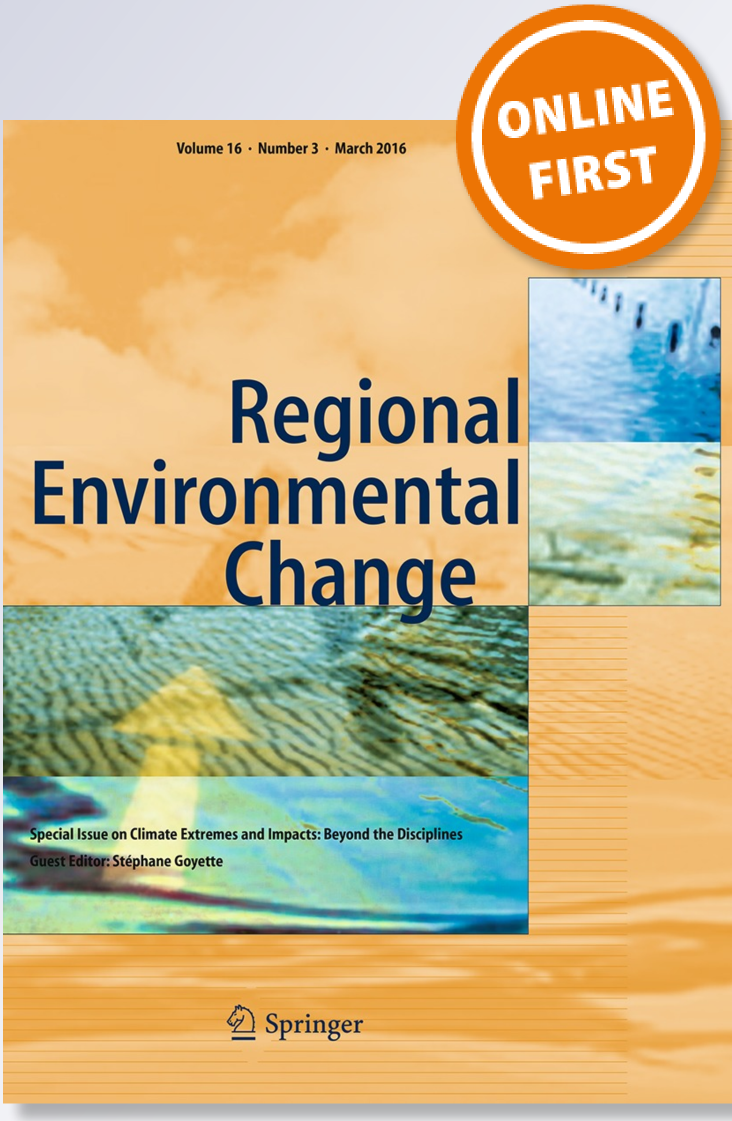

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ORIGINAL ARTICLE

# US exposure to multiple landscape stressors and climate change

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**Abstract** We examined landscape exposure to wildfire potential, insects and disease risk, and urban and exurban development for the conterminous US (CONUS). Our analysis relied on spatial data used by federal agencies to evaluate these stressors nationally. We combined stressor data with a climate change exposure metric to identify when temperature is likely to depart from historical conditions and become "unprecedented." We used a neighborhood analysis procedure based on key stressor thresholds within a geographic information system to examine the extent of landscape exposure to our set of individual and coinciding stressors. Our focus is on identifying large contiguous areas of stress exposure which would be of national concern to identify potential locations most vulnerable to resulting ecological and social disruption. The arrival of record-setting temperatures may be both rapid and widespread within the CONUS under RCP8.5. By 2060, 91 % of the CONUS could depart from the climate of the last century. While much of the CONUS may be impacted by at least one of the landscape stressors we examined, multiple coinciding stressors occurred for less than 9 % of the CONUS. The two most prevalent coinciding stressors were (1) wildfire potential combined with insects and disease risk, and (2) climate departure combined with urban and exurban development. Combined exposure to three or more stressors was rare, but we did identify several localized high-population areas that may be vulnerable to future change. Additional assessment and research for these areas may provide early and proactive approaches to mitigating multiple stressor exposure.

**Keywords** Environmental and ecological monitoring · Vulnerability and risk assessment · Stressors · Forest health · Wildfire · Insects and disease · Urban and exurban development

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## Introduction

Landscape exposure to multiple stressors can pose risks to human health and well-being, biodiversity and ecosystem services and complicate the ability of humans to respond to global change (O'Brien et al. 2004; Thomas et al. 2004; Bigler et al. 2005; Bowman and Johnston 2005). Forest lands, for example, provide critical habitat for plants and animals and potentially mitigate climate change by acting as sinks for atmospheric carbon (e.g., FAO 2013; Smith et al. 2014). Forested lands also play an important role in regulating climate due not only to their role in the carbon cycle but also to their biogeophysical impacts on, and feedbacks to, climate (i.e., albedo, evapotranspiration, roughness, length of the surface, and the impact of these on the radiation budget) (Bonan 2008). These roles are in addition to economic and social benefits that people have

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long derived from forests globally (e.g., Agrawal et al. 2013). Sustaining and enhancing these ecosystem benefits calls for effective monitoring of key landscape stressors to both anticipate potential exposure hazards and devise appropriate policy and management responses regionally and globally. We define stressors broadly to include any agent, condition, or process that can cause stress to an organism or social or ecological system. This definition is similar to usage of the term stressor by others (e.g., O'Brien et al. 2004; McKenzie et al. 2009). The term can be used synonymously with disturbance, but the latter typically only refers to processes that result in biomass removal or structural loss.

In the USA, many landscapes increasingly are susceptible to wildfire, insects and disease outbreaks, and urban and exurban (beyond urban suburbs) development. These stressors can have significant and long-lasting consequences for social and ecological systems and can involve significant costs associated with their control and mitigation. Policymakers and landscape managers are challenged with assessing, managing, and mitigating the exposure of US landscapes to multiple stressors (e.g., Collins and Larry 2007). Despite these concerns, systematic assessments of multiple stressors at broad spatial scales are fairly uncommon. Although decision support approaches for accounting for multiple stressors have been proposed, such as the relative risk model (Landis 2005) and multi-criteria decision analysis (Mendoza and Martins 2006), developing the quantitative data necessary for using such approaches remains a challenge.

There is a body of research that has focused on examining the nature, severity, and ecological effects of stressor interactions using conceptual, empirical, and simulation approaches. For example, conceptual models of stressor interactions and their effects on forests at continental scales have been used to identify the general scale and structure of stressors (Aber et al. 2001; Dale et al. 2001; Allen 2007) as well as potential interaction dynamics (Buma and Wessman 2011), but spatially explicit projections of likely stressor occurrence that incorporate interactions among stressors are lacking. Empirical and simulation models of some natural stressor interactions at landscape scales have also been developed (e.g., He and Mladenoff 1999; Bigler et al. 2005), but these consider a limited set of stressors and results are difficult to extrapolate to larger scales.

Another approach to multiple stress assessment is to sidestep the issue of potential interaction mechanisms and focus instead on identifying geographic areas where multiple stressors—both natural and human-caused—are most prevalent or coincide at broad scales (regional to national), to aid in policy and management efforts, including vulnerability and risk assessments (O'Brien et al. 2004; Metzger and Schroter 2006; Metzger et al. 2008; Kline et al. 2013; Piontek et al. 2014). Some of the challenge in conducting such quantitative multiple stressor assessment arises from difficulties in combining sets of disparate information (O'Brien et al. 2004). One difficulty involves the need to combine measurements for individual stressors that have been gathered using different measurement units. In some cases, this can be addressed using qualitative methods such as ranking and expert opinion (Landis and Wiegers 2005; Mendoza and Martins 2006). However, a related difficulty involves determining an appropriate spatial scale and method for combining, evaluating, and displaying stressor data derived from different sources. For example, many datasets describing forest stressors in the USA are produced at fairly fine spatial scales, such as the wildfire potential data used in this paper, even as sources caution against using them for anything but coarse-scale planning and policy purposes. Given such precautions, it can be difficult for policymakers and managers to know how to appropriately use finely scaled stressor data. Additionally, some stressor data often are reported by political unit (e.g., state, province, county, township, district, census block, village, or parish). Although political units may be important in political contexts, they may not be as useful to evaluate potential stressor effects on landscape-level ecological conditions and processes, which likely transcend political boundaries. Ideally, landscape areas potentially exposed to individual or combined stressors could be shown in a consistent or standardized manner independent of the spatial scale and units initially used to measure them. For combined stressors, the scale of potential interaction should also be considered.

Kline et al. (2013) outlined one way to address these challenges, with a focus on informing regional natural resource policy and planning efforts concerning wildfire, insects and disease, and urban and exurban development stressors in the northwestern USA. Their approach was to use a geographic information system to conduct a neighborhood analysis procedure based on key stressor thresholds to identify locations where each stressor is more prevalent on the landscape than other locations. We follow methods similar to Kline et al. (2013) to examine landscape exposure to wildfire, insects and disease, and urban and exurban development for the conterminous US (CONUS). Our analysis of these stressors relied on spatial data used by the USDA Forest Service and other federal agencies to evaluate these stressors nationally. Additionally, we combined these data with a climate change exposure metric that we applied to identify when temperature is likely to depart from historical conditions and become "unprecedented" (defined here as permanently departing from the historical range of variability) (Mora et al. 2013). Our analysis is intended to map *potential* landscape exposure to multiple coinciding stressors that either may or may not "interact" in a mechanistic sense. We do not intend to imply that particular stressor combinations necessarily do interact. Rather, our analysis provides one approach for examining the geographic locations of concentrated landscape stressors and their coincidence, including climate change, within CONUS to inform national policy, management, and research efforts.

## Landscape stressors in the CONUS

We focus our analysis on wildfire, insects and disease, urban and exurban development, and climate change, which are landscape stressors of major concern to policymakers and landscape managers in the USA. Although some of these—specifically wildfire and insects and disease—are part of naturally functioning ecosystems, alone or in combination these disturbances can result in unpredictable ecosystem responses, reduced ecosystem resiliency, impacts to human health, and changes to socially valued ecosystem services (e.g., Paine et al. 1998; Bowman and Johnston 2005; Groffman et al. 2006). Wildfire destroys hundreds of structures annually in the USA, sometimes with accompanying loss of human lives (GAO 2005). High-intensity wildfires can result in secondary impacts, including flooding, erosion, altered soil conditions, loss of recreation infrastructure, and changes in vegetation successional patterns that reduce habitat diversity (Sampson et al. 2000; Hesseln et al. 2003; Certini 2005; Shakesby and Doerr 2006; Ager et al. 2007). Forest insects and disease attacks can result in tree mortality, slow vegetative growth, economic losses associated with damage to potential wood products, and altered biogeochemical cycling and habitats for birds and animals. Insects and disease outbreaks in forests can affect millions of hectares, reducing aesthetic values and increasing the potential for wildfire (e.g., Logan et al. 2003; Hicke et al. 2012; Hoffman et al. 2012). Tree damage and mortality from fire can create "focus" trees which attract additional insects (McCullough et al. 1998; Schwilk et al. 2006), such as bark beetles (e.g., some *Dendroctonus* species).

Urban and exurban development can lead to a loss of forest, range, and other open-space lands and bring people into close proximity to fire-prone landscapes (e.g., Radeloff et al. 2005a). Expansion of the wildland–urban interface (WUI)—sometimes known outside the USA as peri-urban or rurban lands—has been associated with increased likelihood of fire ignitions in neighboring areas from arson, accidents, and transportation factors (Mercer and Prestemon 2005). The WUI is where wildland fire hazard most directly impacts human communities and threatens lives and property, and where houses exert the strongest influence on the natural environment (Bar-Massada et al. 2013). Urban and exurban development also has been correlated with the occurrence of invasive plants by facilitating the introduction and propagation of exotic species (Maestas et al. 2001; Gavier-Pizarro et al. 2010), which in turn can influence wildfire behavior (D'Antonio and Vitousek 1992). Federal policy and management goals in the USA seek to sustain forest and range lands by preventing significant loss of tree cover to wildfire and insects and disease, replanting lands following significant disturbance events, and reducing forest and range land development (e.g., USDA Forest Service 2006; Collins and Larry 2007). Achieving these goals depends in part on monitoring the prevalence of wildfire potential, insects and disease, and urban and exurban development stressors to aid policymakers and managers in anticipating and weighing the implications of potential stressors and their coincidence on the landscape in regional- and national-level risk and vulnerability assessments (e.g., Kline et al. 2013).

There also is an increasing need to evaluate these stressors in the context of a changing climate. Climate change scenarios predicted by global circulation models suggest that some regions of the USA will experience climatic conditions that are different from those of today, with some regions likely warmer and wetter, and other regions likely warmer and drier (IPCC 2007). Climatic changes may increase or decrease rainfall, increase periods of drought or flooding and could increase natural hazards such as hurricanes, among other changes. These changes are expected to impact social systems by affecting human health, including mortality and morbidity from extreme heat, cold, drought or storms; air and water quality; and the ecology of infectious diseases (Patz et al. 2005). Climate change also is expected to impact ecological systems by affecting changes in vegetation structure and composition, hydrologic systems, terrestrial and aquatic ecosystem processes, as well as the delivery of ecosystem services over the next century (Allen et al. 2009; Vose et al. 2012; Peterson et al. 2014). Moreover, climate change is expected to affect changes in disturbance processes, including wildfire and insects and disease outbreaks (Westerling et al. 2006; Kurz et al. 2008; Weed et al. 2013; Ayres et al. 2014). For example, Bedel et al. (2013) found that regions of the southeastern USA are projected to experience drier and warmer winters and spring, which could increase wildfire activity in select regions. By 2046–2055, total area burned in the western USA could increase by 54 % relative to the present day (Spracklen et al. 2009).

The effects of wildfire, insects and disease, and urban and exurban development, combined with a changing climate, will present new challenges for policymakers and managers. Climate-related impacts already are occurring across the USA. Recent warming trends and periodic anomalous drought conditions have notably influenced wildfire characteristics in the early part of the twenty-first century (IPCC 2007). Recent outbreaks of mountain pine beetles (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson) forests in western North America exemplify how warmer climate can propagate widespread disturbance by insects (Kurz et al. 2008). Many state and local governments are preparing for climate change impacts by developing adaptation strategies to plan for changes that are expected to occur. Although most ecological and social systems may be able to adapt to a changing climate, the magnitude of impacts to these systems will depend on the timing, location, and degree to which climate changes reach unprecedented states (Mora et al. 2013). Climate change projections across a range of timescales have implications for a range of policy and management issues (Hastings 2010). For policymakers and managers, this includes the degree to which the timing and location of the most significant climate changes coincide with existing wildfire, insects and disease, and urban and exurban development stressors.

## Methods

Our analysis relied on available spatial data about wildland fire potential, insects and disease risk, and urban and exurban development used by the USDA Forest Service and other agencies involved in national-level policy and planning activities. We used these data to conduct a neighborhood analysis process using ArcGIS 9.3 focal statistics to highlight locations where potential wildfire, insects and disease, and urban and exurban development stressors are most prevalent across the CONUS. We assumed that regions with relatively more concentrated stressor exposure likely are of greater regional or national policy interest than areas with less concentrated stressor exposure (e.g., Kline et al. 2013). We combined this analysis with additional data describing potential stress from climate change, measured as the year in which mean annual temperatures will depart permanently from the historical range of variability.

### Spatial data

Spatial data describing wildland fire potential were developed by the Fire Modeling Institute, Missoula Fire Sciences Laboratory, in Missoula, Montana (Dillon et al. 2012). The data describe five classes of wildfire potential, including very low, low, moderate, high, and very high. The data integrate estimates of burn probability and conditional probabilities of fire intensity levels using a simulation modeling system called the Large Fire Simulator (FSim; Finney et al. 2011). Although the data are provided as a 270-m raster grid, they are intended to be used only at broader regional and national scales. We defined wildfire exposure as being indicated by the “high” and “very high” classes, to identify lands subject to significant wildfire exposure (high intensity with torching and crowning) across the USA, consistent with other applications assessing wildfire potential (Menakis et al. 2003; Kline et al. 2013). We then resampled these data to an 800-m grid using the majority procedure to match the spatial resolution of our coarsest scaled dataset describing climate change.

Spatial data describing exposure to insects and disease came from the 2012 composite National Insect and Disease Risk Map developed by the USDA Forest Service’s Forest Health Technology Enterprise Team based in Fort Collins, Colorado (Krist et al. 2014). The map estimates the future cumulative risk of tree basal area loss to all major insects and disease over the 15-year period from 2013 to 2027 using a binary 240-m raster grid (FHTET 2012; Krist et al. 2014). The data define insects and disease risk as a threshold of 25 % expected basal area loss of trees greater than 2.54 cm (1 inch) in diameter over the 15-year period, absent remediation. The data are provided only for US forested or “treed” land (areas of measurable tree presence), which totals over 485 million hectares or about 55 % of all land in the CONUS (FHTET 2012), and include urban areas and the Great Plains. Like the wildfire data, we resampled the insects and disease data to an 800-m grid based on the majority procedure. Similar to the wildfire data, the insects and disease data also are intended more for regional planning and policy purposes rather than on the ground management applications (Krist et al. 2014).

Spatial data designating urban and exurban development were created based on US Census housing data (Radeloff et al. 2010). The data describe housing density forecasts for 2030 assuming 1990s housing growth rates applied to 2008 county population forecasts (Radeloff et al. 2010). The original polygon data were constituted as an irregular lattice consistent with US Census block group geography and are intended for regional and national planning applications (Radeloff et al. 2000). We converted the polygon data into an 800-m raster grid using maximum area allocation. We categorized the raster housing density data into two discrete classes of <6.17 housing units per square km and ≥6.17 housing units per square km, with the latter indicating exposure to urban and exurban development (henceforth called development). This threshold is consistent with that used for defining the wildland–urban interface (Radeloff et al. 2005b). The US concept of wildland–urban interface is similar to other terms, including those used in the international literature, such as peri-urban and rurban lands.

Spatial data describing exposure to climate change were derived from the NASA NEX-DCP30 dataset (Thrasher et al. 2013), for which climate projections from 33 global climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) were statistically downscaled (Bias-Correction Spatial Disaggregation) to 30 arc seconds (approximately 800 m) for the CONUS for all four Representative Concentrations Pathways (RCP) (Thrasher et al. 2013). The RCPs describe a set of possible developments in emissions and land use, based on consistent scenarios representative of current literature (van Vuuren et al. 2011). RCP8.5 is a rising pathway scenario, considered the "baseline" pathway because it does not include any specific climate mitigation target (sometimes referred to as "business as usual"), which leads to approximately 1370 ppm $CO_2$ by the end of the century (Riahi et al. 2011). We selected RCP8.5 for this assessment because "business as usual" is a realistic pathway given current conditions and because it does not include any climate mitigation targets and it represents a "worst-case scenario" which can be useful to many risk adverse agencies and decision makers. However, the RCPs do not differ substantially until about 2035 (Moss et al. 2010), and we chose to look at a climate change departure metric (described below) that is based on 2040.

Although most CMIP5 climate projections portray futures starkly different from those of the recent past, selecting a single climate change stress metric is difficult. For North America, changes in mean annual temperature under RCP4.5 and RCP8.5 are projected to occur at broad, continental scales, while projections for precipitation are for little or no change, or for conflicting changes (Romero-Lankao et al. 2014). We characterized potential exposure to climate change stress by determining when projected mean annual temperatures are likely to depart permanently from historical conditions (Mora et al. 2013) under the RCP8.5 emissions scenario for each of the 31 projections (2 of the 33 models did not have RCP8.5 projections). First, we calculated the historical maximum annual mean temperature for every grid cell from 1895 to 2008 using 30 arc-second resolution monthly PRISM Climate Data (Daly et al. 1994). Then, for each of the 31 projections, we calculated a raster representing the climate departure year, defined as the year at which the projected annual mean temperatures rose above the historical maximum without falling below again. The 31 departure year raster data were then averaged to obtain the ensemble mean departure year data.

To overlay the climate departure year data with the other stressors, we classified every cell in the ensemble mean departure year raster into two discrete classes: those with departure year on or before 2040 and those after year 2040. We designated the grid cells with climate departure before 2040 as being exposed to climate change stress to highlight those locations most likely to shift rapidly into a new climate regime. We chose the year 2040 as a time horizon because by then substantial proportions (>10 %) of the CONUS are projected to have departed from historical climate. This time horizon also aligns well with the temporal scale of our insects and disease (risk of basal area loss from 2013 to 2027) and development data (forecasts for 2030). Although the 2040 time horizon may make the departure year appear to be a short-term metric, the metric actually represents long-term exceedance of a reference temperature range.

## Neighborhood analysis

Our neighborhood analysis was designed to display the multiple stressors we examined in a manner consistent with the spatial scale at which the various stressor data were intended to be used, but in a way that transcends political boundaries (e.g., Kline et al. 2013). Our analysis process moved a 20-km circular (1257 square km) window over the landscape to return a value for each stressor for each 800-m grid cell. The 20-km circular window was chosen to be roughly consistent with the size of a typical mid-scale US political unit, the county, based on methods developed in Kline et al. (2013). Most (72 %) US counties are about that size or smaller, with some counties, particularly those in the western USA, considerably larger. Substantially finer scales would not be consistent with recommended usage of our data, and substantially coarser (e.g., 50 km) scales become irrelevant in terms of potential interaction processes. For example, the 20-km scale coincides with the size of many larger and damaging wildfires in the western USA (Ager et al. 2014). Sensitivity analyses done as part of the Kline et al. (2013) analysis revealed that small differences in neighborhood window size (5–10 km) resulted in little change in the results.

The neighborhood analysis resulted in a new 800-m grid for each stressor for which cell values represented the proportion of neighboring cells within the 20-km radius exposed to each stressor. While our window size was motivated by county size, the window in no way conforms to a political boundary since the circular window is applied to every pixel. For example, a grid cell with a value of 0.43 for wildfire would mean that 43 % of the surrounding cells in the 20-km neighborhood were mapped as having high or very high potential for wildfire. We then calculated the national mean exposure concentration plus one standard deviation for each stressor and identified pixels that exceeded that value (Table 1). We consider this concentration of exposure to be "high" relative to the USA as a whole (e.g., Kline et al. 2013).

**Table 1** The national mean and one standard deviation percentage of neighboring cells exposed to each stressor (or stressor concentration) based on a 20-km radius neighborhood for each stressor examined in the continental US

| Stressor | National mean (%) | STDV (%) | Concentrated exposure threshold (%) |
|---|---|---|---|
| Climate departure | 12.7 | 28.7 | 41 |
| Development | 21.0 | 30.0 | 50 |
| Insects/disease | 2.3 | 7.4 | 10 |
| Wildfire | 11.0 | 21.0 | 32 |

Areas were mapped as having concentrated exposure when values exceeded the mean plus one standard deviation or concentrated exposure threshold

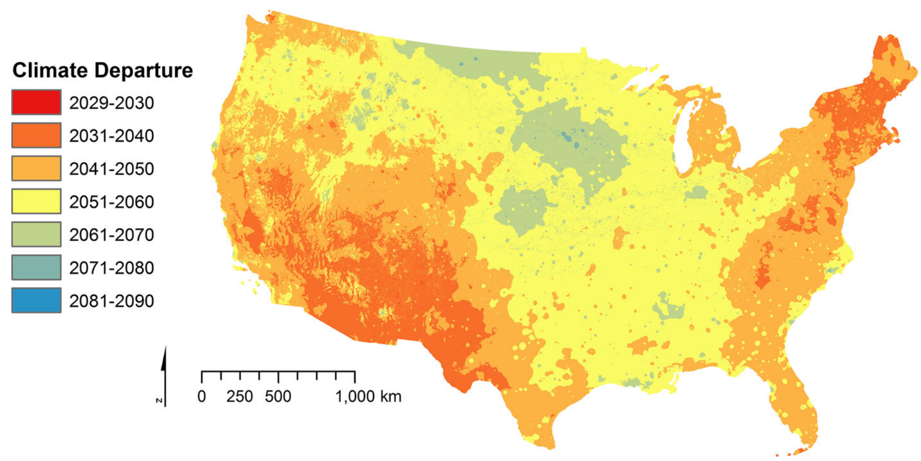


**Fig. 1** Anticipated timing of climate departure from historical conditions for mean annual temperature for the continental US. Areas identified as having anticipated climate departure by 2040 (*deep orange* and *red*) were considered exposed to climate departure (color figure online)

In this way, our analysis identified areas within the CONUS where a given potential stressor is exceptionally high or spatially concentrated relative to all other areas. Although input data existed at an 800-m spatial scale, our 20-km neighborhood analysis approach provides a way to mitigate uncertainties inherent in fine-scale data and create a map usable for national-level policy and planning. To numerically summarize the spatial extent of landscape exposure to each stressor, we computed the proportion of mapped pixels meeting each stressor exposure threshold nationally and then multiplied this value by the known area of the CONUS—767 million hectares (Smith et al. 2009)—resulting in an estimate of the land area exposed to each stressor. We repeated this process with pixels meeting multiple stressor exposure thresholds to estimate the land area exposed to each stressor combination.

## Results

Our climate exposure analysis shows that climate departure as defined in this paper will be rapid and complete across the CONUS under the RCP8.5 climate scenario by about the middle of the century. In the next 25 years, about 13 % of the CONUS could be exposed to mean annual temperatures higher than the maxima of the last century. Under the scenario we used, most of the early departure is likely to occur in the southwest and the northeast (deep orange, Fig. 1). A very limited area ($< 0.1$ %) could experience departures as early as 2030 in New Mexico and southeast Arizona. The anticipated expansion of climate departure is rapid under RCP8.5: By 2060, 91 % of the CONUS could depart from the climate of the last century, with only the north-central Great Plains remaining. Departure from historical range of annual temperatures could be nearly complete by 2070: After 2070, only 0.2 % of the conterminous US remains within the historical range as scattered points in the Great Plains and the Midwest (deep blue).

Table 2 displays the actual area and relative percentage of land area in the CONUS that is mapped as having concentrated exposure to wildfire, insects and disease, development, and climate departure stressors alone or in combination. We found that about 46 % of the CONUS is likely to be exposed to high concentrations of one or more of the four stressors examined now or in the near future (prior to 2040) (Fig. 2). Concentrated exposure to projected development is the most pervasive stressor, alone and in combination with another stressor (Table 2 bottom; Fig. 2). Although some areas of the west—particularly along the west coast—are subject to concentrated exposure to development stress, most exposure is projected in the eastern CONUS.

Concentrated wildfire exposure also is common, potentially impacting about 14 % of the CONUS, alone and in combination with another stressor (Table 2 bottom; Fig. 2). Most is located in the west and southeast. Concentrated

**Table 2** Area of concentrated exposure to landscape stressors for the continental US

| Stressor or stressor combination | Area (Hectares, 1000s) | Percent |
|---|---|---|
| Development | 115,951 | 15.1 |
| Climate departure | 73,985 | 9.6 |
| Wildfire | 66,894 | 8.7 |
| Insects/disease | 29,108 | 3.8 |
| Wildfire and insects/disease | 15,934 | 2.1 |
| Development and climate departure | 15,463 | 2.0 |
| Wildfire and development | 13,569 | 1.8 |
| Wildfire and climate departure | 10,174 | 1.3 |
| Insects/disease and climate departure | 3169 | 0.4 |
| Insects/disease and development | 3119 | 0.4 |
| Wildfire, insects/disease, and climate departure | 2243 | 0.3 |
| Insects/disease, development, and climate departure | 663 | 0.1 |
| Wildfire, development, and climate departure | 378 | 0.1 |
| Wildfire, insects/disease, and development | 64 | <0.01 |
| Wildfire, insects/disease, development, and climate departure | 20 | <0.01 |
| None | 416,033 | 54.3 |
| Total | 766,767 | 100.0 |
| *Area totals of land exposed to each stressor (alone and in combination)*[a] | | |
| Development | 149,520 | 19.5 |
| Wildfire | 109,648 | 14.3 |
| Climate departure | 105,814 | 13.8 |
| Insects/disease | 54,440 | 7.1 |

[a] Note that these stressors will overlap; therefore, addition of these percentages is inapplicable to the data in table above

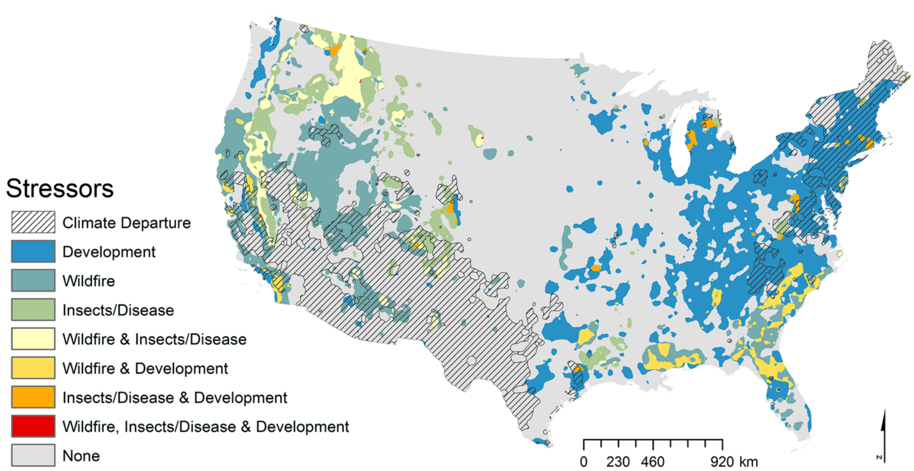


**Fig. 2** Concentrated exposure to wildfire, insects and disease, development, and climate departure stressors for the continental US

exposure to climate departure also could potentially impact almost 14 % of the CONUS, alone and in combination with another stressor (Table 2 bottom). Exposure to concentrated climate stress indicates the greatest impacts in the southwestern and northeastern CONUS (Fig. 2). Forestland exposure to concentrated insects and disease stress is present in about 7 % of the CONUS, alone and in combination with another stressor, most of which is in the western CONUS (Table 2 bottom; Fig. 2). While the overall area of concentrated exposure in the CONUS to basal area loss from insects and disease is low, we emphasize that exposure to the insects and disease stressor is mapped only on "treed" lands. Twenty-two percent of CONUS forested lands have concentrated exposure to insects and disease stress.

Concentrated exposure to two or more stressors (Table 2, top) was predicted for about 8.5 % of the CONUS. The two most common multiple stressor combinations for the CONUS are (1) wildfire and insects and disease, and (2) development and climate departure. The coincidence of wildfire and development is a close third. The wildfire and insect and disease intersection occurs predominantly in the western part of the CONUS, while development combined with climate departure might be anticipated in the northeastern USA, with smaller patches in the southwest (Fig. 2). Wildfire in combination with development is mapped largely in the west and southeast. The spatial extent of areas projected to have three concentrated stressor combinations is limited (<1 %, Table 2; Fig. 2). The most common triple stressor is for concentrated wildfire, insects and disease, and climate departure exposure. This combination exists in small patches near parts of central NV, southwest CO, northern and southern NM and central and eastern AZ, and minor areas of CA. The intersection of all four stressors also is rare, but does occur in three small areas near: Washoe City, NV (just north of Carson City); Gem Village/Bayfield, CO; and Santa Fe, NM.

## Discussion

Our maps highlight the locations and the intersection of areas where a given stressor is likely to exist at notably above-average concentration on the landscape relative to all other areas of the CONUS. There is considerable uncertainty regarding all the spatial data used in our analysis, and our resulting maps should be viewed as potential "what-if" scenarios. The climate departure map indicates that under the RCP8.5 climate scenario—which assumes that global society continues "business as usual," with high emissions, no coordinated climate policy, and high population growth (van Vuuren et al. 2011)—the arrival of record-setting temperatures may be both rapid and widespread within the CONUS. The southwest and northeast may experience these changes earlier than the rest of the CONUS, such that the social and natural systems in these areas may have much less time to prepare and adapt to climate change. Considerable social and ecological change has been shown to have coincided with the emergence of unprecedented climates in the past (Binford et al. 1997; Williams et al. 2010).

Interestingly, a relatively small percentage of the CONUS may have concentrated exposure to the four landscape stressors we examined, and exposure to three or more stressors is very rare. However, policy and decision makers, managers and researchers may want to take a closer look at the multiple stress areas identified in our maps. These areas represent locations that may be highly vulnerable to future ecological or social change. For example, the coincidence of wildfire (note our usage of wildfire exposure refers to high severity wildfire) and insects and disease landscape stressors is one of the more common intersections that we mapped, and the potential interaction between these stressors is a common management concern. However, wildfire and insects and disease interactions are poorly understood (Jenkins et al. 2008), and the areas we mapped may be fruitful research locations. Some of the areas of multiple stressor coincidence we identified may also impact a large number of people. Our climate departure projections coincided largely with development most prevalently in the northeast, where a significant proportion of the US population resides. Policymakers might well anticipate the degree to which climate change might test prevailing social and economic systems in that populated region. Many policymakers are already pondering and planning for potential climate changes in many parts of the country. Our analysis suggests that such planning efforts could reasonably be considered a priority in the northeast. The intersection of wildfire and development appears as if it could affect a relatively small share of the national landscape (about 2 %); however, the issue for policymakers and managers may continue to be a noteworthy policy concern, because of the significant number of people potentially affected and the high costs of wildfire risk mitigation and suppression.

Our maps indicate that exposure to unprecedented warming by 2040 may coincide with high wildfire potential more commonly in the southwest. Human adaptation efforts aimed at lowering wildfire risk, such as fuel reduction treatments, may help to mitigate potential impacts from the combination of wildfire potential and climate departure in these areas. However, current policies focused on fire suppression may only delay the inevitable (Stephens et al. 2013). Although promoting ecosystem resilience to change may be an option in some areas facing unprecedented climate change, intentionally planning for major changes also may become necessary (e.g., "respond"; Millar et al. 2007). Millar et al. (2007) suggest that "proactive ecological response treatments" may accommodate ongoing natural adaptive processes, such as species dispersal and migration, population mortality and colonization, changes in species' dominances and community composition, and changing disturbance regimes. A strategic goal would be to encourage gradual adaptation and transition to inevitable change and thereby avoid rapid threshold or catastrophic conversion that may occur otherwise.

We emphasize that our approach highlights areas of high relative exposure to each stressor based on the spatial distribution and concentration of potential stressors across the landscape and our neighborhood spatial statistical procedure for identifying stress exposure as "high." Pixels that are not surrounded (within a 20-km radius) by a greater than average proportion of pixels meeting a given stressor exposure threshold are not identified as being exposed. For example, areas of the northwestern and north-central US that are mapped as having early climate departure (Fig. 1) do not appear on our 20-km radius neighborhood analysis map (Fig. 2) because of the more fragmented nature of the climate departure stress metric in these areas compared to other areas of the CONUS. By comparison, climate departure data are much less pixelated in southern and northeastern parts of the CONUS, resulting in substantial areas of continuous mapped climate stress. Our analysis assumes that from a national perspective, these large contiguous (or concentrated) areas of exposure to stressors may warrant a closer look or greater policy concern than smaller areas where stressor exposure is more fragmented, especially when we take into account the spatial scale at which the source data were intended to be used. We do not intend to dismiss the importance of fragmented stressor exposure in these areas (e.g., climate departure in the northwest, development in the west, and wildfire in the northeast). Rather, based on our analysis, we suggest that these might reasonably be of more local rather than national or regional concern.

As noted above, there is considerable uncertainty regarding all of the spatial data used in our analysis. All of these data, and our resulting maps, should be viewed as potential "what-if" scenarios, rather than actual predictions or forecasts. For example, the raw data that we used to develop our potential wildfire stressor exposure map build upon and integrate estimates of burn probability and conditional probabilities of fire intensity levels using a simulation modeling system. Data used in this simulation modeling system are often generated from other model-based applications. Therefore, uncertainty may be propagated and considerably high. This issue is relevant to all the spatial data used in this analysis. Data for exposure to the three other stressors (urban and exurban housing development, basal area loss from insects and disease, and climate departure) are all based on model projections about the future. Projections for development and insects and disease risk largely rely on empirical data and statistical models and assume that past processes and trends continue into the future. For the climate change metric, we used an ensemble mean, and multi-model means have been shown to exhibit the best correlation with historical climate in some evaluations (Rupp et al. 2013; Sheffield et al. 2013). However, the interannual variability present in individual GCM data was preserved in our analysis, since departure years were calculated for each GCM-based projection first before the ensemble mean was calculated. However, ensemble means can give undue emphasis to poorly performing models and give extra weight to output from similar models (Knutti et al. 2010). Yet our method for characterizing potential climate changes offers some utility in that it is a single metric easily communicated to a general audience and the timespan is appropriate to use with other common landscape stressors.

## Conclusions

Data describing exposure to landscape stressors are widely used by policymakers and landscape managers. However, to our knowledge, efforts to combine and display the spatial coincidence of multiple stressors have received fairly little attention in research literature. We examined spatial data characterizing wildfire, insects and disease, and urban and exurban development and developed a new climate change metric—climate departure—to examine the potential spatial extent of these stressors in combination within the CONUS. Our analysis suggests that essentially all of the CONUS may experience record-breaking warming by the middle of the century, but the southwest and northeast may experience unprecedented conditions by 2040 or earlier. While much of the country may be impacted by one landscape stressor, from a national perspective, multiple stress combinations were relatively uncommon. Wildfire combined with insects and disease risk, and early climate departure and urban and exurban development are likely to be the most common landscape stressor combinations. Although combined exposure to three or more stressors in the CONUS appears to be quite uncommon, several localized areas were identified as having potentially high combinations of wildfire potential, insects and disease, urban and exurban development, and climate departure. A closer look or additional risk assessment for these areas may provide early and proactive approaches to mitigating multiple stressor exposure. While the current national extent of multiple stress combinations is relatively small, over time as global warming progresses (as demonstrated by our climate departure metric) areas impacted by unprecedented warming will increase and this stressor will undoubtedly coincide with many of the other stressors examined.

Our analysis provides one approach for describing the potential landscape exposure to major individual and combined stressors for the CONUS to inform national policy by identifying those locations potentially most vulnerable to resulting ecological and social disruption. We assume that large contiguous (or concentrated) areas of exposure to stressors may warrant a closer look or greater policy concern than smaller areas where stressor exposure is more fragmented. To our knowledge, this is the only systematic assessment of current and projected exposure to multiple landscape stressors for the continental US. Our maps can be used independently to provide a framework for discussion and interaction among policymakers, managers, local officials, and the public and to both anticipate and prepare for future challenges, and to focus research effort to develop additional information that may be necessary for such processes. The maps also can be used to inform decision support efforts, such as participatory integrated assessment (e.g., Harrison et al. 2013), multi-criteria decision analysis, risk assessment, and vulnerability analysis focused on mitigating risk associated with the stressors examined.

Ideally, assessments of multiple stressors would have available accurate scientific information characterizing stressors of concern and the likely spatial extents over which interactions among different stressors might actually occur (e.g., climate departure and wildfire potential). Often, however, such refined data are not available, particularly at a national scale. In their absence, neighborhood analysis and overlays can help policymakers and managers to locate stressor combinations and consider their implications for human and natural systems. Although our neighborhood analysis may provide a useful method for displaying combined stressor data, our resulting maps should not be interpreted as representing the actual spatial extent of disturbance combinations. Currently such information largely is speculative in most landscape applications. Our approach simply provides a standardized way to geographically display combined stressor data using spatial analysis at a scale appropriate for planning and policy purposes and in a manner that transcends political county boundaries. The approach is relatively straightforward and does not involve "indices" or other metrics which may obscure underlying data characterizing exposure to stressors.

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