

AUTHOR'S PERSONAL COPY

Provided for noncommercial research and educational use.
Not for reproduction, distribution, or commercial use.



This article appeared in a journal published by the Society of American Foresters. The attached copy is furnished to the author for internal noncommercial research and educational use, including instruction at the author's institution and sharing with colleagues.

Other uses, including reproduction and distribution, selling or licensing copies, or posting to personal, institutional, or third-party websites, are prohibited.

Authors are permitted to post a preprint version of their article (e.g., in Word or Tex form), revised if desired to reflect any changes made in the peer-review process, to their personal website or any institutional repository maintained by their employer, provided it includes the complete citation and link to the final published version; the website or repository must not charge a fee for document delivery or article access. Authors requiring further information regarding the Society of American Foresters' archiving and manuscript policies are encouraged to visit www.safnet.org/publications/copyright.cfm.

entomology & pathology

Mapping Multiple Forest Threats in the Northwestern United States

Jeffrey D. Kline, Becky K. Kerns, Michelle A. Day, and Roger B. Hammer

US forestlands are increasingly subject to disturbances including wildfire, insects and disease, and urban and exurban development. Devising strategies for addressing these “forest threats” depends on anticipating where individual disturbances are most likely and where they might occur in combination. However, many spatial data sets describing forest threats are produced at fine scales but are intended only for coarse-scale planning and policy purposes. We demonstrate one way to combine and display forest threat data at their appropriate spatial scales, using spatial data characterizing wildfire, insects and disease, and urban and exurban development in the northwestern United States. We use a novel 25-km radius neighborhood analysis to highlight locations where threats may be more concentrated relative to others and to identify where multiple threats intersect. Such neighborhood analyses and overlays can help policymakers and managers to anticipate and weigh the implications of potential threats and their intersections in regional- and national-level assessments.

Keywords: forest health, landscape planning and assessment, wildfire, insects and disease, wildland-urban interface

US forestlands are increasingly subject to disturbance from wildfire, insect and disease outbreaks, and urban and exurban development (USDA Forest Service 2006). Often called “threats” (e.g., USDA Forest Service 2007), these disturbances can have significant and long-lasting adverse consequences for ecosystems and the ecosystem services on which people depend. They also can involve significant costs associated with their control and mitigation. Policymakers and managers are challenged with assessing and managing forestland threats. However, with limited budgets, choices must be made about where to con-

duct fuel treatments to protect homes and other structures versus restoration to enhance habitat for threatened or endangered species, recreation, and other resources of social value. Policy and management goals call for sustaining forestlands by preventing significant loss of tree cover to wildfire, insects and disease, replanting lands after significant disturbance, and reducing forestland development (e.g., Collins and Larry 2007). Devising strategies for accomplishing these goals necessitates anticipating where individual disturbances are most likely and where they might occur in combination with others.

Policymakers and managers often rely

on maps showing the spatial distribution of threats to assess threats in relation to resources of interest to set priorities and allocate resources for managing threats (e.g., Calkin et al. 2010, Aronson and Kulakowski 2012). However, methods for combining multiple spatial data layers to identify potential threat combinations have received fairly limited attention by forest researchers. A difficulty in mapping forest threats is determining the appropriate spatial scale and approach for examining, displaying, and combining threat data. Many spatial data sets are produced at fine scales but are intended only for coarse-scale planning and policy purposes. Spatial data sources often caution against using fine-scaled maps for on-the-ground planning and management implementation. However, translating fine-scale spatial data into useful coarse-scale information for policy and planning purposes can be challenging.

For example, threat data often are reported at county levels to identify counties subject to a given level threat. To do this, a relevant threshold (e.g., predetermined mean, median, or majority) must be defined to determine whether or not a county or other coarse pixel should “light up” on a threat map. However, such a priori determi-

Received November 8, 2012; accepted March 22, 2013; published online May 2, 2013.

Affiliations: Jeffrey D. Kline (jkline@fs.fed.us), USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR. Becky K. Kerns (bkerns@fs.fed.us), USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR. Michelle A. Day (maday@fs.fed.us), USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR. Roger B. Hammer (rhammer@oregonstate.edu), Oregon State University.

Acknowledgments: The authors acknowledge funding from the USDA Forest Service's Western Wildland Environmental Threat Assessment Center, Prineville, OR, and thank Jim Menakis and Frank Krist for assistance with data.

nations can be somewhat arbitrary and may not be the best indicator of the degree to which individual threats are more concentrated on the landscape relative to other threats. Moreover, although counties as political units can be important to policy and management responses to threats, county delineations are somewhat irrelevant to the determination of threats as they exist on forest landscapes. Rather, threats exist as part of landscape-level conditions and processes that generally transcend county (or political) boundaries. Counties also vary greatly in their sizes and shapes, which can influence the degree to which portions of the landscape are identified as threatened at the sub-county level. Ideally, the locations of likely threats and threat combinations would be portrayed in a consistent or standardized manner using thresholds that identify the degree of threat in specific locations relative to the landscape as a whole.

We examined spatial data characterizing wildfire, insects and disease, and urban and exurban development in the northwestern United States using a novel 25-km radius neighborhood analysis to highlight locations where a given disturbance threat may be more concentrated relative to that for other areas. Concerns about wildfire, insects and disease, and urban and exurban development are prevalent among forest policy-makers and managers throughout the region. We assumed that areas with relatively more concentrated threat are probably of greater policy interest than areas with less concentrated threat. We combined our neighborhood analysis results for individual threats as an overlay to identify where multiple threats intersect. Although the 25-km scale may seem coarse from the perspective of underlying processes related to actual disturbance interactions, we feel that it is appropriate for regional assessment. However, we stress that our assessment is not an attempt to define or suggest a spatial scale at which disturbance interactions or processes are likely to take place. Rather, we draw on existing spatial data describing wildfire and insect and disease threats to examine where they are most likely to intersect and interact with people. The analysis provides a way to combine a variety of data sets describing forest threats to support regional landscape planning and management at appropriate spatial scales and spatial units not tied to political boundaries.

Multiple Forest Threats

Wildland fire, insects, and disease all play important roles in fully functioning forest ecosystems. However, alone or in combination these disturbances can produce nonlinear ecosystem responses that overwhelm ecosystem resiliency and produce undesirable new states from which there may be no return (Paine et al. 1998, Groffman et al. 2006). These changes can threaten socially valued landscape characteristics and lead to significant costs associated with their control and mitigation. For example, wildfire destroys hundreds of structures annually, with periodic loss of human lives (Government Accountability Office 2005). Secondary impacts from high-intensity wildfires in particular can include flooding, erosion, altered soil conditions, loss of recreation opportunities and revenues, and changes in vegetative successional patterns that may reduce habitat diversity (e.g., Covington et al. 1994, Sampson et al. 2000, Kline 2004). Wildfire suppression expenditures by the USDA Forest Service alone exceeded \$1 billion in 2000 (Donovan and Brown 2005) and have exceeded that amount nearly every year since. Although the 2012 fire season was slightly below normal for numbers of reported wildfires, the area burned was 128% of the national 10-year average, with a higher-than-average number of structures burned (National Interagency Coordination Center 2013).

Forest insects and diseases can cause tree mortality, loss of growth, and damage to potential wood products and alter biogeochemical cycling and habitats for birds and

animals. Insect and disease outbreaks can encompass 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). In combination, tree mortality owing to insects and disease coinciding with the threat of wildfire can result in combined adverse consequences greater than the sum of the individual consequences resulting from either disturbance in isolation. Insect infestations and wildfire historically have been dominant influences on successional processes over large areas of the western United States and the synergism between them is widely recognized (e.g., McCullough et al. 1998). Tree damage and mortality from fire can create "focus" trees that attract additional insects (McCullough et al. 1998, Schwilk et al. 2006), such as bark beetles (e.g., some *Dendroctonus* species). Conversely, the likelihood and severity of wildfires can be influenced by insect and disease outbreaks that have left significant numbers of dead or weakened trees (McCullough et al. 1998, Hoffman et al. 2012).

Another trend in the United States has been population growth and development of forestlands located near metropolitan areas and traditionally rural locations. Wildlands featuring recreational and aesthetic amenities have been especially prone to these changes (e.g., McGranahan 2008). Urban and exurban development can lead to a loss of forestlands and forest fragmentation and bring greater numbers of people into close proximity to fire-prone landscapes (e.g., Radeloff et al. 2005b). In addition to the

Management and Policy Implications

Neighborhood analysis and overlays of data characterizing wildfire, insects and disease, and urban and exurban development, can help policymakers and managers evaluate the implications of individual and combined forest threats across landscapes. When data describing individual threats are combined, it is necessary to consider the appropriate spatial scales for analysis and determine relevant thresholds for display. Many spatial data sets are produced at fine spatial scales but are intended for coarse-scale planning and policy purposes. Translating fine-scaled spatial data into useful information for regional threat assessment can be challenging. We examine individual and combined threats data using a standardized GIS neighborhood analysis procedure. Our maps suggest that wildfire combined with insects and disease could affect extensive portions of the forest landscape in the northwestern United States. Wildfire combined with urban and exurban development could affect a much smaller area. Locations identified as subject to triple threat—wildfire, insects and disease, and urban and exurban development—were rare. Our results provide information about where disturbance threats may be more concentrated on the regional landscape and where multiple threats might spatially intersect. Such information could be useful for establishing regional and national priorities regarding threat mitigation measures.

general concern that development reduces the ecosystem services that forests provide (e.g., Collins and Larry 2007), there are more immediate concerns about the loss of homes and other structures to wildfire when new residences are built in fire-prone forests. Expansion of the wildland-urban interface has been associated with increased likelihood of fire ignitions in neighboring forests from arson, accidents, and transportation factors (Mercer and Prestemon 2005). Urban and exurban development has also 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 also can influence wildfire behavior (D'Antonio and Vitousek 1992). Moreover, protecting private property, including homes built near or in fire-prone forests, is a major factor cited for increasing wildfire suppression costs in recent years (e.g., Office of Inspector General, Western Region 2006). Our analysis is intended to identify where each of these forest threats coincide with others to facilitate policy and management.

Methods

Our analysis relies on available spatial data about wildfire potential, insects and disease, and urban and exurban development commonly used by the USDA Forest Service and other agencies in national-level policy and planning activities. We used these data to conduct a neighborhood analysis process using ArcGIS 9.3 focal statistics. Our analysis focused on the five-state region of the northwestern United States, including Idaho, Montana, Oregon, Washington, and Wyoming, encompassing roughly 51.8 million ha.

Wildfire Threat Data

Wildfire threat data were developed by the Fire Modeling Institute, Missoula Fire Sciences Laboratory, Missoula, Montana (Menakis 2008). Estimates of wildfire threat include both crown fire threat and surface fire threat. Crown fire threat was estimated by assigning forest and range cover types to relative categories based on fire intensity, rate of spread, and firebrand production. Likewise, surface fire threat was estimated by categorizing land cover types according to rate of spread and flame length. The estimates of wildfire threat also incorporated the average number of days per year that extreme fire behavior can occur based on

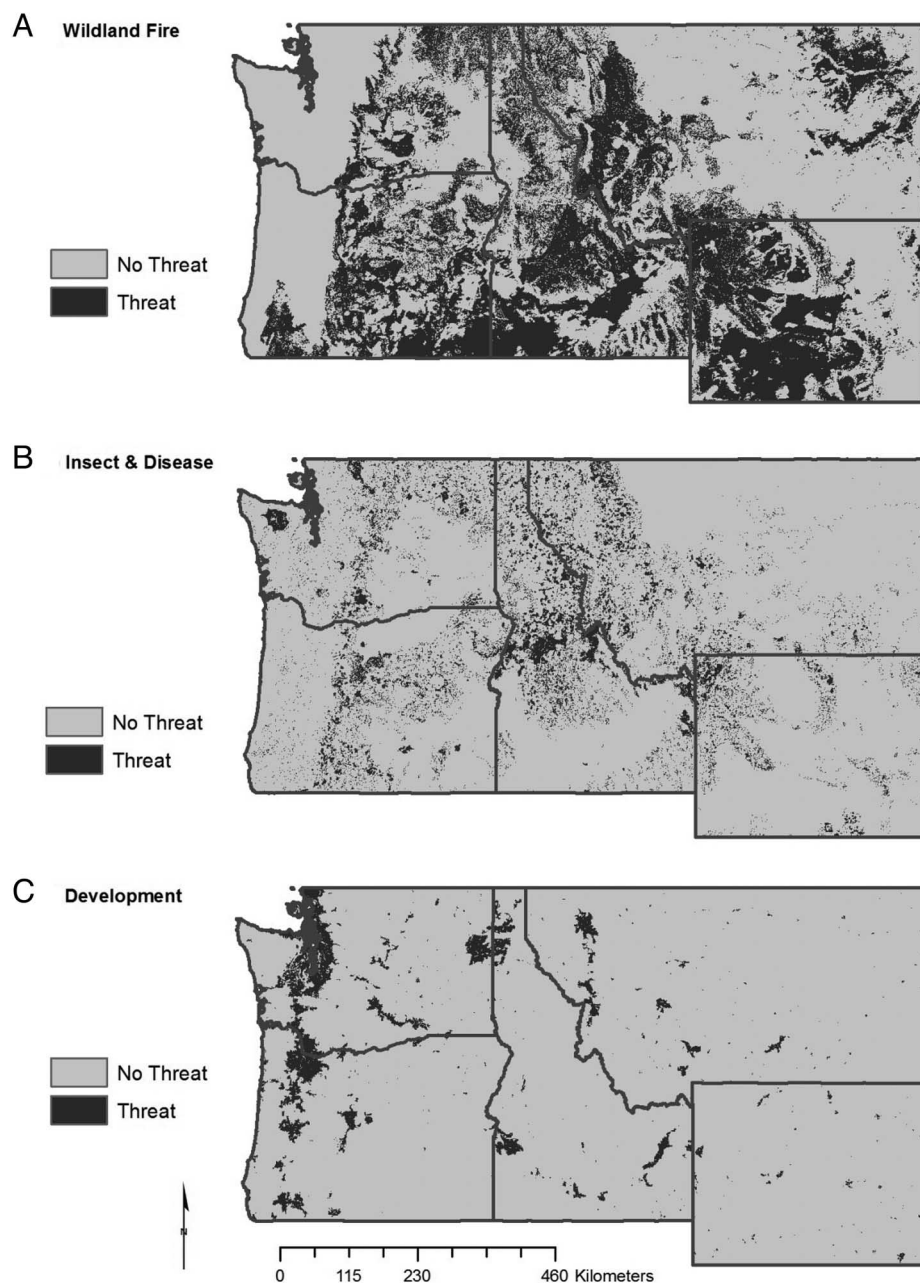


Figure 1. Binary spatial data (1-km raster) layers used to produce the neighborhood maps. Definitions for threat and no threat binary layers are provided in the text.

thresholds of temperature, wind, and humidity and the length of the fire season based on the number of days in which the relative energy release component is greater than 95%. The estimates included both large (greater than 200 ha) and small (less than 0.04 ha) fires (Menakis 2008). The resulting large wildfire threat data describe five classes of fire threat: very low, low, moderate, high, and very high. Although the raster data available are scaled at 1-km spatial resolution, they are intended to be used at no finer than the county level. We used the “high” and “very high” threat classes to identify lands subject to significant wildfire threat

across our five-state study region (Figure 1), consistent with other applications assessing wildfire threat (Menakis et al. 2003).

Insects and Disease Threat Data

Data describing insects and disease came from the 2006 composite National Insect and Disease Risk Map developed by the USDA Forest Service Forest Health Technology Enterprise Team based in Fort Collins, Colorado. The map shows estimates of the future risk of basal area loss to major insects and diseases over a 15-year period (Krist et al. 2007). Building on an earlier

effort (Lewis 2002), the analysis used a multicriteria modeling environment (Eastman et al. 1995, Eastman 2001) to combine 188 individual risk models. Following Krist et al. (2007), we mapped insects and disease threat by defining a risk threshold of 25% expected basal area loss of trees greater than 2.54 cm (1 in.) in diameter over a 15-year period (from 2005 to 2020) absent remediation (Figure 1). The threshold is intended to represent “an uncommon [and] rather extraordinarily high amount of mortality” beyond typical levels that are more than offset by growth of residual trees (Krist et al. 2007, p. 6). The insect and disease data, like the wildfire data, are available at a 1-km spatial resolution, but are intended for planning and policy purposes rather than on-the-ground implementation (Krist et al. 2007).

Problematically for this study, the 2006 composite National Insect and Disease Risk Map includes data gaps resulting from difficulties in estimating risk models and establishing risk thresholds for specific areas, comprising about 12% of our five-state study region. For example, data were missing for some national parks, including Olympic National Park in western Washington and Glacier National Park in northwest Montana, among other areas. We made no attempt to spatially interpolate data values to fill in missing areas. Rather, we examined the insect and disease data, assuming that all missing data met the >25% basal area loss threshold for insect and disease disturbance. The analysis thus presents a “worst-case” scenario.

Urban and Exurban Development Threat Data

Urban and exurban development spatial data were derived from US Census housing data (Radeloff et al. 2010). The data consist of housing density forecasts for 2030 based on 1990s housing growth rates combined with 2008 county population forecasts (Radeloff et al. 2010) and are available for download (Silvis Laboratory 2012). The original polygon data were configured as an irregular lattice defined by US Census block group geography and are considered too coarse for subcounty planning applications (Radeloff et al. 2000). We converted the polygon data into 1-km spatial resolution raster data using maximum area allocation. We categorized the raster housing density data into two discrete classes: <8 housing units per km² and ≥8 housing units per

km², with the latter indicating significant development threat (Figure 1). Our choice of a housing density threshold was based on the threshold for defining the wildland-urban interface (Radeloff et al. 2005b) and the level of urban and exurban development established by previous research (Radeloff et al. 2005a).

Neighborhood Analysis

Our analysis was motivated by the need to display multiple forest threats in a manner that is consistent with the spatial scale at which the source data were intended to be used, and in our case this was the county level. However, we also sought to display combined threats in a manner that transcends the political nature of county boundaries. Our solution was to use a neighborhood analysis process that passed a 25-km circular moving window (1,963 km² in area) over the landscape, returning a value for each disturbance threat for each grid cell (1-km raster cell). We chose a 25-km circular window because it approximated the average size of counties in the five-state study region. The result was a new grid for each individual threat layer in which cell values represented the proportion of neighboring cells indicating threat at the thresholds defined. We then identified individual pixels for which the proportion of neighboring pixels threatened by a given disturbance type was greater than 1 SD above the mean proportion for the entire five-state study region for the given disturbance. We considered this concentration of threat to be “high” relative to the landscape as a whole. The analysis thus identified those areas within the five-state northwestern United States, in which a given disturbance threat may be exceptionally concentrated relative to all other areas. Although data are displayed at 1-km spatial scale, the 25-km neighborhood approach provides a procedure for mitigating the error associated with the individual estimates at the pixel level. The resulting map is applicable for regional level policy and planning purposes. The neighborhood analysis is fairly robust to edge effects because the threat level of every grid cell is contingent on its surrounding 25-km neighborhood.

To illustrate the neighborhood analysis process we used, consider an example pertaining to wildfire (Figure 2). The original wildfire threat layer (Figure 2A) was first converted to a binary threat layer for which threat is defined as no threat (very low, low, and moderate) or high threat (high and very

high; Figure 2B). The 25-km neighborhood analysis then calculated the proportion of surrounding “threat” cells for each pixel within a 25-km circular neighborhood (Figure 2C). The final step identified those locations where wildfire threat within the surrounding 25-km neighborhood is ≥1 SD above the mean neighborhood wildfire threat for the five-state study region (Figure 2D). Note that it is possible for a single pixel initially defined as having high threat to end up defined as having no threat if the pixel is surrounded mostly by other pixels defined as having no threat. The resulting 1-km scale maps show the relative disturbance threat across the study region, highlighting those locations where the threat within a 25-km neighborhood may be greatest in comparison with that at all other locations.

Results

The wildfire threat map (Figure 3A) displays pixels where more than 66% (mean of 36% + 1 SD of 30%) of the surrounding 25-km area was identified as having a high wildfire threat. Based on these criteria, notably higher than average wildfire threat was identified for scattered portions of Washington, southern and central Oregon, central and southwestern Idaho, western Montana, and a large portion of western Wyoming (Figure 3A). Within the five-state region, our neighborhood analysis identified 25 million ha, almost 20% of the land area, as having this notably higher than average concentration of wildfire threat. This wildfire threat was found to involve more land area than both the insects and disease and urban and exurban development threats.

The insect and disease threat map (Figure 3B) displays pixels where more than 20% (mean of 9% + 1 SD of 11%) of the surrounding 25-km area was identified as having a high insect and disease threat. We used a worst-case scenario in which locations with missing data are assumed to meet the >25% basal area loss threshold. In this case, our neighborhood analysis identified about 18.7 million ha or 15% of the study area as having a notably higher than average concentration of insect and disease threat in the five-state region. The neighborhood analysis of the insect and disease data show significant areas of insect and disease threat in western, central, and eastern Washington, central and eastern Oregon, much of central Idaho, parts of western Montana, and the northwest corner of Wyoming (Figure 3B). An example of an implication of our missing

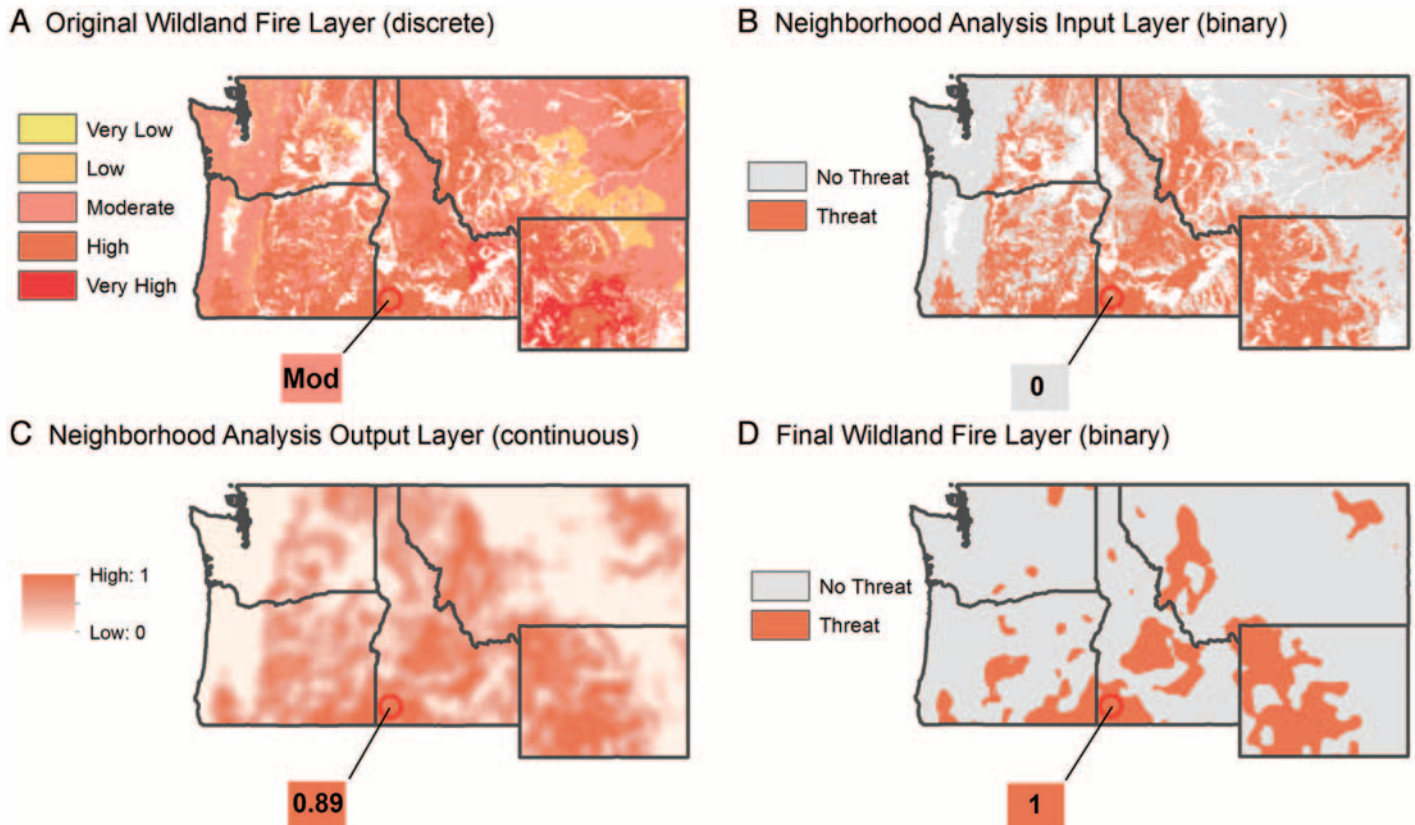


Figure 2. Example of analytical steps of neighborhood analysis for wildfire potential depicting values for one example pixel.

data assumption is that a portion of the Olympic Peninsula in Washington is identified as subject to insect and disease threat but only because we assumed that the missing data for the Olympic National Park met the insect and disease >25% basal area loss threshold.

The urban and exurban development threat map (Figure 3C) displays areas where 19% (mean of 14% + 1 SD of 5%) of the surrounding 25-km area was identified as having a notably higher than average level of urban and exurban development threat. Neighborhood analysis indicates that the greatest concentration of urban and exurban development threat extends from northwest Washington south through western Oregon (Figure 3C). More isolated pockets of development threat appear in southwestern Oregon (around Grants Pass and Medford), central Oregon (Bend and Redmond), central (Yakima, Kennewick, and Richland) and eastern (Spokane) Washington, northern Idaho (Coeur d'Alene), southwest Idaho (Boise, Nampa, and Ontario), southern Idaho (Twin Falls), eastern Idaho (Idaho Falls), and western Montana (Missoula, Helena, Bozeman, and Kalispell). Although it is difficult to detect in some places at the scale of our maps, much of the projected

development threat appears to coincide with existing transportation corridors, such as Interstate 5 in western Washington and Oregon between the Coast and Cascades Mountain ranges. Neighborhood analysis identified about 11.7 million ha (9%) of the five-state study as having a notably higher than average concentration of urban and exurban development threat. Our resulting development threat map appears less pixelated and more similar to the binary data maps in Figure 1C (relative to the wildfire and insects and disease neighborhood maps) largely due to the concentration of projected population growth and development near existing urban areas.

Figure 4 shows combined forest threat intersections based on our three 25-km radius neighborhood analyses. The wildfire and insect and disease threat intersection by far comprises the largest area, covering more than 5.5 million ha for the five-state region. Combinations of insects and disease with urban and exurban development threat are the next largest threat intersection but cover a much smaller land area at <1 million ha. Insects and disease intersected urban and exurban development in central and southern Oregon and in northern Idaho and western Montana. Interestingly, given the

level of concern it garners in public policy settings, wildfire threat intersects with urban and exurban development threat on less than ½ million ha, in places like southwestern Oregon, western Montana, and western Wyoming. The intersection of all three threats occurs in only five pockets within the five-state study region, totaling about 155,400 ha. These “triple threat” areas are found in Oregon’s interior south of Bend and near La Pine, north and south of Missoula, Montana, and near Victor and Wilson on the Idaho/Wyoming border. We examined the implications of our missing data assumption regarding insects and disease by conducting an alternative analysis, assuming that all missing data indicate “no threat.” Using the same threshold (about 20% of the surrounding 25-km area) for a direct comparison, we found that only two areas in the five-state region were identified as having all three threats: the area south of Bend, Oregon and the area south of Missoula, Montana.

Discussion

Our maps highlight the intersection of locations where a given disturbance threat exists at notably above the average concentration relative to other areas in the five-state

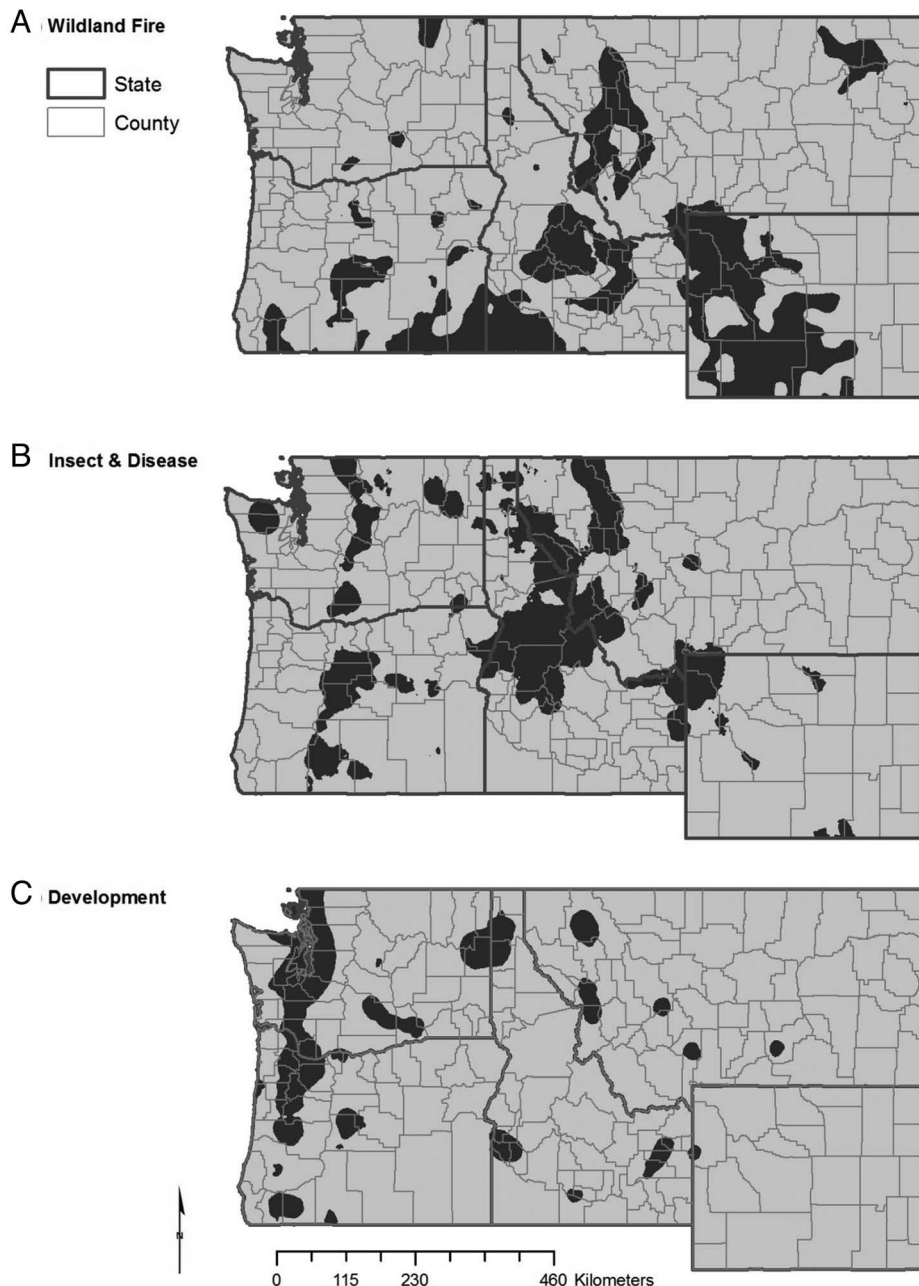


Figure 3. Wildfire, insects and disease, and urban and exurban development threat maps based on a 25-km neighborhood analysis. Threats are mapped where individual pixels are ≥ 1 SD above the mean neighborhood threat for the five-state study region.

study region. Our maps suggest that the combination of wildfire with insects and disease could affect extensive portions of the forest landscape in the northwestern United States. Although prevalent as a policy concern, the combination of wildfire with urban and exurban development appears to intersect over a much smaller area. Although the intersection between wildfire and development appears to occur on a relatively small share of the northwestern United States landscape, the issue for policymakers and managers may still be significant as a policy

concern because conceivably it could affect a substantial number of people even though it may affect a small area of land. Our analysis suggests that the potential for a combined triple threat in the study region—wildfire, insects and disease, and urban and exurban development—is fairly uncommon, despite our worst case assumption regarding the missing data for insects and disease potential.

We stress that our approach highlights areas of high relative threat based on the spatial distribution and concentration of poten-

tial threats across the landscape examined. Therefore, pixels of high threat that were not surrounded (within 25 km) by a greater-than-average proportion of other pixels of high threat were dropped. For example, areas of central Oregon identified as subject to high wildfire potential on the original source map did not appear on the 25-km radius neighborhood analysis map because of the highly fragmented nature of the wildfire potential distribution in this area. In comparison, wildfire potential data were much less pixelated in other areas of the study region, resulting in substantial areas of continuous mapped wildfire threat. Our analysis assumes that from a national or regional perspective, these large continuous (or concentrated) areas of threat may warrant greater concern than smaller areas with more fragmented threat, especially when we take into account the spatial scale at which the wildfire data were intended to be used. We do not intend such results to dismiss the potential for more fragmented wildfire threat in places like central Oregon. Rather, our analysis suggests that this may be an issue of more local rather than national or regional concern.

The urban and exurban development and insect and disease data indicate a much sparser distribution of these threats across the study region, with some local concentrations. Therefore, these threats were characterized by a much lower inclusion threshold, 19 and 20%, respectively. Obviously the treatment of missing insect and disease data influenced our results. We assumed a worst case scenario but suggest that policymakers and managers will want to carefully consider the influence that missing data may have on resulting regional- and national-level assessments. Although this consideration would appear to be intuitively obvious, missing data could make such assessments unreliable for identifying locations where threat mitigation dollars might be targeted. In places where missing data are a concern, local knowledge may be useful for augmenting national and regional threat assessments.

Conclusions

To our knowledge, although data describing forest threats are widely used by policymakers and managers, efforts to combine and display the intersections of multiple threats have received little attention in published research literature. We examined spatial data characterizing wildfire, insects and disease, and urban and exurban devel-

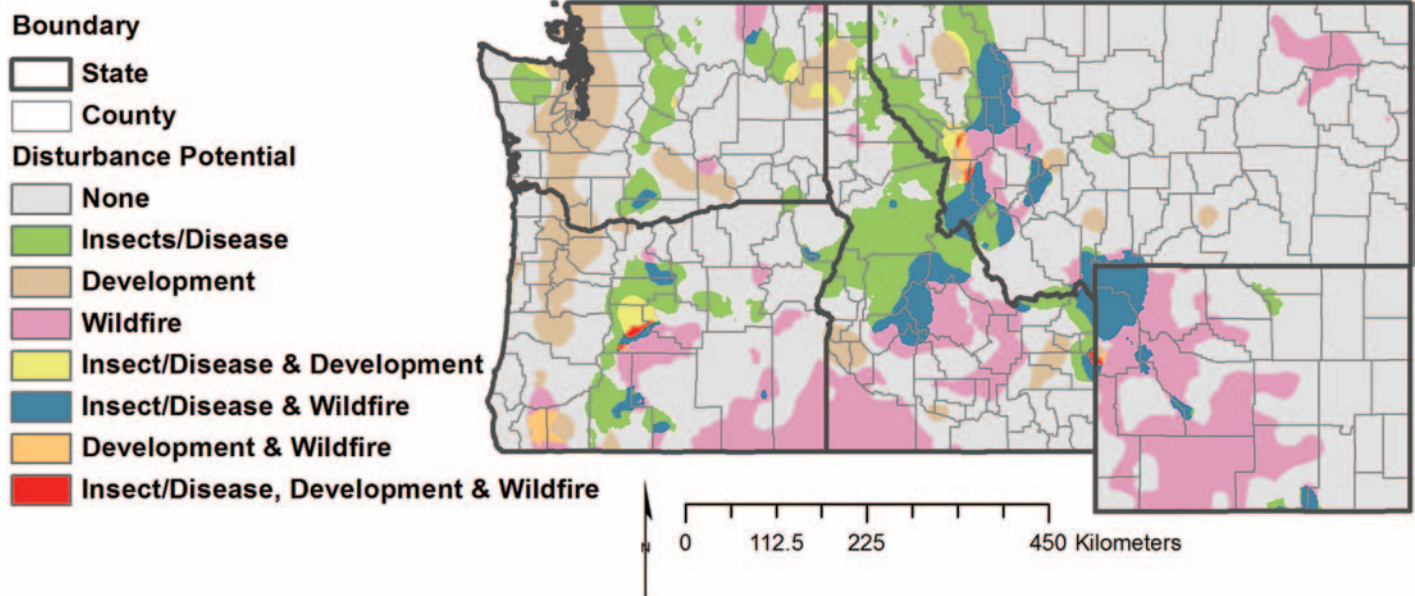


Figure 4. The threat intersection map for wildfire, insects and disease, and urban and exurban development using the 25-km neighborhood maps. Missing insect and disease data were defined as “threat” in this worst-case scenario.

opment in the northwestern United States using a novel 25-km radius neighborhood analysis to highlight the locations where a given disturbance threat might be more concentrated relative to that for all other areas. We assumed that areas with relatively more concentrated threat may be of more policy interest than other areas. Our maps suggest three conclusions: that the combination of wildfire with insects and disease could affect extensive portions of the forest landscape in the northwestern United States; that the combination of wildfire with urban and exurban development appears to intersect over a much smaller area; and that a combined triple threat in the study region, wildfire, insects and disease, and urban and exurban development, is fairly uncommon, despite our worst-case assumption regarding the missing data for insects and disease potential.

Ideally, multiple threat assessments would depend on precise scientific information characterizing disturbance threats and the likely spatial extents over which interactions among different threats might actually occur (e.g., wildfire combined with insects and disease). Such refined data, however, often are lacking at national and regional levels. In this absence, neighborhood analysis and overlays can help policymakers and managers to locate and consider the implications of potential disturbance combinations on forest landscapes. Our approach provides a standardized way to display combined threat data using spatial analysis at a scale appropriate for planning and policy

purposes and in a manner that transcends political county boundaries. The approach also is relatively straightforward and does not involve “indices” or other metrics that may obscure underlying data characterizing forest threats.

We believe that this approach has a few distinct advantages. First, it bases the spatial scale of analysis (25-km) on suggestions from data sources about the appropriate scale of data use, using the coarsest suggestions as a general guide. The approach results in a conservative analysis that reduces the potential for propagating errors that may be present in original fine-scaled maps that are nonetheless based on coarse-scaled data. Second, the approach enables the relevant threshold for determining threats to be driven by data rather than a priori assumptions about pertinent threat thresholds. For our purposes, we defined threat thresholds as 1 SD above mean threat levels for the landscape. The approach highlights places where threat levels are most prevalent in comparison with other locations across a broader landscape of interest. In this way, the approach would be useful for establishing regional and national priorities, for example. Last, by mapping threats in a manner that transcends county boundaries, the approach enables the display of the distribution of threats within any desired political boundary while remaining true to the intended use of the source data.

Future analysis regarding methods for evaluating and displaying forestland threats

would probably benefit by including additional potential threats, specifically climate change. Future analysis also could include consideration of other socioeconomic factors, such as social vulnerability measures (e.g., Cutter and Finch 2008). Also useful would be validation testing of output data, by cross-referencing mapped threats with known facts about specific areas (e.g., comparing recent wildfires to areas recently experiencing insect and disease). Perhaps most importantly, greater research effort is needed to examine how individual disturbances might actually interact, what their combined consequences might be, and over what spatial extent they occur. Ultimately, the appropriate spatial scales at which disturbance data are analyzed depend on the objective of the analysis and the spatial resolution of available data. Limitations imposed by the spatial scales at which disturbance data are created may preclude accounting for the actual variation in spatial scales at which ecological processes influence forest disturbance patterns. Although our neighborhood analysis may provide a useful method for displaying combined threat data, our resulting maps should not be interpreted as representing the actual spatial extent of disturbance combinations. Currently, such information is largely speculative in most landscape applications.

Literature Cited

ARONSON, G., AND D. KULAKOWSKI. 2012. Bark beetle outbreaks, wildfires and defensible

- space: How much area do we need to treat to protect homes and communities? *Int. J. Wildl. Fire* 22(2):256–265.
- CALKIN, D.E., A.A. AGER, AND J. GILBERTSON-DAY, EDS. 2010. *Wildfire risk and hazard: Procedures for the first approximation*. USDA For. Serv., Gen. Tech. Rep. RMRS-GTR-235, Rocky Mountain Research Station, Fort Collins, CO. 62 p.
- COLLINS, S., AND E. LARRY. 2007. *Caring for our natural assets: An ecosystem services perspective*. USDA For. Serv., Washington, DC. 11 p.
- COVINGTON, W.W., R.L. EVERETT, R. STEELE, L.L. IRWIN, T.A. DAER, AND A.N.D. AUCLAIR. 1994. Historical and anticipated changes in forest ecosystems of the inland West of the United States. *J. Sustain. For.* 2(1&2):13–64.
- CUTTER, S.L., AND C. FINCH. 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proc. Natl. Acad. Sci. USA* 105:2301–2306.
- D'ANTONIO, C.M., AND P.M. VITOUSEK. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annu. Rev. Ecol. Syst.* 23:63–87.
- DONOVAN, G.H., AND T.C. BROWN. 2005. An alternative incentive structure for wildland fire management on National Forest land. *For. Sci.* 51:387–395.
- EASTMAN, J.R. 2001. Uncertainty management in GIS: Decision support tools for effective use of spatial data. P. 379–390 in *Spatial uncertainty in ecology: Implications for remote sensing and GIS applications*, Hunsaker, C., M. Goodchild, M. Friedl, and E. Case (eds.). Springer-Verlag, New York.
- EASTMAN, J.R., J. WEIGEN, P.A.K. KYEM, AND F. TOLEDANO. 1995. Raster procedures for multi-criteria/multi-objective decisions. *Photogramm. Eng. Remote Sens.* 61(5):539–547.
- GAVIER-PIZARRO, G.I., V.C. RADELOFF, S.I. STEWART, C.D. HUEBNER, AND N.S. KEULER. 2010. Housing is positively associated with invasive exotic plant species richness in New England, USA. *Ecol. Appl.* 20(7):1913–1925.
- GOVERNMENT ACCOUNTABILITY OFFICE. 2005. *Protecting structures and improving communications during wildland fires: A report to congressional requesters*. GAO-05-380, Washington, DC. 115 p.
- GROFFMAN, P.M., J.S. BARON, T. BLETT, A.J. GOLD, I. GOODMAN, L.H. GUNDERSON, B.M. LEVINSON, ET AL. 2006. Ecological thresholds: The key to successful environmental management or an important concept with no practical application? *Ecosystems* 9:1–13.
- HICKE, J.A., M.C. JOHNSON, J.L. HAYES, AND H.K. PREISLER. 2012. Effects of bark beetle-caused tree mortality on wildfire. *For. Ecol. Manage.* 271:81–90.
- HOFFMAN, C., P. MORGAN, W. MELL, R. PARSONS, E.K. STRAND, AND S. COOK. 2012. Numerical simulation of crown fire hazard immediately after bark beetle-caused mortality in lodgepole pine forests. *For. Sci.* 58(2):178–188.
- KLINE, J.D. 2004. *Issues in evaluating the costs and benefits of fuels treatment to reduce wildland fire in the nation's forests*. USDA For. Serv., Res. Note PNW-RN-542, Pacific Northwest Research Station, Portland, OR. 26 p.
- KRIST, F.J., F.J. SAPIO, AND B.M. TKACZ. 2007. *Mapping risk from forest insects and diseases*. USDA For. Serv., FHTET 2007-06, Washington, DC. 115 p.
- LEWIS, J.W. 2002. *Mapping risk from forest insects and diseases*. USDA For. Serv., FS-754, Washington, DC. 60 p.
- LOGAN, J.A., J. REGNIERE, AND J.A. POWELL. 2003. Assessing the impacts of global warming on forest pest dynamics. *Front. Ecol. Environ.* 1:130–137.
- MAESTAS, J.D., R.L. KNIGHT, AND W.C. GILBERT. 2001. Biodiversity and land-use change in the American Mountain West. *Geogr. Rev.* 91(3):509–524.
- MCCULLOUGH, D.G., R.A. WERNER, AND D. NEUMANN. 1998. Fire and insects in northern and boreal forest ecosystems of North America. *Annu. Rev. Entomol.* 43:107–127.
- MCGRANAHAN, D.A. 2008. Landscape influence on recent rural migration in the US. *Landsc. Urban Plann.* 85:228–240.
- MENAKIS, J. 2008. *Wildland fire risk to flammable structures from Forest Service lands: A ranking of forests*. Unpublished report. On file with J. Menakis, USDA For. Serv., Rocky Mountain Research Station, Fire Modeling Institute, Missoula, MT. 14 p.
- MENAKIS, J.P., J. COHEN, AND L. BRADSHAW. 2003. Mapping wildland fire risk to flammable structures for the conterminous United States. P. 41–49 in *Proc. of Fire conference 2000: The first national congress on fire ecology, prevention, and management*, Galley, K.E.M., R.C. Klinger, and N.G. Sugihara (eds.). Tall Timbers Research Station, Misc. Publ. No. 13, Tallahassee, FL.
- MERCER, D.E., AND J.P. PRESTEMON. 2005. Comparing production function models for wildfire risk analysis in the wildland–urban interface. *Forest Policy Econ.* 7:782–795.
- NATIONAL INTERAGENCY COORDINATION CENTER. 2013. *Wildland fire summary and statistics annual report 2012*. National Interagency Fire Center, Boise, ID. 9 p.
- OFFICE OF INSPECTOR GENERAL, WESTERN REGION. 2006. *Forest Service large fire suppression costs*. USDA, Rep. No. 08601-44-SF, Office of Inspector General, Western Region, Washington, DC. 47 p.
- PAINE, R.T., M.J. TEGNER, AND E.A. JOHNSON. 1998. Compounded perturbations yield ecological surprises. *Ecosystems* 1:535–545.
- RADELOFF, V.C., A.E. HAGEN, P.R. VOSS, D.R. FIELD, AND D.J. MLADENOFF. 2000. Exploring the spatial relationship between census and land-cover data. *Soc. Nat. Resour.* 13(6):599–609.
- RADELOFF, V.C., R.B. HAMMER, AND S.I. STEWART. 2005a. Sprawl and forest fragmentation in the US Midwest from 1940 to 2000. *Conserv. Biol.* 19(3):793–805.
- RADELOFF, V.C., R.B. HAMMER, S.I. STEWART, J.S. FRIED, S.S. HOLCOMB, AND J.F. MCKEEFRY. 2005b. The wildland-urban interface in the United States. *Ecol. Appl.* 15(3):799–805.
- RADELOFF, V.C., S.I. STEWART, T.J. HAWBAKER, U. GIMMI, A.M. PIDGEON, C.H. FLATHER, R.B. HAMMER, AND D.P. HELMERS. 2010. Housing growth in and near United States' protected areas limits their conservation value. *Proc. Natl. Acad. Sci. USA* 107(2):940–945.
- SAMPSON, R.N., R.D. ATKINSON, AND J.W. LEWIS. 2000. *Mapping wildfire hazards and risks*. Food Products Press, New York. 343 p.
- SCHWILK, D.W., E.E. KNAPP, S.M. FERRENBURG, J.E. KEELEY, AND A.C. CAPRIO. 2006. Tree mortality from fire and bark beetles following early and late season prescribed fires in a Sierra Nevada mixed-conifer forest. *For. Ecol. Manage.* 232:36–45.
- SILVIS LABORATORY. 2012. *1940–2030 housing density/growth data and maps*. University of Wisconsin, Madison, WI. Available online at silvis.forest.wisc.edu/maps/housing/pbg_1940_2030; last accessed Mar. 5, 2013.
- USDA FOREST SERVICE. 2006. *Ecosystem restoration: A framework for restructuring and maintaining the national forests and grasslands*. USDA For. Serv., Washington, DC. 24 p.
- USDA FOREST SERVICE. 2007. *USDA Forest Service strategic plan FY 2007–2012*. USDA For. Serv., FS-880, Washington, DC. 32 p.