Development at the wildland–urban interface and the mitigation of forest-fire risk

Vassilis Spyratos[†‡], Patrick S. Bourgeron[§], and Michael Ghil[†¶‖††]

[†]Environmental Research and Teaching Institute, [‡]Physics Department, and [¶]Earth-Atmosphere-Ocean Department and Laboratoire de Météorologie Dynamique (Centre National de la Recherche Scientifique and Institut Pierre-Simon Laplace), Ecole Normale Supérieure, F-75231 Paris Cedex 05, France; [§]Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, UCB 450, Boulder, CO 80309; and [‖]Department of Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095

Communicated by Donald L. Turcotte, University of California, Davis, CA, May 19, 2007 (received for review April 19, 2006)

This work addresses the impacts of development at the wildland–urban interface on forest fires that spread to human habitats. Catastrophic fires in the western United States and elsewhere make these impacts a matter of urgency for decision makers, scientists, and the general public. Using a simple fire-spread model, along with housing and vegetation data, we show that fire size probability distributions can be strongly modified by the density and flammability of houses. We highlight a sharp transition zone in the parameter space of vegetation flammability and house density. Many actual fire landscapes in the United States appear to have spreading properties close to this transition. Thus, the density and flammability of buildings should be taken into account when assessing fire risk at the wildland–urban interface. Moreover, our results highlight ways for regulation at this interface to help mitigate fire risk.

fire-spread model | percolation theory | regime diagram | regulatory policy | threshold behavior

Development at the wildland–urban interface (WUI), as currently defined in the United States (1–3), seriously modifies fire risk in forested areas (3). The WUI occupies 9% of the surface and contains almost 39% of all housing units within the conterminous United States (3). Various impacts of human settlement and land use on fire patterns have been well documented (4–8); however, the way that the presence and flammability properties of houses modify fire size and pattern has not yet been studied. In the present work, we integrate these aspects of WUI houses into a fire-spread model (9–11). Plotting our modeled fire sizes as a function of the vegetation's fire-spread probability p and house density d, we show that fire sizes depend very nonlinearly on p and d, giving rise to a sharp, threshold-like transition zone in the model's parameter space. Fire size in this transition zone is very sensitive to p and d.

Using observational data and an empirical approach to estimate fuel landscape properties (3, 12, 13), we show that many actual WUI fire landscapes have flammability properties close to our simple model's transition zone. The results presented here suggest, therefore, that house densities and flammability should inform fire risk assessments in and near the WUI. Moreover, regulation of construction in the WUI could thus be used to reduce or mitigate fire risk in these areas.

In the next section, we formulate the fire-spread model, in which uniform vegetation is modified by the presence of flammable or fire-proofed houses. We then present the main results, followed by their implications for WUI development. Details on data and methods appear in the final section.

Modified Fire-Spread Model

The effects of forest fires are especially dramatic in the WUI: in this zone, wild-land fuels overlap with homes and communities (14, 15); fire occurrence, therefore, has high human and socioeconomic costs (16, 17). Development in the WUI (1–3), defined here as the construction of houses and other structures within a matrix of forests, shrubs, or grassland (15, 18) that is still close to the original ecosystem (19), greatly modifies fire risk. As previously stated, the WUI occupies ≈10% of the surface and contains ≈40% of all housing units within the conterminous United States (3). The WUI is also widespread across other developed countries, thus requiring the rapid development of tools for assessing fire risks (15) and for hazard mitigation.

Studies on propagation of fires in the WUI have largely focused on the relationships between fuel loading and fire intensity, fuel reduction, and housing protection, as reflected by the study of fire-risk assessment (15), role of fire breaks (18), and restoration strategies (20, 21). Although the relationships between fire intensity, structure ignition, and flammability have been studied (22, 23), the contribution of housing units to the pattern of fire spread is not well understood. In recent comprehensive reviews of fire, fuels, and climate in Rocky Mountain forests (24) and the management of such forests (25, 26), the emphasis is on fuel reduction, prescribed burning, and restoration. Similarly, the role of fire breaks has only been studied in the context of vegetation management (18, 27).

No model so far takes into consideration the direct influence of houses on fire spread at the landscape scale. Simple models of landscape behavior have revealed their ability to successfully replicate major aspects of complex landscape patterns (5, 12, 27–29). Here, we use a simple fire-spread model to investigate whether, because of nonlinear threshold effects, a small density of houses may have substantial impacts on fire propagation at the landscape scale, according to whether they are fire proofed or not.

To explore the qualitative influence of the presence of houses on fire spread, we considered only uniform landscapes and fire spread as a simple percolation process (9–11), with given house densities and flammabilities. Wind, topography, fuel heterogeneities, firebrands, and weather affect actual fire spread (10, 12). The present theoretical results therefore would need to be integrated into more detailed fire models before practical, quantitative applications of the present results could be entirely successful.

Our model represents the landscape as a two-dimensional lattice of 48 × 48 cells (see modeling details in *Data and Methods*). A density d of house cells is distributed at random in a homogeneous grid of vegetation cells. Fire is ignited in a randomly chosen cell and spreads from neighbor to neighbor. Cells burn at most once, and the sides of the lattice are composed of nonburning cells. Fire propagates at the next time step from a burning vegetation cell to any of the unburned cells among its

---

Author contributions: V.S., P.S.B., and M.G. contributed equally to this work; P.S.B. suggested the problem and provided data; M.G. designed research; V.S. performed research; V.S. analyzed data; and V.S., P.S.B., and M.G. wrote the paper.

The authors declare no conflict of interest.

Abbreviation: WUI, wildland–urban interface.

[††]To who correspondence should be addressed at: Environmental Research and Teaching Institute (CERES-ERTI), Ecole Normale Supérieure, 24, Rue Lhomond, F-75231 Paris Cedex 05, France. E-mail: ghil@lmd.ens.fr.

www.pnas.org/cgi/doi/10.1073/pnas.0704488104

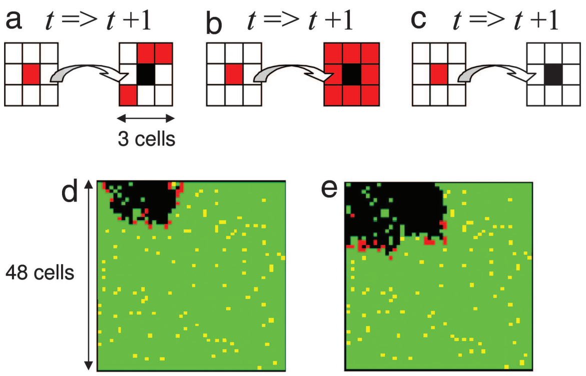

Fig. 1. Schematic diagram of fire spread in our model. (*a*–*c*) Fire spreading from neighbor to neighbor during one time step. The central cell ignited at step *t* is a vegetation cell (*a*), a highly flammable house cell (*b*), or a fire-proofed house cell (*c*). Surrounding cells are unburned and may be either vegetation or house cells. Red cells are on fire; black cells have already burned and cannot burn again; white cells are unburned. (*d* and *e*) Example of fire spread over the entire model landscape (for $p = 0.35$; $d_1 = 0.05$). Red cells are on fire; black cells have already burned and cannot burn again; green cells are unburned vegetation cells; yellow cells are unburned house cells.

eight nearest neighbors as an independent stochastic event with probability p (see Fig. 1).

Actual fuel loadings in a building are typically many times those in a forest (30). On the other hand, the fire proofing of a house and of its immediate vicinity significantly reduces the house's ignition probability (17). Thus, we considered two categories of house cells: those that are highly flammable, with a fire-spread probability $p_h = 1$, so that fire spreads to all of the unburned cells among their nearest neighbors, and those with $p_h = 0$, not propagating fire at all. Within a given simulation, all house cells have the same flammability, i.e., the same value of p_h. We distinguish between house densities d_1 when $p_h = 1$ and d_0 when $p_h = 0$; these densities can vary between 0 and 1 from one simulation to another. Fig. 1 illustrates fire spreading from neighbor to neighbor in our model during one time step, as well as fire spreading across the entire modeled landscape. The simulation ends when no new cell is ignited.

Thus, our model is similar to the simplest version of the forest-fire model EMBYR (12), with homogeneous vegetation and no wind, into which a density d of house cells has been introduced. We define fire size S as the number of burnt cells divided by the total number of cells. For each pair of p and d values, we performed 1,000 simulations to calculate the average fire size $\langle S \rangle$ and fire size distribution $P(S)$.

Model Results

Our model is inspired by percolation theory but goes beyond it in several ways. The former refers to infinite domains and deals with the exact value of critical thresholds p_c (9), whereas any ecological domain has finite size, as do our simulated landscapes. In our finite-domain results, the evaluation of p_c is replaced by the detection of a sharp transition zone in parameter space: across this zone, the landscape's fire-spread properties change radically, as we shall see forthwith.

Homogeneous Flammability. The parameter setting $d = 0$ in our model corresponds to classical percolation over a uniform lattice of finite size, with each cell having eight nearest neighbors. The mean fire size $\langle S \rangle$ is plotted in Fig. 2 as a function of the neighbor-to-neighbor fire-spread probability p; this function has a characteristic sigmoid shape associated with threshold phenomena.

We defined five fire classes. Landscapes with a mean fire size $\langle S \rangle$ between 0% and 20% of the total lattice size belong to fire class 1; classes 2–5 lie in the ranges 20.01–40%, 40.01–60%, 60.01–80%, and 80.01–100%, respectively. The size distribution of all 1,000 fires for each (p, d) pair was calculated, and selected results are shown in Fig. 3. Class 1 landscapes sustain only small fires (Fig. 3*a*); these landscapes lie below our model's generalized percolation threshold and will be called "subcritical." The "transition zone" is composed of classes 2 and 3; these exhibit bimodal fire size distributions and fires that attain all but the largest sizes (Fig. 3 *b* and *c*). More than 90% of the fires in classes 4 and 5 propagate across the entire grid, although unburned areas may be left behind as the fires spread (Fig. 3 *d* and *e*); they lie above our generalized percolation threshold and will be called "supercritical."

In subcritical landscapes, mean fire size is small (Fig. 2), and so is almost every fire (Fig. 3*a*). Mean fire size increases rapidly across the transition zone (Fig. 2). Supercritical landscapes sustain mainly percolating fires (Fig. 3 *d* and *e*), whose mean fire size is close to the total size of the domain (Fig. 2). These patterns are easily explained on physical grounds. For low p, fire

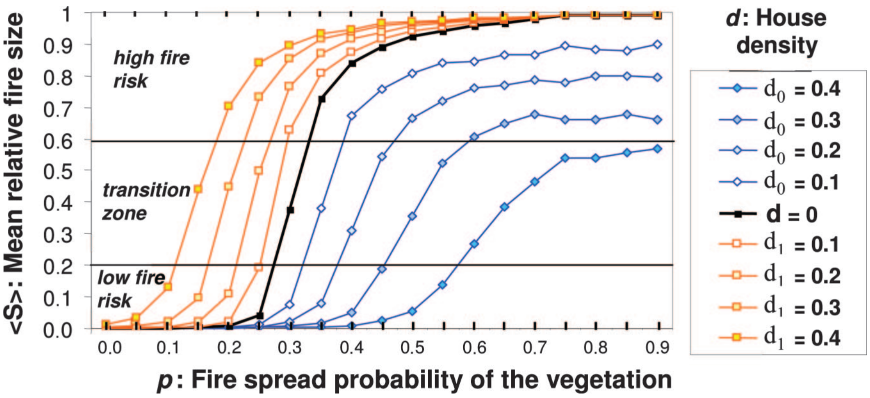

Fig. 2. Mean relative fire size $\langle S \rangle$ as a function of the vegetation's probability p of fire spread for different values of house density d and for different house flammabilities. Size $\langle S \rangle$ is the mean number of burnt cells divided by the total number of cells, and p is the probability of the fire spreading from a given vegetation cell to any of its eight nearest neighbors. The density of house-occupied cells is d; for different house flammabilities, $d = d_0$ or d_1. Here d_0 is the density of houses that are all fire proofed ($p_h = 0$), and d_1 is the density of flammable houses ($p_h = 1$). Mean fire sizes were calculated for 1,000 realizations for each value of p from 0.0 to 0.9 in steps of 0.05 and of d_0 or d_1 from 0.0 to 0.4 in steps of 0.1. Black curve is for a homogeneous, vegetation-only fire landscape, $d = 0$; orange and blue curves are for flammable or fire-proofed houses, respectively, with additional symbols defined in the key. Increasing p or d_1 or decreasing d_0 all increase the mean fire size $\langle S \rangle$; remarkably, this increase is very sharp within the transition zone. Indeed, modifying the value of p or d by only 0.1 often suffices to switch the fire-spread properties of a landscape in or close to the transition zone, from sub- to supercritical or vice versa.

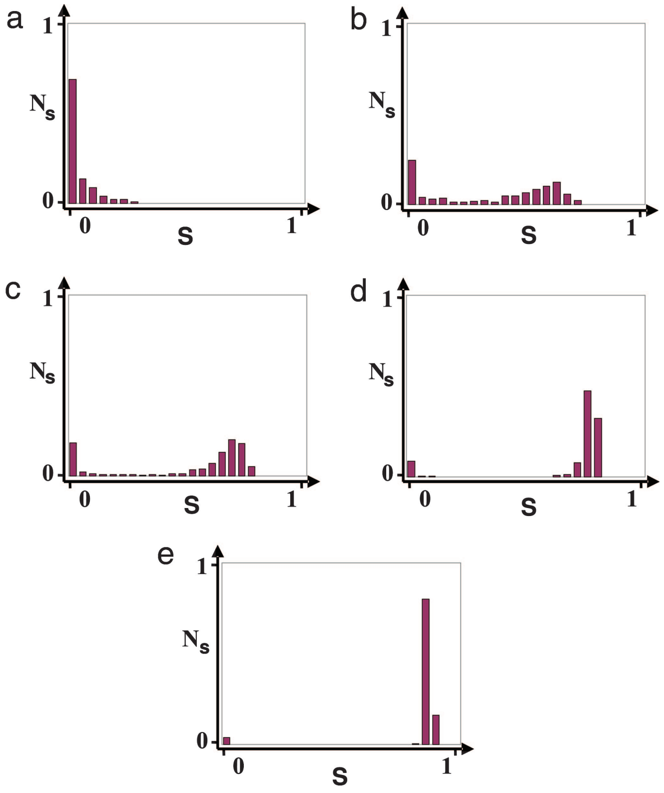

Fig. 3. Histograms $P = P(S)$ of relative fire sizes S for landscapes in each of the five fire classes described in the text. Here N_S is the normalized number of fires of size S, where S is sorted into ''unit'' bins of 100 cells. The histograms are based on 1,000 realizations of the fire-spread process. The fire size distributions in *a*–*e* represent characteristic landscapes in fire classes 1–5, respectively. These histograms were obtained for (p, d) = (0.25, 0.0), (0.30, 0.0), (0.30, 0.05), (0.35, 0.0), and (0.40, 0.0), respectively; the corresponding points a–e are shown in the regime diagram of Fig. 4*a*. No fires in class 1 landscapes reach large size (*a*), whereas almost every fire covers most of the domain in class 5 landscapes (*e*). The sequence of fire size distributions *a*–*e* illustrates details of how the transition zone shown in Fig. 2 is crossed as p or d change, i.e., the sharp increase of the probability that a large fire occurs.

often fails to propagate from a burning cell in all directions: the resulting burned areas are generally small, with a dendritic burn pattern. For values of p close to 1, the probability $(1 - p)^8$ that the first ignition fails to propagate is still nonzero but, once the fire reaches some minimal size, it does propagate rapidly and covers a large portion of the domain in a generally solid pattern. Thus, a large number of extensive fires dominates the resulting fire size distributions $P(S)$, accompanied by a small peak at very small fires. The fact that $(1 - p)^8 \neq 0$ accounts for the fire leaving occasionally unburned patches and thus not covering the entire domain.

Inhomogeneous Flammability. In the presence of houses ($d \neq 0$), the sigmoid aspect of the function $\langle S \rangle = f(p; d)$ is similar to the previous, uniform case (Fig. 2), but the value of the threshold is displaced: to lower p for flammable houses (with $p_{\mathrm{h}} = 1$) and to higher p for fire-proofed ones (with $p_{\mathrm{h}} = 0$). The mean $\langle S \rangle$ is plotted as a function of p and d in Fig. 4*a*. Landscapes that were in the transition zone when no houses were present become subcritical, given a sufficient density d_0 of fire-proofed houses, and supercritical when the density of flammable houses d_1 is sufficiently large.

For any density d, we define the critical vegetation flammability $p^*(d)$ as the p for which $\langle S \rangle(p; d) = S_0$ burnt cells, with $S_0 = 40\%$ of the total lattice size. The curve $p^* = p^*(d)$, visible as the heavy solid line between fire classes 2 and 3 in Fig. 4, highlights the transition zone and shows its displacement with d. Whereas p^* decreases fairly linearly with d_1, it increases almost quadratically with d_0. The transition zone is quite narrow, and even a low density of houses suffices to drastically change the fire-spread properties of landscapes that were in or close to the transition zone.

Thus, in our model, an undeveloped landscape with $p = 0.3$ and $d = 0$ is in the transition zone. Developing such a landscape by the construction of flammable or, to the contrary, fire-proofed houses will lead to a drastically different situation. A density $d_0 = 0.05$ of fire-proofed houses suffices to move the landscape into the subcritical zone, whereas a density $d_1 = 0.10$ of flammable houses moves it into the supercritical zone. For a vegetation flammability of $p = 0.35$, a switch from $d_1 = 0.15$ to $d_0 = 0.15$, i.e., the fire proofing of a density $d = 0.15$ of houses, switches the landscapes all of the way from the supercritical to the subcritical zone (Fig. 4*b*). These switches strongly modify the landscape's distribution of fire sizes, as seen in Fig. 3.

To obtain a similar fire risk reduction of a developed landscape by fuel treatment only would require decreasing p from 0.35 to 0.20; such an approach requires restoration efforts that are quite costly and lengthy, while keeping the landscape at high fire risk during this time. Bold white arrows in Fig. 4*b* show the impact on mean fire size of a reduction of the vegetation's flammability (vertical arrow) vs. fire proofing the houses (horizontal arrow). We conclude that, in our model, fire risk for fuel landscapes that are in or near the transition zone can be easily modified by fire proofing the houses interspersed into the landscape.

Applicability to Existing Data

Comparison of our model results with actual fire-spread data and WUI maps supports the potential of this approach for fire-risk assessment and modification in and near the WUI. For this comparison, we used fire-spread data prepared for the EMBYR model (12). This data set provides estimated probabilities of spread for four successional vegetation stages and three fuel-moisture classes for high-elevation lodgepole pine forest ecosystems in Yellowstone National Park. The corresponding flammability values for the vegetation grids that we considered range from $p = 0.01$ for the wettest recently burned forest to $p = 0.4$ for the driest late successional stages. Wind can increase these values up to 0.6 in extreme fuel and weather conditions. Fire-spread probabilities between 0.3 and 0.4 were prominent in several EMBYR simulations of real fires (12). See *Data and Methods* for details on both this paragraph and the next one; see also the SILVIS laboratory website (www.silvis.forest.wisc.edu) for WUI maps, statistics, and data, and see the LANDFIRE website (www.landfire.gov/products_national.php) for existing vegetation maps.

Next, we used the fuel model approach (13) developed by the U.S. Department of Agriculture Forest Service to extrapolate our results to forest ecosystems with similar fuel properties in regions where significant WUI areas cover the states of Colorado, Montana, New Mexico, Utah, Washington, and Wisconsin (3). Large portions of the WUI in which the vegetation's flammability is in the range of $0.3 \leq p \leq 0.4$ also have 16–128 houses per km^2; for our cell size of 50×50 m, these numbers correspond to densities d of 0.04–0.32. In Fig. 4*a*, a rectangular black-rimmed box delimits this range of actual values of p and d.

It thus appears that a large number of widespread fire ecosystems have flammability properties in or close to our model's transition zone. Therefore, their expected fire-size distributions, as well as the probability for a large fire to occur, might be very sensitive to even small changes in the houses' flammability properties in the WUI. Development within the WUI thus can substantially enhance or mitigate fire risk. All of the areas present in the data set are at great risk of experiencing

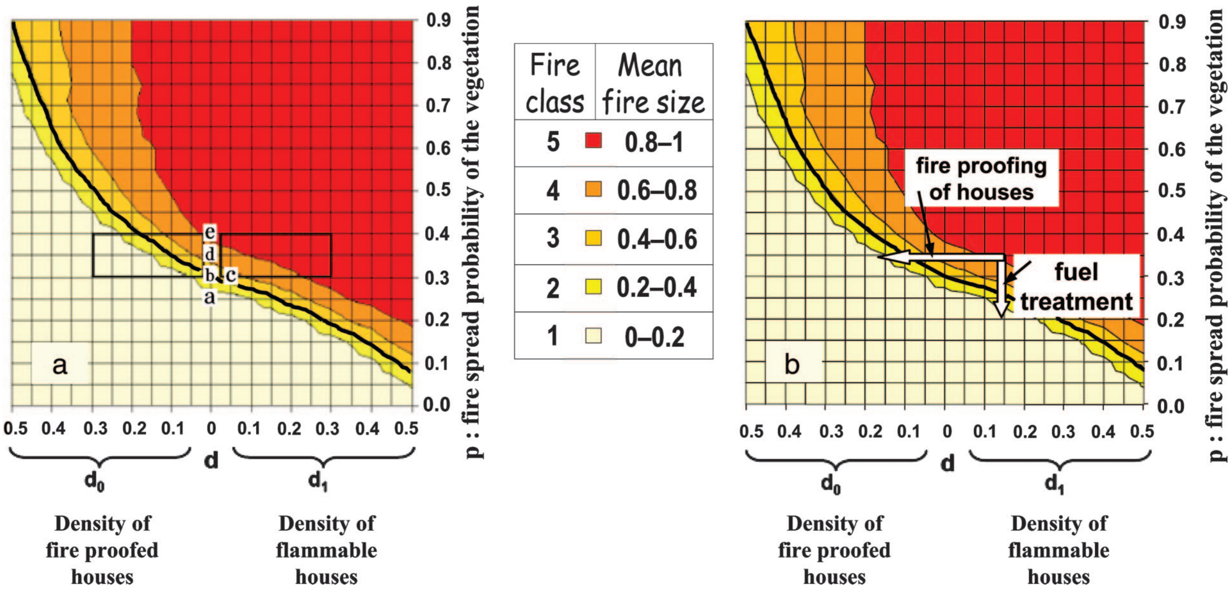

Fig. 4. Regime diagram of the mean relative fire size $\langle S \rangle$ as a function of the vegetation flammability p and the house density d; p, d_0, and d_1 are defined in the Fig. 2 legend. Fire classes 1–5 represent increasing mean fire size. Examples of fire size distributions for each fire class (points a–e in *a*) are shown in Fig. 3. The transition zone is composed of fire classes 2 and 3, separated by the heavy solid curve $p^* = p^*(d)$. The black-rimmed rectangle in *a* represents the estimated range, within our model's parameter space, of actual ecosystems widespread in the United States (see *Applicability to Existing Data* and *Data and Methods* for details). Switching from d_1 to d_0 corresponds to the fire proofing of a given density of houses. (*b*) Bold white arrows show the respective impact on mean fire size, for a landscape characterized by $p = 0.35$ and $d = 0.15$, of a reduction in the vegetation's flammability from $p = 0.35$ to 0.20 (fuel treatment), and of fire proofing the houses.

large fires that may encompass highly flammable, house-occupied sites; these risks could be easily mitigated by fire proofing the houses present in these areas.

There are many other environmental and human-related variables that affect the spread and size of fires (4, 6, 7, 25, 31–33). Despite these additional complexities, our model results have a number of practical implications. First, they suggest that detailed models used for assessing fire risk in the WUI should integrate the density and flammability of houses in these areas. Second, they imply that fire proofing houses and their immediate surroundings within the WUI would not only reduce the houses' flammability and increase the security of the inhabitants (17), but also reduce fire risk for the entire landscape. One thus can considerably reduce fire risk in and near the WUI by regulating construction in this zone to some degree, without the interference being too heavy-handed. Such regulation could be implemented to reduce short-term fire risk, while longer-term and large-scale ecosystem restoration takes place (21, 24, 26)

Data and Methods

Modeling Details. The simulations we report here used a lattice of 48 × 48 cells. Several simulations using a larger lattice of 300 × 300 cells produced similar results (data not shown); therefore, we retained the smaller landscape size for exhaustive exploration of the model's parameter space.

Each cell in our model represents an area of 50 × 50 m. This cell size is a good compromise between the 10-m scale at which fuel distribution heterogeneity becomes significant, and the 100-m scale at which burn patterns are heterogeneous (12). Such a cell size is also characteristic of the fuel landscape modification because of the presence of a house: Cohen (17) defines the building ignition zone as a length scale of a 10-m house, plus a 20-m area surrounding the building.

Detailed fire landscape models (12, 29) typically choose eight neighboring cells for fire spread, whereas classical percolation models (9) use four; the larger number of neighbors diminishes the influence of the square grid geometry on simulated fire patterns (12). The probability of fire spread is constant for all neighbors because corrections for decreased diagonal values, due to increased diagonal distance, induce patterns that are biased in the E–W and N–S directions for those values of p, $0.25 \leq p \leq 0.50$, that are most important for our simulations (12).

Observational Data Preparation. The Department of Agriculture Forest Service's fuel models (13) group vegetation types according to fuel properties that help determine fire ignition, rate of spread, and intensity, regardless of their geographic distribution and floristic composition. Yellowstone lodgepole pine forests are included in fuel model 10, which represents widespread ecosystems, such as spruce–fir and mixed conifer forests, as well as any forest type in which there is heavy deadfall of woody material due to insects, diseases, windthrows, and aged light thinning or partial-cut slash. Other widespread forest ecosystems, such as ponderosa, Jeffrey, and red pine and many hardwood species of the Eastern United States, are included in fuel model 9 (13). Systematic forest fire suppression since the early 20th century (6) has resulted in over 150 years of no fire occurrence in large areas of these forest ecosystems, and fuel conditions exceed their historic range of variability (34) so that they approach those of fuel model 10. Furthermore, many U.S. regions have experienced a long period of severe drought (35). Therefore, forested ecosystems in these areas have probabilities of fire spread between 0.3 and 0.4 (12), which is typical of mid-to-late seral stages of this kind of vegetation during dry years.

Housing densities (housing units per km^2) for our WUI estimates, maps, and data were provided online by the Applied Population Laboratory and the SILVIS laboratory at the University of Wisconsin. The data used in our study cover the states of Colorado, Montana, New Mexico, Utah, Washington, and Wisconsin (3). Our domain size corresponds to a 2.4 km × 2.4 km= 5.76 km^2 area that is fairly typical of the scale at which WUI development takes place in these states.

We thank L. Cugliandolo for crucial input on percolation models in the early stages of the work, H. Humphries for the WUI data, B. Malamud for detailed and constructive comments, and P. Barré, G. Chapron, P. Dumas, S. Fauvel, T. Machado, L. Riboli-Sasco, J. Roux, F. Spyratos, and S. Spyratos for stimulating discussions. The Biology Department of the Ecole Normale Supérieure (ENS) and its Laboratoire Fonctionnement et Evolution des Systèmes Ecologiques (UMR 7625) helped with material and technical support. P.S.B. was supported by the Chaire Blaise Pascal of the Région Ile-de-France at the ENS in Paris, as well as by grants from the U.S. Geological Survey Geography Analysis and Mapping program and from the U.S. National Science Foundation (Niwot Ridge Long Term Ecological Research) to the University of Colorado at Boulder. M.G. was supported in part by the European Commission through its "Extreme Events: Causes and Consequences (E2-C2)" project. V.S. was supported by the ENS and the Sustainable Development Chair of the Ecole Polytechnique.

1. Theobald DM (2004) *Front Ecol Environ* 2:139–144.
2. Theobald DM (2005) *Ecol Soc* 10(1):32.
3. Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) *Ecol Appl* 15:799–805.
4. Veblen TT, Kitzberger T, Donnegan J (2000) *Ecol Appl* 10:1178–1195.
5. Bevers M, Omi PN, Hof J (2004) *Can J For Res* 34:164–173.
6. Keane RE (2002) in *Rocky Mountain Futures: An Ecological Perspective*, ed Baron JS (Island, Washington, DC), pp 133–152.
7. Cardille JA, Ventura SJ, Turner MG (2001) *Ecol Appl* 11:11–127.
8. Prestemon JP, Pye JM, Butry DT, Holmes TP, Mercer DE (2002) *For Sci* 48:685–693.
9. Stauffer D, Aharony A (1985) *Introduction to Percolation Theory* (Taylor & Francis, London).
10. Keane RE, Cary GJ, Davies ID, Flannigan MD, Gardner RH, Lavorel S, Lenihan JM, Li C, Rupp TS (2004) *Ecol Model* 179:3–27.
11. Plotnick RE, Gardner RH (1993) in *Some Mathematical Questions in Biology: Predicting Spatial Effects in Ecological Systems*, ed Gardner RH (Am Math Soc, Providence, RI), Vol 26, pp 129–158.
12. Hargrove WW, Gardner RH, Turner MG, Romme WH, Despain DG (2000) *Ecol Model* 135:243–263.
13. Anderson HE (1982) *Aids to Determining Fuel Models for Estimating Fire Behavior* (USDA Forest Service, Washington, DC), Gen Tech Rep GTR-INT-122.
14. Butler CP (1974) in *Proceedings of Western States Section/Combustion Institute Papers* (Washington State Univ, Spokane, WA), Vol 74, No 15, pp 1–17.
15. Haight RG, Cleland DT, Hammer RB, Radeloff VC, Rupp TS (2004) *J For* 102:41–48.
16. Armstrong GW, Cumming SG (2003) *For Sci* 49:719–730.
17. Cohen JD (2000) *J For* 98:15–21.
18. Keeley JE (2002) *Environ Manage* 29:395–408.
19. Odell EA, Knight RL (2001) *Conservation Biol* 15:1143–1150.
20. Marzluff JM, Bradley GA (2003) in *Ecological Restoration of Southwestern Ponderosa Pine Forests*, ed Friederici P (Island, Washington, DC), pp 353–370.
21. Noss RF, Beier P, Covington WW, Grumbine RE, Lindenmayer DB, Prather JW, Schmiegelow F, Sisk TD, Vosick DJ (2006) *Restor Ecol* 14:4–10.
22. Cohen JD (1995) in: *Proceedings of the Biswell Symposium: Fire Issues and Solutions in Urban Interface and Wildland Ecosystems*, eds Weise DR, Martin RE (USDA Forest Service, Washington, DC), Gen Tech Rep PSW-GTR-158, pp 85–92.
23. Porterie B, Nicolas S, Consalvi JL, Loraud JC, Giroud F, Picard C (2005) *Numer Heat Transfer A* 47:471–489.
24. Schoennagel T, Veblen TT, Romme WH (2004) *BioScience* 54:661–676.
25. Graham, R.T. ed. (2003) *Hayman Fire Case Study* (USDA Forest Service, Washington, DC), Gen Tech Rep GTR-RMRS-114.
26. Noss RF, Franklin JF, Baker WL, Schoennagel T, Moyle PB (2006) *Front Ecol Environ* 4:481–487.
27. Loehle C (2004) *For Ecol Manage* 198:261–267.
28. Malamud BD, Morein G, Turcotte DL (1998) *Science* 281:1840–1842.
29. Peterson GD (2002) *Ecosystems* 5:329–338.
30. Rehm RG, Hamins A, Baum HR, McGrattan KB, Evans DD (2002) in *Proceedings of the California 2001 Wildfire Conference: 10 Years After the 1991 East Bay Hills Fire*, eds Blonski KS, Morales ME, Morales TJ (Univ of California, Oakland, CA), Tech Rep 35.01.462, pp 126–139.
31. Malamud BD, Millington JDA, Perry GLW (2005) *Proc Natl Acad Sci USA* 102:4694–4699.
32. Whitlock C, Shafer SL, Marlon J (2003) *For Ecol Manage* 178:5–21.
33. Turner MG, Romme WH, Tinker DB (2003) *Front Ecol Environ* 1:351–358.
34. Keane RE, Parsons RA, Hessburg PF (2002) *Ecol Mod* 151:29–49.
35. National Assessment Synthesis Team (2000) *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (US Global Change Research Program, Washington, DC).