

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

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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 socio-economic 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 $\approx 10\%$ of the surface and contains $\approx 40\%$ 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, fire-brands, 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

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Abbreviation: WUI, wildland–urban interface.

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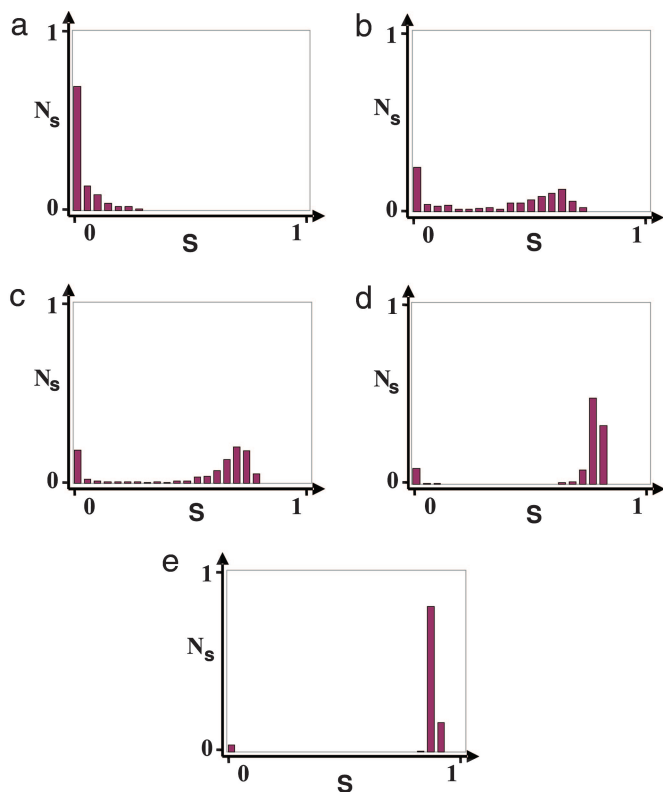


Fig. 3. Histograms $P = P(S)$ of relative fire sizes S for landscapes in each of the five fire classes described in the text. Here N_s is the normalized number of fires of size S , where S is sorted into “unit” bins of 100 cells. The histograms are based on 1,000 realizations of the fire-spread process. 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. 4a. 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 $p_h = 1$) and to higher p for fire-proofed ones (with $p_h = 0$). The mean $\langle S \rangle$ is plotted as a function of p and d in Fig. 4a. 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. 4b). 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. 4b 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. 4a, 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

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