

Quantifying bushfire penetration into urban areas in Australia

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[1] The extent and trajectory of bushfire penetration at the bushland-urban interface are quantified using data from major historical fires in Australia. We find that the maximum distance at which homes are destroyed is typically less than 700 m. The probability of home destruction emerges as a simple linear and decreasing function of distance from the bushland-urban boundary but with a variable slope that presumably depends upon fire regime and human intervention. The collective data suggest that the probability of home destruction at the forest edge is around 60%. Spatial patterns of destroyed homes display significant neighbourhood clustering. Our results provide revealing spatial evidence for estimating fire risk to properties and suggest an ember-attack model. **INDEX TERMS:** 1640 Global Change: Remote sensing; 3210 Mathematical Geophysics: Modeling; 6334 Policy Sciences: Regional planning; 9330 Information Related to Geographic Region: Australia. **Citation:** Chen, K., and J. McAneney (2004), Quantifying bushfire penetration into urban areas in Australia, *Geophys. Res. Lett.*, 31, L12212, doi:10.1029/2004GL020244.

1. Introduction

[2] In 2003, bushfires (or wildland fires) caused devastating property losses in many parts of the world including Australia, southern Europe and California [Munich *Re*, 2004]. Bushfire risk assessment is a complex issue: on the one hand, fire occurrence is subject to a wide range of environmental and human factors [e.g., Cary *et al.*, 2003; Pastor *et al.*, 2003], and, on the other, house survival depends on a multitude of variables including proximity to the firefront, building material, action of emergency services and occupant behaviour [Wilson and Ferguson, 1986; Ramsay *et al.*, 1996; Cohen, 2000]. To date, research on forest fires has largely focused on understanding their physical attributes and landscape-scale influences [Malamud *et al.*, 1998; Johnson and Miyanishi, 2001; Cochrane, 2003], while the spatial characteristics of their impact on vulnerable properties at the bushland-urban interface have been largely ignored. In this study we develop a set of distance-based statistics to quantify fire penetration and damage into urban areas. This information is important to stakeholders ranging from property owners to emergency services, local government and the insurance industry.

2. Study Areas and Data

[3] Bushfire is endemic to the Australian continent especially during the Southern Hemisphere summer – December through February [Luke and McArthur, 1978; Cheney, 1995]

and large bushfires have in the past caused substantial property losses [Leonard and McArthur, 1999]. Here we mainly explore data from three major historical fires – the 18 January 2003 Canberra bushfires (~500 completely destroyed homes) [McLeod, 2003], the 7–8 January 1994 Sydney bushfires (~200 destroyed homes) [Ramsay *et al.*, 1996; Gill and Moore, 1998], and the 16 February 1983 “Ash Wednesday” bushfires (~2500 destroyed homes) [Oliver *et al.*, 1984; Ramsay *et al.*, 1996].

[4] We first concentrate on the suburbs of Duffy (206 destroyed homes) in the Canberra fire and Como-Jannali (76 destroyed homes) from the Sydney fire, two extensive residential suburbs each possessing one or two flanks that experienced rampant fire penetration as well as having reasonably large samples of destroyed homes. Fine spatial resolution pre- and post-fire satellite images (QuickBird and IKONOS-2), aerial photographs and photos taken during site inspections were used to manually identify locations (centroids) of destroyed homes and bushland boundaries. Images taken all within 11 days after the fire proved extremely useful. In what follows we first briefly describe these two fires.

[5] Duffy is a leafy suburb that before the fire was bordered by a densely planted commercial pine plantation (average tree height of ~20 m) on its western and northern boundaries. The suburb slopes up towards the forest fringe. During 2002–2003 and as a consequence of prolonged drought, the forest had accumulated high volumes of dry fuel [McLeod, 2003]. The fire had been burning for some days in rugged terrain to the west and southwest of Canberra before, driven by strong westerly and northwesterly winds (over 65 km h⁻¹), it fell upon Duffy. The Forest Fire Danger Index (FFDI) – a nominal scale of 1–100 and for which 50 is considered extreme [Luke and McArthur, 1978] – peaked at 105 [McLeod, 2003]. Fire intensity has been estimated as 50,000 kW m⁻¹ (J. Gould, CSIRO, personal communication, 2003).

[6] The fire in Como-Jannali, by contrast, was relatively small [Gill and Moore, 1998]. It was initially ignited by the spotting firebrands across the Woronora River and propagated to the Glen Bushland Reserve only about 200 m away from western edge of the suburb. With gusty westerly winds and a FFDI of around 50, properties at the top of the hill were showered by embers from burning bushland on the steep slopes (ca. 30 degrees).

3. Results

[7] Figure 1 shows the distribution of destroyed homes as a function of the shortest distance to adjacent continuous bushlands along the dominant wind and fire propagation direction. The data are presented in cumulative form for easy comparison with other published results [Ahern and

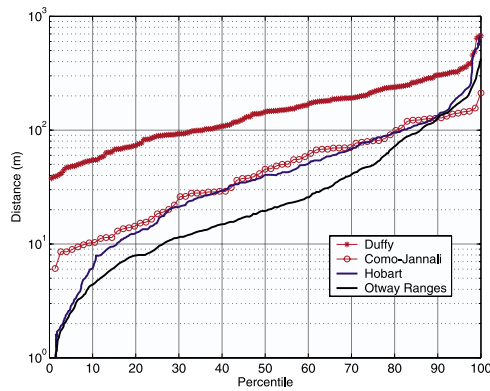


Figure 1. Cumulative distribution of homes destroyed in major bushfires in Australia in relation to distance from nearby bushland. The Otway Ranges curve (648 samples) from the “Ash Wednesday” fires and the Hobart curve (370 samples) from the 7 February 1967 Hobart (Tasmania) fires reported by *Ahern and Chladil* [1999] are also shown.

Chladil, 1999]. While the Como-Jannali curve shows reasonable agreement with previous fires – the Otway Ranges and Hobart fires, the destruction in Duffy is clearly different. The median distance (50 percentile) for Duffy is about three times that of the Como-Jannali fire (145 m versus 45 m) with respective 90 percentile distances being 305 m and 135 m. All this attests to the extreme damage experience in Duffy in part due to enforced home evacuation leaving most homes undefended. Numerous studies have found that suppression activity by residents during and immediately after fires is important in saving homes [e.g., *Wilson and Ferguson*, 1986; *Ramsay et al.*, 1996]. It may also be critical that the conflagration in Duffy was related to adjoining pine forests, whereas the other fires have been mainly associated with Australian eucalypt bushland.

[8] In Duffy and Como-Jannali, the majority of homes were destroyed beyond a separation distance of 40 m, suggesting the main cause of home ignition was airborne embers rather than direct flame contact or radiant heat. In Duffy, no homes lay closer than 37 m to the nearest edge of the forest owing to the presence of two major roads (Eucumbene Drive and Warragamba Avenue) that separated the pine plantation from residential areas. By comparison, homes or small hamlets scattered amongst extensive bushlands, a situation typical of many of the “Ash Wednesday” fires and also the February 1967 Hobart fires, mean that a high number of homes in these fires were destroyed at only small distances from the forest.

[9] There was more consistency in the maximum extent of damage. For Duffy, this distance was 674 m. While the maximum distance of fire spotting can be up to many kilometers [*Luke and McArthur*, 1978], the maximum distance resulting in home destruction for all fires considered here is less than 700 m.

[10] Figure 1 only considers populations of destroyed homes. A more useful statistic is the probability that houses will burn down. Figure 2 shows the probability of destruction, again as a function of distance from adjacent bushland. In Duffy, nearly 60% of all homes within the first 50 m were laid waste whereas at a distance of 300–400 m, only about 10% were destroyed. Distances beyond 400 m were not

considered due to very small sample numbers. Neither the linearity nor its slope is sensitive to plausible changes in dominant wind direction.

[11] Losses for Como-Jannali also show a similar linear relationship, although the decline with distance from bushland is more rapid. Here some 57% of homes were destroyed within the first 50 m. If we extrapolate either relationship in Figure 2, the percentage of destruction at zero distance from the forest boundary is about 60%, a value that agrees closely with the average of 63% for four heavily wooded and severely damaged suburbs in the “Ash Wednesday” fires: Fairhaven (71%, $n = 127$ homes), Aireys Inlet (61%, $n = 98$), Macedon (57%, $n = 97$) and Mount Macedon (62%, $n = 122$). Thus although the environmental settings of these homes may have varied, the percentage destroyed within the first 50 m seems remarkably stable. This statistic may have wide utility for estimating bushfire risk to homes constructed immediately adjacent to bushlands.

[12] It is also revealing to examine patterns of burned urban vegetation. While damage to homes appears discrete, almost binary in nature, i.e., either totally destroyed or relatively unscathed, the spatial distribution of burned vegetation is more continuous, more closely reflecting the trajectory of fire penetration. This can be seen most clearly from false-color or Normalized Difference Vegetation Index (NDVI) images for Duffy in which burned or scorched vegetation can be easily distinguished from healthy trees and grasses (Figure 3). The overall locational correspondence between destroyed homes and burned vegetation is obvious.

[13] Pre- and post-fire healthy urban vegetation in Duffy was classified by using NDVI thresholds and the proportional changes with distance from the forest boundary are shown in Figure 4a. Both curves converge at a distance range of 800–850 m suggesting the limit of fire impact. This range exceeds, yet is of the same order as the maximum extent of home destruction (674 m). For distances less than 400 m, the percentage of vegetated area burned is highly correlated with that of homes destroyed ($r^2 =$

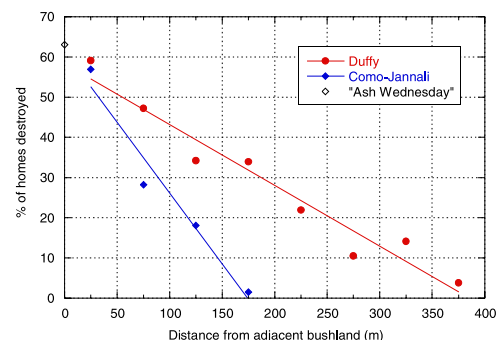


Figure 2. Percentage of homes destroyed at different distance ranges (interval = 50 m). In four suburbs (Fairhaven, Aireys Inlet, Macedon and Mount Macedon) devastated by the “Ash Wednesday” fires, the intermixing of homes and extensive bushlands made the delineation of bushland boundaries difficult and so post-fire aerial photographs were used to estimate percentages of homes destroyed for areas immediately adjacent to bushlands.

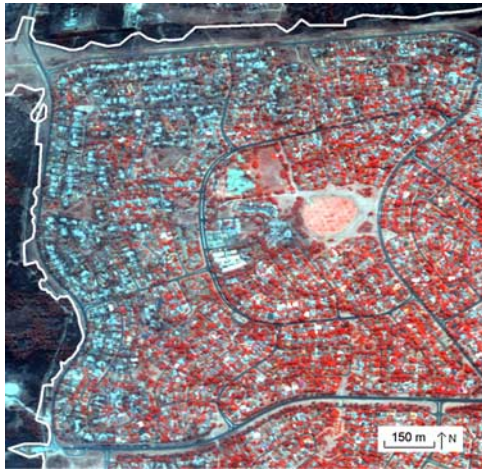


Figure 3. A false-color QuickBird image (with near infrared, green and blue bands) for Duffy. Healthy vegetation is shown in red, whereas burnt vegetation in the west and north appears as grey. White curves indicate bushland boundaries.

0.805, $P = 0.0025$; Figure 4b). The results are insensitive to the NDVI thresholds used to classify healthy vegetation.

[14] Destroyed homes show strong clustering. This is revealed by point pattern profiles calculated with Ripley's K -function [Ripley, 1981] or its related statistic $\hat{L}(d)$ ($\hat{L}(d) = \sqrt{\hat{K}(d)/\pi} - d$); edge effects were corrected by prescribing a common polygon containing all pre-fire homes within 400 m of the bushland [Martinez and Martinez, 2002]. Pre-

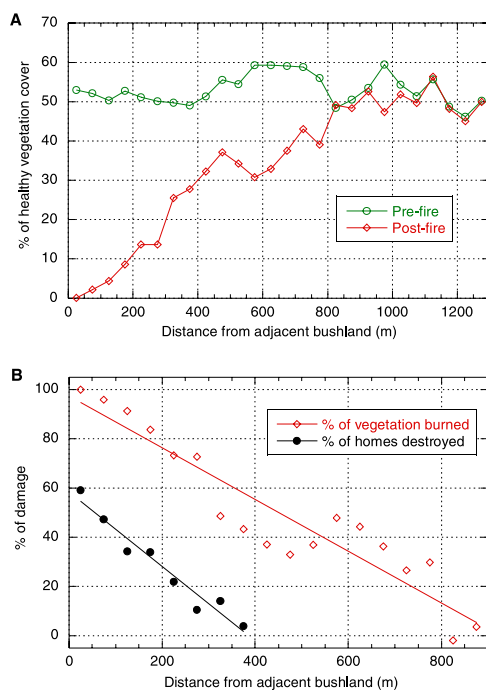


Figure 4. Changes of pre- and post-fire urban vegetation in Duffy. (a) Areal proportions of pre- and post-fire healthy vegetation at different distance ranges (interval = 50 m). (b) Percentage of burned vegetation and probability of home destruction versus distance from the bushland edge.

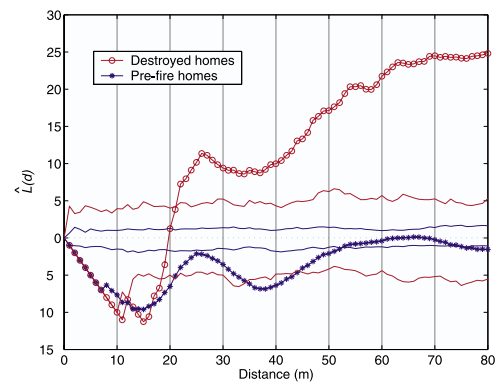


Figure 5. Ripley's K -Function expressed as $\hat{L}(d)$ for destroyed and pre-fire homes in Duffy. The dotted line ($\hat{L}(d) = 0$) indicates the expectation of complete spatial randomness following a homogeneous Poisson point process. If $\hat{L}(d) > 0$, the distribution of homes suggests clustering while negative values indicate spatial regularity. Two solid red curves delimit the upper and lower simulation envelopes for destroyed homes at the 1% level of statistical significance; two blue curves pre-fire homes.

fire homes in Duffy display only overall spatial regularity, whereas destroyed homes exhibit significant clustering at circular radii of 22 m and beyond (Figure 5). The first maximum is reached at a distance of 26 m while for distances beyond 35 m a coarser level of clustering exists. These radii are closely related to the spacing of homes – the average size of housing blocks in Duffy is about 24 m by 35 m. (There is no significance at radii less than 11 m – the minimum separation of centroids of destroyed homes.) Destroyed homes in Como-Jannali similarly show significant clustering. The clustering suggests that many houses were destroyed by contagious property-to-property burning as in urban fires.

4. Discussion

[15] The overall linear nature of the relationship (Figures 2 and 4b) is intriguing especially considering the number of variables involved. One simple mechanistic explanation is to imagine large amounts of burning material transported by the wind to a fixed distance in front of the advancing firefront (i.e., ember spotting) and this source of embers is arrested at the bushland-urban boundary. Dimensional arguments for a line buoyancy source perpendicular to the mean wind direction – a plausible idealization of bushfires – suggest updraught velocities of the order of 60 to 70 km h⁻¹ for fire intensities similar to that experienced in Canberra; when coupled with similar strength ambient wind speeds, such updrafts undoubtedly provide a suitable ember transport mechanism [Raupach, 1990]. Given this mechanism, it can be easily shown that the accumulation of potential fire sources in urban areas decreases linearly downwind from the forest edge. At a local scale, secondary ember sources from nearby burning elements (e.g., garden vegetation, wood piles and other homes) also contribute to this trend.

[16] Evoking embers as a primary cause of subsequent home destruction is hardly new [e.g., Cheney, 1995; Gill and Moore, 1998]. However, the realization that the accumulation of fire sources might exhibit a simple linear

function of distance downwind from the forest edge is. In the two-level ember-attack model, the probability of home destruction per ember 'hit' is low relative to that of vegetation. Collectively, three features of the pattern of house losses – the overall linearity, clustering at neighbourhoods, and binary outcomes observed at an individual level – comprise a fire impact model for at-risk homes.

[17] Detailed observational data of historical fires are often limited in terms of numbers and quality, but the increasing availability of fine-resolution geospatial data now facilitates in-depth analysis [Gollberg *et al.*, 2001; Chen *et al.*, 2003; Chuvieco, 2003]. Our approach has emphasized physical evidence from historical fires in Australia and the distinctive relationships that emerge can help characterize the complex fire penetration process. A clear-cut answer to the true probability of survival for an individual dwelling may never exist; a more immediate goal is to establish ensemble average risks for populations of similarly exposed structures. The distance-based penetration statistics reported here lay the basis for a practical insurance underwriting tool and have implications for defining rational planning regulations dictating distance between settlements and adjacent bushlands.

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