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Research article

Assessing wildfire exposure in the Wildland-Urban Interface area of the mountains of central Argentina

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ABSTRACT

Wildfires are a major threat to people and property in Wildland Urban Interface (WUI) communities worldwide, but while the patterns of the WUI in North America, Europe and Oceania have been studied before, this is not the case in Latin America. Our goals were to a) map WUI areas in central Argentina, and b) assess wildfire exposure for WUI communities in relation to historic fires, with special emphasis on large fires and estimated burn probability based on an empirical model. We mapped the WUI in the mountains of central Argentina (810,000 ha), after digitizing the location of 276,700 buildings and deriving vegetation maps from satellite imagery. The areas where houses and wildland vegetation intermingle were classified as Intermix WUI (housing density > 6.17 hu/km^2 and wildland vegetation cover > 50%), and the areas where wildland vegetation abuts settlements were classified as Interface WUI (housing density > 6.17 hu/km^2, wildland vegetation cover < 50%, but within 600 m of a vegetated patch larger than 5 km^2). We generated burn probability maps based on historical fire data from 1999 to 2011; as well as from an empirical model of fire frequency. WUI areas occupied 15% of our study area and contained 144,000 buildings (52%). Most WUI area was Intermix WUI, but most WUI buildings were in the Interface WUI. Our findings suggest that central Argentina has a WUI fire problem. WUI areas included most of the buildings exposed to wildfires and most of the buildings located in areas of higher burn probability. Our findings can help focus fire management activities in areas of higher risk, and ultimately provide support for landscape management and planning aimed at reducing wildfire risk in WUI communities.

1. Introduction

Fire is a natural disturbance affecting the structure, composition and processes of landscapes worldwide (Bond et al., 2005). However, current fire regimes in many areas are strongly influenced by human activities that often increase the number of ignitions and alters fuel loads (Hantson et al., 2015; Hawbaker et al., 2013; Keeley et al., 1999). At the same time, fire suppression is a common practice in many fire-dependent ecosystems, which can lead to excessive fuel accumulation and ultimately high intensity fires (Keeley et al., 1999) that cause substantial losses to ecosystem services and threaten human lives and property. Similarly, changes in livestock density and agro-pastoral activities can also alter fuel availability and fire ignition rates (Dubinin et al., 2011; Mitsopoulos et al., 2014). Together, these changes in fuel loads and ignition rates make it difficult to predict how humans affect fire regimes, and consequently, to assess wildfire risk.

Wildfires are of particular concern in the Wildland-Urban

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Interface (WUI, Bar-Massada et al., 2014; Cohen, 2000; Lampin-Maillet et al., 2009; Lowell et al., 2009). The WUI is the area where houses intermingle or abut with wildland vegetation (Radeloff et al., 2005) and the proximity of houses and fuels increases both ignition rates and the risk to people and their homes. WUI areas have grown worldwide as a result of people moving closer to natural amenities, and the expansion of exurban housing developments (Haight et al., 2004; Hammer et al., 2007; Sánchez-Guisández et al., 2002). Fires in WUI communities can cause major physical and emotional health problems, including the loss of human lives, and they can also damage or destroy houses and other facilities, causing major economic losses (Gill and Stephens, 2009; Haas et al., 2013; Mitsopoulos et al., 2014). As a consequence, government agencies often focus prevention and mitigation efforts in WUI areas. However, the negative consequences of WUI fires have not decreased (Alexandre et al., 2015; Syphard et al., 2012).

The assessment and management of wildfire risk in the WUI requires robust WUI maps and data about the number of buildings at risk. Different strategies have been proposed to create such WUI maps. At broad scales, WUI areas have been identified based on the number of homes in administrative units, such as census blocks, the finest resolution at which census data is available in the US (Radeloff et al., 2005). Such a zonal approach is useful when mapping the WUI in large areas where the only available information about houses is in aggregated form. However, administrative units differ in their size, meaning that this kind of approach is affected by the Modifiable Areal Unit Problem (MAUP; Openshaw, 1984), and their boundaries do not delineate ecological borders.

Alternative approaches for WUI mapping are based on the actual structure locations, which are utilized to calculate structure density; and land cover maps, which are used to quantify the amount and composition of surrounding vegetation types. The advantage of location-based approaches is the avoidance of the MAUP and the possibility to map WUI areas at different spatial scales (Bar-Massada et al., 2013; Lampin-Maillet et al., 2010). However, some of the location-based approaches do not address all the aspects of the WUI consistently (Bar-Massada et al., 2013), either by neglecting any housing and vegetation density thresholds, or by omitting a buffer zone around large vegetated areas when mapping Interface WUI. If no housing density threshold is employed, even single, isolated buildings become part of the WUI. While an isolated house surrounded by wildland vegetation is indeed at risk from wildfires, we suggest that such a setting does not meet the concept of the WUI because a single house cannot be considered as an "urban" environment in a strict sense. In contrast, when no vegetation threshold is included, then even buildings surrounded by barren areas are considered WUI, but the lack of vegetation means that wildfires would not be a concern.

WUI maps *per se* only highlight the areas where houses and wildland vegetation either intermingle or abut, but do not necessarily depict where there is high fire risk. Fire activity is heterogeneous in space and time and is a consequence of the interaction of multiple factors at a range of scales (Morgan et al., 2001). This complicates fire risk assessments, but the identification of those WUI areas that are more likely to be affected by fires is essential for fire management. Among all wildfires, the occurrence of large fires is of special concern because large fires often occur under extreme weather conditions, are difficult to suppress, and cause the worst damages (Mitsopoulos et al., 2014). Thus, if conducted at relevant temporal and spatial scales, fire risk assessments in the WUI can provide important information about the location and number of houses at risk and help design effective fire management strategies and policies.

Wildfire risk assessment requires quantifying three separate components: potential wildfire intensity, wildfire likelihood, and exposure and susceptibility of valuable resources and assets to wildfire (Bachmann and Allgöwer, 2000; Miller and Ager, 2013; Scott et al., 2013). Fire risk in the WUI can be assessed using different approaches. Some approaches are based on the analysis of the context and characteristics of settlements and houses (Caballero, 2008). Others consider the size and frequency of fires and the flammability of fuel types (Haight et al., 2004), ignition likelihood, burned area, and fire density (Lampin-Maillet et al., 2010). Alternative approaches are based on computer simulations of fire behavior (Bar-Massada et al., 2009; Mitsopoulos et al., 2014; Salis et al., 2013; Sánchez-Guisández et al., 2002), combined with biophysical data (Hardy et al., 2001), and potential damage (Castillo Soto et al., 2013). In terms of identifying houses at risk, approaches that include the location of structures (Bar-Massada et al., 2009; Lampin-Maillet et al., 2010; Lowell et al., 2009), are arguably most realistic, and hence useful for management. In terms of burn probability, simulations offer an alternative to empirical approaches in areas where long-term fire records are lacking (Bar-Massada et al., 2009). However, where such fire records are available, they can provide a strong empirical basis for predictions of the likelihood of future fires, because the accuracy of the predictions can be assessed (Carmel et al., 2009). Conversely, to the best of our knowledge, no previous studies have assessed fire risk for point-based WUI maps using empirical models describing fire frequency.

Although most research on WUI fires has been conducted in North America, Europe and Oceania (Elia et al., 2014; Lampin-Maillet et al., 2010; Lowell et al., 2009; Mitsopoulos et al., 2014; Radeloff et al., 2005; Salis et al., 2013), wildfires in the WUI are not only a problem of wealthy nations (González-Cabán, 2004) and very little is known about fires and WUI patterns in Latin America (Syphard et al., 2009). To the best of our knowledge, most WUI research in low- and middle-income countries have focused on social issues associated to the access to services and infrastructure (Bolay et al., 2004; Farooq and Ahmad, 2008; Makita et al., 2010; Simon, 2008) and impacts on biodiversity (Alston and Richardson, 2006; Gavier-Pizarro et al., 2012; Pauchard et al., 2006), but few have addressed fire activity in WUI areas. Case studies in Northwestern Argentinean Patagonia have shown that the socioeconomic vulnerability affects fire occurrences (de Torres Curth et al., 2012; Dondo Bühler et al., 2013) and multi-scale variables, from species to landscape, were integrated to assess WUI fire hazard (Ghermandi et al., 2016). Additionally, fire risk has been modeled in the Mediterranean ecosystem of Chile based on fire behavior and potential damage (Castillo Soto et al., 2013), and studies of the local perceptions of wildfire risk were carried out in the Federal District of Brazil (Zacharias and de Andrade, 2013). However, all of these studies were performed in relatively small study areas, within the boundaries of a single county.

The mountains of central Argentina provide an excellent opportunity to shed light on the WUI patterns and wildfire exposure in Latin America. Between 1999 and 2013, more than 650,000 ha burned in these mountains, representing 27% of the total area (Argañaraz et al., 2015a). Furthermore, these mountains are of particular concern in terms of housing growth in the WUI, because the population has grown rapidly in the last decades, driven by people moving from big cities to nearby wildland areas (Gavier and Bucher, 2004). Moreover, recent predictions from the Argentinean National Institute of Statistics and Censuses (INDEC, in its Spanish acronym) estimate that the population of this region will grow 33% on average between 2010 and 2025.

The main goal of our research was to assess wildfire exposure in the wildland urban interface of the mountains of central Argentina using burn probability measures. Our specific research objectives were: i) to determine the area, boundaries and spatial distribution of the Wildland-Urban Interface based on the location of buildings and surrounding vegetation, and ii) assess wildfire exposure for WUI communities in relation to historic fires, with special emphasis in large fires and estimations of burn probability. Our research was designed to shed light on WUI patterns in central Argentina and to provide support for landscape planning and fire management. Our hypothesis were that WUI areas, especially Intermix WUI areas, have higher burn probabilities and include the majority of buildings exposed to wildfires due to the proximity between people (source of most ignitions) and wildland vegetation.

2. Methods

2.1. Study area

Our study area was the Sierras Chicas of Córdoba (810,000 ha), in central Argentina (Fig. 1). The Sierras Chicas encompasses the southern portion of the seasonally dry forest of Gran Chaco, specifically the Chaco Serrano subregion. Native forests, dominated by *Lithraea molleoides* are more frequent at lower altitudes (<900 m.a.s.l.). Closed shrublands, dominated by *Acacia caven* and *L. molleoides* are more frequent below 1300 m.a.s.l., while grasslands, dominated by *Festuca hieronymi* are usually found above 900 m.a.s.l. (Giorgis, 2011). Natural vegetation communities have been substantially altered by land use. In lowland areas, most forests have been replaced by crops while mountain vegetation is under pressure from grazing, selective logging, fire and exotic invasive plants (mainly *Ligustrum lucidum*) (Gavier and Bucher, 2004; Giorgis et al., 2013; Zak and Cabido, 2002). Fires are used by ranchers to reduce senescent biomass and promote forage regrowth during the dry season (Fischer et al., 2012), and almost 91% of ignitions are caused by humans (Secretaría de Ambiente y Desarrollo Sustentable, 2001–2013).

Climate in our study area is temperate semiarid with a monsoonal rain regime, average annual rainfall of 850 mm and mean annual temperature of 17.3 °C (National Meteorological Service of Argentina, data from the period 1999–2014). Most rain falls between October and March (spring and summer). Winter is dry and mild with relatively high temperatures in August and September, which is when most fires occur (Argañaraz et al., 2015a). Between 1999 and 2013 near 300,000 ha burned in Sierras Chicas (36% of total area), mainly affecting grasslands, followed by forests and shrublands. Most of these burned areas (77%) were part of the 31 large fires (>1000 ha) observed between 1999 and 2011, although such fires only represent 3.5% of the fire events (Argañaraz et al., 2015a).

The population size of the counties of the Sierras Chicas increased by 63% from 1980 to 2010 (524,000 to 853,000 inhabitants; 2.1% annually), much higher than the population growth for the Province as a whole over those thirty years (37%, INDEC). Furthermore, the census agency estimates an overall

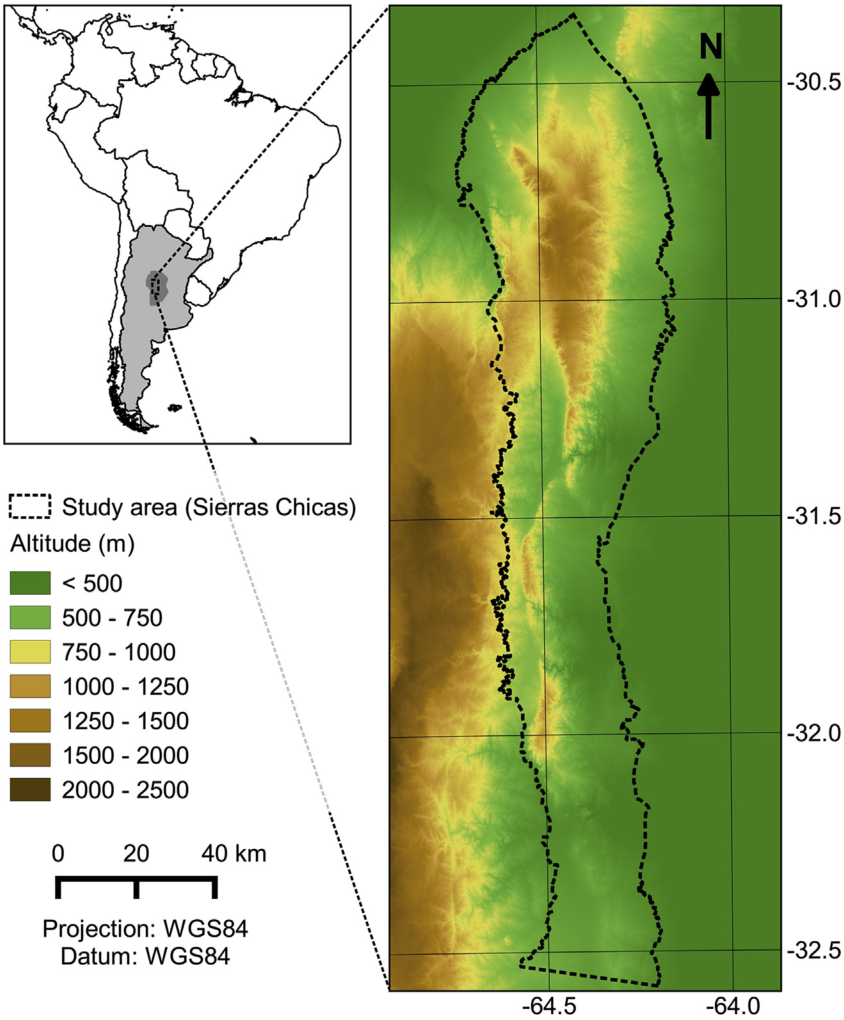

Fig. 1. Location of Sierras Chicas, Córdoba Province, Argentina.

population growth near 33% from 2010 to 2025 for these counties, highlighting that our study area is a place that people increasingly chose to live. This population growth is partly driven by the migration of people from large cities to nearby natural areas (Gavier and Bucher, 2004).

2.2. Characterization of the vegetation

We derived our land cover map by classifying 10-m resolution SPOT 5 imagery acquired on September 7th, 2012. We performed a supervised classification using Support Vector Machines (SVM) and included all spectral bands (Green, Red, Infrared and short-wave infrared), as well as NDVI and a digital elevation model (DEM). We used the 30-m SRTM DEM (Gutman et al., 2008) and resampled it to 10-m resolution using cubic convolution to match the resolution of the satellite imagery. The reference data to train the classifier and to assess the accuracy of the land cover map were obtained from field surveys carried out in 2013 and from Google Earth images. We divided these data via stratified random sampling using land cover type as the strata, separating 70% to train the classifier and 30% to assess the accuracy of the map. Due to the presence of clouds in the northern part of the SPOT mosaic, we classified a Landsat 8 OLI image for this area (Path/Row 229/81) acquired on August 6th, 2013 with SVM. We included the Blue, Green, Red, NIR, SWIR 1 and SWIR 2 bands, NDVI and DEM, and resampled the resulting map to the same resolution as SPOT 5. In both classifications we identified eight land cover classes and obtained an overall accuracy around 90%. Then, we reclassified the original map into wildland vegetation (forests, shrublands, grasslands, cultivated forests, and *L. lucidum* forests) and non-wildland vegetation (urban areas, agricultural lands, and bare soil).

2.3. Residential housing community mapping

We generated the building location data layer via visual interpretation of Google Earth satellite imagery. When the data was collected, the most recent available images were from 2009 to 2014. We included as buildings all primary residences, guest houses and cabins, and also agricultural and industrial facilities. We did not include grain silos, antennas, or bridges. In dense urban areas we used Official Census Data to complete our structure layer. The finest resolution at which census data is publicly available is at the ‘radius’ level (equivalent to census blocks in the US Census hierarchy), which in our study area ranged in size from 3 ha in dense urban areas to 49,000 ha in rural areas. Within a given census block in dense urban areas, we randomly created as many points as there were housing units reported in the Census Data of 2008. The creation of random points did not affect the results of our study substantially because the density of buildings in dense urban areas is considerably higher than the threshold we used as a criterion to define WUI areas (see Section 2.4). Additionally, the individualization of buildings in dense urban areas turns difficult because the boundaries among contiguous structures are often unclear and this might result in an erroneous building count. When visual inspection indicated that actual housing units were not uniformly distributed within the radius and both high and low density urbanized areas coexisted, we manually digitized the buildings in low density urbanized areas and then created random points (Total number of housing units reported by Census Data minus the number of manually digitized housing units) in the remaining dense urban area. The final building layer comprised 276,572 points, of which 190,624 were digitized manually (investing 329 h) and 85,948 were generated randomly in dense urban areas.

2.4. Wildland-Urban Interface mapping

We employed a point based mapping approach to create our fine scale WUI map (Bar-Massada et al., 2013), which required two types of data: point data depicting building locations and a land cover map identifying wildland vegetation. According to the WUI definition, two types of WUI were distinguished. The areas where houses and wildland vegetation intermingle were classified as Intermix WUI, and the areas where wildland vegetation abuts settlements were classified as Interface WUI. To map WUI areas, we conducted our calculations in a raster data environment with 10-m resolution. For each cell Xij we determined: i) the housing density D (measured in housing units (hu) per km^2) for an area of radius r, ii) the percentage of wildland cover within the same radius, and iii) if the cell was located within 600 m far from a patch of wildland vegetation larger than 5 km^2 using a moving window. We used the 600 m distance because local firefighters indicated this was the maximum distance a firebrand can fly ahead of a fire front given the types of vegetation, topography and climate in our study area (Fabián Freccia, from Defensa Civil de Río Ceballos, Personal Communication). We set a minimum-size threshold at 5 km^2 for the areas that are heavily vegetated to avoid including residential areas that are within 600 m of small urban parks (Radeloff et al., 2005).

In the WUI map, we classified a pixel as Intermix WUI if housing density was >6.17 hu/km^2 and wildland vegetation cover >50%). A pixel was classified as Interface WUI if housing density was >6.17 hu/km^2, wildland vegetation cover <50%, but it was located within 600 m of a vegetated patch higher than 5 km^2 (Bar-Massada et al., 2013; Radeloff et al., 2005; Stewart et al., 2007). We used the housing density threshold used in the US (Radeloff et al., 2005), because there was no information regarding a building density threshold valid for Argentina or other Latin-American countries.

In order to determine the most appropriate neighborhood (i.e., buffer distance around each cell) size to define the WUI in our study area, we tested different radii, from100to 1000 m, in 100-m steps (Bar-Massada et al., 2013). Our rationale was that the WUI boundaries should include most of the buildings exposed to wildfires (i.e., those within the fire perimeters). Hence, we calculated the number of buildings included within the fire perimeters of our fire database (Section 2.5) that were also included within the WUI boundaries obtained at different radii. Additionally, we also considered the minimum number of buildings at which the WUI building density threshold is reached.

2.5. Empirical and estimated burn probability/Wildfire likelihood

The fire database that we used to assess wildfire likelihood was derived from Landsat TM/ETM+ imagery (30 m pixel) acquired between 1999 and 2011. Burned scars were extracted using the Automatic Burned Area Mapping Software (ABAMS), based on the two-phase algorithm proposed by Bastarrika et al. (2011). During the first phase, pixels with high chances of being burnt are identified (seeds) and serve as the starting point during the second phase, when a region growing algorithm is applied to delineate the burned patch and its unburned islands within fire perimeters. The minimum mapping unit of the fire database is 5 ha, because smaller areas had higher error rates and accounted only for a small proportion of the total burned area. The producer's accuracy of the fire database ranged from 88 to 97% (i.e. 3–12% omission errors) and user's accuracy ranged from 71 to 96% (i.e., 4–29% commission errors; for details see (Argañaraz et al., 2015a). The empirical annual burn probability (BP) map was calculated by dividing the fire frequency map (1999–2011) by 13, the number of years in our fire database.

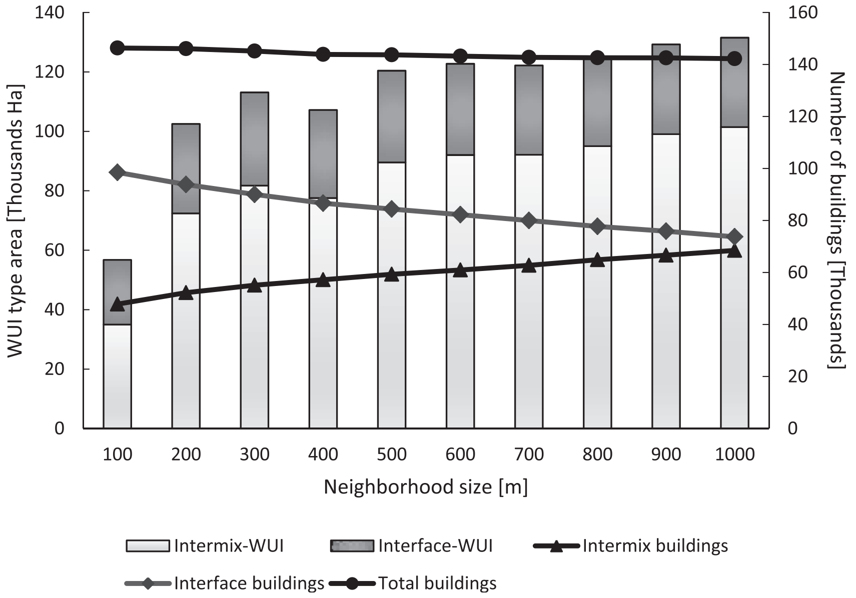

Fig. 2. Area and number of buildings in the Interface and Intermix WUI at different neighborhood sizes.

We also estimated annual burn probability using an empirical model of fire frequency fitted with Boosted Regression Trees. This model identified the biophysical and human variables determining the spatial heterogeneity of fire frequency in our study area and explained 76% of the variation in fire frequency (Argañaraz et al., 2015b). Fire frequency was higher at intermediate levels of precipitation (650–700 mm/year), steeper slopes, lower levels of potential evapotranspiration and intermediate levels of population density and primary productivity. We used this model first to create an estimated fire frequency map for our study area using R (R Core Team, 2016), following the recommendations of Elith et al. (2008) and then we divided it by 13 (the number of years of the fire database used to fit the model) to generate an estimated annual burn probability map. Afterwards, we reclassified the resulting map into three classes of estimated BP: Low ($BP \leq 0.038$; i.e., one fire every 26 years or more), Intermediate ($BP > 0.038$ and ≤ 0.154; i.e., one fire every 6.5–25 years), and High ($BP > 0.154$; i.e., one fire every 6.5 years or less). Estimating BP based on this model offers the advantage of identifying areas that have similar conditions to those that had burnt with high frequency but where fires did not occur because of the absence of ignitions.

Finally, we calculated mean burn probabilities for the dominant land cover classes of Sierras Chicas in order to analyze if there were differences among them, since previous studies have indicated differences in flammability in the following decreasing order: grasses > shrubs > trees (Jaureguiberry et al., 2011).

2.6. Wildfire exposure analysis

We analyzed the WUI extent and number of buildings exposed to wildfires according to: i) historic fires of all sizes; ii) large fires (>1000 ha) and large fires plus a buffer of 600 m around their perimeters, i.e., the maximum distance a firebrand can fly ahead from the fire front in our study area; iii) empirical and estimated BP. Additionally, we analyzed if there were differences in the mean BP for the different types of WUI and we also calculated the percentage of WUI buildings located over the different land cover classes in our study area. The presence of houses within burned areas does not mean that buildings were actually exposed to fires, because not all of them were standing when wildfires burned; however, we considered these areas as fire prone due to their recent fire history. To estimate the percentage of buildings within fire perimeters that were already standing when wildfires burned, we randomly selected 1000 of these buildings and determined their status using Google Earth imagery.

As a way of testing our WUI map and our analysis of wildfire exposure, we used the perimeters of the fires occurring in 2013 (no Landsat images were available for 2012 and few fires occurred in 2014 and 2015). In late winter of 2013, almost 40,000 ha burned in the Sierras Chicas, when temperatures reached 41.3 °C (Meteorological data from INTA Manfredi). We summarized the WUI area burned during these fires and calculated the number of buildings located within the fire perimeters. Additionally, we analyzed the portion of these fires that burned in areas classified as low, intermediate and high estimated BP.

3. Results

3.1. Wildland urban interface map

Our WUI map of the Sierras Chicas revealed that approximately 120,000 ha of our study area ($\approx 15\%$) were designated as WUI. Total WUI area varied with the size of the neighborhood, increasing considerably for neighborhoods between 100 and 500 m, thereafter increasing more slowly (Fig. 2). As neighborhood size increased, additional WUI areas were mostly Intermix WUI while the area of Interface WUI remained relatively constant (Fig. 2). For radii $\leq$300 m, the minimum number of buildings required to reach the density threshold for WUI was reached even when the neighborhoods included only one or two buildings (Table 1). This would imply that isolated houses are classified as WUI and that is why we discarded radii $\leq$300 m from subsequent analyses.

The area classified as WUI ranged from 107,190 ha (400 m radius) to 131,539 ha (1000 m radius) (Fig. 2), which corresponds with 13–16% of the study area, respectively. Most of the WUI areas were Intermix WUI (9.5–12.5% of the study area), while Interface WUI was comparatively rare (3.7%). We found three large and continuous WUI patches, each of them stretched along a north-south axis, and located at both eastern and western slopes of the Sierras Chicas (Fig. 3). Of all the buildings in our study area,

Table 1
Number and proportion of buildings standing within fire perimeters and included in WUI areas for different neighborhood sizes and fire databases.

Neighborhood size	Fires 1999–2011[a]		Fires 2006–2011[a]		Fires 2013[a]		Min. number buildings for >6.17hu/km^2
	# build.	%	# build.	%	# build.	%	
100	4272	63.1	1466	72.4	412	89.8	1
200	4336	64.1	1464	72.3	413	90.0	1
300	4294	63.4	1444	71.3	391	85.2	2
400	4245	62.7	1425	70.3	373	81.3	4
500	4250	62.8	1421	70.1	364	79.3	5
600	4226	62.4	1404	69.3	348	75.8	7
700	4181	61.8	1397	69.0	337	73.4	10
800	4146	61.2	1382	68.2	332	72.3	13
900	4110	60.7	1375	67.9	331	72.1	16
1000	4066	60.1	1342	66.2	330	71.9	20

[a] Total number of buildings included within fire perimeters: 1999–2011: 6769; 2006–2011: 2026; 2013: 459.

approximately 52% were in the WUI. Intermix WUI buildings ranged from 57,220 (400 m radius) to 68,519 (1000 m radius), while Interface WUI buildings ranged from 86,660 to 73,751 with a lower number at larger radii (Fig. 2). The proportion of buildings belonging to each of the WUI classes varied with the size of the neighborhood, increasing from 21 to 25% in the Intermix WUI, and decreasing from 31 to 27% in the Interface WUI. The total number of WUI buildings slightly decreased at larger neighborhood sizes because a larger number of buildings was required (within the neighborhood) to reach the housing density threshold of 6.17 hu/km^2 (Table 1).

The number of Sierras Chicas buildings that were within fire perimeters and part of WUI areas decreased as neighborhood size increased (Table 1). For the same radius, the proportion of buildings within fire perimeters included in WUI areas increased when using more recent fire databases (e.g., for 800 m, the proportion of buildings increased from 61 to 72%, Table 1). Both the 400 and 500-m radii included the highest and similar proportions of buildings within fire perimeters belonging to the WUI, so both radii could be appropriate to define the WUI based on our rationale that WUI boundaries should contain most of the buildings exposed to wildfires (Section 2.4). Ultimately, we identified the 500-m radius as the most appropriate to map the WUI in the Sierras Chicas, because the area classified as WUI was larger (120,400 ha for 500-m radius vs. 107,200 ha for 400-m radius), similar to the larger radii (Fig. 2), which is desirable for a conservative fire risk management strategy.

3.2. *Wildfire likelihood*

Empirical burn probability was heterogeneous in our study area and had values between 0 and 0.461. Higher values of empirical BP were observed at higher altitudes, especially on the hills located between the two large and parallel WUI patches (Fig. 4). A similar pattern was observed for the estimated burn probability which ranged between 0 and 0.679. In terms of the different land cover types, grasslands had the highest mean values of empirical and estimated BP (0.055 and 0.049, respectively), which doubled the values observed for shrublands, the land cover with the second highest mean BP values (0.027 and 0.023).Forests occupied the third place (0.015 and 0.019), while agricultural lands had the lowest mean BP values (0.011 and 0.010).

3.3. *Wildfire exposure*

More than 14% of WUI areas (17,300 ha) overlapped with fires that occurred from 1999 to 2011 and most of this area belonged to the Intermix WUI (Table 2). These burned WUI areas, representing only 2% of our study area, included 63% of the total number of buildings potentially exposed to wildfires in this period (4250 out of 6769, Table 1). Sixty one percent of the WUI area affected by fires was burnt by large fires and included 77% of the Sierras Chicas buildings located within large fire perimeters. Most of these areas and buildings were in the IntermixWUI (Table 2). Additionally, when considering a 600-m buffer around large fires, the number of WUI buildings increased nearly 12 times, and included 25% of WUI area (Table 2).The sample that we took to determine if buildings existed when the fires occurred indicated that 85% of them were built after fires, while 8% existed during fires and 7% was uncertain.

Considering empirical annual burn probability, nearly15% of the WUI had values different than zero. Twelve percent of the WUI had empirical BP of 0.077 and included the vast majority of the buildings with BP values higher than zero (5495 out of 6769). Three percent of WUI areas (3300 ha) had empirical BP $\geq$ 0.15 (Table 2). WUI areas included most of the buildings located in areas with empirical BP values between 0.077 and 0.154 ($\approx$64%), while only 26% of the buildings located in areas with higher empirical BP belonged to the WUI (Table 2).

Considering the estimated annual burn probability map, we observed that most of the WUI was included in areas of low empirical BP ($\approx$89%), while the area with intermediate and high empirical BP represented 11and 0.5%, respectively (Fig. 5, Table 3). In all three BP categories, Intermix WUI represented the main WUI type (73–86%). WUI areas included the majority of buildings located in areas with intermediate and high burn probabilities (67% or 5342 out of 8001 buildings, Table 3). Regarding the different types of WUI, Intermix WUI had higher mean burn probabilities than Interface WUI (empirical BP = 0.018 vs. 0.007; estimated BP = 0.016 vs. 0.010).

In terms of the types of land cover where WUI buildings are located, 84% of Interface WUI buildings lie in cultural lands (agricultural + urban areas), 9% in forests, 4.5% in shrublands and 1% in grasslands. In contrast, the majority of Intermix WUI buildings (56%) lie in wildland vegetation (28% in forests, 18% in shrublands and 10% in grasslands. The proportion of Intermix WUI buildings located in cultural lands is nearly half of the proportion of Interface WUI buildings in cultural lands (43%).

The fires of 2013 burned 10,000 ha in the WUI, representing 8.2% of the total WUI area. These fires have burnt in a single year 58% of the area burned from 1999 to 2011. The number of buildings within the fire perimeters was 459 and more than 79% of them belonged to WUI communities (Fig. 5, Table 1).The 2013 fires affected mostly the areas with higher estimated BP, burning 21% of the areas with high BP (2384 ha), 12% of the areas with intermediate BP (16,587 ha) and only 3% of the areas with low BP (21,260 ha).

4. Discussion

We mapped the WUI at a fine spatial scale across the Sierras

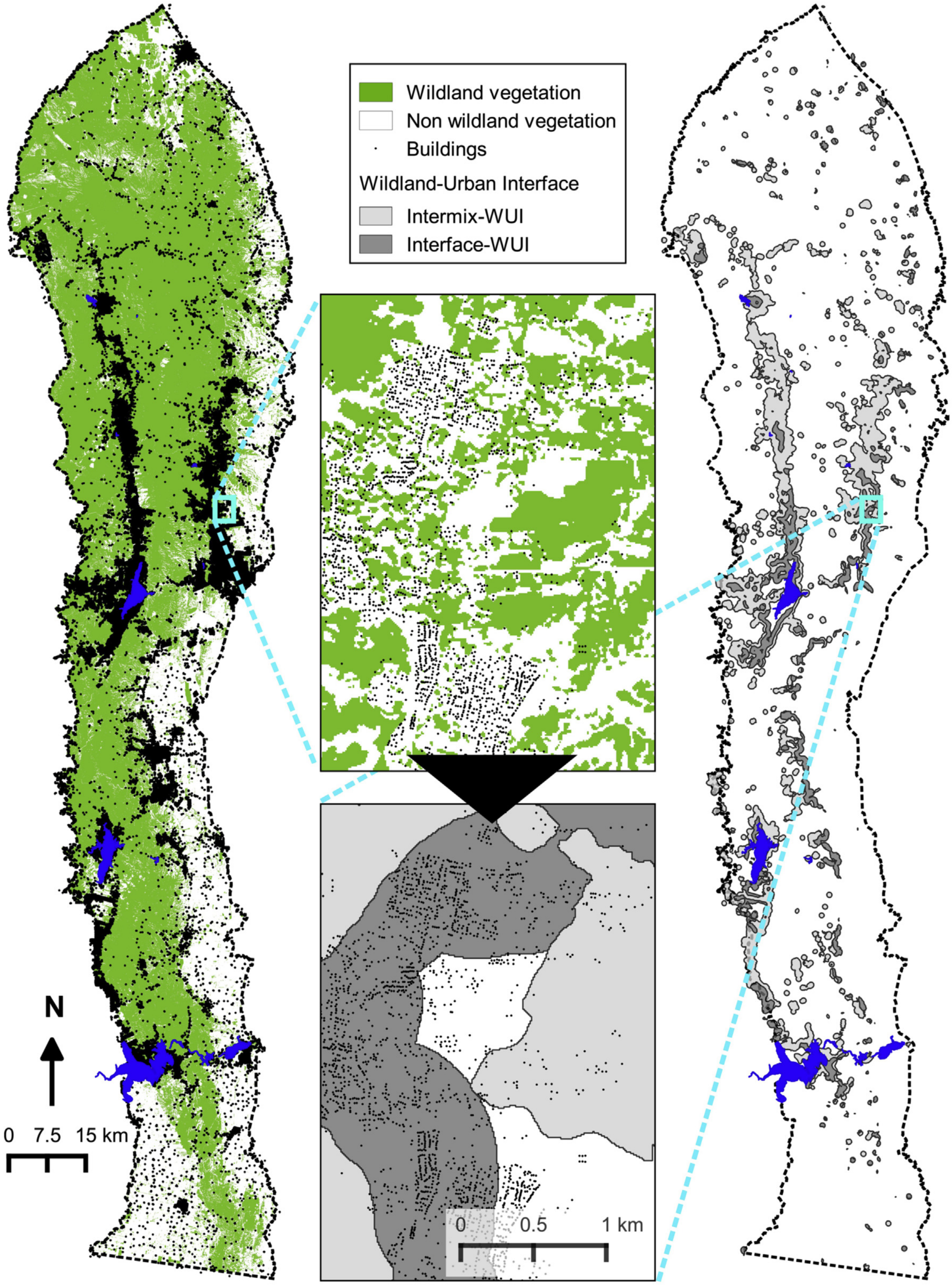

Fig. 3. Wildland-Urban Interface map for the Sierras Chicas of Córdoba (Argentina), based on the location of buildings and surrounding wildland vegetation.

Chicas of Córdoba (Argentina), and assessed wildfire exposure according to recent fires and burn probability maps. We delineate the WUI based on building locations and vegetation patterns, and proposed a criterion to determine the most appropriate neighborhood size to define WUI areas. WUI areas represented only 15% of our study area; however, they included most of the buildings exposed to wildfires and most of the buildings located in areas with higher burn probabilities, supporting the notion that WUI areas have higher fire risk than non-WUI areas. To the best of our knowledge, this is the first landscape scale WUI map created for Latin America to aid fire risk assessment and management.

Few maps of WUI areas exist at the national level even for high-

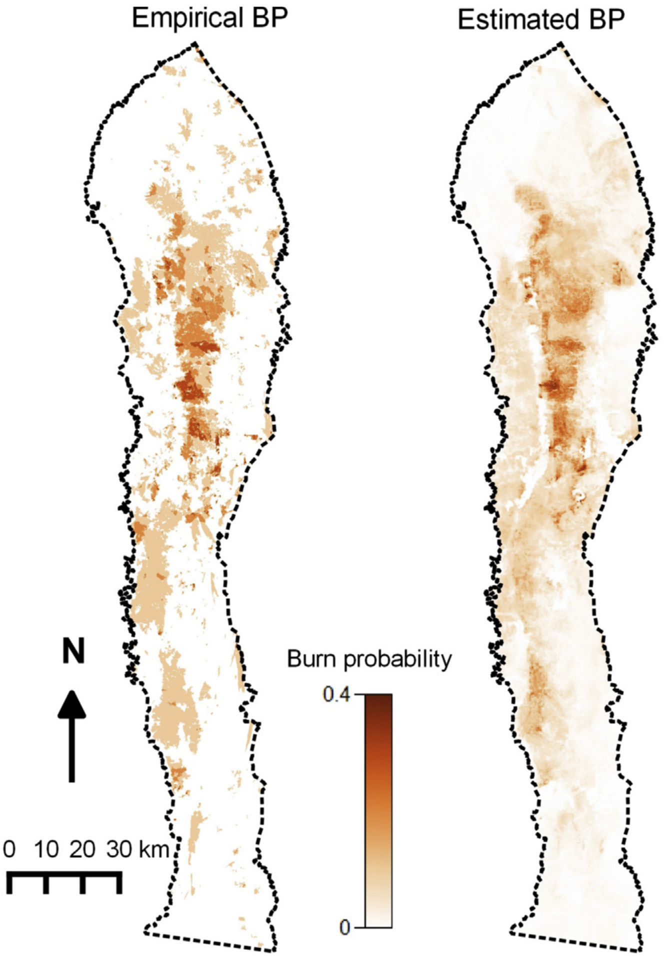

Fig. 4. Empirical and estimated annual burn probability maps for Sierras Chicas (Córdoba, Argentina). Empirical BP was calculated using historic fires from 1999 to 2011 and estimated BP was derived from a model predicting fire frequency. Burned areas were obtained at 30 m resolution using Landsat TM/ETM+ imagery (Argañaraz et al., 2015a).

Table 2
Wildfire exposure assessment in the Wildland-Urban Interface (500 m radius neighborhood) for Sierras Chicas according to historical fires from the period 1999–2011 and empirical annual burn probability.

Exposure variable	Area [ha]				Number of Buildings				
	IMWUI	IFWUI	Total WUI	% of WUI	IMWUI	IFWUI	Total WUI	Study Area	% in WUI
Fires									
All fires	15,073	2273	17,346	14.4	2878	1372	4250	6769	62.8
Large fires (>1000 ha)	9946	713	10,659	8.9	1310	311	1621	2117	76.6
Large fires + buffer 600 m	26,990	3533	30,523	25.3	13,800	5298	19,098	24,471	78.0
Empirical burn probability									
0	71,970	27,198	99,168	85.3	54,395	81,038	135,433	269,803	50.2
0.077	12,080	1690	13,770	11.8	2541	1017	3558	5495	64.7
0.154	2401	354	2755	2.4	313	300	613	983	62.4
0.231	381	101	482	0.4	22	40	62	219	28.3
≥0.308	48	55	103	0.1	3	14	17	72	23.6

IMWUI: Intermix WUI; IFWUI: Interface WUI. Burn probability was calculated as the number of times a pixel was burned, divided by the number of years of the fire database (0.077 = 1/13, once in 13 years; 0.154 = 2/13, twice in 13 years, and so on).

income countries. In Spain and the US, WUI areas occupy 2% and 9% of their territory, respectively (Radeloff et al., 2005; Silva et al., 2010). At the landscape scale, WUI areas vary in their proportion, occupying 30% in south-eastern France (Lampin-Maillet et al., 2010), 20% in western Madrid (Herrero-Corral et al., 2012) and less than 10% in other regions of Spain (Silva et al., 2010). In the US, WUI areas occupy between 7 and 55% (Bar-Massada et al., 2013) and include more than 87% of total buildings. Our results show that the WUI in central Argentina contains a similar proportion of homes as WUI areas in other countries.

Regarding our WUI mapping approach, the 500-m neighborhood size that we selected to define the WUI boundaries represented a balance between the percentage of buildings within fire perimeters belonging to the WUI and the total area classified as WUI. A conservative risk management strategy minimizes both the omission of buildings under risk and the inclusion of areas of low risk, to reduce the high costs needed for fire management (Schoennagel et al., 2009). This is why fire management in WUI areas must be based on fire risk assessments, not just WUI maps, to identify structures at risk and focus prevention and mitigation expenditures in the most risky areas (Elia et al., 2014; Haas et al., 2013; Syphard et al., 2012). In addition, fire risk assessments in WUI areas can be improved using socioeconomic information (Romero-Calcerrada et al., 2008), since socioeconomic vulnerability can be positively related to fire occurrence, which worsens the negative impacts of fires (de Torres Curth et al., 2012; Dondo Bühler et al., 2013).

Most of the WUI buildings in the Sierras Chicas belonged to the Interface WUI (59%), at the edge of urban areas. Since urban areas tend to occupy lower and flatter areas, where winds are typically weaker, the wildfire exposure of many of these buildings is probably negligible because embers may not be able to fly the full 600 m that we used to define the WUI. In fact, property loss is lower when structures are surrounded by urban areas (Syphard et al., 2012). Even though the information about the type of building materials of each building would be a great improvement to evaluate fire susceptibility individually, this data is not available for our study area. Nevertheless, most buildings in Argentina are made of bricks, which reduce both the chances that embers can ignite a house, and fire propagation through houses. This is different from the situation in the US (Calkin et al., 2014; Syphard et al., 2012), where buildings can be a major source of fuels in WUI areas (Haas et al., 2013). As far as we know, there have been no local cases of buildings located within the boundaries of urban areas ignited by embers. However, homeowners in the natural areas of Sierras Chicas tend to use more flammable materials in their buildings (J.P. Argañaraz, Pers. Obs.).

Most of Sierras Chicas buildings located in areas with intermediate to high estimated BP belong to the WUI, especially the Intermix WUI. This is of great concern since fire occurrence tends to be higher in this type of WUI (Lampin-Maillet et al., 2011) due to the vicinity of fuels and buildings and most buildings in the

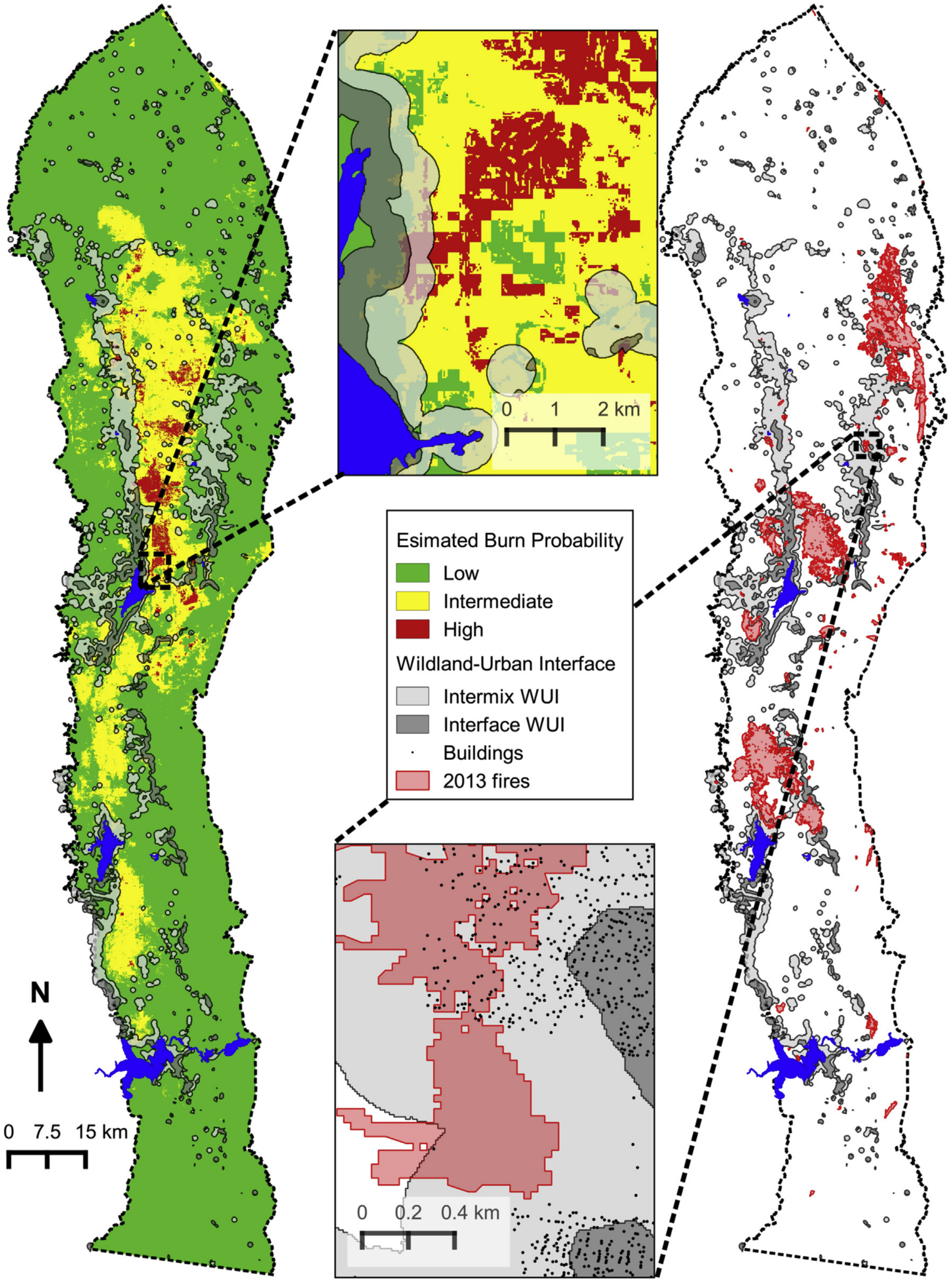

Fig. 5. Wildfire exposure assessment in the Wildland-Urban Interface of Sierras Chicas (Córdoba, Argentina) based on estimated annual burn probability derived from a model predicting fire frequency (left) and incidence of the fires of 2013 on the WUI (right).

Intermix WUI lie in wildland vegetation. Additionally, the ability of firefighters to suppress fires and protect structures in the Intermix WUI can be reduced (Haight et al., 2004) by the low accessibility to many of these areas, and the reduced visibility caused by the smoke that also complicate the evacuation procedures (Cova et al., 2013). This is why the integration of WUI maps with road maps layers can be helpful for decision making before and during a fire event (Cova et al., 2013; Haight et al., 2004).

The fires of 2013 mainly affected areas with higher estimated BP, and most of the buildings exposed to these fires belonged to the

Table 3
Wildfire exposure assessment in the Wildland-Urban interface (neighborhood size of 500 m radius) for Sierras Chicas according to estimated annual burn probability classes.

Burn probability class	Area [ha]				Number of Buildings					
	IMWUI	IFWUI	WUI Total	% of WUI	IMWUI	IFWUI	WUI Total	% WUI	Study Area	% in WUI
Low	77,776	28,978	106,754	88.6	55,888	82,505	138,393	96.3	268,571	51.5
Intermediate	11,305	1805	13,109	10.9	3300	1798	5098	3.5	7569	67.4
High	449	101	550	0.5	146	98	244	0.2	432	56.5

IMWUI: Intermix WUI; IFWUI: Interface WUI.

WUI. This suggests that the burn probability map estimated considering all the relatively static variables determining wildfire likelihood (climate, topography and fuels) (Argañaraz et al., 2015b) was sufficient for assessing wildfire likelihood and exposure in Sierras Chicas. Wildfire exposure is a fundamental component of the fire risk assessment framework (Ager et al., 2012), and even though it does not include a quantification of the expected wildfire impacts, fire effects on buildings are probably uniformly negative (Finney, 2005; Miller and Ager, 2013).

The fact that the majority of the buildings within fire perimeters belonged to the WUI emphasizes the need for specific prevention strategies in WUI areas, particularly in the Intermix WUI. On the one hand, homeowners should reduce the ignitability of buildings in relation to the building materials and their immediate surroundings (Cohen, 2000; Mell et al., 2010), an area termed the Defensible Space, which in Argentina is defined as the 10 m surrounding the house (BCFS-PNMF, 2002). However, burning experiments in the US have indicated that, depending on flame length and fire intensity, home ignitions are likely to happen if flames and firebrand ignitions occur within 40 m of the building (Cohen, 2000). Therefore, it is possible that different sizes of defensible spaces are needed depending on the type of surrounding vegetation, location of structures and building materials. On the other hand, authorities and landowners should be responsible for the reduction of fuels in public and private lands close to urban settlements. Fuel management prioritization at broad scales is recommended to reduce the area and costs of treatments and to maximize benefits (Ager et al., 2010; Bar-Massada et al., 2011; Elia et al., 2014).

Unfortunately though, fuel removals can be detrimental for biodiversity conservation and other ecosystem services (Bar-Massada et al., 2014; Gill and Stephens, 2009), which are among the main reasons why people choose to live in WUI areas. In our study area, herbaceous fuel types may also require fuel treatments, in addition to Chaco shrublands and forests, because grasslands have the highest burn probabilities and in the US some of the most fire-affected buildings were surrounded by low fuel-volume grasslands and burned during surface fires (Calkin et al., 2014; Syphard et al., 2012). Adequately dealing with both wildfire and conservation problems will involve landscape level planning across ownership boundaries (Elia et al., 2014; Radeloff et al., 2005).

5. Conclusions

Our results indicated that even though WUI areas in Sierras Chicas occupy 15% of the territory, they contain most of the buildings exposed to wildfires and most of the buildings located in areas with intermediate and high annual burn probabilities. For this reason, WUI areas in Sierras Chicas constitute a hotspot for wildfire risk management aimed at minimizing potential negative effects on people and their property. In agreement with our initial hypothesis, we found that intermix WUI areas are characterized by the highest burn probability values, regardless of model type, indicating the need for special attention. Our findings can be helpful to delineate future landscape planning strategies, including future urban settlements, for an area that is home to more than 850,000 people and that is expected to grow considerably in the near future. Our approach provides a template for WUI assessment in order to focus fire management towards riskier areas aiming at reducing damages, and to improve early detection, warning alerts and evacuation systems.

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