CSIRO PUBLISHING

International Journal of Wildland Fire **2019**, *28*, 473–484
https://doi.org/10.1071/WF18097

Rapid WUI growth in a natural amenity-rich region in central-western Patagonia, Argentina

Maria Marcela Godoy[A,D], *Sebastian Martinuzzi*[B,*], *H. Anu Kramer*[B,*], *Guillermo E. Defossé*[A,*], *Juan Argañaraz*[C] *and Volker C. Radeloff*[B]

[A]National Scientific and Technical Research Council (CONICET), Andean Patagonian Forest Research and Extension Center (CIEFAP) and Forest Engineering University of Patagonia, Ruta 259 km 16.24 Esquel 9200, Chubut, Argentina.
[B]SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin–Madison, 1630 Linden Drive, Madison, WI 53706, USA.
[C]The Gulich Institute, National Space Agency and CONICET – Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Avenida Vélez Sarsfield 299, 5000 Córdoba, Argentina.
[D]Corresponding author. Email: mmgodoy@ciefap.org.ar

Abstract. The wildland–urban interface (WUI) is a focal area for human environmental conflicts including wildfires. The WUI grows because new houses are built, and in developed countries, housing growth can be very rapid in areas with natural amenities. However, it is not clear if natural amenity-driven WUI growth is limited to developed countries, or also prevalent in developing countries. Amenity-driven WUI growth may be particularly rapid there, owing to a rapidly growing middle class. Our objectives were to (i) map the current WUI; (ii) quantify recent WUI growth; and (iii) analyse relationships between the WUI and both fire ignition points and wildfire perimeters in the region of El Bolson, in Central Andean Patagonia, Argentina. We mapped the current WUI based on housing information derived from census data, topographic maps, high-resolution imagery and land-cover data. We found that the WUI contained 96.6% of all buildings in 2016 even though the WUI covered only 6.4% of the study area. Between 1981 and 2016, the WUI increased in area by 76%, and the number of houses by 74%. Furthermore, 77% of the recent fires in the region occurred in the WUI, highlighting the need to balance development with wildfire risk and other human–environmental problems.

Additional keywords: Andean Patagonian Region, fire ignitions, land-use planning, wildfire management, wildfire risk.

Received 4 July 2018, accepted 21 March 2019, published online 15 May 2019

Introduction

The wildland–urban interface, or WUI, is the area of transition between unoccupied vegetated land and urban development (USDA and USDI 2001). These WUI areas are focal zones for human–environmental problems (Johnson 2001; Radeloff *et al.* 2005, 2018), including those related to wildfires (Alavalapati *et al.* 2005), habitat fragmentation (Theobald *et al.* 1997) and biodiversity loss (McKinney 2006). Different approaches and methodologies have been developed to study and interpret the many processes occurring in WUI areas around the world (Radeloff *et al.* 2005; Caballero 2008; Beverly *et al.* 2010; Lampin Maillet *et al.* 2010; Galiana Martín 2012). In the USA, to create maps to guide strategic planning related to wildfires, the Federal Register (USDA and USDI 2001) distinguishes between intermix and interface WUI. Intermix WUI is defined as areas that have at least 6.17 houses km^{-2} intermingled with wildland vegetation, whereas interface WUI is developed areas near wildland vegetation. Based on this definition, Radeloff *et al.* (2005) set a threshold of 50% of vegetation cover for a given census block for intermix WUI. Interface WUI, however, are those areas with >6.17 housing units km^{-2} that contain <50% of wildland vegetation, but are within 2.4 km of heavily vegetated areas (75% of wildland vegetation) and larger than 5 km^2. The California Fire Alliance (2001) set a 2.4-km distance for the interface WUI based on how far firebrands could fly ahead of a fire front. The stability and robustness of this methodology were demonstrated by Stewart *et al.* (2007), and it was later used to map the WUI of the conterminous United States (Martinuzzi *et al.* 2015), and a WUI located in a mountainous area of central Argentina (Argañaraz *et al.* 2017).

The presence of houses in some fire-prone WUI may be linked to the frequency of wildfire ignitions (Chas-Amil *et al.* 2013; Radeloff *et al.* 2018), because most of the fires occurring in WUI areas are initiated by people dwelling in these houses

[*]S. Martinuzzi, H. A. Kramer and G. E. Defossé equally contributed to the authorship of this paper.

(Bond and van Wilgen 1996; Syphard *et al.* 2009; Bowman *et al.* 2011; Moreira *et al.* 2011). Ignitions tend to be most frequent at intermediate population densities (Mundo *et al.* 2013), because fuels are typically lacking in urban areas with very high population densities (Syphard *et al.* 2009). However, in unpopulated areas, lightning, not people, is the main cause of wildfire ignitions (Defossé *et al.* 2006).

One of the problems of increased wildfire ignitions in the WUI is a consequence of the worldwide-applied policy of fire exclusion. Where human lives and houses are at risk, managers often have little choice but to fight fires, although the combination of fire exclusion policies and increasing urbanisation in the conterminous USA has resulted in major changes in fire regimes (Morgan *et al.* 2001), both altering the number of ignitions and increasing fuel availability (Hawbaker *et al.* 2013). Indeed, these vicious circles occur in many parts of the world with WUI fire-prone areas, in which large seasonal drought periods (sometimes exacerbated by the process of global warming) acclimatise vegetation to rapidly burn given an ignition source. Examples of these areas can be found in western North America (Swetnam *et al.* 2016; Radeloff *et al.* 2018), Australia (McAneney *et al.* 2009; Collins *et al.* 2015) and Chile (Castillo Soto and Alvear 2012; Reszka and Fuentes 2015), and in Portugal (Gómez González *et al.* 2018), Spain and Greece in Europe (San-Miguel-Ayanz *et al.* 2013). The western Patagonian region of Argentina is no exception. A fire exclusion policy was introduced in Andean Patagonia in the 1940s with the creation of several National Parks (Tortorelli 1947). Enforcement of this policy allowed unprecedented build-up of dead biomass (Veblen and Lorenz 1988; Kitzberger and Veblen 1999), modifying natural fire regimes and leading to more severe fires when they occur (Veblen *et al.* 1999; Veblen and Kitzberger 2002; Ghermandi *et al.* 2016). The drying effects of climate change may have enhanced this fact. Climatic data from 1961 to 2016 for the study region showed a consistent trend of increasing temperatures (~2°C during summer, from 1 to 1.5°C during fall (autumn), and ~0.5°C during winter and spring), and a diminution in mean annual precipitation. This diminution has been especially notable during summer, fall and winter periods, and remained stable during spring (Secretaría de Ambiente y Desarrollo Sustentable (SAyDS) 2015; Servicio Meteorológico Nacional (SMN) 2019). Predictive models for the region indicate that this trend may continue into the future, favouring conditions for increasing fire frequency and severity. Nevertheless, although fuel accumulation due to the fire exclusion policy is still one of the main causes of wildfire initiation and subsequent spread, the seasonal pattern of wildfire occurrence has remained unchanged. However, the combination of these biotic and climatic factors, coupled with new human settlements, may help explain increases in wildfire ignitions in the expanding WUI around west-central Patagonian towns (Mermoz *et al.* 2005; Veblen *et al.* 2008; de Torres Curth *et al.* 2012; Defossé *et al.* 2015).

Problems related to wildfires in the WUI, as well as other environmental problems that are concentrated there (Bar-Massada *et al.* 2013) are likely to increase because the WUI is growing in many countries (Theobald and Romme 2007; Lampin-Maillet *et al.* 2010; Galiana Martín 2012). For example, in the conterminous US, the number of houses in the WUI grew from 30.8 to 43.4 million from 1990 to 2010, representing 41% growth, and the area of the WUI grew from 581 000 to 770 000 km^2 in the same period, which is equivalent to 33% growth. However, whereas the expansion of the WUI in developed countries of North America and Europe has been well documented (Lampin *et al.* 2006; Stewart *et al.* 2007; Catry *et al.* 2010; Galiana Martín 2012; Martinuzzi *et al.* 2015), much less is known about the extent and the growth of the WUI in developing countries. Case studies from South America suggest, though, that the WUI are prevalent in some regions of developing countries too. These are the cases of Córdoba (Argañaraz *et al.* 2015, 2017) and Patagonia (de Torres Curth *et al.* 2012) in Argentina, and Chile (Castillo Soto 2015; Reszka and Fuentes 2015), Bolivia (McDaniel *et al.* 2005) and Brazil (Pivello 2011; Ferreira-Leite *et al.* 2015).

In regards to WUI growth, the pattern in developed countries is that WUI growth tends to be strong both at the fringe of urban and metropolitan areas, but also in places that are rich in natural amenities, which draws people in (Stetler *et al.* 2010; Gill *et al.* 2015). Such amenity-driven housing and hence WUI growth is fostered by a larger number of retirees in the population, the ability to telecommute, and rising second-home ownership rates, all of which allow people to live, at least for parts of the year, at a distance from centres of employment. However, it is an open question if such amenity-driven housing growth is also a major driver of WUI growth in developing countries. On one hand, there is less wealth in developing countries, which may limit such housing growth, but on the other hand, there may also be different land-use planning rules, and the middle class is growing in many developing countries, which may foster amenity-driven housing growth.

One region that exemplifies both rapid housing growth and major problems with wildfires is located on the eastern side of the central Patagonian Andes in Argentina. This region lies, from north to south, from approximately the 38° to the 43° South Latitude (SL) parallels, and from approximately the 70° meridian in the east to the high mountain peaks of the Andean Cordillera to the west, which marks the border with Chile (Fig. 1*a*). This encompasses a territory of stunning natural beauty due to the nearby mountains, large glacial lakes, multi-species temperate forests, and several national, provincial and municipal parks with magnificent scenery (Beccaceci 1998). Here, in the foothills of the Andes, there has been a steady growth of the number of people and buildings in fire-prone areas, both in the form of permanent housing and of second homes owned for recreational activities (Veblen *et al.* 2008; Defossé *et al.* 2015). Indeed, the average number of houses and people in this region is rising two to three times faster than in the rest of Argentina (Argentinean National Institute of Statistics and Censuses, INDEC in its Spanish acronym (INDEC) 2016). This growth may be explained, in part, because people seek better economic opportunities (Ghermandi *et al.* 2016) and to improve their quality of life in a natural amenity-rich region surrounded by beautiful national and provincial parks.

Unfortunately, wildfire incidence is high in this foothills of the Andean region of Patagonia. This is partly due to the prevalent Mediterranean climate, which presents low relative humidity, high winds and low soil water availability from late spring (October) to early fall (April in the southern hemisphere).

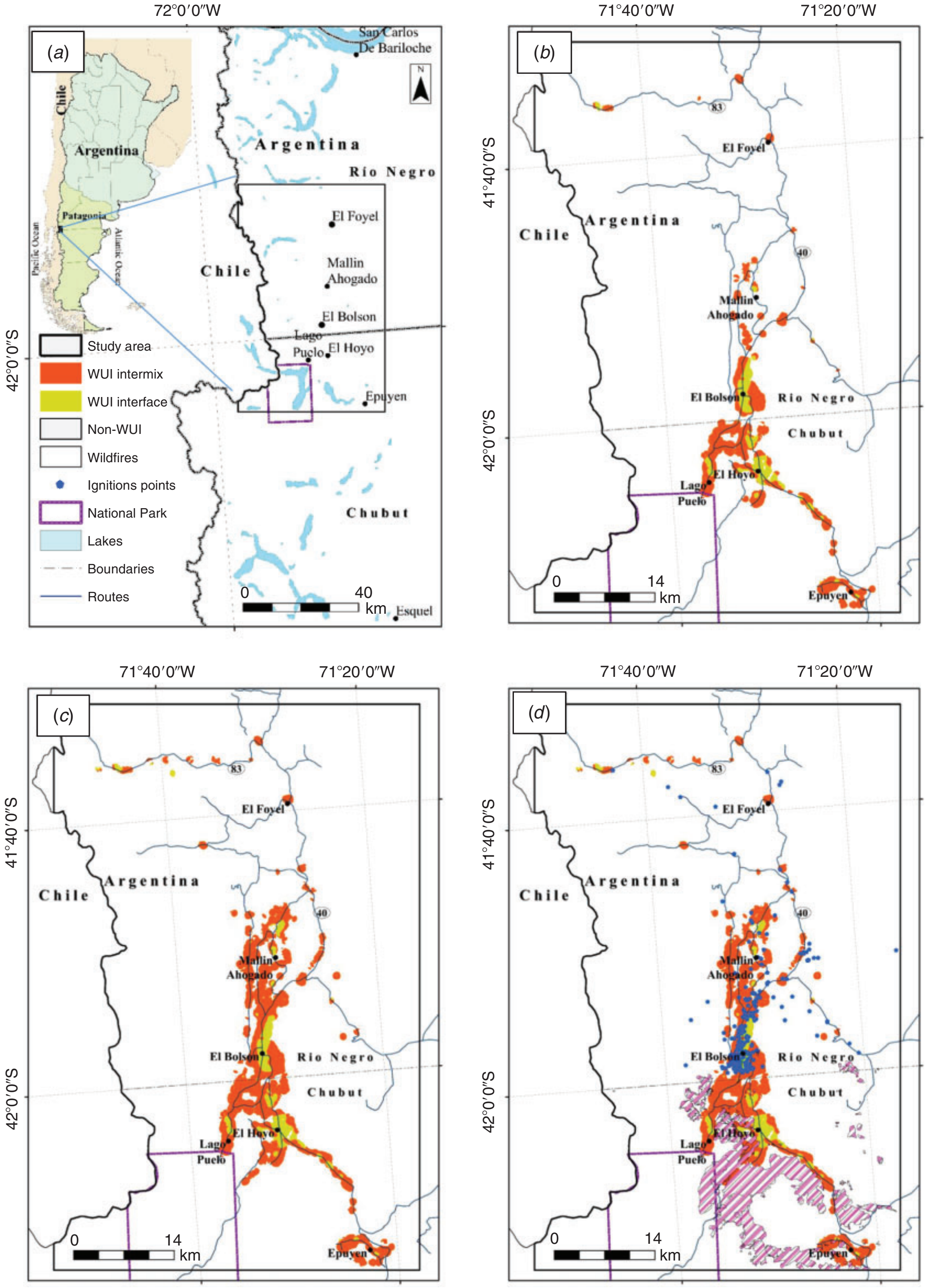

Fig. 1. (*a*) Location of the study area in the western part of Río Negro and Chubut provinces in Patagonia, Argentina; (*b*) WUI in 1981–1982; (*c*) WUI in 2016; (*d*) Ignition points and area covered by wildfires between 2010 and 2015, superimposed to the present WUI area.

Under these environmental conditions, native and planted vegetation is ready to burn, and given an ignition source, wildfires of different magnitude can occur (Dentoni *et al.* 2001; Defossé *et al.* 2011; Godoy *et al.* 2013). Indeed, recent catastrophic fires have occurred in this Andean Patagonian region during hot, dry years between 1999 and 2015, burning 236 007 ha of wildland

and WUI areas (Dentoni *et al.* 1999; SAyDS 2003, 2004, 2005, 2006, 2011, 2012, 2013; Ministerio de Ambiente y Desarrollo Sustentable (MAyDS) 2015). Similarities in fire regimes and WUI growth and development between the central Andean region of Patagonia and some regions of the western US are remarkable. In the case of fires, these similarities are represented in the parallels in the fire history of the Colorado Front Range and central north-western Patagonia (Veblen and Kitzberger 2002) and in the interhemispheric synchrony of forest fires and the influence of El Niño-Southern Oscillation (ENSO) activity in both regions (Kitzberger *et al.* 2001). In relation to WUI growth and development, central north-western Patagonia is experiencing a similar expanding trend (Mermoz *et al.* 2005; Veblen *et al.* 2008; de Torres Curth *et al.* 2012) to that Hammer *et al.* (2007) described for California, Oregon and Washington in the USA. Perhaps a slight difference is that in Patagonia, a higher proportion of ignitions are thought to be caused by arsonists as compared with the western US. However, scientific literature about how WUI areas are expanding and affected by wildfires is still rather scarce for many areas in central north-western Patagonia.

In the present study, we examined the WUI and WUI growth in a particular area that surrounds the city of El Bolsón, located within a fire-prone region of central north-western Andean Patagonia in Argentina, which has witnessed strong amenity-driven housing growth in recent decades. Our specific objectives were to: (i) assess the current WUI; (ii) quantify recent WUI growth; and (iii) analyse the relationships between the WUI and both fire ignition points and burned areas.

Methods

Study area

Our study area covered 337 000 ha around the city of El Bolsón, one of the most populated regions of the central Patagonian Andes in southern Argentina. The study area extends from the Argentina–Chile border in the Andean Cordillera to the west (2316 m elevation in Cerro Aguja), to lower elevations of the Patagonian steppe to the east (240 m), and includes parts of two Argentinian provinces: Rio Negro to the north, and Chubut to the south. In addition to the city of El Bolsón (422 m elevation), there are other small towns, including Lago Puelo, El Hoyo and Epuyén (Fig. 1*a*).

As for the whole region, the climate of the study area is mediterranean, with most of the annual precipitation occurring during the winter months (June to September), followed by a drought period that goes from early spring (October) to late summer (April in the southern Hemisphere). Annual rainfall is lowest in the steppe (400–600 mm), moderate at middle elevations (600–1500 mm) and highest at the timberline (3000–4000+ mm) (Defossé *et al.* 2015). Vegetation types also change rapidly along the elevation and precipitation gradients from east to west (Veblen and Lorenz 1988). Most of the area is covered by mixed forests dominated by *Nothofagus antarctica* (G. Forst) Oesrt. and *Austrocedrus chilensis* (D. Don) Florin et Boutleje as well as shrubs and grasses that are typical of the Occidental District of the Patagonian Steppe (Defossé *et al.* 2015).

In the past and up to the 90s of the last century, the most important economic activities based on natural resources were both timber and extensive livestock production. Since then, these activities have slowly declined because of depletion and overuse of these resources (Defossé *et al.* 2015). The valleys, instead, along with a concentration of most of the urban centres, are still used for intensive agriculture. Hops, berries, aromatic plants, high-quality organic vegetables, dairy products and freshwater fishing hatcheries and their industrialisation are important economic activities that characterise the area. However, although these activities move part of the regional economy, the primary employer in the region is government administration, followed by tourism and leisure activities. Another aspect that should not be neglected related to an economic boost in the area is that since the late 90s, an important number of wealthy families from different regions of Argentina or from other countries bought land and built permanent or second homes within the WUI that encompasses this area. Most of these families came attracted by the beauty of the landscape, the relatively low price of land compared to similar areas found in the USA or Europe, and perhaps the laissez-faire policy based on the flexibility (or in some cases the absence) of urban planning codes. This flexibility (allowing people to do almost whatever they want on their land) has often been a source of conflicts among the different social groups that inhabit the study area. Although most of the land is private, there exist differences in tenure rights among landowners. There is one large national park (Parque Nacional Lago Puelo, 27 674 ha in size) in the south-west zone of the study area (Fig. 1*a*).

Wildfires, together with overgrazing, land-use change, and more recently WUI growth and development, are today the major environmental problems in western Patagonia. Wildfires occur in the region during the summer, i.e. from late October to early April in the southern hemisphere. From ancient times to nowadays, wildfires have helped shape the structure and functioning of Patagonian vegetation (Kitzberger *et al.* 1997; Ghermandi 2006; Defossé *et al.* 2015). At millennial time scales, studies have shown that there is abundant sedimentary charcoal evidence of past burning across the full range of ecosystems types throughout the Holocene from 41° to 42°30′ SL in western Patagonia, which includes our study area (Goldammer *et al.* 1996; Kitzberger *et al.* 2005; Whitlock *et al.* 2006). At the beginning of the 20th century, Willis (1914) and Rothkugel (1916) reported 52 000 and 692 000 ha respectively (37% of the forest area) as recently burned. Later, Tortorelli (1947) reported 275 000 ha of burned forests in the 1943–44 period in this region, including our study area. Tree ring records taken in the same region clearly document years of synchronous and widespread fires during the 19th century and before permanent European settlement (Kitzberger *et al.* 1997; Veblen *et al.* 1999; Veblen *et al.* 2008; Defossé *et al.* 2015). This evidence, plus the fact that the WUI is increasing in the area and that the number of human-set fires increased in the WUI as compared with the non-WUI in a nearby area of the same region (Mermoz *et al.* 2005; Veblen *et al.* 2008), clearly indicate that wildfires and WUI growth are big issues in north-western Patagonia.

Although 93% of ignitions are reported to be caused by humans (either by negligence, recreational activities or other causes; Rodríguez 2000); lightning-ignited fires are not uncommon in western Patagonia, especially at higher altitudes of the Andean Cordillera (Veblen and Lorenz 1987; Goldammer *et al.* 1996;

Defossé *et al.* 2006; Veblen *et al.* 2008). However, and considering the percentage of fires caused by humans, the statistics only reveal ignition points detected and not wildfires, and there have still been no investigations of fire causes carried out by trained people. In some cases, lightning strikes have generated wildfires of extreme behaviour, especially when they occurred in remote wilderness areas during late summer, when severe drought conditions prevail (Dentoni *et al.* 1999; Roveta *et al.* 2015). The historic fire regime in the region varies according to the different vegetation traits found in the environmental gradient (Kitzberger *et al.* 1997). In general, fire frequency is high (from 4–5 to 7 years) and severity low at low-altitude areas in the ecotone between the forest and the steppe, and steadily diminishes in frequency (~50 years) and increases in severity going up the Andean mountains (Kitzberger *et al.* 1997; Veblen *et al.* 2008). Evidence of big wildfire events was recorded near Bariloche in the summer of 1913–14 (Rothkugel 1916), and other fires even before that (Willis 1914) because maps from the early 1900s show them as burned areas. Similarly, Tortorelli (1947) mapped burned areas near our study area in January and February of 1944. The timing of the largest fires is often related to the flowering and subsequent dying of the native *Chusquea culeou* E. Desv., a highly flammable bamboo cane (Bianchi and Defossé 2015). Particularly within the study area, records show that wildfires occurred during the summer seasons of 1960, 1963, 1979, 1987, 1998, 2004, 2011, 2012 (Strobl and Zacconi 2012), and also in 2015; most of them burned unpopulated wilderness areas. The fires of 2011 and 2012, in contrast, covered 1300 and 4300 ha respectively, and occurred in WUI areas. Both fires presented extreme behaviour and the 2012 fire destroyed 16 houses, although no human losses were registered. The last large fire occurred in 2015, and burned 39 994 ha, mostly in wilderness areas.

The Argentine Management Fire Law dictates that when there is an ignition source, local and provincial authorities are responsible for the initial attack. If local and provincial firefighting capacities are surpassed, they can ask for additional assistance from the National Fire Management Service, which provides terrestrial and aerial support (hotshot crews, aircraft tankers and helicopters) as requested by the single Incident Command System.

According to the 2010 census (Strobl and Zacconi 2012), there were 29 973 people and 12 657 homes in the study area. From 2001 to 2010, population increased by 49% in Epuyen, 36% in El Hoyo, 22% in El Bolsón and 17% in Lago Puelo. Furthermore, the National Census Institute estimates that the population in our study area will grow by ~30% by 2025 (INDEC 2016). The main reasons for this population growth are migration from other areas due to better economic opportunities, the desire for second homes for recreational purposes, abundant natural amenities, and – partly – a good quality of life for residents (Veblen *et al.* 2008).

Data and approach

Objective 1 – mapping the current WUI

Of the different methodologies available, we used that proposed by Radeloff *et al.* (2005) to determine and map the current WUI. We selected this method because of the availability of data, and because it provides a well-documented approach with metrics that allow comparison with other areas or regions of the world. Furthermore, its precise metrics clearly define intermix and interface WUI areas. This fact allows comparison of WUI areas not only with those of other countries (Martinuzzi *et al.* 2015) but also with other WUIs of Argentina (Argañaraz *et al.* 2017). Another reason to use this methodology was that many similarities in landscape and population densities exist between our study area and western USA, in which this methodology has proved suitable.

Another reason for choosing this methodology was that for the purpose of our study, we had previously tried both the census block and point-based (Bar-Massada *et al.* 2013) approaches to map the WUI. However, census blocks in our study area were large (often >10 000 ha), and the resulting WUI map showed artefacts due to the census block borders, rather than the true patterns of housing. This fact convinced us that the point-based approach was the best choice for determining WUI patterns in our study area.

The housing density in the WUI was assessed by using the point-based approach based on the location of individual buildings according to Bar-Massada *et al.* (2013). For this purpose, we used two spatial datasets: (i) building locations, and (ii) wildland vegetation cover. We digitised building locations from current (~2016) high-spatial-resolution satellite imagery (15-m resolution on average), as available in Google Earth (2016, ver. 7.3.2; https://www.google.com/earth/, accessed 30 November 2016). While digitising, we considered the number of homes within 2010 census blocks (INDEC 2016) as the lower bound of the number of buildings in that census block. Furthermore, in the census blocks with very high housing density (>500 houses km^{-2}), which encompassed 23 census blocks in the city of El Bolson, we did not digitise the buildings, but instead assigned the number of buildings according to the census data randomly within the corresponding census block, following Bar–Massada *et al.* (2013) and Argañaraz *et al.* (2017). We suggest that this is an acceptable shortcut because the housing density within any moving windows covering these blocks will always be $\geq$6.17 km^{-2}, irrespective of the exact location of the housing units.

We extracted the wildland vegetation cover from a recent land-cover map derived from 10-m pixel SPOT 5, and 30-m LANDSAT Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI) imagery (Andean Patagonian Forest Research and Extension Center (CIEFAP) and MAyDS 2016). We reclassified the vegetation map into wildland and non-wildland vegetation following Bar-Massada *et al.* (2013) and Martinuzzi *et al.* (2015), where wildland vegetation included forests, woodlands, grasslands and wetlands, and non-wildland vegetation included horticultural lands, water bodies, rocks, urban areas and infrastructure.

We mapped the WUI using a moving window of 500 m, following Bar-Massada *et al.* (2013) and Argañaraz *et al.* (2017). Moving windows where the density was high enough were tested to see if wildland vegetation reached 50% in the moving window (in which case the central pixel was mapped as intermix WUI), or if it was close to a large area of wildland fuels (in which case those areas not already mapped as intermix WUI were mapped as interface WUI). Areas not mapped as WUI (interface or intermix) were categorised as non-WUI. As a

Table 1. Area and number of houses in the study area for the periods 1981–82 and 2016

Wildland–urban interface (WUI) type	Area				Houses			
	1981–82		2016		1981–82		2016	
	(ha)	(%)	(ha)	(%)	no.	(%)	no.	(%)
Intermix	9669	2.9	18 360	5.5	3469	35.7	6205	47.4
Interface	2442	0.7	3006	0.9	5923	61	6452	49.2
Intermix + interface	12 141	3.6	21 366	6.4	9392	96.7	12 657	96.6
Non-WUI	324 590	96.4	315 366	93.7	313	3.2	444	3.4
Total	336 732	100	336 732	100	9705	100	13 101	100

sensitivity test, we mapped the WUI with a range of window sizes (100, 200 to 1000) to see how much our results changed with changes in window size. For each WUI maps, we calculated the area of the WUI, and the number of buildings in the WUI.

Objective 2 – quantifying changes in WUI area

To quantify changes in the WUI from the early 1980s to 2016, we analysed topographic maps from the National Geographic Institute of Argentina (IGN) to map houses, vegetation and WUI in 1981–82. In the 1981–82 topographic maps, houses were not mapped individually, and groups of houses were instead indicated by a symbol. To create the map of houses in 1981–82, we started with the 2016 digitised building locations, and removed houses in areas where land use in the 1981–82 maps indicated that there were no houses (e.g. forest, wetlands). In areas where the 1981–82 maps showed houses, we assumed that all the houses that we mapped in 2016 were already there at the earlier date. This represented a conservative approach, because areas with houses in the 1981–82 topographic maps could have seen an increase in the number of houses by 2016. However, as we could not quantify the changes in houses in areas that were already developed in 1980, this was the most parsimonious approach and it captured the expansion of houses into natural areas well, which was what we were most interested in. To assess the accuracy of our method, we compared our estimates of total homes in 1981–82 with the number of houses reported in the official census of 1980 (INDEC 2016).

As our data source for wildland vegetation in the early 1980s, we again used the 2016 land-cover map. We suggest that this is justified because, except for the expansion of urban areas, changes in land use have been small. Using the same wildland vegetation cover data therefore represents a conservative estimate of wildland vegetation in the 1980s. We calculated WUI changes both in terms of area (ha and percentage change) and buildings (quantity and percentage change).

Objective 3 – quantifying the incidence of wildfires in the WUI

In regards to our third objective, we quantified the incidence of wildfires from 2010 to 2015 that occurred in the 2016 WUI versus those that did not. Because data were not consistent across provinces, we used two types of fire data: ignition points in Río Negro Province (M. Bachfischer from Forest Fire Fighting and Prevention Service (SPLIF) Río Negro Province, pers. comm.), and burned area polygons in Chubut Province (Subsecretaría de Bosques e Incendios from Chubut Province). Combined, these data represent all wildfires in our study area.

For the northern part of our study area, for which only ignition points were available, we calculated the proportion of ignition points that occurred inside and outside the 2016 WUI ($n = 252$). The ignition source (either human or natural) was not specified, but ignitions were always in wildland vegetation and recorded on the ground using Global Positioning System (GPS).

For the southern part of our study area, where burned area polygons were available, we calculated the number of wildfire polygons that burned either in part or entirely in the WUI versus those that burned entirely in non-WUI areas ($n = 36$; mean area = 50 ha). Burned-area polygons were mapped by taking GPS points on the ground, as well as digitising satellite images. The minimum wildfire size that was mapped was 5 ha.

Results

Current WUI

We mapped 13 101 buildings in our study area in 2016, which is very similar to the 13 717 houses and 33 287 people that inhabited our study area in 2016 according to projections of the Argentinean Census Bureau (INDEC 2016). The WUI covered 21 366 ha, which was equal to only 6% of the entire study area, yet the WUI contained 97% of all buildings (Table 1). Within the WUI, the area of intermix WUI was approximately six times larger than that of the interface WUI (i.e. 18 000 vs 3000 ha). However, both intermix and interface areas contained similar numbers of houses (6452 and 6205 for interface and intermix WUI respectively; Table 1). WUI areas were concentrated along valleys and included all urban centres (i.e. El Bolson, Lago Puelo, El Hoyo and Epuyen), as well as surrounding areas with low-density housing such as the towns of Mallín Ahogado and El Foyel (Fig. 1*c*). All the interface areas were surrounded by intermix areas.

WUI change 1981–82 to 2016

The WUI grew substantially in our study area. We found an increase in the number of WUI buildings of 35%, rising from 9705 in 1982 to 13 101 in 2016 (Table 1), and the area of WUI grew by 75%, from 12 141 to 21 366 ha (Table 1). Most of the growth in WUI area occurred in the form of intermix WUI (8660 of a total of 9224 ha of new WUI area; Table 2). The WUI grew especially fast north of the town of El Bolsón, south of the town of El Hoyo, and around Mallín Ahogado and El Foyel. Growth of interface

Table 2. Differences in wildland–urban interface (WUI) area (ha) and number of houses between 1981–82 and 2016
Both types of WUI (intermix + interface) grew 76% in 35 years. The number of houses grew much more in the WUI intermix

WUI type	Area		Houses	
	(ha)	(%)	No.	(%)
Intermix	8660	89	2736	79
Interface	564	23	529	9
Total WUI difference	9224	76	131	42

Table 3. Ignition points and wildfires in the study area
Most of the ignition points in Río Negro Province were found in the wildland–urban interface (WUI) intermix. In contrast, most of the area burned in Chubut Province lay in the non-WUI area

WUI type	Ignition points in Río Negro		Wildfires in Chubut
	No.	(%)	Area burned (ha)
Intermix	140	56	982
Interface	53	21	
Non-WUI	59	23	11 594
Total	252	100	12 576

WUI was quite minor, but did occur along the El Manso River and along provincial route RP 83 in the north of the study area (Fig. 1*b* and *c*). For the most part though, the patterns and location of the 1981–82 WUI were similar to that of the 2016 WUI.

Incidence of wildfires in the WUI

We found that wildfires were concentrated in the WUI, both in terms of ignition points and in terms of burned area of the fires that occurred from 2010 to 2015. Of the 252 ignition points in the northern half of the study area, 77% occurred within the WUI (Table 3, Fig. 1*d*), and most of them were in the intermix WUI (140 points) and fewer in the interface WUI (53 points). Similarly, of the 36 wildfires reported in the southern half of the study area, 46% of them burned at least partially in the WUI (Table 3, Fig. 1*d*). The total area burned was 12 600 ha for the southern portion of the study area, of which 980 ha (7.8%) was in the WUI.

Discussion

We mapped the WUI and its recent growth in a fire-prone and rapidly growing area in central-western Patagonia. We found that although the WUI represented only a relatively small portion of our study area at 6.4%, it contained 97% of all housing units that were present in 2016, and both WUI area and the number of houses in the WUI grew rapidly since 1981–82. The maps provided information in which houses and wildland vegetation coincided, and it is part of the information resource planners must assemble in developing fire and fuel management plans, urban and road planning, and community awareness activities as well. Given that both types of WUI – interface and intermix – are in fire-prone areas, the WUI assessed should be considered as a fire risk area. These findings are of considerable importance in regards to wildfires, which are natural here, and we found indeed that most ignitions and burned area were at least partially in the WUI. More broadly, our results show that areas that are rich in natural amenities and fire-prone as well – and our study area is certainly one of these areas – are susceptible to all the problems related to the WUI in the developed world as they are in the USA as stated by Paveglio *et al.* (2015). Indeed, 97% of all homes being in WUI far exceeds what had been previously reported in other study areas. In Sierras Chicas de Córdoba, Argentina, ~52% of the buildings were in the WUI (Argañaraz *et al.* 2017). In the conterminous US, 33% of houses are located in the WUI, although this varies depending on the region. In large unpopulated areas of the Rocky Mountains in Wyoming, which resembles Patagonia, 82% of the houses are in WUI areas (Martinuzzi *et al.* 2015). The fact we chose the analytical definition of the USDA and USDI (2001) to determine our WUI was because houses and density distribution in Patagonia resemble how it is in the USA in general but not in Europe, where housing density is higher and the WUI is closer to wildland areas and homogenously overcrowded. Further, in Europe, there is no standardised legal framework to define WUI areas for either fire risk management or spatial planning (Modugno *et al.* 2016).

Current WUI

The WUI in our study area was located around both established and newly developing towns and villages, as well as along the roads that connect cities in our study area with other important towns of Patagonia. These towns are Bariloche (129 km to the north) and Esquel (150 km to the south); this location aligns with WUI areas in Europe, which occur around several suburban areas and touristic regions (Lampin-Maillet *et al.* 2011; Modugno *et al.* 2016). Our study area is a tourism destination with many hotels and resorts in the towns and around them, which is one of the reasons for the increase in number of people living in this WUI, as occurs in western WUI communities of the USA (Paveglio *et al.* 2015). Although the WUI represented only

6.4% of the study area, it contained 15 of the wildfires (42%) and 193 of the ignition points (77%) that occurred from 2010 to 2015. Among these, most occurred in the intermix WUI, which is consistent with studies conducted elsewhere that observed higher fire activity in the intermix WUI than in both the interface WUI and non-WUI areas (Argañaraz *et al.* 2017), or where housing density was lower in the WUI (Lampin-Maillet *et al.* 2010, 2011). The lower fire activity recorded in interface WUI is probably because it has less wildland vegetation (Lampin-Maillet *et al.* 2011), an early detection system and better firefighter accessibility (Bar-Massada *et al.* 2009). Better fire-fighting responses and awareness of fire-wise communities also reduce the impact of wildfires in WUI areas (Kramer *et al.* 2018). However, lower fire activity in non-WUI areas is due to the absence of people, given that humans are responsible for the majority of ignitions (Parisien *et al.* 2016), as in the western USA (Balch *et al.* 2017). This preponderance of ignitions in the intermix WUI suggests strategically concentrating suppression and control efforts in these areas to limit wildfire incidence in the future, as in the US Forests Service lands (Stephens 2005).

In our WUI map, the methodology used (Google Earth Imagery) allowed us to visualise, count and digitise every house at its location. This direct counting minimised spatial errors and has previously been used in similar studies by Bar-Massada *et al.* (2013) and by Argañaraz *et al.* (2017). However, minor errors could have occurred when buildings or houses are hidden below tree canopies (occlusion, resulting in fewer counts) or by confusing sheds or barns with houses (increasing the counts). In our study, our counting slightly underestimated (only 4.7%) the number of houses estimated and reported by the Argentinean Census Bureau (13 101 houses counted in our study using Google Earth Imagery, and 13 717 reported by the Argentinean Census Bureau). These numbers allow us to infer that spatial errors are minor and that the methodology used was successful in house detection and did not affect the overall results of our WUI assessment.

WUI Change 1982–2016

The 2016 WUI area was 9225 ha larger than the WUI in 1981–82, and 89% of the new WUI area was intermix WUI. However, this finding may be partly due to the fact that the 1981–82 topographic maps did not contain sufficient information to map increases in the number of houses that were already developed back then. Our change analysis thus focused on new houses in areas that were forested in 1981–82 and this is why it is not surprising that the intermix WUI grew in area and did so at a rate that was 8 times higher than that of the interface WUI. The trend in this area from the late 1990s to the present showed that the rate of houses built in the intermix WUI remained higher than in the interface WUI. Little of this expansion of intermix WUI is done at expense of sacrificing agricultural lands, because the majority of this WUI expansion is done by occupying non-agricultural wildland areas with native vegetation away from urban and suburban areas (the most preferred by new builders and developers).

Concomitantly, it is likely that the interface WUI grew in terms of the number of houses and people in the WUI as interface areas became more densely settled. Indeed, similar patterns of WUI growth and expansion have occurred in the USA (Hammer *et al.* 2007; Radeloff *et al.* 2018), Europe (Lampin Maillet *et al.* 2009), Argentina in the Sierras Chicas of Córdoba Province (Argañaraz *et al.* 2017) and in other regions worldwide (Bar-Massada *et al.* 2014).

We also found that the number of houses in the WUI has been growing rapidly in our study area from the 1980s to 2016 (see differences in Fig. 1*b* and *c*, and Table 2), and areas north and south of our study area have also grown rapidly in population (INDEC 2016). Trevelin, for example, a small town located 170 km south of our study area, increased in population by 20% between 2000 and 2010, and San Martín de los Andes, located ~350 km to the north, grew 17% in population during the same period.

The difference in WUI growth in intermix and interface areas highlights a difficult land-use and fire management problem, and is somewhat similar to that in the states of Washington, California and Oregon in the USA (Hammer *et al.* 2007). Furthermore, the proximity of houses and vegetation creates a difficult situation for wildland firefighters, as they are trained to fight wildland fires and not structural fires. The WUI expansion we show here could raise awareness about wildfires in the expanding urban area of El Bolsón and its surroundings.

Incidence of wildfires in the WUI

In regards to wildfire patterns, we found that 77% of wildfire ignition points occurred in the WUI, and half of those in the intermix WUI. This suggests that wildfire ignitions are more frequent in areas where both houses and wildland vegetation are present, similarly to Europe and the US (Syphard *et al.* 2009; Catry *et al.* 2010; Chas-Amil *et al.* 2013). From a fire prevention standpoint, the concentration of ignitions in the WUI shows where education efforts should focus, and where resources to fight wildfires are mostly needed (Liu *et al.* 2007).

The burned areas that we analysed affected mostly non-WUI areas, which is not surprising, because WUI areas were rare, because wildfires are most vigorously fought where houses are at risk, and – maybe – because there are fewer fuels in the WUI. Furthermore, fire detection in populated areas is immediate, allowing early fire attack by fire brigades. In other words, although ignitions occur primarily in the WUI, suppression is also most effective at stopping wildfires in the WUI (Bar-Massada *et al.* 2009).

Looking ahead, the Argentine Census Office projects continued population growth in our study area, and between 2010 and 2025, the provinces of Río Negro and Chubut are expected to grow in population by 30 and 23% respectively (INDEC 2016). This population growth will likely cause further growth of the WUI, increasing wildfire ignitions, as well as social conflicts. This means that the time is now for the government and other institutions involved in managing natural ecosystems and urbanisation to plan and organise activities that can reduce wildfire risks for people and for the ecosystems themselves. Examples of measures that could be taken include regulations on development, education and outreach programs, forest and fuel management programs, and requirements set by insurance companies. In addition, there is a need for more research on the interactions between people and fire in north-western Patagonia, especially in regards to fire spread and fire behaviour in both wildland areas and in the WUI, with its complex mosaic of houses and vegetation fuels. These education efforts should take into account that most of the non-residents that come to settle and build in this area are unaware of the fire risk this area has. This special group should be the target population in new education programs.

In summary, we found in our assessment of the WUI in northwestern Patagonia that essentially all houses were in the WUI, and that this WUI is growing rapidly both in area and in the number of houses. We also found that the WUI concentrates most of the ignition points registered. We expect that our WUI maps will be useful for developing guidelines and public policies aimed at creating awareness in the whole community about the risk of building and living in this fire-prone environment. The maps will also help managers, housing developers and city authorities to create building codes that, taking into account the particularities of each area, propose prevention and mitigation measures (fuel treatments, escape routes, safer construction codes, design of safety areas, etc.). As such, we consider this map a very valuable tool for motivating prevention and mitigation actions in this WUI, and it can be replicated in other areas of the Patagonian region or elsewhere. Our study thus highlights the need for proactive measures to manage housing and WUI growth in areas that are rich in natural amenities but are located in fire-prone environments.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Acknowledgements

We thank CONICET who provided a Fellowship to support an internship at the SILVIS Laboratory, Department of Forest and Wildlife Ecology, University of Wisconsin (UW)–Madison, USA, and the US Forest Service Northern Research Station. We are grateful to the SILVIS Laboratory at UW–Madison for providing great working facilities, the technical assistance of D. Helmers, and helpful comments and technical assistance by M. Nita and the rest of the staff of the SILVIS Laboratory, who were all very collaborative. We also thank all the staff of the Geomatic Laboratory of CIEFAP in Argentina for providing the SPOT 5 imagery. Special thanks to M. Bachfischer, M. Rey, A. Siebert, H. Claverie, M. Ledesma and A.J. Pérez for providing useful data and specially to P. Masera for his valuable suggestions. Special thanks also to G. A. Loguercio for providing personal help and supporting data used in this study. This study is part of the PhD thesis in fire ecology and management pursued by M. M. Godoy at the University of Patagonia. It was funded, in part, by a grant from CONICET (PUE-CIEFAP 4116/16).

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