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Title: A wildfire risk oriented GIS tool for mapping Rural-Urban Interfaces

Running Title: *a Rural-Urban Interface Mapping tool*

Costantino Sirca[1, 2, *], Franco Casula[3], Christophe Bouillon[4], Belén Fierro García[5], Monica Maria Fernández Ramiro[5], Beatriz Vila Molina[5], Donatella Spano[1, 2]

1 DIPNET – Department of Science for Nature and Environmental Resources, University of Sassari. Via de Nicola 9, 07100 Sassari, Italy

2 CMCC – Euro-Mediterranean Centre on Climate Change Foundation, IAFES Division. Via de Nicola 9 - 07100 Sassari, Italy

3 CFVA – Regional Forestry Corp of Sardinia. Via Biasi 9 – 09131 Cagliari, Italy

4 IRSTEA – National Research Institute of Science and Technology for Environment and Agriculture. Aix-en-Provence Regional Centre, 3275 route de Cézanne, CS 40061 - 13182 Aix en Provence Cedex 5, France

5 TRAGSATEC – Tecnologías y Servicios Agrarios. C/Julián Camarillo 6B, 1B - 28037 Madrid, Spain

* Corresponding author:

Name: Costantino Sirca.

Address: c/o DIPNET, University of Sassari. Via De Nicola, 9 - 07100 Sassari, ITALY

Tel.:+39 079229372; fax: +39 079229339; email: cosirca@uniss.it

Keywords: WUI, wildland–urban interface, GIS, Mediterranean, fire risk

Software availability

Name of software: *RUImap*

Developers: Christophe Bouillon, Beatriz Vila Molina, Belén Fierro García, Mónica Mª Fernández Ramiro.

Contact information: christophe.bouillon@irstea.fr

Hardware required: General-purpose computer (4-16 Gb RAM).

Software required: ArcGis™ 9.3 or superior.

Programming languages: Python© 2.6 and Microsoft™ VBA.

Availability: Contact the developers.

Main *RUImap* interface

Abstract

The Rural–Urban Interfaces (RUI, synonym of WUI, Wildland–Urban Interface) are conceptually defined as areas where houses and burnable vegetation are in contact or intermingled. Raising concerns related to wildfire occurrence in the RUI areas of Europe have been recognized. In this paper we describe a methodology, implemented in an easy-to-use tool, which gives a fire risk oriented RUI definition and which is capable of mapping such surfaces. The tool, called *RUImap*, contains three mapping options and, using easily obtainable input data, offers the possibility to customize most of the parameters used in the mapping process. *RUImap* has been tested in Sardinia (Italy), the second largest island of the Mediterranean Basin. The methodology and the tool can help to overcome difficulties of most of the users to go from the theoretical RUI definition to data and statistics on these areas.

Highlights

- A methodology and a tool for the Rural–Urban interface (RUI) mapping is presented
- A representative Mediterranean case study has been mapped
- The fire number is higher in RUI than elsewhere
- Fire prevention efforts per unit of housing are higher in lower than higher dense housed areas

Introduction

Inhabited areas where people, houses, and burnable vegetation are in contact or intermingled, i.e. the so-called Wildland–Urban Interface (WUI), worryingly started to face Mediterranean wildfires as highlighted by the impressive events occurred in the last years (Lampin-Maillet, 2008; Viegas et al., 2009). The WUI concept and analysis on potential consequences of fire issues historically involved countries other than Europe (e.g. USA, Russia, Australia) where fires cause human fatalities and damage in billions of dollars (Keeley et al., 2004; Theobald and Romme, 2007; Teague et al., 2010; Vasquez, 2011). In the United States a raising awareness of the problem led to a substantial revision of the wildland fire policy, evidencing the need of more information about extension, typologies and location of the WUI areas (Stewart et al., 2007). Worldwide, the growth of the WUI areas and of the population living therein (Stewart et al., 2003; Radeloff et al., 2005; Hughes and Mercer, 2009; Mell et al., 2010), and the burnable vegetation (fuel) load increasing as a consequence of fire suppression activities and the underutilisation of forested and shrubland zones, make the WUI as primacy areas for fire concern (Stephens, 2005; Cohen, 2008). Furthermore, the problem can potentially increase due to the expected impacts of climate changes on fire regimes and behaviour (Pinõl et al., 1998; Pausas, 2004; Liu et al., 2010). The fire risk in RUI areas is often increased by the multi-emergency scenario emerging during the evacuation activities capable to cause domino effects due to the synergic interaction of different risk factors (fire, panic, gas explosions, toxic smokes, intoxication of people and firefighters, traffic difficulties and/or street accidents during the concurrent evacuation of residents and arrival of firefight crews).

In this work we use the acronym RUI (Rural Urban Interface) proposed in the European FP7 Research Project FUME instead of the more classical North American concept of WUI, so as to extend the context of the interface to houses and urbanised areas in contact or intermingled with any potentially burnable vegetation present in these areas, e.g. natural herbaceous and woody species, orchards, gardens, and so on. Besides the vegetation, also other burnable materials (e.g. firewood stocks, garden furnitures, cars, waste, fuel tanks, awnings, etc.) contribute to dramatically increase the fire risk.

Defining criteria and related methodologies for mapping the RUI from a fire risk oriented point of view entails accounting for factors interacting with the fire occurrence and potential impacts on people and goods living in these areas. The human presence is a relevant factor for fire ignitions (Badia-Perpinyá and Pallares-Barbera, 2006; Bar-Massada et al., 2011; Price and Bradstock, 2014), and it is also correlated to the housing spatial distribution and density (Stewart et al., 2007). On the other hand, the housing spatial distribution and density is strictly related to the fire exposure and, accordingly, many papers report classifications based on the housing density (Theobald, 2001; Hammer et al., 2004; Lampin-Maillet et al., 2009b; Galiana-Martin et al., 2011). With respect to these mapping methodologies, it has been recognized that high resolution RUI mapping (i.e., micro and mesoscales) is often limited by the scarce housing data availability (Bar-Massada et al., 2013). Besides, the chance of fire ignition and spread is influenced by the typology, spatial distribution and structure of the burnable vegetation, its water content (also related to the presence of irrigation systems) and flammability. Other important factors conditioning fire propagation are the vegetation spatial continuity, assessable with landscape metrics (Viedma et al., 2009) and the interaction with weather and topography (Pyne et al., 1996; Díaz-Delgado et al., 2004; Caballero et al., 2007; Koetz et al., 2008). Only a multi-spatial mapping process can provide a broader view of the issue and can help in RUI planning under fire-related concerns (Calvo, 2001; Myszewski and Kundell, 2005).

Although the theoretical definition of the RUI (environment where there is a coexistence of vegetation and houses) is widely accepted, a shared fire risk oriented definition in terms of housing densities, buffering size, vegetational types is still missing in Europe, where each working group implements the conceptual RUI definition into different practical mapping processes. This fact limits our knowledge on these areas and on the related statistics (e.g. location, extension, structural characteristics, evolution along time), which is essential to plan activities related to fire issues at local as well as at regional scale.

In this work we describe a methodology for a "fire risk oriented" RUI mapping that was developed and implemented in an easy-to-use tool, called *RUImap*, under the activities of the EU FP7 research

Project FUME. *RUImap* is, essentially, a geographical tool aiming to detect where the RUI is located and its main features with respect to the housing and vegetation, allowing to:

i) come up with user-defined rules for RUI mapping through the application of adjustable parameters (buffer distances, housing, and vegetation characteristics);

ii) produce data on RUI areas (location, size, characteristics) and on fire issues through the analysis of ignitions and burned areas.

Three different mapping methodologies are implemented, that differ for the theoretical approach and the spatial scale of the mapping process, and that are able to map the neighbourhood characters of the RUI. The *RUImap* mapping process can represent a first step for the fire risk assessment and the management of these areas with respect to the wildfire risk issue.

To show the *RUImap* potential, we applied it to a representative Mediterranean case study, giving preliminary information on the RUI characteristics in these environments.

Materials and methods

RUImap is able to perform a coarse identification and classification of the RUI at regional scale, where an European country (NUTS-0) can be mapped. At local scale (roughly correspondent to a NUTS-3 region), two mapping methodologies are available. The first one detects the fire-prone areas (i.e. areas with burnable vegetation) and then maps the houses and dwellings located inside it allowing the classification of the RUI. The second local mapping methodology first focuses on the reconnaissance of the urban structures and, then, on the surrounding vegetation. The software is designed to work with a common office PC (4-8 Gb of RAM) and it is implemented as an extension for ESRI™ ArcGis™. It requires the installation of ArcGis™ 9.3 or superior. The programming languages are Python© 2.6 and Microsoft™ VBA.

Mapping RUI at regional scale

The regional scale mapping process aims to obtain a synoptic view of the RUI distribution on wide territories and coarse statistic data at regional level. *RUImap* identifies and maps the RUI using the European Corine Land Cover (CLC) and the Soil Sealing (SS) map as input data. These layers were chosen because there are no other available consistent datasets at European level at higher resolution. The user should be aware of the unavoidable degree of uncertainty in the data contained in the CLC and SS maps given to its 100 m resolution (raster format).

The mapping process is implemented in 4 main steps:

1. Buffering and reclassification of the CLC layer. The land cover typologies are reclassified into 3 classes: mineral (not vegetated or with herbaceous vegetation), agricultural, and forested areas. A buffer (adjustable, 200 m was chosen in the case study shown in this paper) is drawn around these areas. This first step identifies all areas that can contain a RUI.
2. Reclassification of the Soil Sealing layer into 3 classes. Houses located inside the reclassified CLC map are classified as: isolated housing (soil sealing between 0 and 29%); scattered housing (soil

sealing between 30 and 79%, thresholds comparable to ceiling of CLC class 1.1.2); dense clustered housing (soil sealing between 80 and 100%, thresholds comparable to ceiling of CLC class 1.1.1).

3. Identification of the RUI areas through the application of a 400 m buffer (4 pixels surrounding the pixels with housing obtained in step 2);
4. Classification of the RUI areas. The final combination of the two layers (reclassified Corine Land Cover map and the reclassified, integrated and clipped Soil Sealing map) allows to recognize the following 9 RUI categories:

	Housing	Soil cover typology
1	Isolated	Mineral
2	Isolated	Agricultural or scattered vegetated
3	Isolated	Forested
4	Scattered	Mineral
5	Scattered	Agricultural or scattered vegetated
6	Scattered	Forested
7	Dense clustered	Mineral
8	Dense clustered	Agricultural or scattered vegetated
9	Dense clustered	Forested

Mapping RUI at local scale: methodology 1

This methodology, an improvement of a previous approach developed in the framework of the EU FP6 FIREPARADOX project (Lampin-Maillet et al., 2009a), focuses on the burnable areas (vegetated areas chosen by the user) that are classified in function of its spatial fuel continuity before the mapping process. A buffering process is then applied to recognise the housing and categorize the RUI.

The mapping process requires the following input files:

1. housing layer (vectorial) in which each feature (polygon) corresponds to a house/dwelling;
2. "Brush-Clearing Zone" (BCZ) map (raster), obtained by adding a buffer to the areas covered by burnable vegetation (200 m was applied in the case study of this paper). The BCZ map can be obtained using raster or vectorial layers as input data;
3. Aggregation Index (AI) map (raster) reporting the vegetation AI values that, among the existing metrics enabling the description of composition and structure of the vegetation in a landscape, is

suitable for measuring the vegetation spatial continuity (Turner, 1990). The specific software FRAGSTATS 3.3© (McGarigal and Marks, 1994) allows to calculate the AI for each pixel. It requires, as input data, a Land Cover or Vegetation map in raster format (0.5 through 10 m resolution) that can be created starting from a land use map or through satellite imagery interpretation. The input for FRAGSTATS 3.3© calculation is obtained by rasterizing (5 m resolution) the vegetation map used to create the BCZ map and reclassifying it into 2 categories: vegetation (forests and maquis) and no vegetation (the remaining categories).

The mapping process works in 2 sequential steps.

1. A 50 m buffer in each building located in the BCZ creates the housing configuration map. The buffers are then dissolved and the polygons are classified as isolated housing (containing 0-3 dwellings), scattered housing (3-50 dwellings), and grouped housing (>50 dwellings). A further buffer of 15 m is applied to the grouped housing, where the very dense housing (>10 dwellings) or dense housing (≤ 10 dwellings) polygons are finally recognized.
2. *RUImap* reclassifies the AI map (AI values can range from 0 to 100) into the three classes: no AI, low AI, and high AI, according to the following thresholds: i) AI = 0, corresponding to areas without or with very discontinuous vegetation; ii) AI = low (0< AI ≤95%), corresponding to discontinuous/scattered vegetation or edges; iii) AI = high (AI >95%), which corresponds to dense and continuous vegetation. These AI thresholds come from previous studies on landscape ecology (He et al., 2000; Lampin-Maillet et al., 2010). The conceptual scheme of the mapping process is showed in Figure 2.

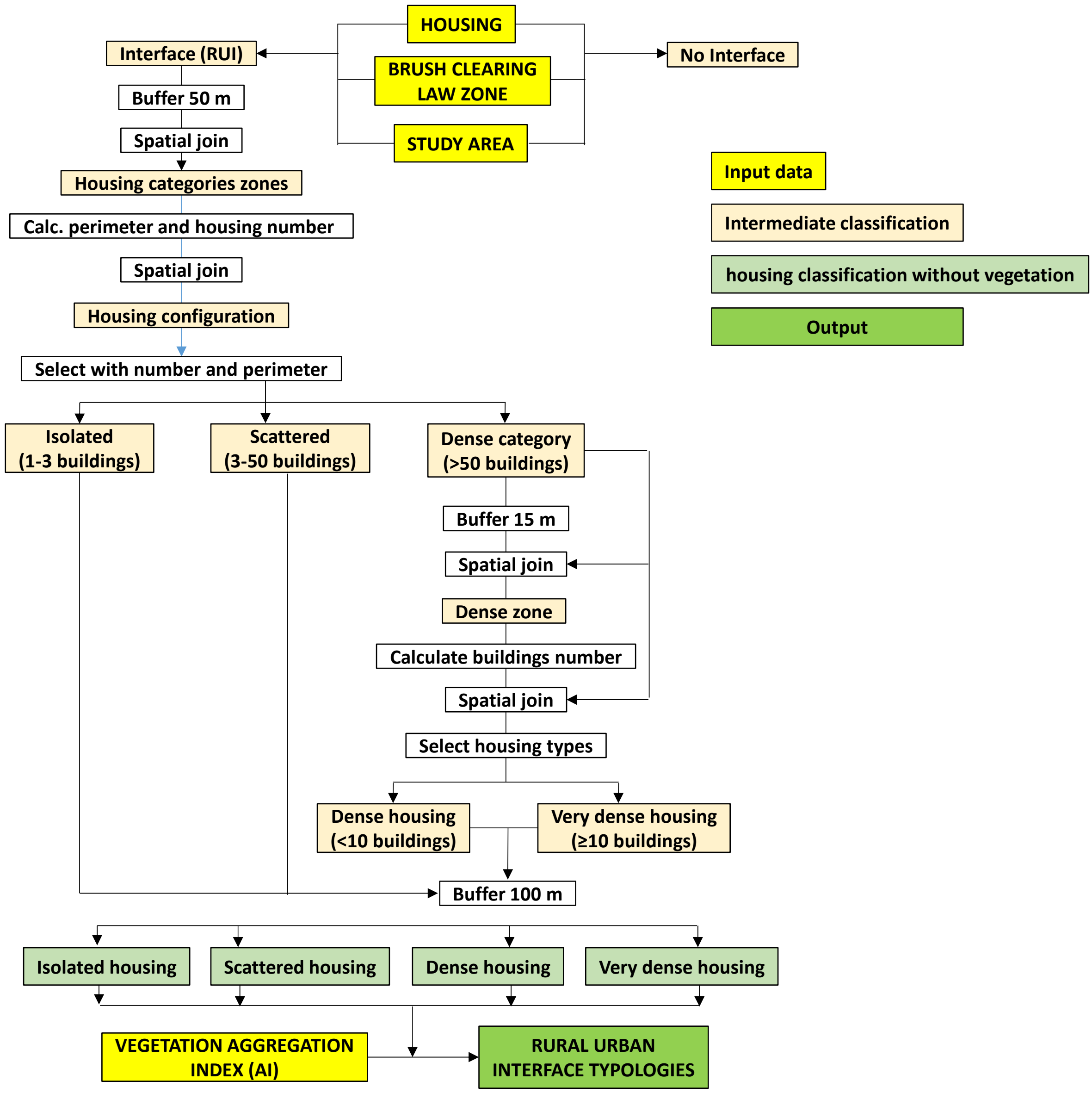

Figure 2 - Option 1: conceptual mapping process scheme.

The RUI is classified into 12 categories obtained by crossing the 4 categories of housing and the 3 categories of AI (also RUI with AI = 0 is accounted due to the eventual seasonal presence of dry herbaceous vegetation). The resulting layer (vectorial) is automatically converted into a raster format with a combination priority process based on the class densities. The final output is a *tiff* file (2.5 m resolution). When the AI map is not used (e.g. due to the unavailability of vegetation data), only the housing configuration map is produced.

Mapping RUI at local scale: methodology 2

This mapping methodology focuses on the housing as indicator of people presence and goods to be protected. It first analyses how the houses are distributed in the land, creating a layer of settlement type, and then identifies the border of each settlement to recognise in which context the settlements are located (forested, agricultural, urban).

Before running the mapping process, a reclassification of the land cover map into 5 categories (forested, agricultural, urban, unproductive, water), whose resolution depends by the available vegetation maps used as input data, is performed with user-defined criteria. Only buffers containing agricultural and/or forested surfaces are considered (users must be aware that also urban areas may contain fuels that can influence the fire risk).

Two vectorial layers (housing and land cover maps) are needed. *RUImap* applies the following steps for the mapping process:

1. Drawing a 25 m buffer around houses (the contiguous or overlapped areas are dissolved). According to its surface and the surrounding land cover, the obtained polygons are classified as: urban settlements (>50 ha), settlements in agricultural/forested area (1 – 50 ha or <1 ha containing more than 5 houses), dispersed/isolated building in agricultural/forested area (<1 ha). In the dispersed/isolated building a new buffer of 100 m is drawn around houses obtaining new polygons that are classified as dispersed buildings in agricultural/forested areas (3−5 houses) or isolated buildings in agricultural/forested areas (1−2 houses).
2. Drawing 1 m buffer around these polygons (except for urban settlements) to recognize if they are located in agricultural or forested areas. The polygon is classified as forested if 30% or more of its buffer area is covered by forest; if the forested buffer area is <30% it is classified as agricultural. The conceptual scheme of the mapping process is reported in Figure 3.

RUImap now classifies each polygon (see Table 1 for the classes). A new buffer around each polygon, (adjustable by the user), maps out the RUI. Besides, also urban settlements are recognizable by *RUImap*. In the case study shown in this work we applied a buffer size ranging from 100 to 400 m, with higher values in forested and lower ones in agricultural areas.

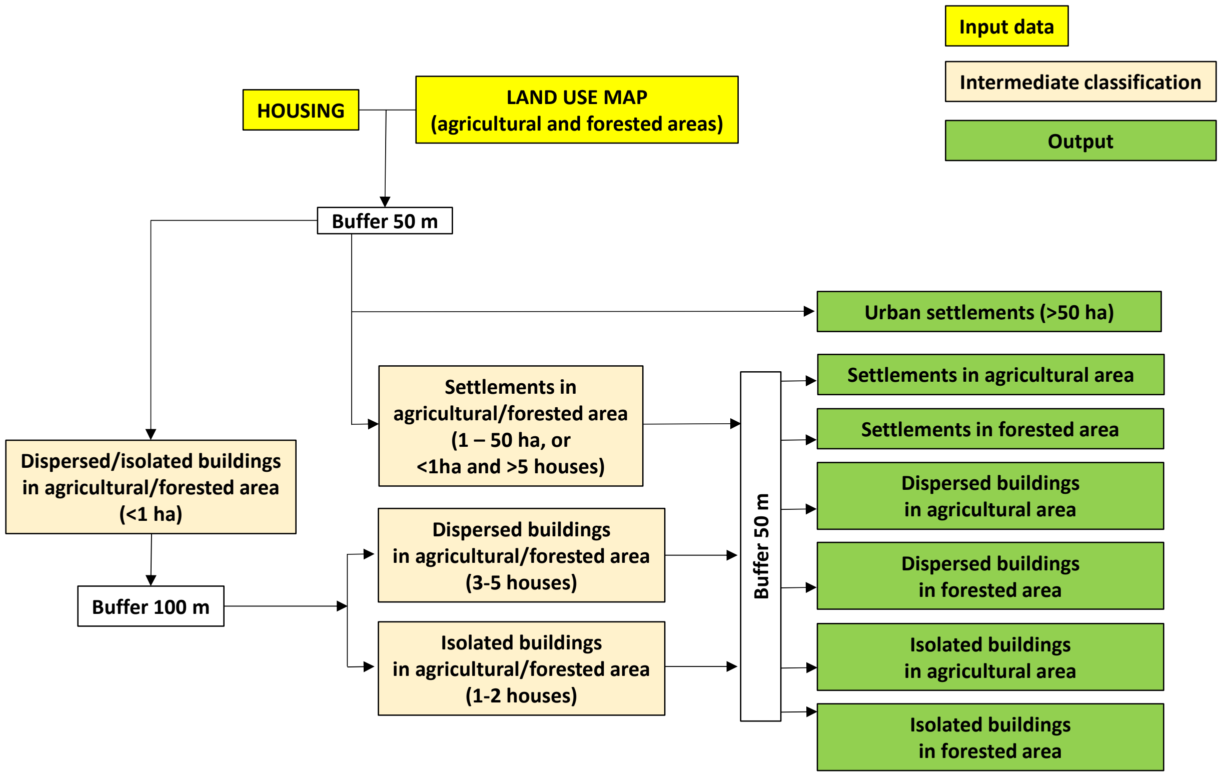

Figure 3 - Option 2: conceptual mapping process scheme.

Table 1 – RUI classes obtained with RUImap *Option 2 mapping methodology*

Housing typology	**Buffer size* (m)**
Urban settlements	400
Settlements in Agricultural area	200
Settlements in Forested area	300
Dispersed buildings in Agricultural area	100
Dispersed buildings in Forested area	300
Isolated buildings in Agricultural area	100
Isolated buildings in Forested area	200

** used in the case study*

Case study

RUImap was tested in Sardinia (Italy), the second largest island of the Mediterranean Basin (~24,000 km^2). Sardinia is the Italian region where, on average, the highest number of wildfire events is recorded at national scale. In the years 2000–2015, 2,948 fires per year occurred, with an annual burned area of 17,817 ha. Most fires occur from May through October, and July is the month with the highest fire number and burned area (official data provided by the CFVA-Regional Forestry Corp of Sardinia). RUI areas are mainly located on the coastline or nearby urban centres. On the coastline the presence of the RUI is related to the touristic flow. In the last decades, a significant increase of coastal RUI has been recorded in Sardinia, mainly due to houses inhabited only during the summer holiday season (Pellizzaro et al., 2012). In these areas fire risk increases dramatically during the late spring and the summer season due to a co-occurrence of a high fire danger (related to weather and fuel conditions) and increasing of population due to tourism. In the urban centres the RUI is represented by industrial and residential peripheral areas where houses and dwellings meet burnable vegetation often causing a synergic action on the fire risk due to the presence of several emergencies. Because of fires, a rising number of dangerous situations in the Sardinian RUI areas is reported, with loss of houses, goods, and threat to people.

The whole Sardinia surface was mapped with the regional scale methodology using the Corine Land Cover and the Soil Sealing maps of the year 2006 (CLC2006 and SS2006), freely downloadable from: *http://www.eea.europa.eu*. The housing and vegetation input data used for the local mapping options has been provided by the Regional Government of Sardinia (Housing Layer Map and Soil Use Map of Sardinia edition 2008 -vectorial, both available at *http://www.sardegnageoportale.it/*). The municipality of Alghero was chosen to apply both local scale methodologies. This area (about 225 km^2 and 9500 buildings) shows a diffuse and complex urban structure, where several housing densities and configuration typologies are represented. The vegetation also ranges from mature forest stands to typical agricultural landscapes. Due to the data availability, and aiming to test *RUImap* on a wider area, the Olbia-Tempio Province (about 3200 km^2 and 108,000 buildings) was also mapped applying only one of the two local mapping methodologies. The location of the case studies is shown in Figure 1.

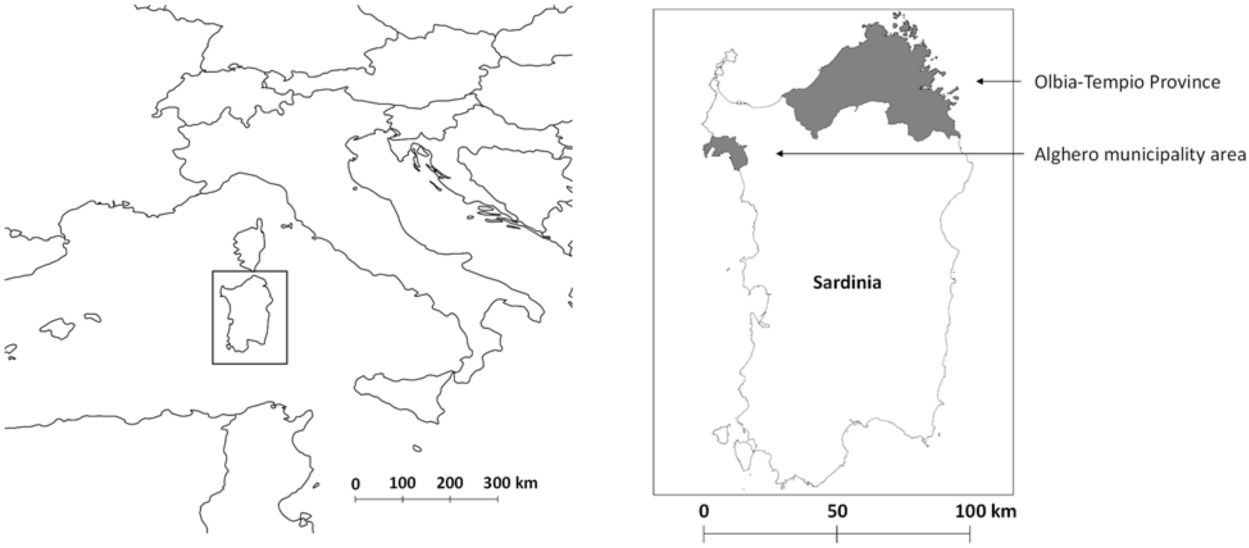

Figure 1 - Case study location.

Besides the mapping process we have analysed the relationship between the housing density and the surrounding area by the calculation of two numerical indicators: the mean area (area/housing; $m^2 m^{-2}$) and the mean perimeter (perimeter/housing; $m m^{-2}$) per unit of housing. These parameters give an indication about the effort needed to manage areas around the houses in function of the housing density.

We have also performed a characterisation of the fire occurrence in terms both of ignition densities and burned area. Because of the data availability, the ignitions of the years 1998–2010, and the burned areas of the years 2005–2011 (years where the fire scars are available in digital format) were used as input data. Both ignitions and fire scars data were provided by the CFVA-Regional Forestry Corp of Sardinia.

Results

The pattern of the RUI typologies defined and mapped with *RUImap* in the case study are here reported at regional and local scale. For providing a more complete characterization of the study areas we decided also to include in the analysis areas with housing/settlements in contact or intermingled with low vegetation density (i.e. mineral land cover, or A.I. = 0) due to the likely presence of burnable herbaceous vegetation during the summer months.

Regional RUI mapping

The regional RUI map is shown in Figure 4. RUI represents the 9.3% of the island surface (Table 2). Isolated housing is the widest RUI category (6.1%), followed by scattered (2.8%) and dense clustered housing (0.3%). With respect to the land cover typologies, the RUI located in forested areas is the most represented class (4.9% of Sardinia surface and 53% of the total RUI surface); this is partially explained with the fact that, in Sardinia, forests and maquis vegetation areas cover about 50% of the whole island surface. The map also shows a dense presence of the RUI areas on the north−western coastline, where the housing sprawl is mainly related to the tourist dwellings expansion.

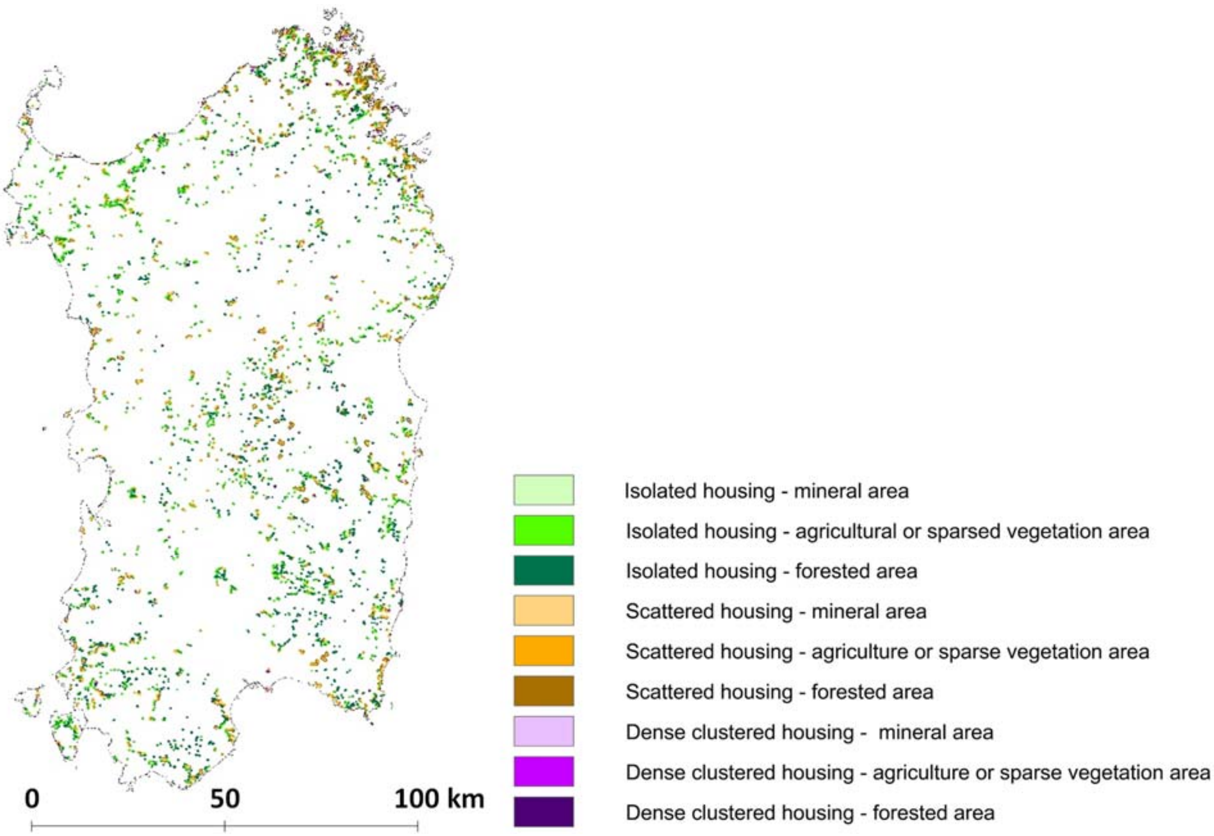

Figure 4 - RUI map of Sardinia produced with the regional mapping methodology.

Table 2 - RUI categories (= housing + soil cover typology) mapped with the RUImap *regional mapping methodology.*

RUI categories		RUI surface	
Housing	**Soil cover typology**	(km^2)	(%)
Isolated	Mineral	28.37	0.12
Isolated	Agricultural or scattered vegetated	601.47	2.50
Isolated	Forested	848.08	3.52
Scattered	Mineral	176.69	0.73
Scattered	Agricultural or scattered vegetated	192.71	0.80
Scattered	Forested	313.27	1.30
Dense clustered	Mineral	30.33	0.13
Dense clustered	Agricultural or scattered vegetated	14.49	0.06
Dense clustered	Forested	30.60	0.13
RUI areas		2236.01	9.28
not RUI areas		21847.61	90.72
Sardinia		24083.62	100.00

Local scale mapping, methodology 1

The Figure 5 shows the map of the Alghero municipality area obtained using the 1st local scale mapping methodology. RUI surface covers 15.8% of the whole area while dwellings cover 2.08% of the RUI area (Table 3). With respect to the housing classification, the Scattered housing (56.4%) is the widest category, followed by the Isolated housing (32.5%). Most of the RUI are located in zones with AI = 0 (68%) and AI = high (24.8%). The Scattered and the Isolated housing with AI = 0 are the widest RUI categories (6.0% and 3.8% of the whole municipality area, respectively).

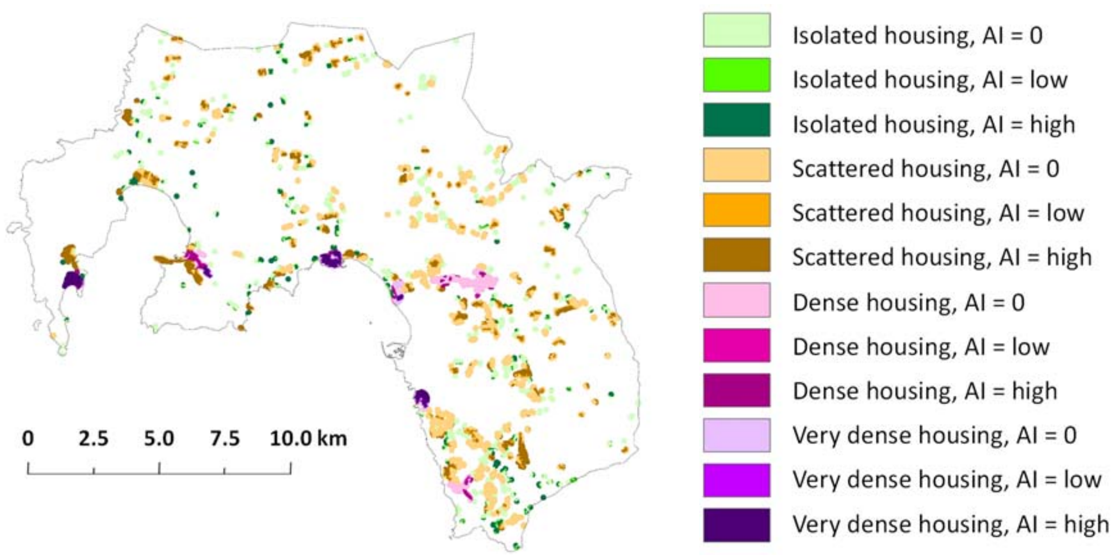

Figure 5 - RUI map of the Alghero case study produced with the mapping methodology 1 (AI = Aggregation Index).

Table 3 - Surface and characteristics of the RUI categories (= housing + AI) recognized with RUImap *at local scale (methodology 1) in the Alghero municipality area. Data are related to the year 2008. (AI = Aggregation Index).*

RUI category		**Surface**		**Dwellings/ RUI**	**Surface/ dwellings**	**Perimeter/ dwellings**
Housing	**AI**	(ha)	(%)	(%)	(m^2 m^{-2})	(m m^{-2})
Isolated	0	857.4	3.81	1.12	88.3	2.0
Isolated	low	74.4	0.33	0.61	162.9	22.3
Isolated	high	225.4	1.00	1.95	50.3	3.2
Scattered	0	1347.3	5.98	1.48	66.5	1.4
Scattered	low	150.0	0.67	1.23	80.0	10.9
Scattered	high	508.6	2.26	3.34	28.9	1.5
Dense	0	176.8	0.78	1.83	53.7	0.9
Dense	low	16.8	0.07	1.78	55.3	7.8
Dense	high	49.1	0.22	3.29	29.4	2.0
Very dense	0	40.8	0.18	4.14	23.1	0.9
Very dense	low	13.7	0.06	3.60	26.7	3.7
Very dense	high	98.3	0.44	13.62	6.3	0.2
RUI areas		3558.8	15.80	2.08	47.1	1.8
Not RUI areas		18965.5	84.20	0.91	109.4	
Alghero area		22524.3	100.00	1.09	90.6	

The same analysis was carried out in a wider area, the Olbia–Tempio Province, covering a surface of 316,828 ha (Figure 6, Table 4). RUI represents the 19.2% of the territory, with a mean housing density of 2.1%. Isolated and Scattered housing configurations are almost equally represented, with about 38% of the RUI surface, followed by Very dense (15.5%) and Dense (8.7%) housing. With respect to the Aggregation Index, the AI = 0 and AI = low cover 44.2% and 40.7% of the RUI, respectively. The most widespread RUI categories are the Isolated and Scattered housing with AI = 0 whereas the Dense and Very dense housing with AI = low are the less diffuse RUI categories. These results are in accordance with the previous Alghero case study.

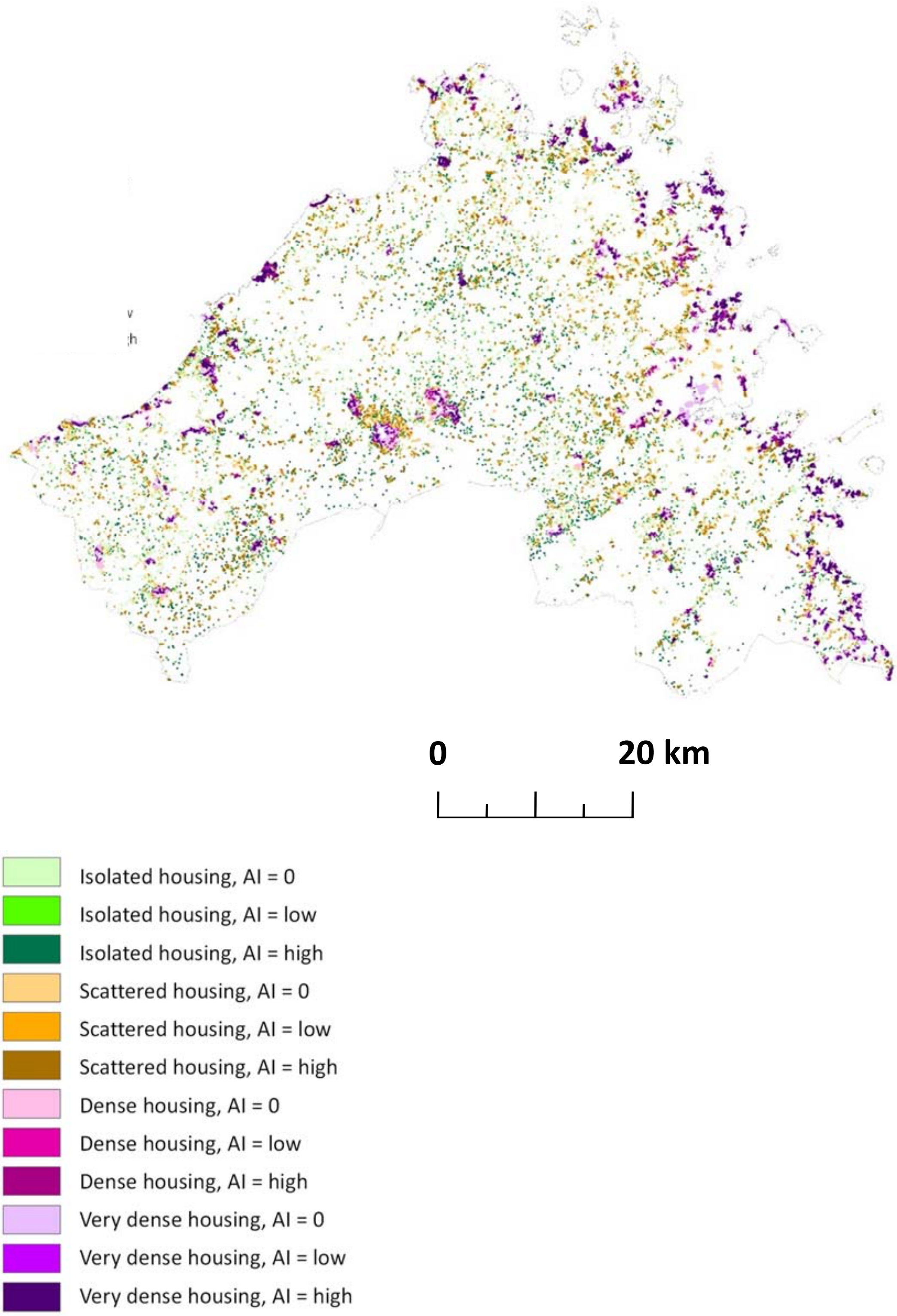

Figure 6 - RUI map of the Olbia–Tempio Province case study obtained with the local mapping methodology 1 (AI = Aggregation Index).

Table 4 - Surface and characteristics of the RUI categories (= housing + AI) recognized with RUImap *at local scale (methodology 1) in the Olbia-Tempio Province. Data are related to the year 2008. (AI = Aggregation Index).*

RUI category		**Surface**		**Dwellings/ RUI**	**Surface/ dwellings**	**Perimeter/ Dwellings**
Housing	**AI**	(ha)	(%)	(%)	(m^2 m^{-2})	(m m^{-2})
Isolated	0	11302.0	3.57	0.42	236.9	7.1
Isolated	low	3219.9	1.02	0.43	234.1	21.5
Isolated	high	8761.7	2.77	0.38	265.0	13.1
Scattered	0	10173.0	3.21	1.02	97.1	2.7
Scattered	low	3644.1	1.15	0.98	101.5	8.8
Scattered	high	8894.7	2.81	1.55	63.7	3.0
Dense	0	2583.8	0.82	1.22	80.9	2.5
Dense	low	811.2	0.26	1.18	83.8	7.7
Dense	high	1874.9	0.59	2.09	46.8	2.6
Very dense	0	2752.2	0.87	9.65	9.4	0.3
Very dense	low	1482.4	0.47	4.62	20.7	1.8
Very dense	high	5204.2	1.64	9.71	9.3	0.3
RUI areas		60704.0	19.16	2.13	46.0	2.1
Not RUI areas		256123.6	80.84	0.24	411.3	
Olbia-Tempio		316827.6		0.60	164.7	

Local scale mapping, methodology 2

The RUI map obtained with this methodology identifies a wider RUI surface in Alghero than with the first one (29.8 vs 15.8%, respectively) (Figure 7, Table 5). The RUI with dispersed buildings is now 58.9% of the whole RUI area, followed by settlements (27.5%) and isolated buildings (13.5%). Most of the RUI is located in agricultural (58.6%) and forested (27.3%) areas. The widest RUI categories are the Dispersed buildings in agricultural and forested areas. The mean dwelling/RUI ratio is lower than the one in methodology 1 (0.48 vs 2.08%, respectively).

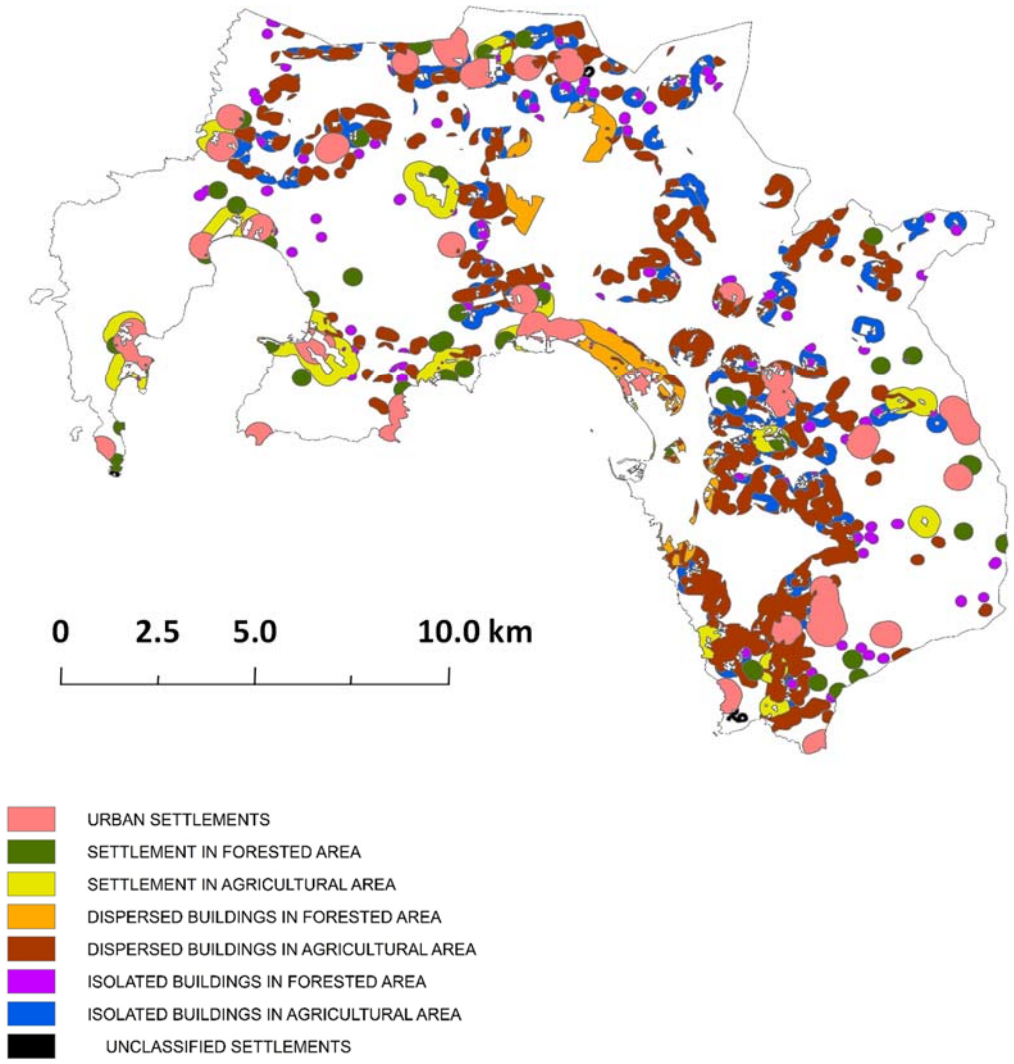

Figure 7 - RUI map of the Alghero case study obtained with the local mapping methodology 2.

Table 5 - Surface and characteristics of the RUI categories recognized with RUImap *at local scale (methodology 2) in the Alghero municipality area. Data are related to the year 2008.*

RUI category	**Surface**	
	(ha)	(%)
Isolated buildings in agricultural area	425.1	1.89
Isolated buildings in forested area	534.3	2.37
Dispersed buildings in agricultural area	2827.1	12.55
Dispersed buildings in forested area	1356.4	6.02
Settlements in agricultural area	907.9	4.03
Settlements in forested area	661.0	2.93
RUI areas	6711.8	29.8
not RUI areas	15812.5	70.2
Alghero	22524.3	

Spatial indicators related to fire risk

With respect to the housing density the results indicate that there is a clear relationship in terms of area and perimeter per housing surface unit. In Alghero and the Olbia–Tempio Province (Figure 8, Tables 3 and 4) the isolated housing has the highest mean area per m^2 of housing (100.5 and 245.3 m^2 m^{-2} on average, respectively). This value decreases when the housing density becomes higher (from isolated to very dense housing). A similar pattern was observed calculating the units of perimeter per unit of housing surface, with the isolated housing showing the highest values of this indicator (Figure 9, Tables 3 and 4). The results clearly point out that a stronger effort for managing these areas per unit of housing surface would be required in isolated housing conditions rather than in the ones with higher densities.

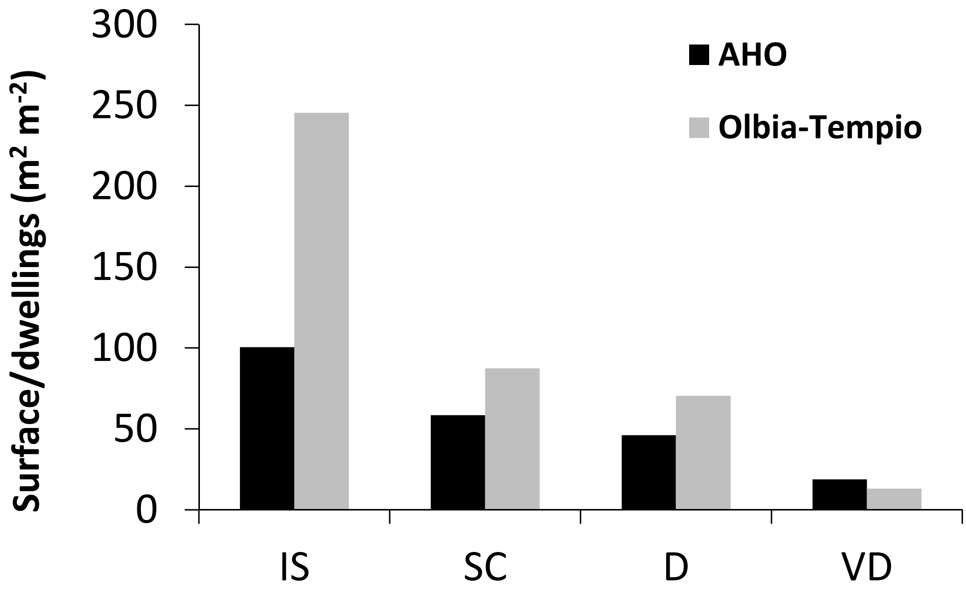

Figure 8 - Relationship between the housing configuration categories and surface per unit of housing. (IS = isolated; SC = scattered; D = dense; VD = very dense housing).

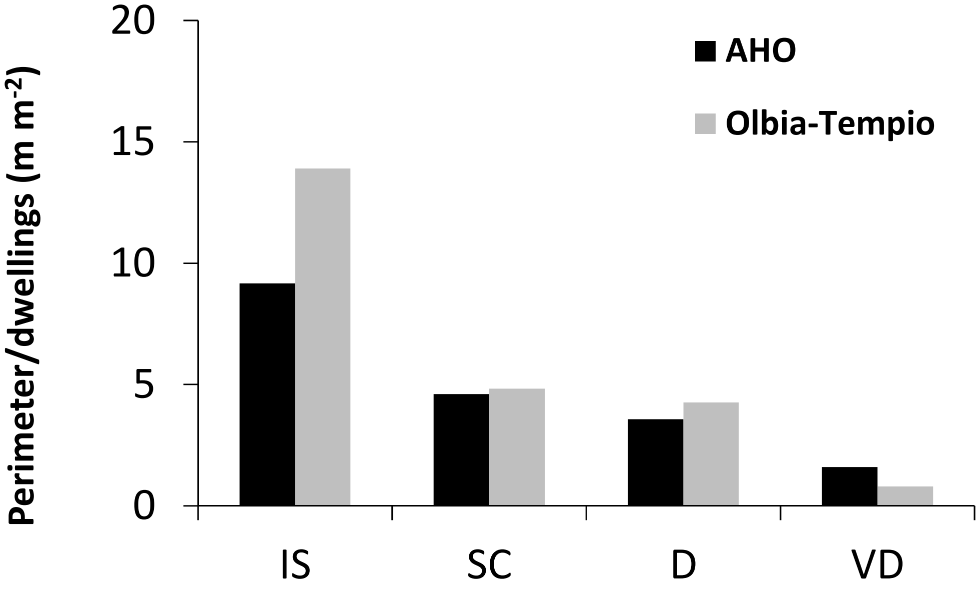

Figure 9 - Relationship between the housing configuration categories and perimeter. (IS = isolated; SC = scattered; D = dense; VD = very dense housing).

In the mapping process applied with the methodology 2 , as a result of the raster-vector conversion, not all of the dwellings are accounted. Therefore the statistics related to Option 2 are not shown.

Fire occurrence in the RUI

In the period 1998–2010, 36,747 ignitions have been recorded in Sardinia (2,827 per year, on average), burning 132,294 ha (Table 6). The analysis of the fire ignition densities has shown interesting results. The 15.7% of fires were ignited inside the RUI mapped with the regional scale methodology. The ignitions in RUI areas mapped with the methodology 1 range from 24.7% (Alghero) to 39.2% (Olbia–Tempio) of the total occurrences (Table 7). With respect to the methodology 2 (Alghero case study), the wider RUI area consequential to the different mapping method indicates that 50.3% of ignitions occurred in RUI areas (Table 8).

Table 6 - Ignitions and burned areas in the RUI areas mapped at regional scale. (Ignition points data: years 1998–2010; burned areas data: years 2005–2011) (n = number of ignitions).

RUI categories		Ignitions			Burned area	
Housing	**Soil cover typology**	**n**	**%**	**n km^{-2}**	**ha**	**%**
Isolated	Mineral	92	0.3	3.24	57	2.01
Isolated	Agricultural or scattered vegetated	1641	4.5	2.73	2728	4.54
Isolated	Forested	1113	3.0	1.31	3283	3.87
Scattered	Mineral	824	2.2	4.66	228	1.29
Scattered	Agricultural or scattered vegetated	925	2.5	4.80	1018	5.28
Scattered	Forested	941	2.6	3.00	1311	4.18
Dense clustered	Mineral	92	0.3	3.03	011	0.36
Dense clustered	Agricultural or scattered vegetated	48	0.1	3.31	033	2.28
Dense clustered	Forested	106	0.3	3.46	122	3.99
RUI areas		5782	15.7	2.59	8791	3.93
not RUI areas		30965	84.3	1.42	123503	5.65
Sardinia		36747	100.0	1.53	132294	5.49

Table 7 - Local scale, methodology 1: ignition points density and burned areas. Data: years 1998–2010. (n = number of ignition points).

		Ignitions				Burned area			
		Alghero		Olbia–Tempio		Alghero		Olbia–Tempio	
Housing	**AI**	**n km$^{-2(*)}$**	**%**	**n km$^{-2(*)}$**	**%**	**ha**	**%**	**ha**	**%**
Isolated	0	2.36	4.1	0.91	4.8	4.86	0.57	332.15	2.9
Isolated	Low	5.41	0.8	0.78	1.2	1.10	1.47	66.22	2.1
Isolated	High	3.17	1.4	0.71	2.9	2.12	0.94	179.13	2.0
Scattered	0	2.71	7.4	1.24	5.8	10.23	0.76	255.34	2.5
Scattered	Low	4.73	1.4	0.80	1.4	1.61	1.08	72.87	2.0
Scattered	High	3.86	3.9	0.90	3.7	5.03	0.99	185.03	2.1
Dense	0	5.19	1.8	3.37	4.0	0.56	0.32	60.94	2.4
Dense	Low	12.12	0.4	3.99	1.5	0.11	0.63	18.72	2.3
Dense	High	2.11	0.2	2.72	2.3	0.07	0.14	46.56	2.5
Very dense	0	23.01	1.8	3.86	4.5	0.32	0.78	46.19	1.7
Very dense	Low	30.29	0.8	2.40	1.6	0.00	0.00	27.33	1.8
Very dense	High	3.53	0.6	2.55	5.6	0.00	0.00	71.78	1.4
RUI areas		3.47	24.7	1.41	39.2	26.01	0.73	1362.26	2.2
Not RUI areas		1.96	75.3	0.51	60.8	393.33	2.07	6433.06	2.5
Whole area		2.19	100.0	0.68	100.0	419.34	1.86	7795.32	2.5

* *surfaces without dwellings*

Table 8 - Local scale, methodology 2: ignition points density and burned surfaces in the Alghero municipality area. Data: years 1998-2010. (n = number of ignition points).

	Ignitions		**Burned area**	
RUI category	**n km^{-2} (*)**	**%**	**ha**	**%**
Isolated buildings in agricultural area	2.82	2.5	3.89	0.9
Isolated buildings in forested area	2.99	3.3	16.87	3.2
Dispersed buildings in agricultural area	1.98	11.5	21.06	0.7
Dispersed buildings in forested area	3.76	10.4	18.41	1.4
Settlements in agricultural area	3.30	6.1	20.13	2.2
Settlements in forested area	4.54	6.1	5.06	0.8
Urban settlements	13.90	10.4	4.33	1.2
RUI areas	3.48	50.3	89.75	1.3
Not RUI areas	1.57	49.7	329.60	2.1
Alghero	2.17	100.0	419.34	1.9

* *surfaces are accounted without dwellings*

At regional scale the highest mean density value (4.2 ignitions per km^2) was recorded at intermediate housing density (Table 6). At local scale the ignition density values are, on average, higher in dense housing RUI categories than in lower ones.

Discussion and conclusions

In the present work we have described a mapping process, implemented in an easy-to-use tool called *RUImap*, for a fire risk oriented RUI mapping. The three mapping methodologies offer a way to couple the conceptual definition of the RUI (a combination of human presence, dwellings, and vegetation) with a concrete mapping process based on easily available input data.

The mapping methodologies implemented in *RUImap* are basically oriented to obtain maps and data related to the RUI distribution and patterns. *RUImap* is a geographic tool and is not suitable to perform a fire risk assessment in the RUI, where other factors than those accounted in the mapping process need to be included. In the *RUImap* mapping process, anyway, important factors involved in the fire risk are accounted, (i.e. vegetation continuity and typology, housing distribution). At local scale the two mapping methodologies led to differences in the RUI maps and data. In the Alghero case study, the local mapping Option 2 methodology has identified a RUI area almost double than the one obtained with Option 1. Likewise, Stewart et al. (2009) showed that the RUI maps could greatly differ depending on the adopted methodology. These authors compared two RUI mapping methodologies on the same study area and with the same input data, identifying as RUI an area of 59.6 km^2 with the first and 28.5 km^2 with the second method. Platt (2010) point out the impact of the mapping purposes and the related different results obtained from the mapping processes.

The housing density has shown to be clearly related to the two calculated indicators (RUI surface and perimeter per unit of housing surface), indicating that the effort to manage the areas surrounding houses are higher in low density housing environment than in higher dense ones. Similar results were observed by Lampin-Maillet et al. (2010) in south–eastern France.

The density of fire ignitions has shown a relationship with the housing aggregation degree. No matter how RUI are mapped, the ignitions increase with the housing density up to intermediate-high urban filling levels, except for RUI areas mapped with the local methodology 1. Similar results were reported by Syphard et al. (2007). This may be due to the lower fuel load and continuity in dense urbanised RUI zones. Higher ignition densities did not cause an increase in burned areas, and the percentage of burned area in the RUI was always lower than outside RUI areas probably due to the faster and more efficient fire-fighting activity in these areas, often combined with a lower fire spread rate related to the discontinuity of fuels, lower fuel loads, gardens irrigation, as already suggested by Radtke et al. (1982) and Cardille et al. (2001).

In conclusion, *RUImap* confirms to be a tool that could improve our knowledge on RUI characteristics, and support the effectiveness of fire risk prevention and dwelling expansion plans in RUI areas.

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