

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

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1 **Post-print version**

2

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

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

5

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24

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

26

27 **Software availability**

28 Name of software: *RUImap*

29 Developers: Christophe Bouillon, Beatriz Vila Molina, Belén Fierro García, Mónica M^a Fernández
30 Ramiro.

31 Contact information: christophe.bouillon@irstea.fr

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

33 Software required: ArcGis™ 9.3 or superior.

34 Programming languages: Python© 2.6 and Microsoft™ VBA.

35 Availability: Contact the developers.

36

37



38

39 Main *RUImap* interface

40

41

42 **Abstract**

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

53

54 **Highlights**

- 55 - A methodology and a tool for the Rural–Urban interface (RUI) mapping is presented
- 56 - A representative Mediterranean case study has been mapped
- 57 - The fire number is higher in RUI than elsewhere
- 58 - Fire prevention efforts per unit of housing are higher in lower than higher dense housed areas
- 59

60 **Introduction**

61 Inhabited areas where people, houses, and burnable vegetation are in contact or intermingled, i.e. the
62 so-called Wildland–Urban Interface (WUI), worryingly started to face Mediterranean wildfires as
63 highlighted by the impressive events occurred in the last years (Lampin-Maillet, 2008; Viegas et al.,
64 2009). The WUI concept and analysis on potential consequences of fire issues historically involved
65 countries other than Europe (e.g. USA, Russia, Australia) where fires cause human fatalities and
66 damage in billions of dollars (Keeley et al., 2004; Theobald and Romme, 2007; Teague et al., 2010;
67 Vasquez, 2011). In the United States a raising awareness of the problem led to a substantial revision
68 of the wildland fire policy, evidencing the need of more information about extension, typologies and
69 location of the WUI areas (Stewart et al., 2007). Worldwide, the growth of the WUI areas and of the
70 population living therein (Stewart et al., 2003; Radeloff et al., 2005; Hughes and Mercer, 2009; Mell
71 et al., 2010), and the burnable vegetation (fuel) load increasing as a consequence of fire suppression
72 activities and the underutilisation of forested and shrubland zones, make the WUI as primacy areas
73 for fire concern (Stephens, 2005; Cohen, 2008). Furthermore, the problem can potentially increase
74 due to the expected impacts of climate changes on fire regimes and behaviour (Pinõl et al., 1998;
75 Pausas, 2004; Liu et al., 2010). The fire risk in RUI areas is often increased by the multi-emergency
76 scenario emerging during the evacuation activities capable to cause domino effects due to the synergic
77 interaction of different risk factors (fire, panic, gas explosions, toxic smokes, intoxication of people
78 and firefighters, traffic difficulties and/or street accidents during the concurrent evacuation of
79 residents and arrival of firefight crews).

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

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

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

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

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

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

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

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

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

124

125 **Materials and methods**

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

135

136 *Mapping RUI at regional scale*

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

143 The mapping process is implemented in 4 main steps:

144 1. Buffering and reclassification of the CLC layer. The land cover typologies are reclassified into 3
145 classes: mineral (not vegetated or with herbaceous vegetation), agricultural, and forested areas. A
146 buffer (adjustable, 200 m was chosen in the case study shown in this paper) is drawn around these
147 areas. This first step identifies all areas that can contain a RUI.

148 2. Reclassification of the Soil Sealing layer into 3 classes. Houses located inside the reclassified CLC
149 map are classified as: isolated housing (soil sealing between 0 and 29%); scattered housing (soil

150 sealing between 30 and 79%, thresholds comparable to ceiling of CLC class 1.1.2); dense clustered
 151 housing (soil sealing between 80 and 100%, thresholds comparable to ceiling of CLC class 1.1.1).
 152 3. Identification of the RUI areas through the application of a 400 m buffer (4 pixels surrounding the
 153 pixels with housing obtained in step 2);
 154 4. Classification of the RUI areas. The final combination of the two layers (reclassified Corine Land
 155 Cover map and the reclassified, integrated and clipped Soil Sealing map) allows to recognize the
 156 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

157

158 *Mapping RUI at local scale: methodology 1*

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

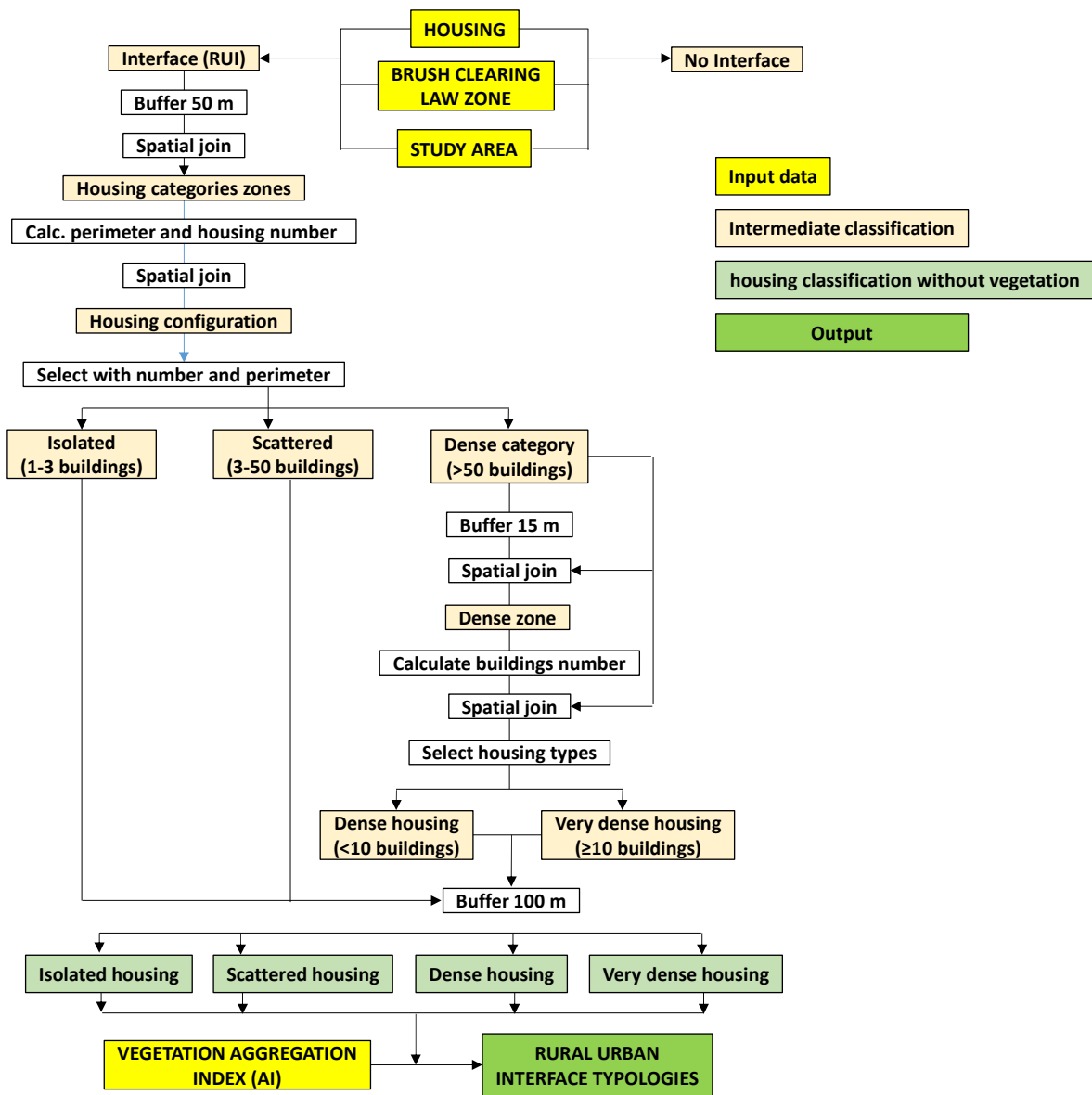
164 The mapping process requires the following input files:

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

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

178 The mapping process works in 2 sequential steps.

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



191

192 *Figure 2 - Option 1: conceptual mapping process scheme.*

193

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

200

201 *Mapping RUI at local scale: methodology 2*

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

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

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

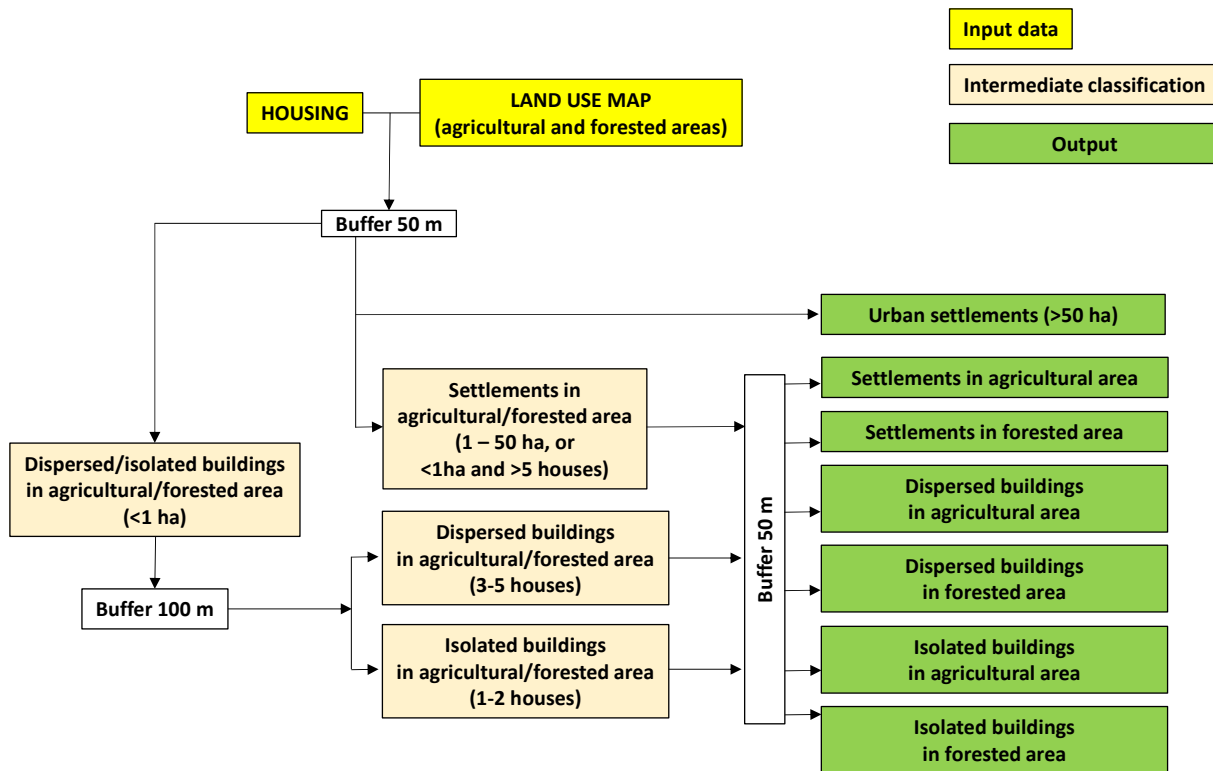
213 1. Drawing a 25 m buffer around houses (the contiguous or overlapped areas are dissolved).

214 According to its surface and the surrounding land cover, the obtained polygons are classified as:
215 urban settlements (>50 ha), settlements in agricultural/forested area (1 – 50 ha or <1 ha containing
216 more than 5 houses), dispersed/isolated building in agricultural/forested area (<1 ha). In the
217 dispersed/isolated building a new buffer of 100 m is drawn around houses obtaining new polygons
218 that are classified as dispersed buildings in agricultural/forested areas (3–5 houses) or isolated
219 buildings in agricultural/forested areas (1–2 houses).

220 2. Drawing 1 m buffer around these polygons (except for urban settlements) to recognize if they are
221 located in agricultural or forested areas. The polygon is classified as forested if 30% or more of its
222 buffer area is covered by forest; if the forested buffer area is <30% it is classified as agricultural.

223 The conceptual scheme of the mapping process is reported in Figure 3.

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



228

229 *Figure 3 - Option 2: conceptual mapping process scheme.*

230

231

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

233

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

238

** used in the case study*

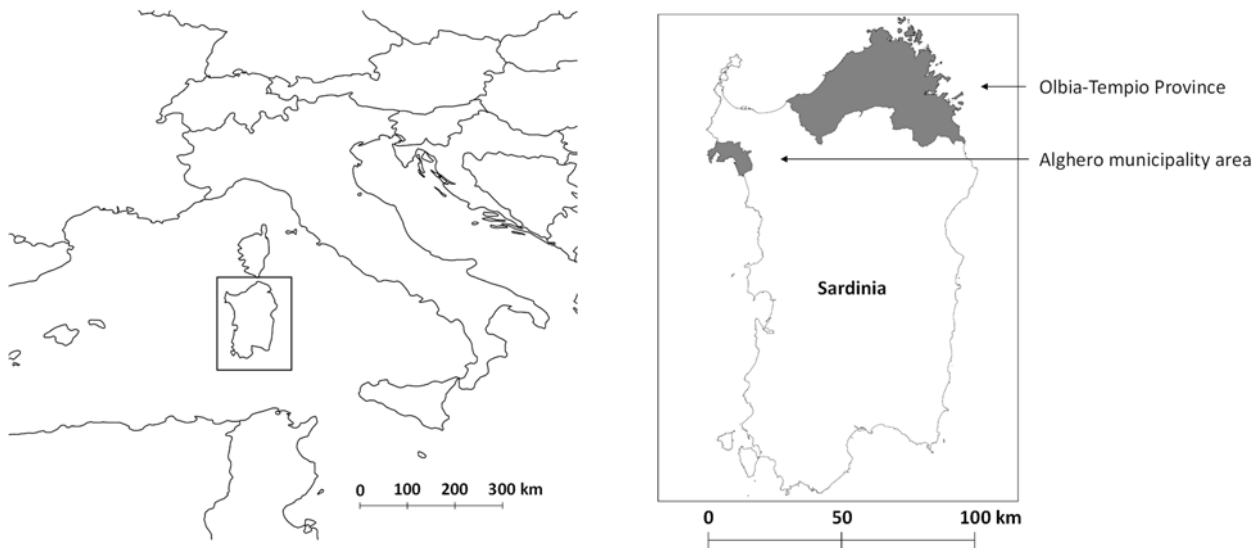
239

240 *Case study*

241 *RUImap* was tested in Sardinia (Italy), the second largest island of the Mediterranean Basin (~24,000
 242 km²). Sardinia is the Italian region where, on average, the highest number of wildfire events is
 243 recorded at national scale. In the years 2000–2015, 2,948 fires per year occurred, with an annual
 244 burned area of 17,817 ha. Most fires occur from May through October, and July is the month with
 245 the highest fire number and burned area (official data provided by the CFVA-Regional Forestry Corp

246 of Sardinia). RUI areas are mainly located on the coastline or nearby urban centres. On the coastline
247 the presence of the RUI is related to the touristic flow. In the last decades, a significant increase of
248 coastal RUI has been recorded in Sardinia, mainly due to houses inhabited only during the summer
249 holiday season (Pellizzaro et al., 2012). In these areas fire risk increases dramatically during the late
250 spring and the summer season due to a co-occurrence of a high fire danger (related to weather and
251 fuel conditions) and increasing of population due to tourism. In the urban centres the RUI is
252 represented by industrial and residential peripheral areas where houses and dwellings meet burnable
253 vegetation often causing a synergic action on the fire risk due to the presence of several emergencies.
254 Because of fires, a rising number of dangerous situations in the Sardinian RUI areas is reported, with
255 loss of houses, goods, and threat to people.

256 The whole Sardinia surface was mapped with the regional scale methodology using the Corine Land
257 Cover and the Soil Sealing maps of the year 2006 (CLC2006 and SS2006), freely downloadable from:
258 <http://www.eea.europa.eu>. The housing and vegetation input data used for the local mapping options
259 has been provided by the Regional Government of Sardinia (Housing Layer Map and Soil Use Map
260 of Sardinia edition 2008 -vectorial, both available at <http://www.sardegnageoportale.it/>). The
261 municipality of Alghero was chosen to apply both local scale methodologies. This area (about 225
262 km² and 9500 buildings) shows a diffuse and complex urban structure, where several housing
263 densities and configuration typologies are represented. The vegetation also ranges from mature forest
264 stands to typical agricultural landscapes. Due to the data availability, and aiming to test *RUImap* on
265 a wider area, the Olbia-Tempio Province (about 3200 km² and 108,000 buildings) was also mapped
266 applying only one of the two local mapping methodologies. The location of the case studies is shown
267 in Figure 1.



268

269 *Figure 1 - Case study location.*

270

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

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

281

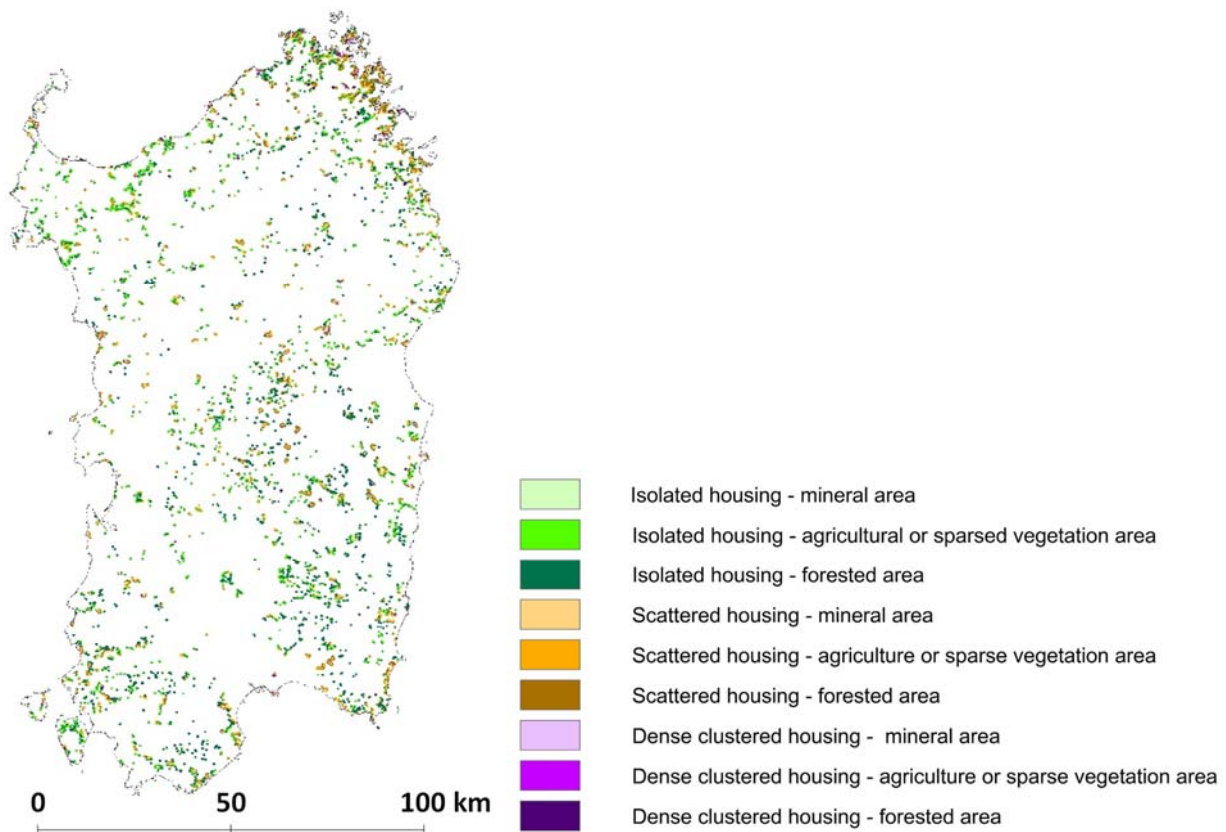
282 **Results**

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

288

289 *Regional RUI mapping*

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



297

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

299

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

RUI categories		RUI surface	
Housing	Soil cover typology	(km²)	(%)
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

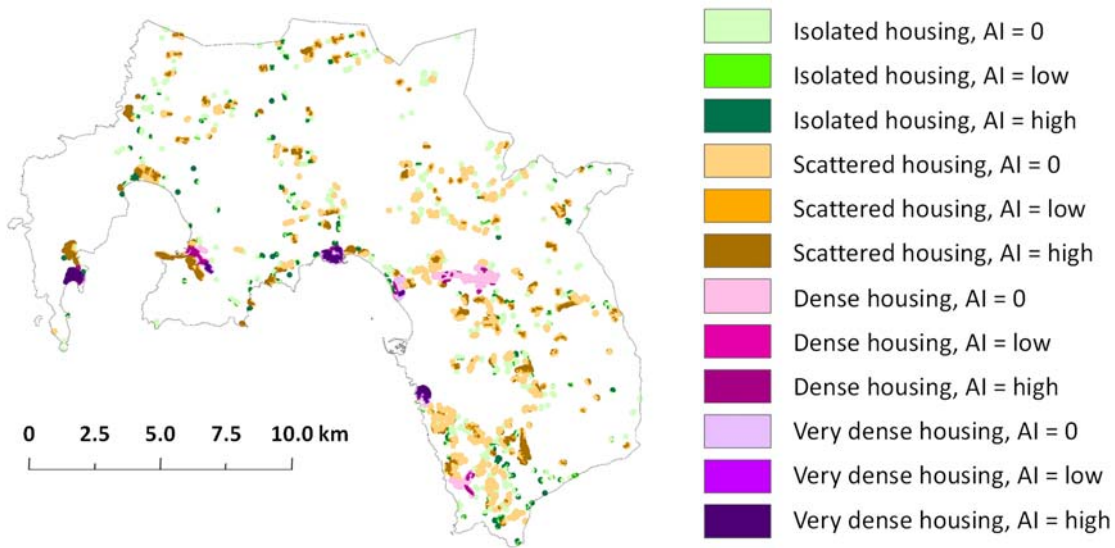
302

303

304 *Local scale mapping, methodology 1*

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

311



312

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

315

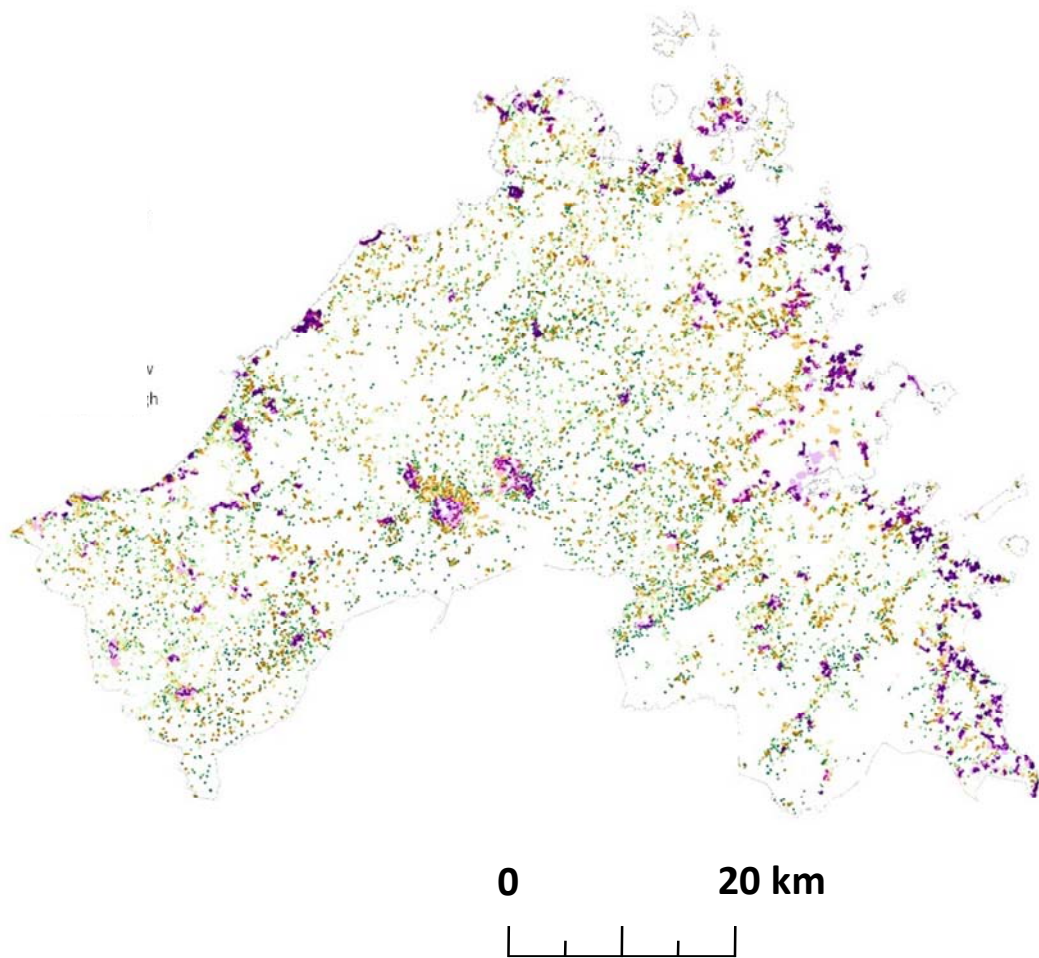
316

317 *Table 3 - Surface and characteristics of the RUI categories (= housing + AI) recognized with*
 318 *RUImap at local scale (methodology 1) in the Alghero municipality area. Data are related to the*
 319 *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	

320

321 The same analysis was carried out in a wider area, the Olbia–Tempio Province, covering a surface of
322 316,828 ha (Figure 6, Table 4). RUI represents the 19.2% of the territory, with a mean housing density
323 of 2.1%. Isolated and Scattered housing configurations are almost equally represented, with about
324 38% of the RUI surface, followed by Very dense (15.5%) and Dense (8.7%) housing. With respect
325 to the Aggregation Index, the AI = 0 and AI = low cover 44.2% and 40.7% of the RUI, respectively.
326 The most widespread RUI categories are the Isolated and Scattered housing with AI = 0 whereas the
327 Dense and Very dense housing with AI = low are the less diffuse RUI categories. These results are
328 in accordance with the previous Alghero case study.
329



331

- Isolated housing, AI = 0
- Isolated housing, AI = low
- Isolated housing, AI = high
- Scattered housing, AI = 0
- Scattered housing, AI = low
- Scattered housing, AI = high
- Dense housing, AI = 0
- Dense housing, AI = low
- Dense housing, AI = high
- Very dense housing, AI = 0
- Very dense housing, AI = low
- Very dense housing, AI = high

332

333 *Figure 6 - RUI map of the Olbia–Tempio Province case study obtained with the local mapping*

334 *methodology 1 (AI = Aggregation Index).*

335

336 *Table 4 - Surface and characteristics of the RUI categories (= housing + AI) recognized with*
 337 *RUImap at local scale (methodology 1) in the Olbia-Tempio Province. Data are related to the year*
 338 *2008. (AI = Aggregation Index).*

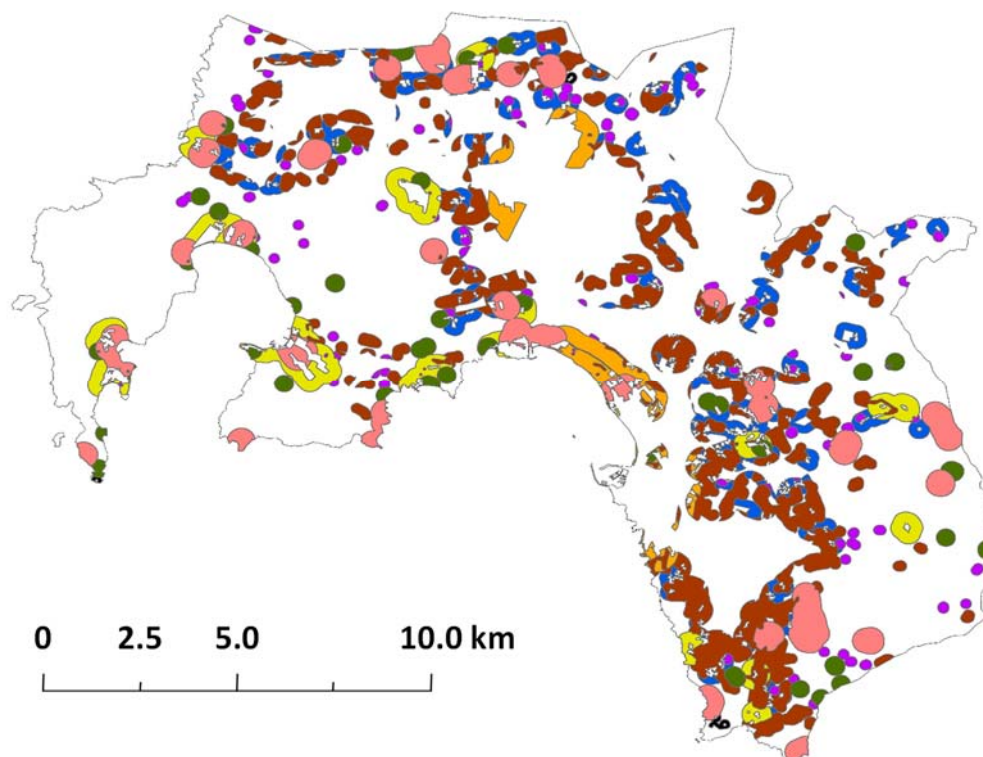
RUI category		Surface		Dwellings/ RUI	Surface/ dwellings	Perimeter/ Dwellings
Housing	AI	(ha)	(%)	(%)	(m ² m ⁻²)	(m m ⁻²)
Isolated	0	11302.0	3.57	0.42	236.9	7.1
Isolated	low	3219.9	1.02	0.43	234.1	21.5
Isolated	high	8761.7	2.77	0.38	265.0	13.1
Scattered	0	10173.0	3.21	1.02	97.1	2.7
Scattered	low	3644.1	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	

339

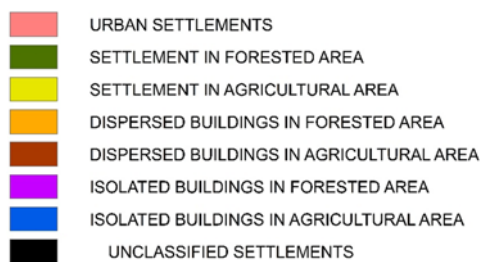
340

341 *Local scale mapping, methodology 2*

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



348



349

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

351

352

353 *Table 5 - Surface and characteristics of the RUI categories recognized with RUImap at local scale*

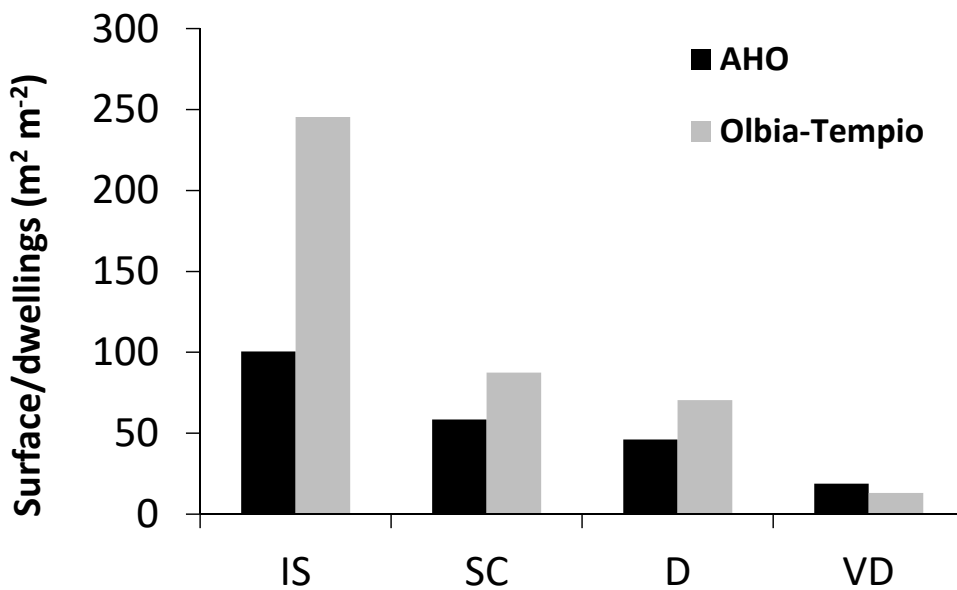
354 *(methodology 2) in the Alghero municipality area. Data are related to the year 2008.*

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	

355

356 *Spatial indicators related to fire risk*

357 With respect to the housing density the results indicate that there is a clear relationship in terms of
358 area and perimeter per housing surface unit. In Alghero and the Olbia–Tempio Province (Figure 8,
359 Tables 3 and 4) the isolated housing has the highest mean area per m² of housing (100.5 and 245.3
360 m² m⁻² on average, respectively). This value decreases when the housing density becomes higher
361 (from isolated to very dense housing). A similar pattern was observed calculating the units of
362 perimeter per unit of housing surface, with the isolated housing showing the highest values of this
363 indicator (Figure 9, Tables 3 and 4). The results clearly point out that a stronger effort for managing
364 these areas per unit of housing surface would be required in isolated housing conditions rather than
365 in the ones with higher densities.

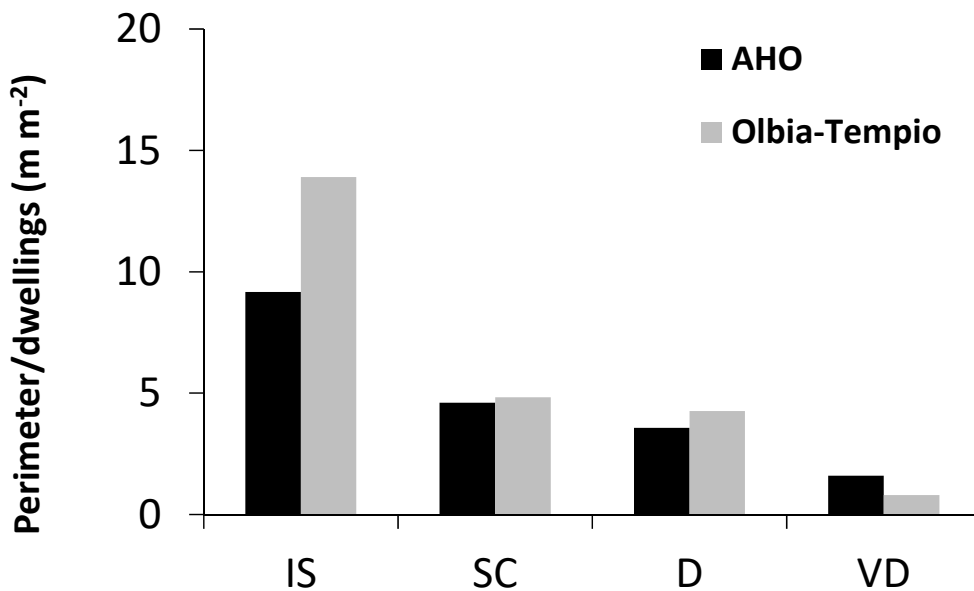


366

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

369

370



371

372 *Figure 9 - Relationship between the housing configuration categories and perimeter. (IS = isolated;*

373 *SC = scattered; D = dense; VD = very dense housing).*

374

375 In the mapping process applied with the methodology 2 , as a result of the raster-vector conversion,

376 not all of the dwellings are accounted. Therefore the statistics related to Option 2 are not shown.

377

378 *Fire occurrence in the RUI*

379 In the period 1998–2010, 36,747 ignitions have been recorded in Sardinia (2,827 per year, on

380 average), burning 132,294 ha (Table 6). The analysis of the fire ignition densities has shown

381 interesting results. The 15.7% of fires were ignited inside the RUI mapped with the regional scale

382 methodology. The ignitions in RUI areas mapped with the methodology 1 range from 24.7%

383 (Alghero) to 39.2% (Olbia–Tempio) of the total occurrences (Table 7). With respect to the

384 methodology 2 (Alghero case study), the wider RUI area consequential to the different mapping

385 method indicates that 50.3% of ignitions occurred in RUI areas (Table 8).

386

387 *Table 6 - Ignitions and burned areas in the RUI areas mapped at regional scale. (Ignition points*

388 *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

389

390

391 *Table 7 - Local scale, methodology 1: ignition points density and burned areas. Data: years*392 *1998–2010. (n = number of ignition points).*

Housing	AI	Ignitions				Burned area			
		Alghero		Olbia–Tempio		Alghero		Olbia–Tempio	
		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

393 ** surfaces without dwellings*

394

395

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

RUI category	Ignitions		Burned area	
	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

398 * *surfaces are accounted without dwellings*

399

400 At regional scale the highest mean density value (4.2 ignitions per km²) was recorded at intermediate
 401 housing density (Table 6). At local scale the ignition density values are, on average, higher in dense
 402 housing RUI categories than in lower ones.

403

404 **Discussion and conclusions**

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

409 The mapping methodologies implemented in *RUImap* are basically oriented to obtain maps and data
410 related to the RUI distribution and patterns. *RUImap* is a geographic tool and is not suitable to perform
411 a fire risk assessment in the RUI, where other factors than those accounted in the mapping process
412 need to be included. In the *RUImap* mapping process, anyway, important factors involved in the fire
413 risk are accounted, (i.e. vegetation continuity and typology, housing distribution). At local scale the
414 two mapping methodologies led to differences in the RUI maps and data. In the Alghero case study,
415 the local mapping Option 2 methodology has identified a RUI area almost double than the one
416 obtained with Option 1. Likewise, Stewart et al. (2009) showed that the RUI maps could greatly differ
417 depending on the adopted methodology. These authors compared two RUI mapping methodologies
418 on the same study area and with the same input data, identifying as RUI an area of 59.6 km² with the
419 first and 28.5 km² with the second method. Platt (2010) point out the impact of the mapping purposes
420 and the related different results obtained from the mapping processes.

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

425 The density of fire ignitions has shown a relationship with the housing aggregation degree. No matter
426 how RUI are mapped, the ignitions increase with the housing density up to intermediate-high urban
427 filling levels, except for RUI areas mapped with the local methodology 1. Similar results were
428 reported by Syphard et al. (2007). This may be due to the lower fuel load and continuity in dense
429 urbanised RUI zones. Higher ignition densities did not cause an increase in burned areas, and the

430 percentage of burned area in the RUI was always lower than outside RUI areas probably due to the
431 faster and more efficient fire-fighting activity in these areas, often combined with a lower fire spread
432 rate related to the discontinuity of fuels, lower fuel loads, gardens irrigation, as already suggested by
433 Radtke et al. (1982) and Cardille et al. (2001).

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

437

438

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448

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