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Wildland Urban Interface:
Mapping and Wildfire Risk Assessment

Dr. Casula Franco

Direttore della Scuola Prof. Pusino Alba
Referente di Indirizzo Prof. Spano Donatella
Docente Guida Dr. Sirca Costantino

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Franco Casula

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Abstract

The Rural Urban Interfaces (RUI), are those areas in which vegetation and houses are in contact or intermingled. Vegetation constitutes the prerequisite for wildfire propagation and, given the high number of values exposed to wildfire and the fact that the highest ignition densities are recorded inside RUI, the worst consequences of wildfires usually occur in these environments. It is, hence, particularly important to map and to create models for wildfire risk assessment in RUI.

The work of the present thesis is organized into two parts:

- In the first one RUI are defined, mapped and classified into RUI typologies, and a characterization of the relation between RUI and fire regime is performed.
  Three different operational definitions of RUI are used and in the study it is shown how RUI area largely depends on the adopted definition. Although the maps obtained using various methods differ in identifying portions of the territory as RUI, all methodologies consistently recognise that inside RUI the ignition density is higher and the burned areas are smaller than elsewhere.
  A section of the study compares the different kinds of RUI demonstrating that not all RUI typologies imply similar complications for wildfire protection and in particular that the Isolated Housings are the most difficult to manage for preventing wildfire damage.
  A case study of diachronic mapping shows the utility of RUI classification for describing the evolution on time of RUI phenomenon.
- In the second part three models for wildfire risk assessment in RUI are presented. In particular, aside an application of a classical overlay mapping methodology taking into account the principal risk factors, other two methodologies are developed and applied:
  - Multicriteria approach: the model has been developed through the Analytic Hierarchy Process and optimized thanks to thirty interviews to experts. An application to a case study is also presented.
  - Multisimulation approach: it is based on the use of wildfire simulator for quantifying house exposure in terms of wildfire probability and intensity and on the use of RUI maps for assessing the presence and vulnerability of values exposed to risk. The model has finally been applied to a case study.
  The three risk models work at different scales, using different inputs; all of them are capable to produce risk maps showing the spatial distribution of risk and their results show to be consistent.

Extended Abstract

Wildfires, as part of the ecosystem functionality and as a natural phenomenon, have always participated in modelling the landscape. Nevertheless, they are considered a very important global issue because they can damage economic values and threaten human lives, often requiring professional intervention by civil protection.

In Mediterranean areas wildfires have a broad diffusion because of the particular hot and dry climate during summers and of the high population density. In this area wildfire regime is strongly influenced by human presence since the majority of ignitions are related to human activities (arson or negligent/inexperienced actions). In Europe, every year, an average of 60,000 wildfires occur, burning about 6,000 km^2 (EEA, 2003; JRC, 2007), and the majority of them happens in Mediterranean countries.

Fire regimes are in constant evolution and a negative influence may be expected, due to climate changes (higher hydric deficits, higher temperatures) and to social changes.

The phenomenon of land abandonment is augmenting fuel continuity on the landscape and, at the same time, urban centres are expanding toward the countryside creating periurban residential neighbourhoods characterized by an intermingle of low-density housing and almost continuous fuels.

These wide areas where houses and vegetation co-exist are called either "Rural-Urban Interfaces (RUIs)" or "Wildland-Urban Interfaces (WUIs)".

The great number of houses located in vegetated contexts and hence exposed to wildfires constitutes a high-risk situation and, although RUI usually covers a small percentage of land, it is there that the highest rate of ignition points, the most severe damage and the worst problems of Civil Protection due to wildfires occur.

It is, then, especially important to have a particular focus on RUIs and to assess wildfire risk in these special areas.

Mapping out RUIs is the first step for creating appropriate methodologies for **Wildfire RUI Risk Assessment**, that is the process by which the likelihood and magnitude of the occurrence of an unwanted, adverse effect is estimated together with the likelihood of a possible damage for values exposed to it.

The aims of this thesis are to produce maps of the Interface and to develop and apply methodologies for wildfire risk assessment in RUIs.

The thesis work is organised into two main parts:

- the first one concerns RUI definitions and mapping;
- the second one deals with methodologies for wildfire risk assessment in RUI.

<u>In the first part</u> three mapping methodologies of RUI environments have been used. They are available in the *RUImap®* tool that is a main product software of the European Project FUME (7th EC program). The thesis work has been carried out in the framework of FUME project and has contributed to the development of *RUImap®*, an easy-to-use software for automated RUI mapping, now protected by intellectual property right.

In *RUImap®*, a Global Scale and two Local Scale RUI mapping methodologies are available. They work at different scales, use different inputs and operational definitions of RUI and produce different kinds of RUI maps. The three methodologies not only identify the perimeter of RUI area but they also classify RUI according to three set of RUI typologies which have been created to better assess wildfire risk. Classification of RUI has been found to be much more useful than just the definition of its perimeter because it allows distinguishing between different kinds of RUI.

A section of the work studies the interaction RUI/fire regime, finding out that the distribution of ignitions and burned area vary not only between RUI and non-RUI areas but also when comparing the different RUI typologies: in particular, all the methodologies and all mapped study areas show higher ignition densities and lower percentage of burned area inside RUI than elsewhere and that ignition density grows and burned areas lessen in the RUI typologies of denser housing.
Another section of the study shows how the various RUI typologies are characterized by different surface to be brush-cleared for house safety, and hence by different economic effort to be sustained by the community and the house owners; in particular it is much more onerous to manage the houses located in Isolated Housing RUI typologies than the ones in Dense and Very Dense Housing RUI typologies.
A diachronic mapping for studying the RUI evolution over time has also been performed on a case study, finding out a general increase of RUI surfaces especially in disperse housing categories.

In the second part of the thesis two methodologies for wildfire risk assessment in RUI are developed: a Multicriteria approach and a Multisimulation approach. They are applied along with a classical overlay mapping and a comparison between the three methodologies is also performed.
The risk definition we adopted takes into account on one side the hazard factors describing the source of risk (fire probability and intensity) and on the other the factors related to the values exposed to the source of risk (house distribution and vulnerability).
One of the risk models has been created using Multicriteria techniques and in particular the structure of the model has been developed through the Analytic Hierarchy Process and has been optimized thanks to thirty interviews to experts. The model has also been applied to a case study and a territorial map of wildfire risk in RUI has been produced.
In the Multisimulation approach the software Randig, capable to simulate the wildfire spatial propagation, has been used for assessing hazard on the territory and in particular the exposure to wildfire of houses located in RUI. Randig results have provided the simulated spatial distribution of Burn Probability and Flame Length and they have been found strictly consistent with real distribution of burned areas in RUI.
The Burn Probability and the Flame Length maps produced by Randig have been combined with the map produced by the Global Scale mapping methodology whose RUI typologies are able to distinguish among areas characterized by different densities of values exposed to risk (houses). RUI typologies located in forested areas have been considered more vulnerable than the ones located on disperse vegetation contexts. The RUI typologies report not only the housing density but also the context in which the houses are located and hence the Global Scale map has been used to assess both the presence of values exposed and their vulnerability. Having the four factors Burn Probability, Flame Length, Vulnerability, Values exposed, we have finally produced a map of wildfire risk in RUI.
The three risk models differs in the scale at which they work, in the inputs they need, in the complexity of their implementation, in the time they require to be applied, but all of them are capable to produce risk maps showing the spatial distribution of risk. The results can be judged consistent: in particular the overlay mapping methodology and multicriteria methodology show to be able to identify same areas as high risky ones, putting on evidence similar patterns in the risk maps. Their acuity in classifying the landscape is different and the multicriteria methodology which takes into account many more parameters and inputs looks to be the most accurate in creating wildfire risk maps of RUI.

PART 1: Introduction

Foreword

Wildfires are considered a very important global issue. They are a natural phenomenon and have always been part of the ecosystem, but being able to cause severe damage to people, their belongings, economic goods and activities and to the environment itself, they often become a critical problem, requiring professional intervention by civil protection. Fire is an important natural element that participate in landscape and ecosystems evolution, and if, on one side, in the dry and hot season it can cause severe damage, on the other, the controlled use of fire can be helpful in forestry as a tool to manage fuel charge and protect ecosystems and human values.
Wildfires occur almost all over the world, except in the tropical desert areas and at the highest latitude (>70°) (Mack et al. 2011)[i]. They are more common in the inter-tropical latitudes and at medium latitudes, because in these areas, which are densely populated, there is a strong presence of vegetation (fuel of various types).
It is widely accepted that, almost all over the world, the main causes of wildfire ignition are related to human activities: arson or negligent/inexperienced actions (typically, unattended campfires account for a substantial number). Anyway, in many regions of the North America continent, an important cause of wildfire ignition is the atmospheric phenomenon of lightening, especially when it is not accompanied by precipitation,
(http://www.ecowest.org/2013/06/04/wildfire-ignition-trends-humans-versus-lightning/).
Although in terms of the number of ignitions also in the United States, people cause the majority of wildfires, lightning caused fire often occur in unpopulated areas, and they accounts for some of the largest burned areas in many of the states of conterminous U.S.
In Europe, every year, an average of 60,000 wildfires occur, burning about 6,000 km^2 (EEA, 2003; JRC, 2007), and scientific studies demonstrate that nowadays there are more fires than a century ago (Moreno et al., 1998[ii]; Mouillot et al., 2005[iii]; Mouillot and Field, 2005[iv]).
Wildfires cause severe environmental and economic damage, resulting sometimes in the loss of human lives. The Mediterranean part of Europe is the most exposed to wildfires because the summer season is usually long, warm and dry. An important consideration is that the phenomenon of wildfires is in constant evolution and that fire regimes are continuously changing, driven by climate and social changes. A negative influence on fire regimes may be expected, due to climate changes. According to projections:

- Summer hydric deficits will become more severe and temperatures will rise;
- The physical areas of concern will be widen (including, for instance, the Alps and the northern part of Euro-Asiatic and American continent that, at present, are not experiencing a great number of fires);
- The length of the warm, dry season will extend.

Along with climate change, profound social changes have been taking place especially in Mediterranean Europe, particularly since WWII. The region has become more densely populated and, in the 20th century, has undergone deep social change. The proportion of workers employed in primary, secondary and tertiary sectors has changed drastically, with shifts of the workforce from the primary to the secondary, and, especially, the tertiary sector. The activities of the tertiary sector are mainly commerce and services, and, hence, are typically practiced in towns and cities, and it is for this reason that the phenomena of migration from the countryside to urban centres took place. Land use also underwent drastic change, resulting in a general abandonment of the countryside and in an inferior surface used for agriculture or grazing. With abandonment of the countryside many fields that were cultivated and were a natural interruption of fuel

continuity underwent to reforestation natural process. As a consequence not only the fuel charge but also their continuity has drastically increased because of the loss of natural fire-brakes.
At the same time, urban centres underwent great expansion including substantial construction of peripheral residential neighbourhoods characterized by low-density housing. These wide areas are often an intermingling of vegetation and houses, of human presence and natural environment.
Delineated urban centres, with a definite and clear transition to the countryside are now rare, while a wide peri-urban area, in which vegetation and houses co-exist, is usually the most common situation. Although the word “intermix” appears to be more suitable than “interface” to define these wide areas where houses and vegetation intermingle, the common names by which they are referred to in the relevant literature are "Rural-Urban Interfaces (RUIs)" and "Wildland-Urban Interfaces (WUIs)".
It should also be considered that the amenity-driven phenomenon of constructing houses in natural contexts, together with urban population growth, is predicted to have a great and continuing impact and to exacerbate an increase in the trend for WUIs to occur (Hammer et al. 2009)[v]. It is now becoming clear that size of burned areas or number of fire occurrences no longer serve as good metrics to assess wildfire-caused economic impact, simply because damage is not proportional to those metrics, and it is in WUIs that the damage is most severe. For this reason, it is especially important to have greater focus on these complex environments.
Among the most-used definitions of the Wild-land-Urban Interface, a very clear and general one was provided by USDA Forest Service in 2001: “(The) WUI is the area where houses meet or intermingle with undeveloped wild-land vegetation”. WUIs are seen as focal areas for human-environment conflicts, such as wild-land fires, habitat fragmentation, invasive species, and biodiversity decline (Stewart et al., 2007)[vi]. In the WUI, the presence of people, activity and all kind of goods and benefits (houses, cars etc.) is remarkable and, simultaneously, vegetation and its continuity create a high fuel charge context. The great number of values exposed to wildfires constitutes a high-risk situation and, although the WUI usually covers a small percentage of territory, it is there that the most severe damage, the highest rate of ignition points and the worst problems of Civil Protection due to wildfires occur.
Especially in Europe, referring to the same areas in which human presence and vegetation interact, the term Rural-Urban Interface (RUI) is more frequently used than Wildland-Urban Interface (WUI). The definition of RUI takes into account all kind of interfaces between the urban environment and surrounding areas just not only the direct interface with wildland, which is the most common situation in North America. Generally speaking, in Europe the density of buildings gradually decreases as one moves from the centre of towns and villages, but the surrounding context of villages and town is not usually a Wildland or a forest. It is more common for the urban centre to be located in the countryside, where agriculture and breeding are practiced.

Nowadays, Rural-Urban Interfaces and Wild-land-Urban Interfaces are actually considered to be synonyms and, also in this thesis, RUI and WUI will be used as synonyms.
It must also be taken into account that in RUIs, wildfire-extinguishing operations are very difficult, for the follow reasons:

- The presence of a human population;
- The high number and value of goods and amenities (houses, cars, etc.);
- The presence of electric lines, that usually make the use of aircrafts and helicopters very difficult;
- Complications that comes with evacuation actions of residents;

- Toxic smoke from tires or other combustible materials.

Since it is very difficult to extinguish the fire and, simultaneously, to preserve the considerable number of values at risk, the best strategy for coping with wildfire risk is universally recognized to be prevention. So, if on one side it is true that, during a wildfire, fire-fighters have the key role in extinguishment, on the other side, which takes in a wider view the phenomena, the most important actors in wildfire risk management in WUI are planners and fire managers who can consider all possible strategies to organize and manage the land in order to prevent and therefore, greatly reduce the risk of severe damage.
The scientific community is working hard to create tools capable of classifying WUI types and to produce maps that are thought to be useful for planning, prevision, prevention, protection and, in the operative phases during possible emergency. Many scientific projects, in particular the European Projects "WARM" (5th Framework Programme of the European Commission) and "Fire Paradox" (6th Framework Programme of the European Commission), developed different WUI-type classifications (Caballero, 2004)[vii], (Caballero et al. 2007)[viii].
Since WUI are very complex environments, they can be studied with many purposes in mind. If we think that the WUI concept evolved over time, that maps of WUIs can be produced with different main aims and that, virtually, there are countless ways to classify WUI, we can understand that it is very hard to find a common operational definition of the WUI.
Nevertheless, there is a growing need to have maps of WUIs as reliable tools helpful to face the problems of strategic planning. "A good WUI map provides a graphic representation that matches the conceptual understanding of what and where the WUI is. This conceptual understanding of the WUI has evolved over time; the area where houses and forests meet has attracted attention for many years." (Stewart et al. 2007)[ix].
Mapping out WUIs is also the first step for creating appropriate methodologies for Wildfire WUI Risk Assessment that can be useful for planning the future developments of urban centres. In this sense, a good methodology for mapping WUIs must be able to identify and distinguish WUI types, to produce maps, which permit recognition and localization of areas that are at different level of wildfire risk. Maps, together with an appropriate wildfire risk assessment methodology, are the main means by which we can plan a safer expansion of human presence in the territory.

Risk assessment is the process by which the likelihood and magnitude of the occurrence of an unwanted, adverse effect is estimated together with the likelihood of a possible damage for values exposed to it. Wildfire risk assessment is a very complex topic and it becomes particularly complicated in a WUI. Many methodologies for evaluating risk have been developed and used. There are methodologies using economic instruments, which can assess the probable loss of value of houses in case of wildfire, which are mainly used for the purpose of insurance and when there are economic transactions, e.g., in the housing market. Other methodologies work *ex post* on an already happened wildfire, taking into account the direct costs for extinguishment and loss of goods, indirect costs and short-and-long-term damage (Lynch, 2004)[x], (by Dale, 2010)[xi]. Then, through statistical projection, it becomes possible to produce wildfire-risk assessments for similar situations in other WUIs starting from the impacts already documented and from the likelihood of a new event.

The aims of this thesis are to produce and compare different kind of RUI maps according to various operational definition of the RUI and to develop methodologies for wildfire risk assessment in RUIs. Comparisons of different mapping methodologies and different wildfire risk-assessment methodologies are thought to contribute to create useful planning aids and to protect increasingly scarce and valuable land resources from irrational and problematic human expansions.

The thesis is organised into two main parts:

- the first part concerns WUI/RUI definitions and mapping;
- the second part deals with methodologies for wildfire risk assessment in these highly vulnerable interfaces.

Defining Rural-Urban Interface

The study and the classification of RUI (or its synonym WUI) areas is a preliminary work for the production of RUI maps which is intended to be a useful means to assess wildfire risk on the land. There are many theoretical difficulties in the definition of RUI and numerous technical obstacles in implementing an operational applied definition.

The general definition of WUI given by USDA Forest Service in 2001[xii] is: "WUI is the area where houses meet or intermingle with undeveloped wildland vegetation". The WUI classical subdivision by Davis (1990)[xiii] into:

- "P**ure interface** community", where urban land directly abuts wildland fuels;
- "**Intermix** community", where there is no clear boundary between urban and wild areas and a wide surface presents an intermingle of vegetation and structures;
- "**Occluded** community", patches of wildland vegetation that lie in an urban matrix,

is a topological classification that can give some information but does not synergistically describe the whole complexity of the phenomenon. It has not been thought to be used for wildfire risk assessment and to distinguish between different areas at various levels of risk.

Some important factors of complexity in RUI include:

- Those environments in which human activities and vegetation, belongings and natural landscape co-exist are usually complicated and not homogeneous;
- There are infinite possible configurations of the urban patterns, house densities, distances between dwellings, widths and densities of streets;
- There are many local aspects that can significantly change the vulnerability of a house to wildfire; for example, annual maintenance and removal of fuels surrounding the house, the presence of wide roads that can interrupt fuel continuity, the presence of water supply in case of fire, the presence of a secondary way to access the house in case of wildfire. It must be considered that vulnerability is very sensible to the distance fuels/house. All these aspects and many others can result in completely different situations from the point of view of fire risk.

The technical complexity poses a great difficulty in RUI studies but the major obstacle is an epistemological issue about the same subject of study. The definition is not concrete enough to make us determine exactly which situation is RUI and which is not. Scientific community found many difficulties in stating a single operational definition implementing the general concept of RUI and being simultaneously capable to univocally include in (or exclude from) RUI all possible situations of vegetation/houses coexistence. RUI general concept works as an umbrella notion encompassing an archipelago of different concrete situations. A particular housing configuration located in vegetated area, can be considered RUI by one operational definition but can be excluded from RUI area according to another.

For a scientist, to study RUI is to be in a particular condition: although the houses in natural environment are real and concrete and the problems in RUI are real and concrete as well, RUI is a theoretical concept that generically refers to the coexistence of fuels and human values and belongings. It is an abstraction of many unique real situations but, without an operational definition, the object under study is not self-evident and univocally defined. So it is up to the researcher to adopt a definite operational methodology and then, what is enclosed in RUI and what is not depends on his/her choice.

An operational definition of RUI is a conceptual framework internally organised in different classes of *theoretical standard RUI types*, prearranged to distinguish the situations according to the level of risk they present; it is supposed to be capable of categorising every concrete specific situation into one of the types. It is generally implemented establishing the threshold distances of houses from forested areas or between them so that the area in which houses are built can be assigned to a certain RUI type. The technical implementation can be operated in a Geographic Information System (GIS), through the use of already available functions like the ones for creating buffers around single dwelling or around polygons of vegetation, or the ones for calculating house density, street density, vegetation continuity etc.
It is through the thresholds and rules we define that it can be established what is to be considered RUI, which areas and houses are included in RUI and which are outside it. Through the operational definition each area classified as RUI can be assigned to a RUI type. Since the researcher is the one who creates the set of theoretical RUI categories and who fixes all the thresholds and parameters, his/her influence on the object of study is enormous. The percentage of land that will be included in RUI largely depends on his/her operational definition of RUI, on the rules, thresholds, buffers he/she stated.
The researcher is not in the same position that usually is supposed to have in applied sciences where reality presents a clear and self-evidently-defined object of study. RUI is not a real and defined entity whose existence is univocally self-evident and does depend on the chosen definition adopted: the researcher definition of RUI creates the object of study, putting on evidence a short circuit between “observer and observed”. This constitutes an epistemological additional complication and a not-avoidable responsibility.

To implement an operational definition mainly means to create a set of theoretical RUI types and to specify parameters (rules, buffer, distances etc.) and it has a great influence on mapping. Changing the operational definition:

- The entity of RUI areas can greatly change;
- A given low density housing situation can be included in RUI or be located outside;
- A specific RUI environment can be classified according to various set of theoretical types and a given house can belong to different RUI categories;
- Since different maps are obtained if working with different operational definition and since the use of maps conditions planner decisions (like establish preeminent surfaces for fuel reduction treatment with prescribed burning, brush-clearing, pruning operations etc.), two operational definitions can result in different planning strategies, different amount of area to be treated for fuel reduction and different costs for wildfire prevention.

The study of the “object” RUI is very complex for the concrete complications given by dealing with virtually infinite possible house/vegetation configurations, and for the epistemological peculiarity of being very influent on the object of study itself. Some examples in the following pages would illustrate the epistemological concept.

Two important and very used operational WUI definitions implemented by the use of GIS, appeared in literature almost simultaneously in 2005 (Wilmer and Aplet, 2005)[xiv], (Radeloff et al., 2005)[xv]. Both WUI identification methodologies distinguish and inspect “intermix” and “interface”; the intermix are the areas where there is co-existence and intermingling of human properties and fuels while the interface are urban areas in close proximity with wildland. The methodology of Wilmer and Aplet to identify WUI works on three steps: selection of areas with more than 6.2 houses per km^2 (in the original article: house number >1 each 40 acres), buffer of

0.805 km (in the original article: 0.5 miles) of the selected areas, removal of areas with no vegetation. Also, the approach developed by Radeloff et al. works on three steps: selection of areas with more than 6.2 houses per km^2, removal of areas with vegetation coverture <50%, addition of areas with vegetation coverture >75% located within a buffer of 2.414 km (in the original article: 1.5 miles) from the selected areas.

In 2009, a very interesting study (Stewart et al., 2009)[xvi] compared the two methodologies applying it on the same study area. Stewart et al. demonstrated that the WUI areas could greatly differ, depending on the chosen methodology. In the case study considered by the authors that performed the comparison of WUI mapping, the first method (Wilmer and Aplet) identified RUI as an area of 59.55 km^2, the second one (Radeloff et al.) as an area of 28.55 km^2, and the surface that both methods recognized as RUI was 21.09 km^2. There have been 38.46 km^2 that only the first method considered RUI and other 7.46 km^2 that were considered RUI just by the second approach but not by the first one.
The study is particularly interesting because, given the same input data and same first step of calculation for both methodologies, the obtained results are very different. It illustrates how influent the researcher's choice of the operative methodology to map RUI can be on the surfaces he/she will study.

Depending on input data availability, on characteristics of the territory, environmental context, local fire regime, local laws and on the aim of RUI mapping, some simplified methodologies have been implemented; for example, some counties in the USA created plans in which WUI has been considered as all areas within a buffer distance of ~2 km around houses because, actually, 2 km can be considered a limit distance for spot fire ignitions.
It can be an easy solution for putting on evidence which areas can become a threat to houses if fire arrives from the nearby wildland, and can be acceptable in an environmental context of wide forests where fire regime is mainly natural and driven by the phenomenon of lightning. In other more populated contexts like Europe (or other counties of U.S.), a so wide buffer means to identify an enormous part of the territory as RUI and means not to have the possibility to make distinctions between very different conditions. Moreover it implies to neglect the fact that in Europe the majority of fires is caused by human activities and that fire does not arrive to homes as a threat coming from wildland. So, a definition that can be useful in one context is not suitable for another.

Another example is the definition adopted by the Southwest Region (Region 3) of the US Forest Service which defines Wildland-Urban Interfaces as the areas surrounding the houses, "but also the continuous slopes and fuels that lead directly to the sites, regardless of the distance involved" ([xvii]). This definition is more strictly bound to the concept of fire danger (which takes into account the predisposing factors making likely a fire to occur) and does not pre-define a threshold distance for considering or not a given area as RUI. This definition is not convenient for creating an operational procedure to map WUI. Many different WUI mapping methodologies could be consistent with this definition, but each of them (as shown in Rutherford et al., 2010[xviii], Stewart et al., 2007[xix]) would produce different WUI perimeter occupying different portions of land, would indicate different locations as principal area of intervention for fuel reduction and creation of fuel brakes, would imply different economic costs for maintenance.

Two new approaches that have recently been applied in Switzerland (Kanevski et al., 2012)[xx] can be counted among the most innovative and promising ones:

- Landsat analysis for wide scale RUI evolution over time (Cere et al. 2012)[xxi],

- the new proposed concept of WUI, based on City Clustering Algorithm (CCA) which uses demographic data to define urban centre and its spatial distribution and evolution (Rozenfeld et al., 2008)[xxii].

Historically, the first wildfire problems in WUI date back to the second half of XIX° century. The first recorded big wildfires affecting many houses occurred in North America (U.S.A. and Canada) because of the rapid expansion of colonist farmers who created settlements of wooden houses in wildland forested territories. At that time, Europe, the "old continent", was already "colonised" and the rural management of the territory had reached an equilibrium between human presence and natural processes. A short list of historic very big fires with severe damage for houses can be found in (Cohen, 2008)[xxiii (integrated)]:

- "Peshtigo" (Wisconsin, U.S.A., 1871),
- "Michigan" (Michigan, U.S.A., 1881),
- "Three Forks" (British Columbia, Canada, 1890),
- "Hinckley" (Minnesota, U.S.A., 1894),
- "Sandon" (British Columbia, Canada, 1895),
- "Adirondack" (New York, U.S.A., 1903),
- "the Big Blowup" (Idaho-Montana, U.S.A., 1910),
- "Mc Guigan" (British Columbia, Canada, 1910),
- "Cloquet" (Minnesota, U.S.A., 1918).

One of the most impacting fires in public opinion was the "Hinckley fire" (Minnesota, 1894). The fire caused at least 480 deaths, completely destroyed the urban centre of Hinckley and burned a forested area of about 800 km^2. But many other important events had to happen before the concept of WUI was pointed out as one of the main problems of wildfire management (http://www3.gendisasters.com/category/disasters/fires).
The very first attempt to define the new kind of environment that WUI represented at that time, was by Butler who, in 1974, described it as "any point where fuel feeding a wildfire changes from natural [wildland] fuel to man-made [urban] fuel" (Butler, 1974)[xxiv]. Then a series of discussions on the rising debate tried to specify the definition. It is during the years '80s of the XX° century that the debate on wildfire started to focus on WUI. Henry J. Vaux (Vaux, 1982) and Gordon A. Bradley (Bradley, 1984) provided important contributions to the debate by viewing WUI as a major forestry issue. WUI was seen as special areas that were:

- Vulnerable for biodiversity due to the introduction of non-indigenous species;
- Fragmented habitats;
- and above all, they were particularly at risk of wildfire.

Vaux and Bradley were the first to propose fuel reduction treatments to manage the equilibrium between human presence and natural environment in these special areas.
Under the pressure of growing wildfire problems in RUI and thanks to the efforts of scientific community and of public institutions directly operating on the terrain, the theoretical concept of RUI has been evolving since 1974 when its first definition appeared in literature. During the '90s for these areas, a progressive focus was put on wildfire risk and nowadays the term WUI is almost exclusively used in the wildfire field.
The increasing importance of the concrete problems in RUI implies a growing need for useful RUI maps of which many have been developed improving the knowledge of the phenomenon. Different approaches were tested and applied by scientific community and institutions directly operating on the territory (Forest Services, Civil Protection, Fire-fight Management). The

accumulation of experience and knowledge helped in selecting the most useful approaches and in progressively “defining the definition” of RUI.
It is only after having adopted a WUI definition that it becomes possible to create maps. These useful geographic devices are helpful for planners because they are able to describe and embody the spatial representation of the phenomenon. During the evolution of the WUI debate, many different approaches were used and many definitions were provided and applied to map RUI with different purposes. The concept became richer while the knowledge about WUI was progressing and becoming more profound. Although all definitions refer to the co-existence of human presence and vegetation, many different points of view were adopted:

- ***The human belongings centred***: it is oriented towards protection of houses and human lives (Cohen, 2000)[xxv]; its focus is on vulnerability/resistance of values at risk and in particular on the building itself and on the area immediately surrounding it. That area is called “home ignition zone”, and it has been demonstrated that, if within a radius of 30 meters from the house there is no fuel and vegetation, the probability for a house to burn is negligible. According to this approach the building materials and the house maintenance (in particular to remove leaves from the roof) are very important and the absence of fuels and vegetation around the house is an almost completely safe way for owners to manage their property. The importance of the approach is to have been capable to focus on the values exposed to risk rather than on the source of risk. The building itself and the conscientious management of it are considered the main factors for house protection from the fire and fire suppression is not seen as the only strategy to reduce damage to houses.
- ***The ecological impact centred***: it deals with the interface problems using a focus on sustainability of WUI for the ecosystems and on regulation of human activities/natural processes co-habitation[xxvi]. The approach treats the human impact on the wildland due to the WUI. The concept can be better explained using the exact words of some leading figures of this approach: “In the publication, *Human Influences on Forest Ecosystems: The Southern Wildland-Urban Interface Assessment*, the interface is defined from a natural resource perspective as an area where increased human influence and land-use conversion are changing natural resource goods, services, and management techniques (Macie and Hermansen 2002). Under this definition, the interface is a set of conditions that affect resources and how they can be managed, rather than a geographic place.” (Hermansen-Baez et al., 2009)[xxvii]
- ***The emergency centred***: it is the typical approach useful for Civil Protection plans and intervention, for fire-fighters and population safety. Its focus is on management of possible emergencies and the most important factors taken into account are the number of residents, the fuel charge and continuity, the number of accesses to the WUI and to each house, the water availability, the engagement of residents into “fire adapted communities” (Toman et al., 2013)[xxviii], and everything that can be useful to produce strategic emergency plans and for protection of population and values from the possibility of wildfire damage.
- ***The planning approach***: it is a more integrated point of view, which takes into account the human and the ecological values and all the possible ways in which human activities interact with natural processes and *vice versa*. It is characterised by studying WUI phenomenon at different spatial scales (from the local community to the regional scale) and by looking at WUI using a time frame of several years. It is a general approach that disregards the single wildfire events, the weather conditions (but not the local climate),

and the yearly maintenance operations that a house-owner can/must do. It is more focused on arranging the land to better withstand the safety problems through multiple purpose management of fuels (Randall et al., 2006, reviewed 2012)[xxix], and through disposition of houses and wide streets in the best way to attain a safer territory.

This planning-geographic approach is the most useful, not only for prevention strategies, but also to organize human expansion on the territory. It can be suitable to design the patterns of future urban development and to manage the territory with safety purposes. The main aim is to obtain a "passively safe" configuration of the territory: it means to work on the possible urban configurations to select the ones that require the minimum of active interventions in order to be safe. Among the most important parameters:

- Housing density;
- Distance between dwellings;
- Width of streets that interrupts the spatial continuity of fuel and provides escape routes in case of evacuation and simultaneously safe access to fire-fighters;
- Rules on distances between fuels and structures, on construction material and on presence of water supply.

Last but not least, for the aim of the present work, the planning approach is also the most suitable to translate the disembodied concept of RUI into an operational definition capable to take into account the generality of factors defining the landscape and to lead us to the production of that fundamental planning device that is the RUI map.

"A good WUI map provides a graphic representation that matches the conceptual understanding of what and where the WUI is.", (Stewart et al., 2007)[xxx].
Although a unique and clear operational definition of RUI could be very useful to compare different situations and to observe RUI dynamic evolution over time, a broader theoretical concept can be more valuable for revising maps produced using a specific operational definition, and for manual inclusion or exclusion of RUI areas.
The operational definition can be considered a specific way to model in abstract concrete situations. Each operational definition is a model and represents a different simplification of real RUI complexity. According to RUI concept every operational definition must consider at least three main factors:

- Vegetation presence (type, quantity and spatial continuity);
- House presence (mutual distances between houses, house density);
- Interaction between houses and fuels (distance, points of contact).

Working at a regional scale for producing WUI maps the operational definition can be simple and just capable to identify those areas where vegetation and houses co-exist. Only the thresholds of house density and canopy cover must be established.
This can be the case of a national general survey to assess RUI diffusion and distribution and can be useful for theoretical as well as practical knowledge. For instance, it can be a good means to visualize the distribution of RUI on wide areas and hence for planning according to RUI presence the allocation of resources such as aircraft for fire-fighting.
Working at a communal level many other factors describing vegetation (continuity patterns, fuel charge, presence of dead fuels, % of thin and thick branches, etc.) and urban factors (distances between houses, width of the roads, street density etc.) can be included to obtain a deeper knowledge of local interfaces and to produce a useful WUI classification into types.

This can be the case of a single municipality that maps its WUIs, categorizing them in order to be ready in case of emergency, or to impose different rules about management of the immediate surroundings of the houses depending on the RUI type in which they are located. WUI mapping can be useful to imagine various future scenarios of peri-urban expansions, and to visualize in advance the WUI that each scenario would create and hence it is a good resource for communal level planning.

Working at a still more detailed scale: the mapping of a single neighbourhood can be meticulous, and might, for example, take into account the points of direct contact between fuels and structures. The inventory could include the building construction material of each dwelling or the presence of more than one access to each house; list the presence of firewood or gas tanks, of water supply or swimming pools useful in case of fire; and note year by year if the mandatory maintenance of house surrounding has been respected by each owner.

This mapping can be helpful for creating an emergency plan of evacuation, or can be a fundamental tool for fire-adapted communities that are involved in wildfire risk self-management.

RUI maps are useful devices to describe and to quantify the phenomenon, to see its evolution over time and the progressive diffusion on the territory. They provide quantitative spatial information on presence, diffusion and distribution patterns of the interfaces on the territory, can be used to study the interaction between RUI phenomenon and Wildfire frequency and distribution, and are indirect means to model human factor influence on fire regime.

An ideal operational definition of WUI oriented to wildfire risk assessment would take into account all the possible factors influencing ignition and propagation of wildfires. In the present thesis we adopt a point of view of middle-scale planning that can be, for example, the RUI mapping on the communal territory of a municipality.

The chosen perspective neglects some aspects that can be considered only on very small areas:

- It is not related to the evolution and propagation of a single fire event;
- It is not oriented to the management of the emergencies;
- It does not incorporate single houses characteristics (construction materials, presence of water supply, stocks of wood etc.);
- It does not consider annual maintenance of houses and surroundings by private owners.
- Regarding the time scale, the middle-scale planning approach oriented to wildfire risk assessment works in a timeframe of several years and neglects the weather evolution: it considers constant severe weather conditions (low R.H., strong wind, very high temperatures) because they are likely to happen in a time lapse of several years.

On the contrary, this mapping approach focuses on urban/vegetation patterns and configurations. The RUI maps are mainly based on structural characteristics of urbanity and vegetation: housing configuration metrics (density, clustering, distances, width of streets etc.), and vegetation descriptors (type, quantity and continuity).

Finally the planning approach to RUI phenomenon tries to adopt the most useful perspective and operational definition of RUI for producing maps capable to identify the dwellings that are most likely to be affected by wildland fire. The RUI theoretical types used to classify the interfaces are designed and thought to be maximally useful in order to distinguish the zones according to their wildfire risk level.

As every practical approach to RUI phenomenon, the middle-scale planning can be seen as a compromise between usefulness and complexity.

These kinds of planning models are in general implemented in a GIS environment. They require input data layers with sufficiently detailed resolution and precise georeferencing.

Part 2: Rural-Urban Interface Mapping

Foreword

Mapping methodologies – Generalities

The WUI mapping using a planning approach at communal/provincial scale is the chosen approach for the development of the present thesis work, mainly because of its capability to categorise RUIs into classes whose theoretical meaning is strictly bound to wildfire risk assessment. RUI typologies are created and organized with the aim of distinguishing different levels of wildfire risk in the infinite possible RUI configurations.

RUI maps are typically constructed in a GIS environment where we can analyse structural characteristics of urbanization and vegetation, and characterize house distribution and the patterns of vegetation presence and connection.

Those variables that become observable just in either a local spatial scale (single house characteristics) or a very short temporal scale (weather) can be really influent on a micro-scale punctual evaluation of wildfire risk day by day and house by house. Nevertheless, the chosen approach neglects this kind of variables.

The basic spatial unit for the mapping process is the house, nonetheless, its specific characteristics (construction material, presence of water supply, number of accesses etc.) are not taken into account. Our approach is interested just in the mutual distances between houses, the densities, the clustering and disposition patterns of houses. Similarly, referring to time scale, we can affirm that the temporal horizon of reference used in this approach is pluri-annual. The average climate, and, eventually, the worst weather conditions that are likely to occur in a time lapse of several years are the fundamental time scale which the approach is interested in.

If more localized and detailed information is needed for an improved wildfire risk assessment, or if it is needed a daily or hourly evaluation of fire hazard, or, again, if we must put on evidence differences in risk level in a neighbourhood among single houses, it is possible to overlay to the RUI maps some other layers which take into account additional risk factors. We can, for example, detail the assessment by overlaying the characteristics of the single houses (material of construction, water availability, etc.), the execution of annual maintenance works (brush clearing, etc.), the hourly changing weather condition and its local microclimatic variations, and all the other factors capable to locally influence risk.

This RUI mapping approach requires the availability of detailed and reliable urbanization and vegetation data. Subsequently, the access to fire regime data is required to assess wildfire risk in RUI

Among the research projects of the Seventh Framework Programme (2007-2013) founded by the European Commission, a very important one, FUME - Forest fire under climate, social and economic changes, provides a particular focus on RUI areas. As one of the FUME Project partners, the University of Sassari is carrying out research on Rural Urban Interfaces in collaboration with other institutions. In the framework of the FUME project, previous approaches to RUI phenomenon, have undergone to ulterior developments. The previous works on RUI characterization and mapping from which FUME improvements started, had mainly been carried out during the EU Project FireParadox (6th EU Framework Programme) and WARM (5TH Framework Programme of European Commission) by IRSTEA (ex-Cemagref, France) and TRAGSATEC (Spain).

IRSTEA (Institut National de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture) and in particular EMAX, one of its laboratories in Aix-en-Provence, has been working on mapping of Rural Urban Interfaces for almost 10 years, defining a theoretical approach and implementing the correspondent operational definition into a GIS software.

At the same time, the Spanish group Tragsatec was providing an alternative theoretical definition or RUI and creating an automatic GIS tool for mapping RUI according to their own definition.
With the FUME project, many improvements have been implemented on methodologies to map RUI along with a new software tool for automated RUI mapping according to three different RUI definitions. The software is called ***RUImap®*** and during the FUME project, the University of Sassari used and tested it contributing through this applied use to optimize and certify it for use. The research work of the present thesis has been conducted in the framework of FUME and it has contributed to the implementation of RUI methodologies and to the optimization of *RUImap®* tool, a main product of the FUME project which is now registered and protected by intellectual property rights.
While a first version of automated mapping called *WUImap* (by IRSTEA) was born in the framework of FireParadox project, it is with the FUME project that the more complex software *RUImap®* has been implemented. Thanks to the latest optimizations, it now provides three different RUI mapping methodologies integrated in an easy-to-use tool that allows choosing the preferred approach through a user-friendly interface. Depending on:

- The main aim of the mapping (quantification of RUI phenomenon on the land, emergency RUI map, planning of fire-fight resource distribution, urban planning etc.);
- The input data availability;
- The spatial resolution at which we need to operate,

it can be chosen to map the territory using one or more of the three available methodologies and RUIs can be classified in different ways.
The scientific community has been optimizing the theoretical definitions and the operational mapping methods for about ten years through many different contextual applications. Having been considered in, implemented for and unceasingly improved upon mainly in European environments, the tool is particularly suitable and useful for European urban patterns and for classifying Rural Urban Interfaces. As already pointed out earlier, RUI and WUI are being used as synonyms in the literature but the first definition (RUI) refers to houses or settlements that can be immersed in many kinds of matrices, from agricultural to partially vegetated or to forested, while WUI explicitly refers to the direct contact of urbanized areas with wildland forested areas. The methodologies, developed in Europe, reflect the environmental condition in which they have been provided, but nevertheless, they are useful (and used) to classify the intermix areas that exist all over the world: Asia, north Africa, south Africa, Australia, Tasmania, north, central and south America. For the typical Euro-Mediterranean habitat across Sardinia, the tool seems to be particularly valid and apt and hence was chosen to map Sardinian RUIs.
The three methodologies implemented in RUImap® tool, were conceived with ***different*** theoretical paradigms which use ***different*** points of view and aim to model the phenomenon with ***different*** main purposes. Nowadays, in the latest version, the richness of approaches is still evident and the dissimilar theoretical lines result in maps that can differ very much in classifying and describing the same areas. The maps obtained using each of them are complementary and far from representing contradictory results, offer the possibility to a more cogent description and of a deeper knowledge of the RUI phenomenon in the territory.
Each methodology include in RUI (or exclude from it) different zones and defines a set of theoretical RUI typologies (we will call them RUI Types). "RUI types" are abstract model classes that are created according to different theoretical paradigm and that are used to classify all possible real RUI configurations. Usually there is no one-to-one correspondence between categories of different methodologies, and no way to convert one classification into another.

The three methodologies that the tool makes available permit mapping RUI at different scales: we can create maps with the Global Scale mapping methodology that works on regional-national-continental scales or with two Local Scale mapping methodologies that work at local-communal-county-provincial scales.

Study areas

The administration of Sardinia Island (Italy), provides many certified GIS strata within its official Sardegna Geoportale section. At the internet URL address http://www.sardegnageoportale.it/index.php?xsl=1594&s=40&v=9&c=8753&n=10 (last access 11/24th/2013) ortho-photo and many certified data layers in vector and raster formats are freely available; in particular:

- All human construction on the territory (buildings, structures, streets, industrial sites, dams, railways, etc.);
- Vegetation map, Land Use map and Land Cover map;
- Digital Terrain Elevation Models (1-5 m resolution);
- Burned areas (obtained with certified GPS surveys);
- Satellite images with resolution ranging from 1m to 5-10m, which are very useful for photo-interpretation.

The "Corpo Forestale e di Vigilanza Ambientale", the Sardinian Forest Service, kindly provided its certified database of ignition points that have been GPS recorded since 2004 and manually recorded, directly on Italian Military Maps (I.G.M. - 1:25000), until 2003 with a precision of 30-50 m.

Because of the high number of fires and the large burned areas as well as for the availability of accurate data, Sardinia has been chosen as study area to carry out the present work.

Sardinia, the second largest Island in Mediterranean Basin after Sicily, is a fire prone area which suffers a lot of wildfire damage since it experiences, almost every year, the highest number of fires and the largest burned areas among all Italian regions.
It is located in the occidental part of the Basin, between Spain and Italy and its surface area is 24,083.62 km^2.
The average elevation is 338 m a.s.l., with approximately 38% of the surface at less than 200 m a.s.l., 50% of surface between 200 and 700 m a.s.l. and just 12% of the territory above 700 m a.s.l.
Although the highest Sardinian mountains do not reach the elevation of 2000 m (Gennargentu 1,834 m a.s.l.), it can be considered a hilly-mountainous island because only about the 20% of the surface is flat while more commonly the landscape is rugged.
The climate is typically Mediterranean and has mainly two seasons, a cool and wet winter and a warm and dry summer with relatively short transition periods.
All over the island climate is mild, but especially near the coast related to the moderating action of the sea. Due to its particular placement, the island is exposed to the NW currents (Atlantic flux) as well as to the Saharan influence arriving from Northern Africa. During summer a particular synoptic configuration can generate extreme heat waves.
Moreover, during summer, the day/night breezes are constantly blowing and, during the hottest hours of the day especially close to the coastline, these local winds can also become high winds.
Summers are usually long, dry, windy and warm. Each year an average of 600 mm of precipitation falls in Sardinia but, excepting the mountains, May-September rain accumulation are usually very low (<100 mm) and sometimes almost null.
The meteo-climatic station, located in Valliciola in the northern part of the island, at 1040 m a.s.l., is a Sardinian meteorological station that usually records values of annual precipitation among the highest amounts for the isle (with a mean of 1343 mm). It also registers one of the shortest dry

period during summer. The mean annual dry period of consecutive days without rain in Valliciola is 62 days, with a summer hydric deficit of 157 mm.[xxxi]

The meteo-climatic station, located in Cagliari in the southern part of the island, very close to the sea, is one of the stations in Sardinia that usually records very low annual precipitation (with a mean of 430 mm) and one of the longest dry period during summer. The mean annual dry period of consecutive days without rain in Cagliari is 135 days, with a summer hydric deficit of 468 mm.[xxxii]

More than one third of the surface (8,625 km^2) is covered with spontaneous broadleaf forests, implanted conifer forests and high maquis. The land that is not classified as forested is normally used for agriculture or grazing. The abandonment of the countryside is increasingly causing those patches of land that are not used for agriculture, to be covered by bushes or low maquis (Erica spp., Cistus spp., Genista spp.). This low-fuel-load vegetation can provide continuity to forested patches and favour wildfire propagation. Wildfires are nowadays caused mainly by human activities (arson or negligence), but Sardinian ecosystems appear to have been modelled by fire for a long time, given the broad diffusion of cork oak (Quercus suber), cistus, and other fire adapted species.

Although it is not densely populated (68.07 pers/km^2), Sardinia is the Italian region that usually experiences the highest number of fire ignitions and often the annual largest burned surfaces.

Statistics of the Regional Forest Service (Corpo Forestale e di Vigilanza Ambientale della Regione Autonoma della Sardegna) for the period 1998-2010 show that each year approximately 2,800 fires are ignited in Sardinia with 20,000 hectares of total burnt areas.

The fire regime has high year-to-year variability, corresponding to a symmetric variability of Mediterranean meteo-climate conditions: dry-warm season length, precipitation, winds, heat waves, temperatures and humidity are highly capricious and vary considerably from year to year.

Almost all fires occur from May to October; July is usually the month with the highest number of fires and the largest burned area.

During this period Sardinia receives an important increase of tourism, mostly directed to the coasts where many structures (second houses, hotels, camping etc.) are built in WUI-intermix environment with Mediterranean maquis.

Although isolated building in the countryside can be found all over Sardinia, the RUI areas of the isle are mainly located on the coastline or near urban centres. During the recent decades a significant increase of RUI areas was recorded in Sardinia, mainly due to the construction of second houses that are inhabited, above all, during the summer holiday season. Each year new houses and hotels are built and the phenomenon is likely to continue in the future so that the sprawl of RUIs in Sardinia is predicted to be more and more significant. In these areas during summertime, fire risk is particularly high because of the co-occurrence of high fire danger conditions and tourist presence.

The surroundings of urban centres (industrial and residential areas), and the numerous isolated buildings diffused on the whole territory, constitute the RUI that are not strictly bound to the summer touristic increase of presence.

In the recent years a rising number of dangerous situations of wildfires in RUI has been reported in Sardinia, with loss of goods and threat to people's lives. Sardinia is hence a representative Mediterranean environment and it is an ideal case study for mapping RUI, for analysing *fire regime/RUI* mutual relation and for assessing wildfire risk in RUI.

We chose to use *RUImap®* for characterizing Sardinian RUI. In particular we used it in all its available configurations and we created several RUI maps in Sardinia:

- RUI map of the whole Sardinia island according to the Global Scale mapping methodology;
- The Local Scale mapping methodology – option 1 has been used at communal level for mapping the territory of Alghero, a small town in the NW of the Island, and at county/provincial level for mapping the north-east part of the island;
- The Local Scale mapping methodology – option 2 has been used at the communal level for mapping the territory of Alghero. The use of both Local Scale mapping methodologies to map the same municipal scale area allow us comparing the two Local Scale definitions of RUI, at Communal level.

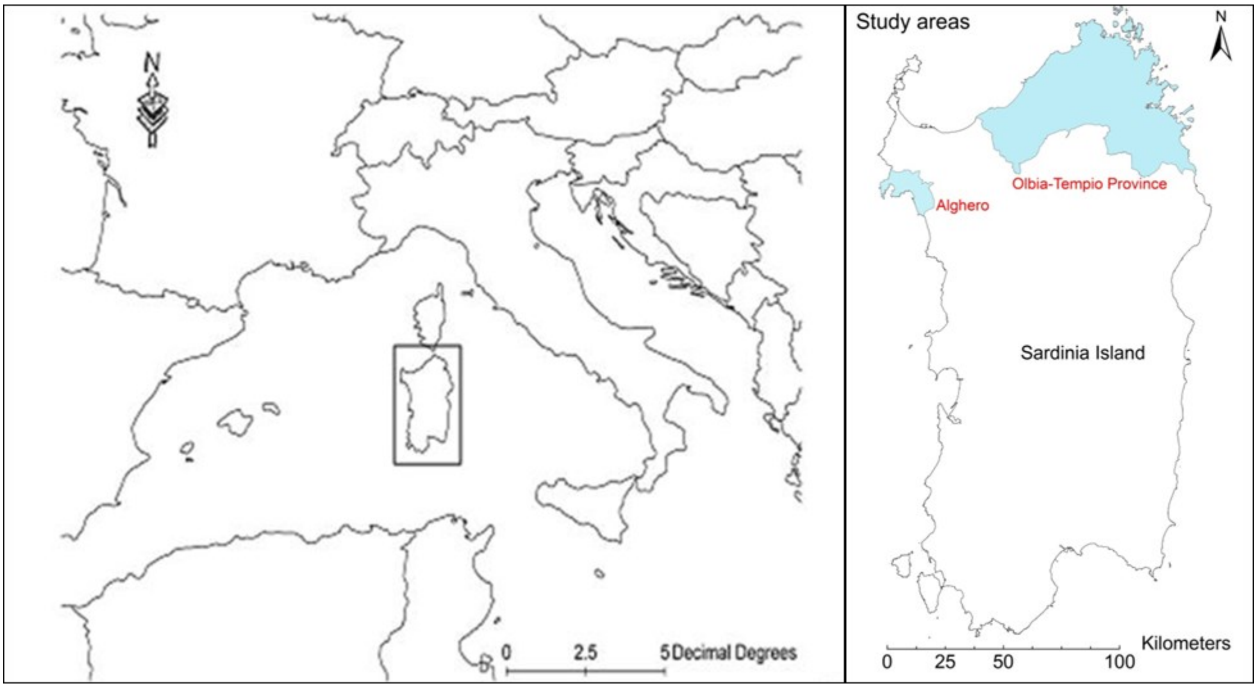

Figure 1. The Island of Sardinia in the Mediterranean Basin and, in blue, the two study areas: Alghero commune (NW) and the NE part of Sardinia roughly corresponding to the Olbia-Tempio province.

<u>The municipality of Alghero</u> (~225 km^2 and 9,500 buildings) shows a diffuse and complex urban structure, where several housing densities and urban configuration typologies are represented. The vegetation presents a broad variety ranging from mature forest stands to typical agricultural landscapes. RUI occupies large areas of Alghero territory and is representative of the coastal RUI that has been building in Sardinia since the '70s of last century. Especially during the summer period, the whole Alghero area experiences an intense tourism flux that causes a noticeable increase in total population density.

<u>The North–Eastern part of Sardinia</u>, roughly corresponding to the ex-province of Olbia-Tempio (~3200 km^2 and about 108,000 features each one corresponding to a building), is the second sub-area chosen for RUI studying in Sardinia. The north-east portion of the island encompasses all kinds of RUI from coastal to peri-urban and isolated housings in the countryside. It is widely representative of Sardinian RUI environments.

For the global option the required data are Corine Land Cover and Soil Sealing raster datasets, while for the two local options the required layers to create input data are vector housing layer and the Land Use layer.

Before running the tool, especially in local scale configurations, relatively time consuming preliminary work must be done, though the tool runs can be considered fast.
A standard personal computer with 4Gb ram, running *RUImap®*, takes:

- ~45 minutes to map the RUI of the whole Sardinia using the global methodology;
- ~30 minutes to map the municipality area of Alghero (local scale option 1);
- ~40 minutes to map the municipality area of Alghero (local scale option 2);
- ~8 hours for the north-eastern area of Sardinia (local scale option 1).

Part 2: Rural-Urban Interface Mapping

Materials and methods

Global Scale mapping

The "Global Scale mapping methodology" is a RUI mapping technique capable to analyse the territory on national/continental scales.

The usefulness of the method is evident when comparing RUI presence and importance in different regions. Used at a supra-national level, the global methodology gives the possibility to look beyond the different definitions of RUI (where they exist) that each state adopts, obtaining a general map based on common parameters. For national-regional levels it is an easy way to concretely visualize the spatial distribution of RUI, and it can be helpful for many other purposes, for instance:

- For allocating and organizing firefighting resources;
- As a basic knowledge to quantify the phenomenon;
- To identify macro-areas with the highest presence of RUI. They usually are the ones that require a more detailed mapping procedure (Local Scale options).

Table 1. Input files required by Global Scale mapping methodology

Name	Type	Resolution	Projection	Source
2006 Corine Land Cover	Raster (grid)	100 m	ETRS 1989 LAEA	European Topic Centre on Land Use and Spatial Information
2006 Soil sealing	Raster (grid)	100 m	ETRS 1989 LAEA	European Environment Agency
Study area	Polygon Shape file		ETRS 1989 LAEA	User

The theoretical basic idea of this approach, which aims to identify and locate RUI distribution on wide areas, is to study the overlay of two informative strata at adequate resolution: urban patterns and vegetation presence-structure.

Required input data are the European Corine Land Cover map (CLC) and the European Soil Sealing map (SS). In this work we used the Corine Land Cover 2006 (CLC2006) and the Soil Sealing map of the 2006 coverage. Both CLC2006 and SS2006 are raster GIS layers at 100 m resolution (each pixel measures 1 ha). They can be freely downloaded with ETRS89 - European Terrestrial Reference System 1989 (geographical system), and LAEA - Lambert Azimuthal Equal Area (map projection) from:

- http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/3acef3566070caf3a8fd3351b7ffb4a9 - (CLC2006), and
- http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/57ecd963002327759d99a3f2d1e1dfe1 - (SS2006).

The SS layer is used by the process to refine the distribution of scattered housing and urban settlements which is already contained in CLC informative stratum.

The global methodology has been implemented in Python computing language and is available in the user-friendly interface of *RUImap®* tool. The Python code works by calling the functions already available in Esri ArcGis, and through their use it manipulates the input files and creates as output the RUI map. For this reason, Esri ArcGis 9.3 (or a more recent version) is required to run *RUImap®* tool in Global Scale mapping methodology configuration.

The methodology defines nine WUI theoretical typologies for classifying the real interface situations. They result by crossing three categories of housing with three categories of vegetation. The different types of housing at growing density are **Isolated Housing**, **Scattered Housing**, **Dense Clustered Housing**, while the three different types of vegetation are **Mineral Area** (no land cover), **Agricultural or Sparse Vegetated Area** and **Forested Area**.

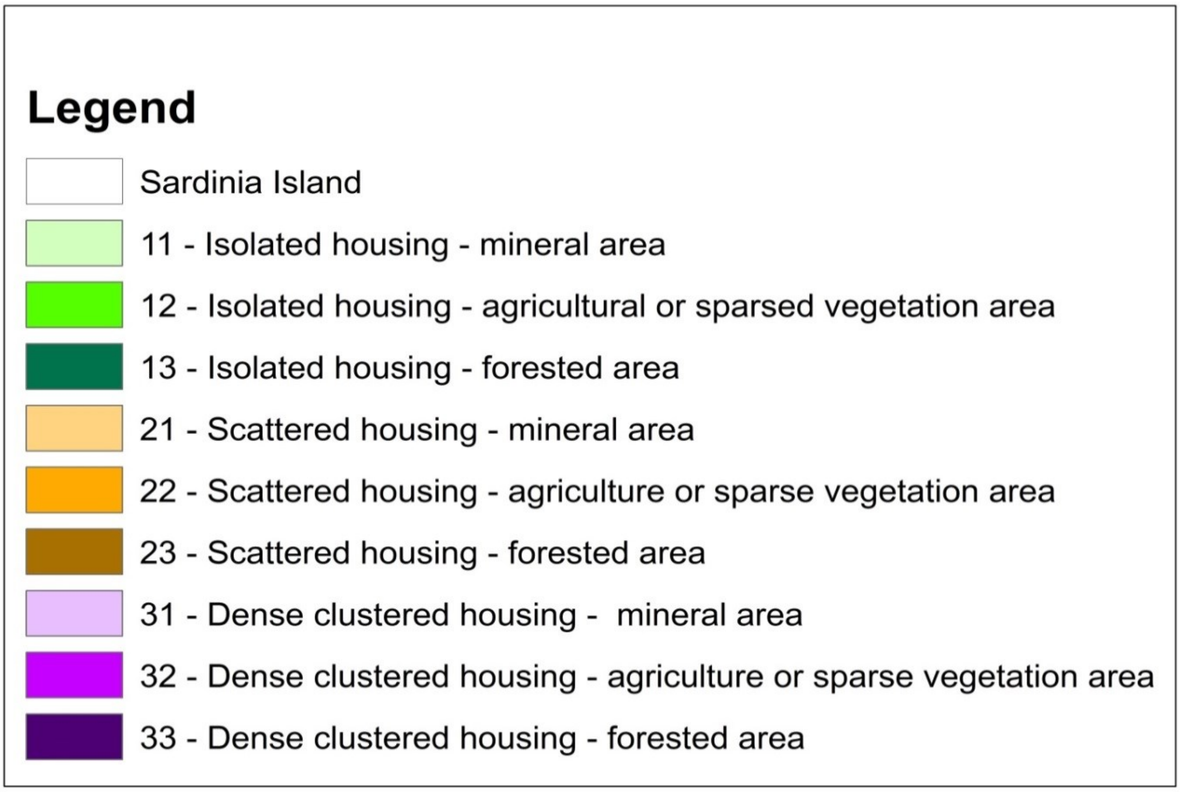

Figure 2. Set of theoretical RUI typologies of Global Scale RUI mapping methodology.

Each category has a two-digit code in which the first digit represents the housing type and the second digit represents the vegetation type.

Table 2. description of theoretical RUI typologies of Global Scale RUI mapping methodology

	Vegetation		
Housing	1 – Mineral	2 – Agricultural or Sparse Vegetated	3 – Forested
1 – Isolated	11	12	13
2 – Dispersed	21	22	23
3 – Dense Clustered	31	32	33

RUI type
11 – Isolated Housing in Mineral area
12 – Isolated Housing in Agricultural or Sparse Vegetated area
13 – Isolated Housing in Forested area
21 – Dispersed Housing in Mineral area
22 – Dispersed Housing in Agricultural or Sparse Vegetated area
23 – Dispersed Housing in Forested area
31 – Dense Clustered Housing in Mineral area
32 – Dense Clustered Housing in Agricultural or Sparse Vegetated area
33 – Dense Clustered Housing in Forested area

This theoretical set of RUI typologies was prearranged aiming to distinguish interfaces into classes characterized on one side by different presence of **fuels** and on the other by diverse density of **values** eventually exposed to the risk of wildfire. In this sense, we can affirm that the organization given to the set of theoretical categories was conceived considering these parameters that are maximally useful for assessing wildfire risk.

The definition adopted in the Global Scale mapping methodology, considers that RUI is *the area within a 400 m radius around those houses that are located at less than 200 m from forested or shrubland surfaces*.

The 200 m distance was chosen to select those areas that are inside or very close to forested areas, while the 400 m distance from houses was chosen because many national laws establish a similar radius to identify the surfaces where homeowners can be compelled to undertake an annual Brush-Clearing. Although spot fire can ignite also at bigger distances, 400 m was also estimated to be a safety threshold for a possible ignition of houses by spot fires. With respect to the objectives of the analysis, the buffer size can be adjusted operating in the software program.

Starting from this operational definition, the mapping process of the Global Scale method is implemented into the following three main logic steps:

1. Identification of forested areas and creation of a buffer of 2 pixels (200 m);
2. Analysis into the area selected at point 1, of house presence through the combination of information contained in CLC and SS;
3. Selection of all the pixels located inside the area selected at point 1 and simultaneously containing housing according to point 2, and creation of a 4 pixel (400 m) buffer around them.

The final Global Rural-Urban Interface map is realized using the combination of the following two informative strata that we obtained through a series of operations done on the inputs by the ArcGis functions called by the python code:

- the general land cover characterization (mineral area, agricultural and sparse vegetated area, forested area) resulting from the simplification of the Corine Land Cover database;
- the housing characterization (isolated housing, scattered housing, dense cluster housing) resulting from the combination of urban fabric classes of the CLC database and the SS database.

The first layer is the reclassification of CLC into three classes describing vegetation:

- bare soil, urban contexts, water, rocks, beaches and sand are classified as “Mineral area”;
- forests, maquis, Shrubland is classified as “Forested area”;
- the rest of the territory that is used for cultivations, grazing, or is not continuously vegetated is classified as “Agricultural or Sparse Vegetated area”.

The second layer, the housing characterization, is not the result of a simple reclassification but is created through a more complex series of operations made on CLC and SS. It provides three housing classes:

- Isolated Housing;
- Dispersed Housing;
- Dense Clustered Housing.

The real mapping process is more complex and works in many sequential single steps that are illustrated in Appendix A.

Local Scale mapping – Option 1

The *RUImap®* tool provides two methodologies for WUI mapping on a scale that we will call "local" which roughly corresponds to communal/provincial scale. One of them has been ideated by Irstea (France), the other one by TRAGSATEC (Spain). Both of them were improved in the framework of FUME Project (7th FP founded by EU). They have been optimized through the use and in particular they have been tested by University of Sassari in Sardinia.

The approach developed by IRSTEA (France) is an improvement of a previous version implemented in the framework of FIREPARADOX project (6th FP – European Commission), (Lampin et al., 2006a)[xxxiii], (Lampin et al., 2006b)[xxxiv], (Lampin et al., 2010)[xxxv].

What we call the Local Scale mapping methodology – option 1, is the IRSTEA approach which works at a much higher resolution than the Global one, but, at the same time, requires more detailed input file describing vegetation and houses (vector format in which each house is represented by a single polygon).

The Corine Land Cover that is a raster dataset of 100X100m resolution cannot be useful for the purpose. To map the territory at local scale, we need more detailed description of vegetation presence, continuity in space and distribution.

The basic philosophy of the methodology is that vegetation presence and continuity is the first necessary condition for a wildfire to spread. Focus, hence, ought to be on those areas where fuel has a strong presence. Actually, only houses located in those contexts can be run over by wildfires and can be damaged. It is, therefore on these areas that the methodology studies house presence, density, and mutual distances to identify the housing type and the perimeter of RUI area for finally classifying RUI into types. For this methodology the distance of houses from the village/settlement is not important; it does not consider, as a relevant factor, if houses are or not in peri-urban belt. Its first focus is on vegetation (fuel) and then, it just analyses housing patterns and distribution in areas inside or close to forested areas.

In this method, vegetation is characterized through the use of the Vegetation Aggregation Index (AI) a descriptor created by Landscape Ecology. The necessary condition for fires to propagate is the spatial connection of vegetated patches on the landscape and the AI has been found to be the most useful means accounting for presence and connection of vegetation (Lampin, PhD thesis, 2009)[xxxvi].

The number of RUI types, that this method uses to classify the territory, is 12. They are derived by crossing 3 AI levels (0, Low, High), with 4 housing configuration classes (Isolated, Scattered, Dense, Very Dense).

The operational definition of the methodology considers RUI: *the area within a radius of 100 meters around each house located at a distance of less than 200 metres from forests or shrub-lands*.

Historically this definition has been chosen because of the French Forest Orientation Law (9th of July 2002), which makes Brush-Clearing obligatory for all owners of houses located at less than 200 m from forested areas. The maximum distance that they can be compelled to clean from underbrush and groundcover is 100 m.

Input data must be carefully prepared because the tool cannot bring the classification to completion if geometry and topology of the vector layers reports errors (open polygons, null geometries etc.). The required inputs are:

1. Study Area, (vector polygon shape file);
2. Building Layer (vector polygon shape file);

3. Brush-Clearing Zone (vector polygon shape file);
4. Vegetation Aggregation Index Map (raster Tiff file).

Study Area is a polygon shape file defined by user; the **Building Layer** is directly usable after having corrected it. The **Brush-Clearing Zone** is a polygon obtained through the creation of a buffer of 200 m radius around highly vegetated areas (forests, maquis etc.). It represents our area of interest, where wildfire can propagate with high intensity and possibly affect houses.

The Vegetation Aggregation Index Map must be calculated in advance, through the use of the specific software *Fragstat©* (McGarigal et al., 1994)[xxxvii]. The land cover description must come from a detailed survey, because the usefulness of AI decreases with the size of pixels. A pixel of 20 m can be considered as the ceiling value (see analysis of sensibility in Lampin PhD thesis, 2009[xxxviii]). *Fragstat©* input are calculated starting from the vegetation informative stratum and its output is converted into a raster (.tif) whose values of AI range from 0 to 100. Each pixel value reports the local AI relative to its surrounding area (we shall call it "window"). The width of the window can be chosen by the user but, usually, its radius varies between 2 and 5 pixels. *Fragstat©* analyses the window built around a pixel and accounts for the connections between vegetated pixel belonging to the window; then, it calculates the AI and assigns the value to the central pixel of the window before moving to the next pixel. Higher values mean higher contiguity of vegetated pixels and higher vegetation connectivity.

Once all the input files are created, the tool can be run.

It works on two steps, a first one in which the housing is classified in four types, Isolated Housing, Scattered Housing, Dense Housing, Very Dense Housing; and a second one in which the AI layer is reclassified into 3 classes (0, Low, High) and then crossed with the housing layer to result in the 12 RUI types classification.

The technical details of the methodology are reported in the appendix B.

Local Scale mapping – Option 2

In *RUImap®* a third option to map RUI developed by TRAGSATEC (Spain) is available. It is a second Local Scale mapping methodology whose bases are different from option 1 approach since its main emphasis is not on forested areas but on values at risk and its main objective is to protect population and their belongings against wildfires. To better fulfil its value-protective purposes, the Local Scale RUI mapping methodology – option 2 focuses on the urban structures as goods to be protected and as indicators of people presence emphasising more on houses than on vegetation. Its logic is to first recognize how the houses are distributed in the land, creating a layer of settlement type that aggregate houses and then to study the border of each settlement to see in which environment they are located (forested, agricultural, urban etc.). The location, the type of settlement, its connection with vegetation on its border, are factors that are thought to have big influence on fire propagation and on risk and, moreover, they are seen as key factors for fast, coordinate and efficient evaluation and intervention for possible emergencies. The different categories of RUI are recognized and mapped through two steps in which, first, houses are encompassed into polygon of settlement type and then, a RUI category is assigned to each settlement polygon according to its surroundings.
The categories to classify RUI were created according to a theoretical approach whose main aim was to be able to recognize different kinds of urban-vegetation configurations and, hence, to be capable of developing a set of tailored intervention strategies in case of wildfire for each category. The RUI types into which RUI are classified by this methodology are 7:

Table 3. RUI typologies of Local Scale mapping methodology – Option 1

Urban Settlement
Settlement in Forested Area
Settlement in Agricultural Area
Dispersed Buildings in Forested Area
Dispersed Buildings in Agricultural Area
Isolated Buildings in Forested Area
Isolated Buildings in Agricultural Area

Actually, each one of them is characterized by different house density and different surrounding environment. The categories are thought to involve different problems to cope with, in case of wildfire.

Three vector layers are required as input data:

- The study area (polygon shape file containing one or more features);
- The Land use map (polygon shape file);
- The buildings map (polygon shape file with one feature per building).

Besides the correction of topological and geometrical errors in the shape files, an input data preparation is required. Before running the RUImap®, it is necessary to:

- Reclassify the Land use map into 5 categories: “Urban”, “Forest and Shrubs”, “Water”, “Agricultural”, “Unproductive”, and a string field must be added to the land use dbf file reporting exactly the string of the five categories name;

- Add a field to the house layer dbf file in which, for every feature corresponding to a house, the string “urb” must be written.

In order to be sufficiently flexible to be used in different environments and with different kinds of land use maps, the methodology does not define how to reclassify and combine the land use categories into the final 5 categories that are needed to run the tool. Criteria to aggregate the Land Use classes are defined by the user.

The methodology works into two steps. In the first mapping step (Settlement Map Calculation),

1. the study area,
2. the reclassified Land Use map
3. the modified House Layer

are the required inputs.
The output of this step is the Settlement map, a vector layer, where all houses are included in polygons coded in different classes representing the type of housing: Settlement, Dispersed Buildings, and Isolated Buildings.
In the next step, the reclassified Land Use map and the Settlement map layer created by the first step are used to generate the RUI map. Firstly, a 1 m buffer is drawn around the polygon of housing to identify the context where each urban feature is located; with this buffer we can see if it is located in forested area, agricultural area or urban area. Then a second buffer, whose wideness depends on the type, is created around the settlement polygons according to the following schema:

Table 4. Sizes of buffers per each RUI typology of Local Scale mapping methodology – Option 2

SETTLEMENT TYPE & SURROUNDING ENVIRONMENT	Buffer size [m]
Urban Settlement	400
Settlement in Forested Area	300
Settlement in Agricultural Area	200
Dispersed buildings in Forested Area	300
Dispersed buildings in Agricultural Area	100
Isolated buildings in Forested Area	200
Isolated buildings in Agricultural Area	100

The surface included in the last buffer is the RUI as defined by Local Scale mapping methodology – Option 2. In accordance with its basic philosophy, the methodology differentiates the buffers between urban types because each of them is considered characterized by a different fuel charge and continuity and above all by a different density of people, goods, properties and belongings so that the risk is higher for Settlements than for Isolated Buildings. Moreover, urban unities inserted in a forested context are more difficult to be defended while, for the ones located in agricultural areas wildfire intensity is lower-grade and they are easier to protect.

The methodology does not include into RUI those houses located at more than 400 m from forested areas. This is the default distance used by the tool and it refers to the Spanish Forest Law, but it can be modified in the settings of the tool according to the laws of each country.

Part 2: Rural-Urban Interface Mapping

Results

Global Scale mapping

A – Mapping

The input data for global methodology are:

Table 5. Input files required by Global Scale mapping methodology

Name	Type	Resolution	Datum	Source
2006 Corine Land Cover	Raster (grid)	100 m	ETRS 1989 LAEA	European Topic Centre on Land Use and Spatial Information
2006 Soil sealing	Raster (grid)	100 m	ETRS 1989 LAEA	European Environment Agency
Study area	Polygon Shape file		ETRS 1989 LAEA	User

We created a single polygon for the entire Sardinia Isle as study area, and we got the required raster dataset from the respective internet site:

- the Corine Land Cover raster dataset was obtained at the internet site http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/3acef3566070caf3a8fd3351b7ffb4a9 (or http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1)
- and the Soil Sealing raster dataset is available at the internet site http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/57ecd963002327759d99a3f2d1e1dfe1 (or http://www.eea.europa.eu/data-and-maps/data/eea-fast-track-service-precursor-on-land-monitoring-degree-of-soil-sealing-100m-1)

Then, we run the tool in configuration Global Scale obtaining the map of Sardinian RUI according to the chosen method. Like the inputs, the output is also a raster dataset whose resolution is 100X100m.

RUI are categorized according to the nine theoretical typologies ranging from bare soil to forest on one side and on the other from isolated housing to dense clustered housing.

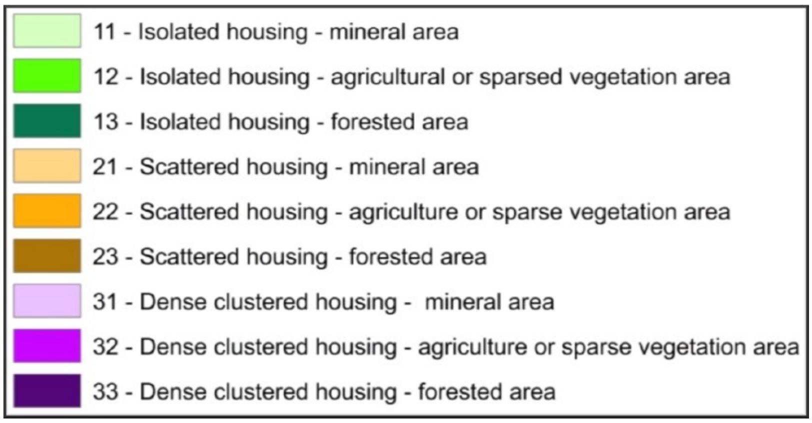

Figure 3. Set of theoretical RUI typologies of Global Scale RUI mapping methodology.

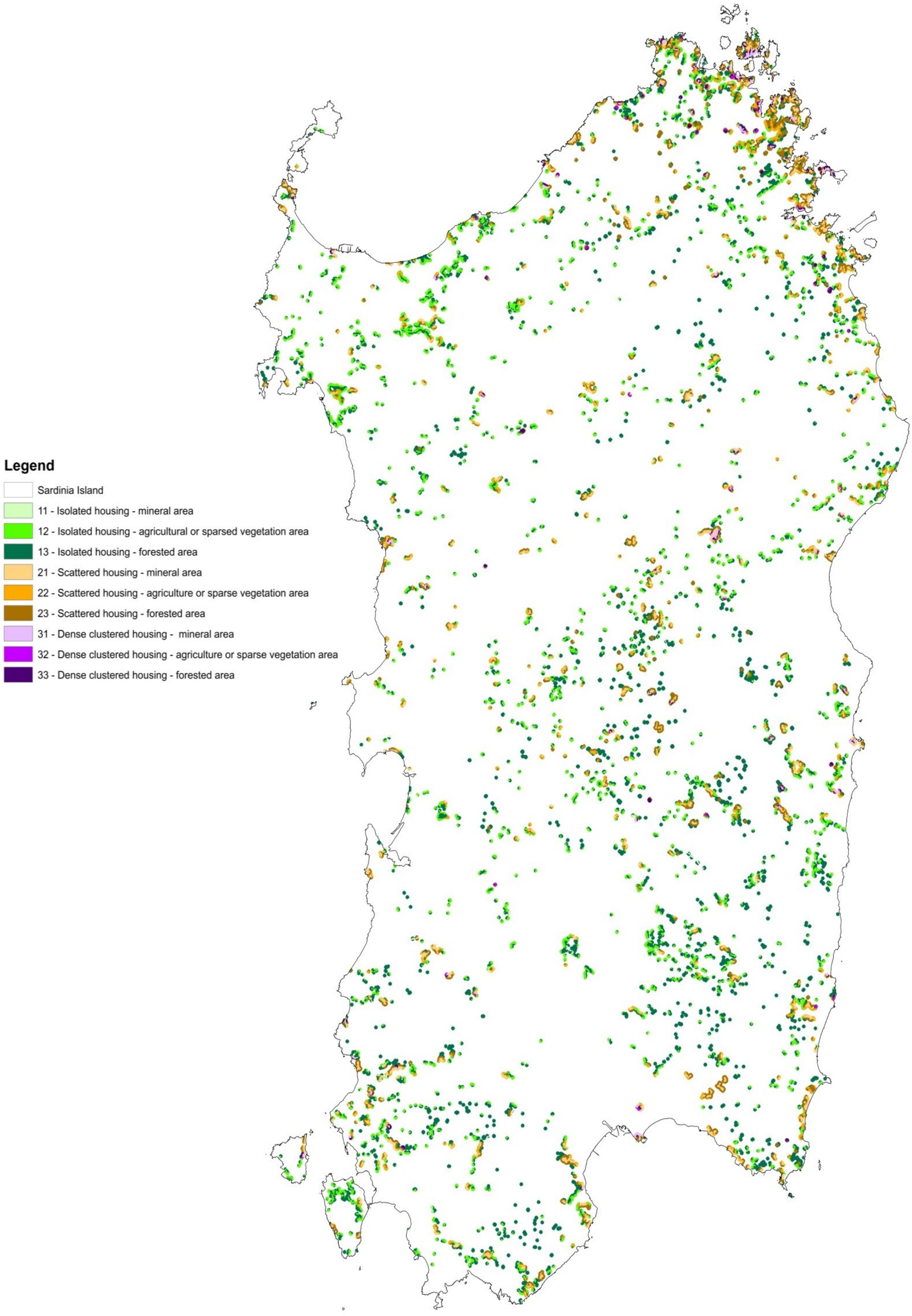

Figure 4. Sardinian RUI calculated according to the Global Scale RUI mapping methodology.

The map drown by the global methodology is very useful to locate immediately the presence and types of RUI. The legend we chose allows seeing the distribution of RUI easily. Paying attention to the colour prevalence we can directly see the predominant kind of RUI: greens indicate isolated housing, browns indicate scattered housing and violets indicate dense clustered housing.

We can see the diffusion of RUI all over the territory but it is also evident:

- The prevalence of Isolated-scattered housing in the countryside;
- A significant presence of scattered and dense RUI on the coastline, in particular on the North-east and South-east coasts where the housing is mainly due to touristic dwelling expansion.

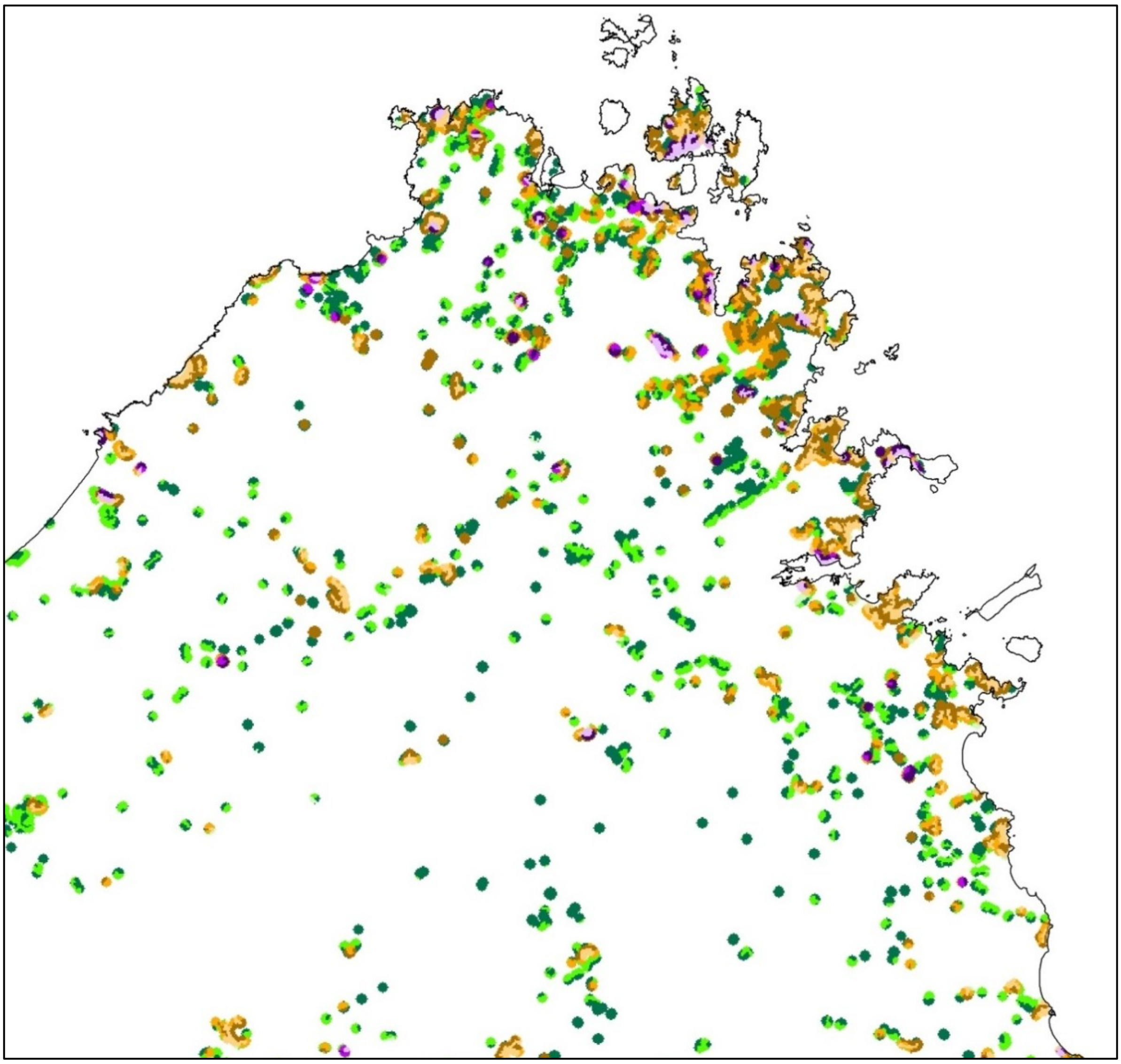

Figure 5. RUI calculated according to the Global Scale RUI mapping methodology; detail of the NE part of the Isle.

Some areas do not show any presence of RUI and it can be due to the lack of vegetation or to the lack of housing. In particular in figure 6:

1. in red we put on evidence those areas that are not covered by forest like the agricultural plans (Campidano) and the urban areas of the main towns Sassari, Cagliari, Olbia;
2. in blue we put on evidence the highly natural areas in which human presence is very low and there are no houses (Supramontes, Gennargentu).

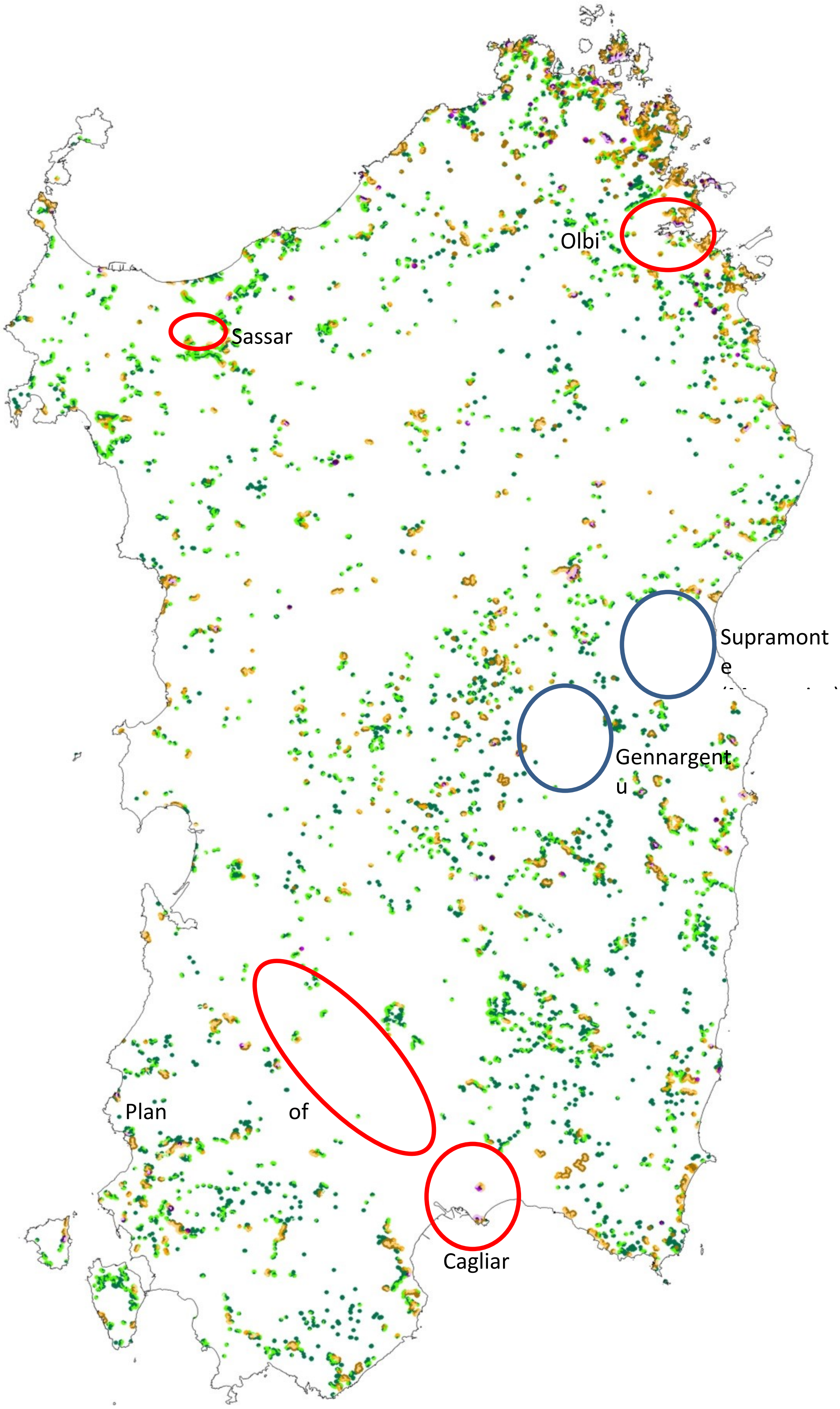

Figure 6. Sardinian RUI calculated according to the Global Scale mapping methodology; in red the areas without RUI because of the lack of forested vegetation (the agricultural plan and major urban centers); in bleu the areas without RUI because of the lack of houses (high natural contexts of Gennargentu and Supramontes)

We also extracted aggregated data from the maps.

Table 6. Aggregated data of Sardinian RUI calculated according to Global Scale mapping methodology. Area occupied by each category and per-cent of territory.

RUI categories		Surface		% of all RUI
Housing	**Soil cover typology**	**km^2**	**%**	
Isolated	Mineral	28.37	0.12	1.26
Isolated	agricultural or scattered vegetated	601.47	2.50	26.92
Isolated	Forested	848.08	3.52	37.91
Scattered	Mineral	176.69	0.73	7.86
Scattered	agricultural or scattered vegetated	192.71	0.80	8.62
Scattered	Forested	313.27	1.30	14.01
Dense clustered	Mineral	30.33	0.13	1.39
Dense clustered	agricultural or scattered vegetated	14.49	0.06	0.63
Dense clustered	Forested	30.60	0.13	1.40
RUI areas		2236.01	9.28	100.00
non RUI areas		21847.61	90.72	
Sardinia		**24083.62**	**100.00**	

Referring to table 6 and 7 we can see that RUI represents the 9.3% of the whole surface. Isolated housing are the widest RUI categories (6.1% of land = 66.1% of all RUI), followed by RUI of Scattered housing (2.8% of land = 30.5% of all RUI), while the Dense Clustered housing RUI types occupy just 0.3% of the surface (3.4% of all RUI).

This distribution can be partially interpreted as a consequence of defining RUI as the 400 m buffer area surrounding pixels with houses. While isolated houses have their own buffer, when housing density increases the various buffers start to overlay more and more reducing the relative RUI wideness.

With respect to the land cover typologies, the RUI located in forested areas represents 4.9% of the territory (= 53.3% of the RUI surface) while 3.4% of the territory (= 36.2% of all RUI surface) is

Table 7. Surfaces of Sardinian RUI calculated according to Global Scale mapping methodology. Percentage of RUI area occupied by each category on the whole RUI area

SARDINIA RUI Type area/tot RUI area [%]		Housing Types		
		Isolated	Scattered	Dense Clustered
Land Cover Types	Mineral	1.26	7.86	1.39
	Agriculture or Sparse Vegetation	26.92	8.62	0.63
	Forested	37.91	14.01	1.40

RUI Type area/tot RUI area [%] per aggregated Housing Types and aggregated Land Cover Types

HOUSING TYPE		LAND COVER TYPE	
Isolated	66.1	Mineral	10.5
Scattered	30.5	Agriculture or Sparse Vegetation	36.2
Dense Clustered	3.4	Forested	53.3

occupied by RUI located in agricultural or scattered vegetated areas. Only 1% of the territory is covered by RUI located in bare soil contexts (10.5% of all RUI).

This distribution can be explained through two main factors:

1. the relatively large diffusion of forested area in Sardinia (36% of the territory);
2. it can be considered a direct consequence of the operational definition of RUI implemented in the global methodology which categorizes as RUI the areas surrounding buildings which are located in forested area or within a 200 m distance from forested areas.

If, for instance, implementing the methodology it was chosen to create a buffer of 200 m around those houses located in forested areas or at less than 400 m from forested areas, the resulting map would be different because of an increase of RUI located in non-forested areas and also of the reduction of the overlapping effect on scattered/dense housing RUI.

B – Studying the relation RUI-fire regime.

The Sardinian map of RUI according to the global methodology has been useful to study the relation between RUI and fire regime. The fire regime descriptors that have been used are: the ignition points and the burned areas. The Sardinian Forest Service (Corpo Forestale e di Vigilanza Ambientale) has been recording since 2005 both of them using GPS technology. Before 2005 the ignition points were recorded directly on Italian official maps (I.G.M. - Istituto Geografico Militare, scale 1:25,000) with a precision of, at least, 100 m (usually 30-50 m). The perimeter of the most important fires before 2005 was drawn directly on the IGM maps to record the burned areas but the precision was very low. We chose not to consider the survey of burned areas dating before 2005, and finally the utilized databases are:

1. the GPS georeferenced ignition point (database 2005-2010), and 30-50 m precision georeferenced ignition point for the years 1998-2004;
1. the GPS georeferenced perimeters of burned areas (database 2005-2011).

Table 8. Ignition points recorded from 1998 to 2010 in Sardinia: distribution inside/outside RUI and in each RUI category of number of ignitions, percentage on the total number and ignition density

RUI category		Ignitions		
Housing	**Vegetation type**	**Ignitions**	**% of Ignitions**	**Ignitions/km²**
Isolated	Mineral	92	0.3	3.24
Isolated	Agricultural or Scattered Vegetated	1641	4.5	2.73
Isolated	Forested	1113	3.0	1.31
Scattered	Mineral	824	2.2	4.66
Scattered	Agricultural or Scattered Vegetated	925	2.5	4.80
Scattered	Forested	941	2.6	3.00
Dense clustered	Mineral	92	0.3	3.03
Dense clustered	Agricultural or Scattered Vegetated	48	0.1	3.31
Dense clustered	Forested	106	0.3	3.46
RUI areas		5782	15.7	2.59
non RUI areas		30965	84.3	1.42
Sardinia		**36747**	**100.0**	**1.53**

In the period 1998-2010, 36747 ignitions were recorded in Sardinia (on average 2,827 per year). Analysing their distribution in Sardinia we found (ref. to table 8) that the majority were recorded elsewhere than in the RUI (84.3%) but accounting for the entity of RUI surface we have that the ignition density is higher in RUI than outside. A clear difference between RUI/non RUI areas can be observed, since we recorded an ignition density in RUI that is almost the double than outside RUI (2.59 and 1.42 ignitions/km^2, respectively).

The maximum density of ignition in RUI are presented by **Scattered Housing in Mineral Area** and **Scattered Housing in Agricultural or Sparse Vegetated Area** whose values (respectively 4.66 and 4.80 ignitions/km^2) are more than three time the Sardinian average (1.53 ignitions/km^2).
The minimum value is shown by **Isolated Housing in Forested Area**, 1.31 ignitions/km^2, and can be considered peculiar since:

1. It is lower than the Sardinian average 1.53 ignitions/km^2 (only this RUI type has an ignition density lower than the average);
2. It is about the half of RUI average 2.59 ignitions/km^2;
3. It is less than the half of the value of Isolated Housing in Agricultural of Sparse Vegetated Areas which is the RUI type presenting the second lowest value (2.73 ignition/km^2).

Aggregating data for housing type, we can see in table 9 that the lowest density of ignition is in Isolated Housing (1.93 ignition/km^2) and the highest is recorded in Scattered Housing (3.94 ignition/km^2). We can also notice that while for Isolated Housing and Scattered Housing located in Forested Areas the ignition density is lower than for the same kind of housing located in less vegetated contexts, among the Dense Clustered Housing, the highest ignition density is recorded in Forested Areas.
Aggregating data for land cover type, we can see that the lowest ignition density is recorded in Forested Areas (1.81 ignition/km^2) and the highest in Mineral Areas (4.28 ignition/km^2). We can also notice that the housing type with the highest ignition density in Mineral Areas and Agricultural or Sparse Vegetated Areas is Scattered Housing, while for the Forested Areas the ignition density raises with the housing density.

Table 9. Ignition densities in Sardinian RUI calculated according to Global Scale mapping methodology

	Density of Ignition [ignitions/km^2]	Housing Types		
		Isolated	Scattered	Dense Clustered
Land Cover Types	Mineral	3.24	4.66	3.03
	Agriculture or Sparse Vegetation	2.73	4.80	3.31
	Forested	1.31	3.00	3.46

Ignition Density per aggregated Housing Type of RUI and aggregated Land Cover Type of RUI

HOUSING TYPE		LAND COVER TYPE	
Isolated	1.93	Mineral	4.28
Scattered	3.94	Agriculture or Sparse Vegetation	3.23
Dense Clustered	3.26	Forested	1.81

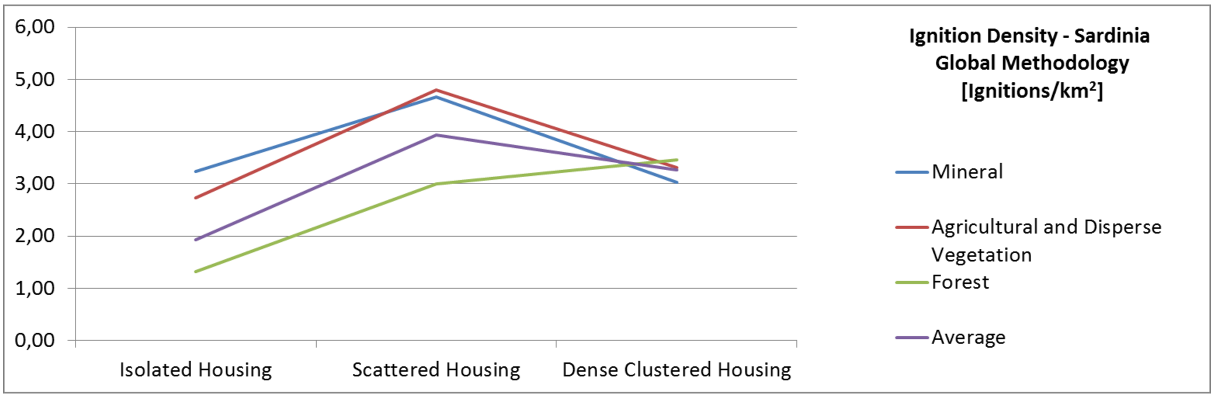

Figure 7. Ignition density varying with housing density in Sardinian RUI calculated with the Global Scale mapping methodology.

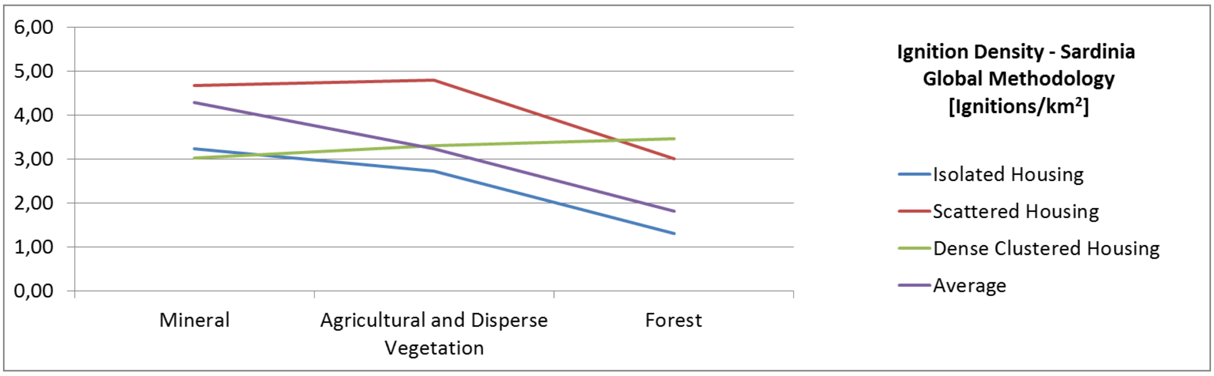

Figure 8. Ignition density varying with vegetation type in Sardinian RUI calculated with the Global Scale mapping methodology

The presence of RUI seems to have a strong influence on the ignition point distribution. If on one side we put on evidence that the ignition density in RUI is almost the double than outside RUI, we also noticed differences among RUI types. Some particular situations can be pointed out:

1. Isolated Housing in Forested Areas presents a very low ignition density;
2. In Dense Clustered Housing types the ignition density grows with the fuel load (the highest is recorded in Forested Areas and the lowest in Mineral Area), while for the other housing types the forested areas present the lowest density of ignition;
3. In Forested Areas the ignition density grows with the Housing density while for the other land cover types the maximum is recorded in Scattered Housing.

Regarding burned areas, data in table 10 show that in the period 2005-2011, a surface of 1322.94 km^2 was burned in Sardinia (an average of 18,899 ha per year).

Since the RUI area is much smaller than the non-RUI area, as expected, we found that the majority of burned areas were recorded in not-RUI areas (1235.03 km^2 meaning the 93.35%) and just 87.91 km^2 (= 6.65%) in RUI. Further, taking into account the relative surfaces we can see that RUI areas burned less than non-RUI areas: the 3.93% of RUI surface vs the 5.65% of not-RUI surface was burned. Although the ignition density is higher in RUI, it is less likely to burn than not-RUI areas.

Table 10. Burned areas in Sardinia recorded from 2005 to 2011: distribution of burned area inside/outside RUI and in each RUI category

RUI category Housing	Vegetation type	Area [km²]	Burned Area [km²]	% of Area
Isolated	Mineral	28.37	0.57	2.01
Isolated	Agricultural or Scattered Vegetated	601.47	27.28	4.54
Isolated	Forested	848.08	32.83	3.87
Scattered	Mineral	176.69	2.28	1.29
Scattered	Agricultural or Scattered Vegetated	192.71	10.18	5.28
Scattered	Forested	313.27	13.11	4.18
Dense clustered	Mineral	30.33	0.11	0.36
Dense clustered	Agricultural or Scattered Vegetated	14.49	0.33	2.27
Dense clustered	Forested	30.60	1.22	3.97
RUI areas		2236.01	87.91	3.93
non-RUI areas		21847.61	1235.03	5.65
Sardinia		24083.62	1322.94	5.49

Also the maximum percentage of burned area in RUI, which is presented by **Scattered Housing in Agricultural or Sparse Vegetated Area** (5.28%), is anyway less than the Sardinian average (5.49%). In Sardinia in this 7 years none of the RUI types burned as much as the rest of the territory.

The minimum value is shown by **Dense Clustered Housing in Mineral Area** whose value, 0.36%, is particularly low:

1. it is about 15 time lower than the Sardinian average (5.49%),
2. it is about 11 time less than RUI average (3.93%),
3. it is less than one third of the value of Scattered Housing in Mineral Areas which is the RUI type presenting the second lowest value (1.29%).

This difference can be interpreted as the consequence of the lack of fuel and, being densely populated, of the quick response of firefight and residents to protect goods exposed to wildfire risk.

Table 11. Burned areas in Sardinia recorded from 2005 to 2011: distribution of burned area in each RUI category, and in types of RUI aggregated per housing type and per vegetation type

% of area in RUI types which was burned		Housing Types: Isolated	Scattered	Dense Clustered
Land Cover Types	Mineral	2.01	1.29	0.36
	Agriculture or Sparse Vegetation	4.54	5.28	2.27
	Forested	3.87	4.18	3.97

% of area that was burned per aggregated Housing Type of RUI and aggregated Land Cover Type of RUI

HOUSING TYPE		LAND COVER TYPE	
Isolated	4.11	Mineral	1.26
Scattered	3.75	Agriculture or Sparse Vegetation	4.67
Dense Clustered	2.19	Forested	3.96

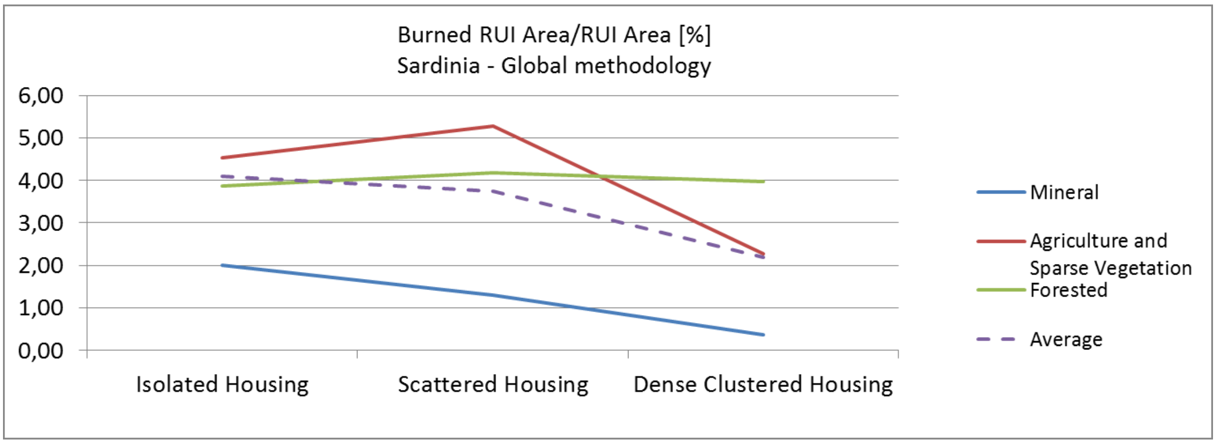

Figure 9. Burned area in Sardinian RUI calculated according to Global Scale mapping methodology: variation with housing density.

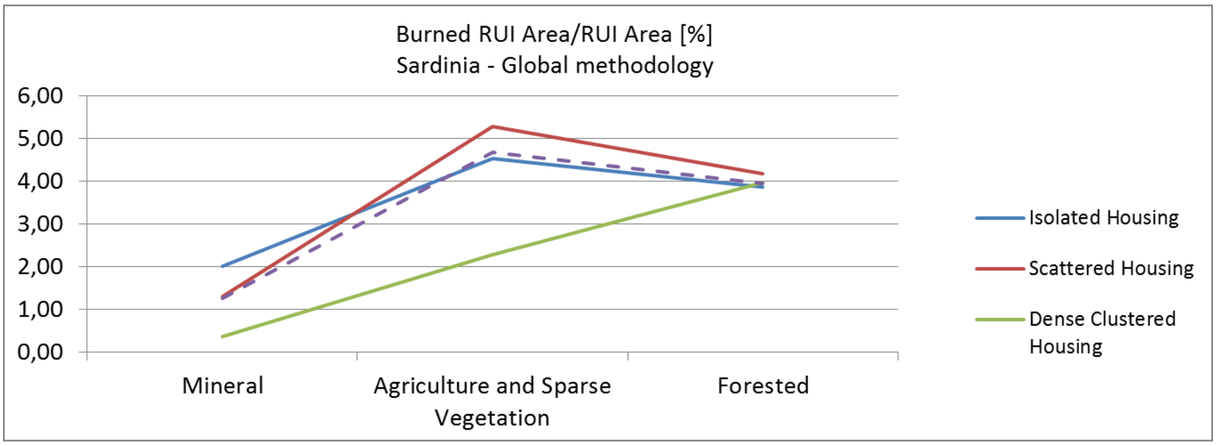

Figure 10. Burned area in Sardinian RUI calculated according to Global Scale mapping methodology: variation with vegetation type

Aggregating data for housing type, we can see that the lowest per cent of burned areas is recorded in Dense Clustered Housing (2.19%) and the highest is recorded in Isolated Housing (4.11%). Also in this case the quick response of residents and firefighters can be a determinant factor for explaining this difference. All categories presents low values in low fuel charge contexts (Mineral Areas) because of the difficulty of fire in finding continuous fuels but we can also notice that while for Isolated Housing and Scattered Housing, the Agricultural and sparsely vegetated areas record the highest percentages of burned areas, for Dense Clustered Housing the percentage grows with fuel load and reaches the maximum in Forested Areas.

Aggregating data for land cover type, we can see that the lowest percentage of burned area is recorded in Mineral Areas (1.26%) and the highest in Agricultural or Sparse Vegetated Areas (4.67%). While the Agricultural or Sparse Vegetated Areas presents a percentage similar to Forested area, the difference between this two categories and Mineral areas is more important. It can be interpreted as a consequence of fuel load and continuity in the different environments.

We can also notice that the housing type is not so influent on percentages of burned areas for RUI located in Forested Areas where the intensity of fire is higher while it is a very important variable for the other two categories where the increasing density of houses looks to be related to discontinuity of fuels which reduces wildfire possibility to propagate.

The presence of RUI shows to have a strong influence on burning patterns and fire propagation probably due mainly to fragmentation of fuels and quick interventions against wildfires.
Summarising the results, wildfires look to be favoured in their propagation outside RUI. All RUI types present percentage of burned areas inferior to Sardinia average. Some particular situations have been recorded:

1. Mineral Areas does not provide sufficient continuity to fuels and show low percentages of burned areas;
2. Forested Areas present high percentages that are not much influenced by housing types;
3. Dense Clustered Housing presents the lowest percentages: it is probably due 1) to higher fragmentation of fuels by houses and gardens; 2) to quick intervention of residents; 3) to emergency plans and tools (water supply net in touristic villages etc.); 4) to intense response of firefighters that especially in this environments concentrate forces and use aircraft for massive water supply. Anyway these effects become less important in Forested environment where fuels are more continuous and wildfires behaviour is usually more intense and resistant to direct attack with water.

Local Scale mapping – Option 1

A – Mapping

In order to generate the input data required for running *RUImap®* tool in configuration local methodology option 1 a Land Use map and a Building map have been downloaded from the official site of Regione Autonoma della Sardegna which provides georeferenced certified layer at the URL http://www.sardegnageoportale.it/index.php?xsl=1594&s=40&v=9&c=8753&n=10
They were checked to find topological and geometric errors (disconnected features, null geometries etc.) and corrected through transformation into coverage format and the use of coverage functions and tools of Esri ArcGis 9.3. Successively, strata were used to create the input files required by the mapping tool.
We created a single polygon .shp file for each of our study areas:

- Commune of Alghero in the NW part of the island;
- North East part of the island roughly corresponding to the ex Olbia-Tempio Province.

We extracted from both downloaded layers the parts of the territory corresponding to our chosen study areas, and then we dissolved the Land Use map into two categories Forested and not-Forested. The dissolved land use map was used:

- to create the Brush-Clearing Zone Layer by the application of a 200m buffer to Forested Areas;
- to create the Vegetation Aggregation Index map through the use of *Fragstat© 3.3*.

Table 12. Input files required by Local Scale mapping methodology – option 1

Name	Type	Source
Study Area	Polygon Shape file	User (usually Commune or Province administrative borders)
Brush-Clearing Zone	Polygon Shape file	User (buffer of 200 m to Forested areas)
Building dataset stratum	Polygon Shape file	Regione Autonoma della Sardegna http://www.sardegnageoportale.it/index.php?xsl=1594&s=40&v=9&c=8753&n=10
Vegetation Aggregation Index map	Raster TIFF format (.tif), resolution 2.5–10m	Created from Land Use (or Vegetation Map) using *Fragstat© 3.3*

Then, we executed two runs of the tool in configuration local option 1 obtaining the RUI maps of Alghero territory and of the NE part of Sardinia according to the selected local methodology. The default output is a raster dataset whose resolution is 2.5X2.5m but it can be easily adjusted by the operator using the IDLE editor of Python code.

The outputs we obtained are:

- Housing Configuration Map of Alghero territory (resolution 2.5X2.5m);

- RUI Type Map of Alghero territory (resolution 2.5X2.5m);
- Housing Configuration Map of NE part of the isle (resolution 10X10m);
- RUI Type Map of NE part of the isle (resolution 10X10m).

The mapped surfaces not only are classified in RUI and non-RUI, but those areas recognized as RUIs are categorized according to the twelve theoretical typologies provided by the methodology.

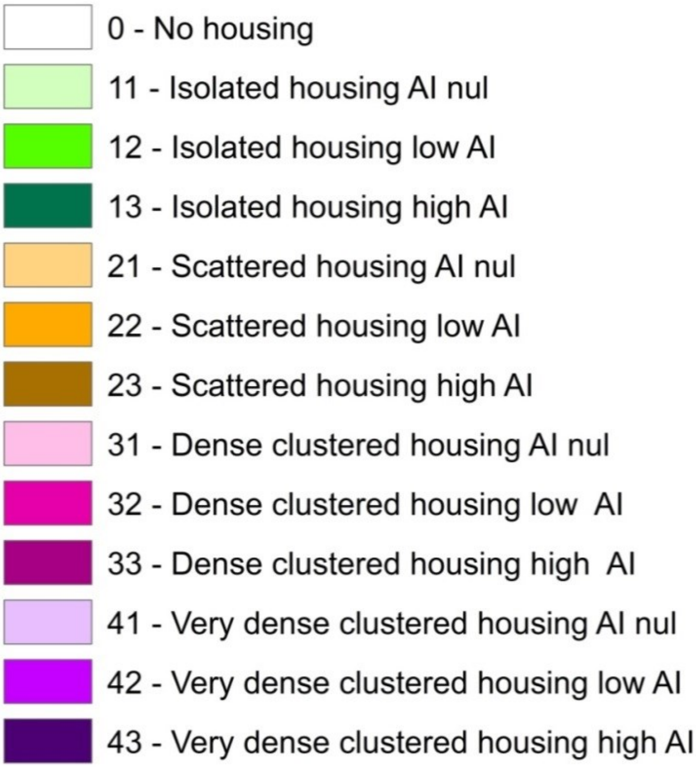

Figure 11. Set of RUI typologies used by the Local Scale mapping methodology - option 1 to classify RUI

As for global methodology, RUI maps appear to be suitable means to visualize at a glance the presence, distribution and type of RUI on the area. The chosen legend favours the immediacy of interpretation. Paying attention to the colours we can directly see the predominant kind of RUI: greens indicate isolated housing, browns indicate scattered housing, and rose-violets indicate dense clustered housing and dark-violets indicates very dense clustered housing.

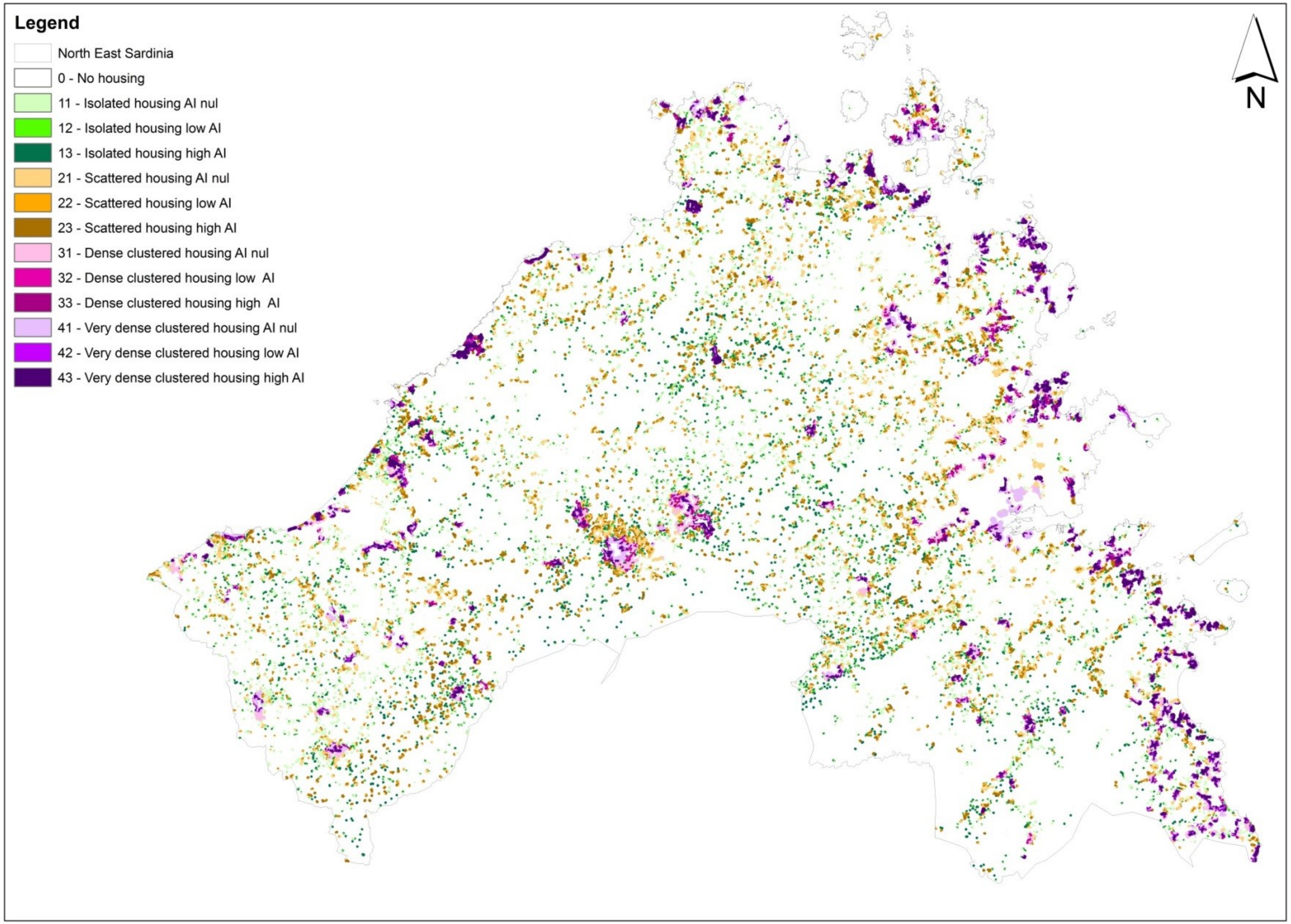

Figure 12. RUI of the NE part of the Island calculated according to the Local Scale mapping methodology - option 1.

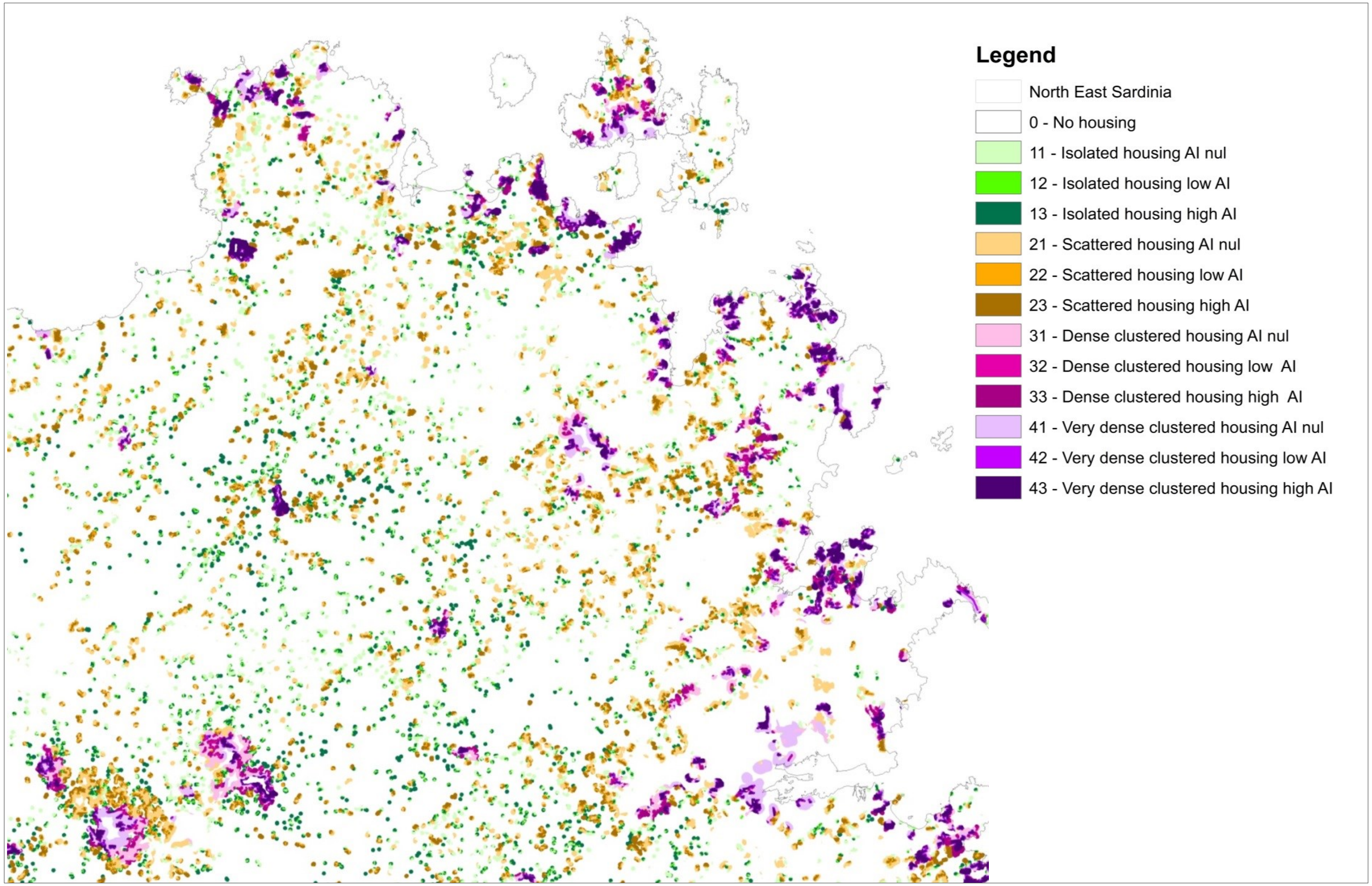

Figure 13. Detail of RUI of the NE part of the Island calculated according to the Local Scale mapping methodology - option 1.

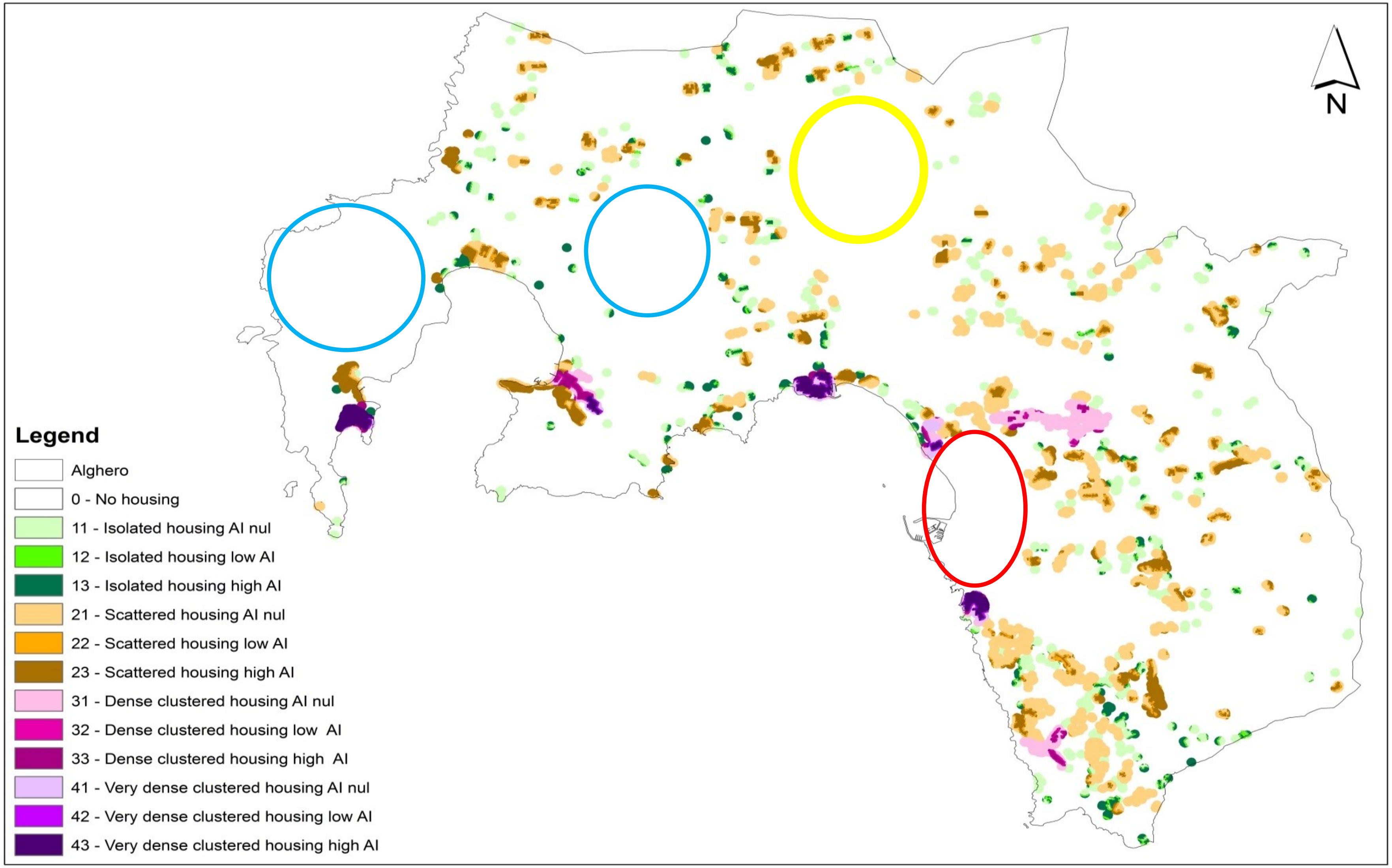

Figure 14. RUI of the Alghero territory calculated using the Local Scale mapping methodology - option 1. In the circles the areas in which there is no RUI are put on evidence: in red the urban center of Alghero, in yellow the agricultural environment of the plan, in blue the natural park of Porto Conte.

The maps of northeast Sardinia present a wide RUI diffusion all over the land but it is also evident:

- the prevalence of Isolated and Scattered housing in the countryside;
- a significant presence of Dense and Very Dense RUI on the coastline (buildings related to summer touristic flux);
- in the immediate surroundings of urban centres there is Dense/Very Dense Housing which, moving towards the countryside, progressively turn into Scattered housing.

Also Alghero RUI map shows a broad diffusion of RUI on the communal territory, anyway there are some differences:

- the countryside is densely populated and, unlike NE Sardinia, Scattered housing prevails over Isolated housing;
- although some RUI spots of buildings related to touristic presence are located all along the coastline, their density increases close to the town while the coasts of the northwest part of the territory host very few houses;
- As shown by the coloured circles on the map there are wide surfaces without RUI which appear to be non-homogeneously diffused.

On the map of Alghero territory we put on evidence areas devoid of RUIs for different causes:

- In red the urban centre of the town of Alghero;
- In yellow an agricultural area where, although there are many dwellings there is absence of forested area;
- In pale-blue the forested area included in the Regional Park of Porto Conte, a protected area where human incidence in terms of buildings is very low.

Alghero countryside is characterized by a relative separation of natural-forested environment and diffused low density residential rural contexts. On one side there are wide forested areas which are not inhabited and on the other there are populated rural areas which occupy a huge portion of the territory but are located not so close to forested areas to be considered Rural-Urban Interfaces.

Table 13. Surfaces occupied by each RUI type in NE Sardinia according to Local Scale mapping methodology – option 1

RUI categories		**Surface**		**% of all RUI**
Housing	**Aggregation Index**	**Ha**	**%**	
Isolated	Null	11302.0	3.57	18.62
Isolated	Low	3219.9	1.02	5.30
Isolated	High	8761.7	2.77	14.43
Scattered	Null	10173.0	3.21	16.76
Scattered	Low	3644.1	1.15	6.00
Scattered	High	8894.7	2.81	14.65
Dense	Null	2583.8	0.82	4.26
Dense	Low	811.2	0.26	1.34
Dense	High	1874.9	0.59	3.09
Very Dense	Null	2752.2	0.87	4.53
Very Dense	Low	1482.4	0.47	2.44
Very Dense	High	5204.2	1.64	8.57
RUI areas		60704.0	19.16	100.00
non-RUI areas		256123.6	80.84	
NE Sardinia		**316827.6**		

We extracted aggregated data from both maps. Data are presented in tables 13, 14, 15 and 16.

NE SARDINIA. RUI calculated according to the local methodology option 1, represents the 19.2% of NE Sardinia. The four classes Isolated Housing AI null, Scattered housing AI null, Scattered Housing AI high, Isolated housing AI high, occupy the widest areas totalling up to 2/3 of all RUI areas. It can be noticed that

- Dense and Very Dense Housing occupy about 1/4 of the RUI surface while the majority of it (3/4) is constituted by Isolated and Scattered Housing RUI. This distribution is related to the prevalent Housing type existing in Sardinia countryside (lone houses or very low density dwelling) but it is also an effect of geometric overlay of house buffers that reduces the entity of RUI surface for denser housing types.
- RUI located in areas with AI low are just about 15% of the total. They are less common than RUI located in areas with AI null (~44%) or AI high (~41%) which represents about 85% of RUI. It can be partially explained by the particular pattern of landscape patches in NE of Sardinia characterized by an alternation of forested and agricultural/grazing areas with narrow transition belts.

Table 14. RUI of NE Sardinia according to Local Scale mapping methodology – option 1 Percentage of each RUI type on all RUI area

NE SARDINIA		Housing Types			
RUI Type area/tot RUI area [%]		Isolated	Scattered	Dense	Very Dense
AI	Null	18.62	16.76	4.26	4.53
	Low	5.30	6.00	1.34	2.44
	High	14.43	14.65	3.09	8.57

RUI Type area/tot RUI area [%] per aggregated Housing Type of RUI and aggregated AI Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	38.35	Null	44.17
Scattered	37.41	Low	15.08
Dense	8.69	High	40.74
Very Dense	15.54		

ALGHERO. RUI calculated according to the local methodology option 1, represents the 15.8% of Alghero territory. Also in this second case study, the same four classes of NE Sardinia (Isolated Housing AI null, Scattered housing AI null, Scattered Housing AI high, Isolated housing AI high), have the maximum diffusion. In Alghero their prevalence is still more important: they represent 82% of RUIs and the lone class Scattered housing AI null occupied 38% of all RUI.

In Alghero territory it can be noticed that:

- Dense and Very Dense housing occupy about 11% of the RUI surface while the majority of it is constituted by Isolated and Scattered housing RUI (89%). This distribution is related to the huge diffusion of houses in the whole territory and to a certain separation existing in Alghero landscape between forested areas and populated areas. Dense and Very Dense housing are mostly located in periurban areas close to the town and, on average, far from forested areas and for this reason denser housings are less common among Alghero RUI than it is in NE Sardinia. Also the overlay effect of house buffers which lessens the Dense housings RUI surface must be taken into account.
- RUI located in areas with AI low are only around 7% of the total. They are less common than RUI located in areas with AI null (~68%) or AI high (~25%) which represents about

93% of RUI. It can be partially explained by the particular structure of Alghero landscape characterized by a certain split-up of forested and agricultural/grazing areas with a short and narrow interface.

Table 15. Surfaces occupied by each RUI type in Alghero Territory according to Local Scale mapping methodology – option 1

RUI categories		**Surface**		**% of all RUI**
Housing	**Aggregation Index**	**Ha**	**%**	
Isolated	Null	857.4	3.81	24.09
Isolated	Low	74.4	0.33	2.09
Isolated	High	225.4	1.00	6.33
Scattered	Null	1347.3	5.98	37.86
Scattered	Low	150.0	0.67	4.21
Scattered	High	508.6	2.26	14.29
Dense	Null	176.8	0.78	4.97
Dense	Low	16.8	0.07	0.47
Dense	High	49.1	0.22	1.38
Very Dense	Null	40.8	0.18	1.15
Very Dense	Low	13.7	0.06	0.38
Very Dense	High	98.3	0.44	2.76
RUI areas		3558.8	15.80	100.00
non-RUI areas		18965.5	84.20	
Alghero		**22524.3**		

Table 16. RUI of Alghero territory according to Local Scale mapping methodology – option 1 Percentage of each RUI type on all RUI area

Alghero		Housing Types			
RUI Type area/tot RUI area [%]		Isolated	Scattered	Dense	Very Dense
AI	Null	24.09	37.86	4.97	1.15
	Low	2.09	4.21	0.47	0.38
	High	6.33	14.29	1.38	2.76

RUI Type area/tot RUI area [%] per aggregated Housing Type of RUI and aggregated AI Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	32.51	Null	68.07
Scattered	56.36	Low	7.15
Dense	6.82	High	24.76
Very Dense	4.29		

B – Studying the geometries of different RUI type to analyse spatial indicators related to fire risk

The local method option 1 produces detailed maps, that, once converted into polygon shape file, enable to calculate spatial indicators related to fire risk.
In particular we calculated for each class of RUI two fractions; we shall call them A and B:

$$A = \frac{perimeter\ length\ of\ a\ given\ RUI\ class\ polygon}{surface\ of\ houses\ inside\ the\ polygon}$$

$$B = \frac{surface\ of\ a\ given\ RUI\ class\ polygon}{surface\ of\ houses\ inside\ the\ polygon}$$

The first fraction is the perimeter to be protected against fires per unit of housing surface. It gauges the house exposure to fire propagation and can be interpreted as the entity of efforts that must be done to defend the perimeter of a given RUI type. High values correspond to polygons with long perimeters and few houses inside, and are thought to be very difficult to be defended. It means that they are wide-open to wildfires and that few residents must take care of the security and maintenance of long perimeters. On the contrary, low values of the fraction are likely to be typical of less risky situation: they are measured where polygons presenting short perimeters are characterized by hosting many houses.

Table 17. Average A and B calculated for all RUI types of Local Scale mapping methodology – option 1, on the NE part of Sardinia Island

RUI category		Surface		Perimeter	Dwellings	Dwellings/ RUI	BCZ/ dwellings	Perimeter/ Dwellings
Housing	**A.I.**	(ha)	(%)	(km)	($m^2 \cdot 10^3$)	(%)	($m^2\ m^{-2}$)	($m\ m^{-2}$)
Isolated	0	11302.0	3.57	3360.4	475.1	0.42	236.9	7.1
Isolated	Low	3219.9	1.02	2945.7	137.0	0.43	234.1	21.5
Isolated	High	8761.7	2.77	4324.4	329.4	0.38	265.0	13.1
Scattered	0	10173.0	3.21	2840.3	1036.7	1.02	97.1	2.7
Scattered	Low	3644.1	1.15	3124.8	355.5	0.98	101.5	8.8
Scattered	High	8894.7	2.81	4154.0	1374.4	1.55	63.7	3.0
Dense	0	2583.8	0.82	777.3	315.3	1.22	80.9	2.5
Dense	Low	811.2	0.26	740.4	95.7	1.18	83.8	7.7
Dense	High	1874.9	0.59	1028.0	392.6	2.09	46.8	2.6
Very dense	0	2752.2	0.87	840.1	2655.9	9.65	9.4	0.3
Very dense	Low	1482.4	0.47	1217.7	684.2	4.62	20.7	1.8
Very dense	High	5204.2	1.64	1533.2	5055.8	9.71	9.3	0.3
RUI		60704.0	19.16	26886.4	12907.7	2.13	46.0	2.1
Non-RUI		256123.6	80.84		6211.7	0.24	411.3	
NE Sardinia		**316827.6**			**19119.4**	**0.60**	**164.7**	

The numerator of the second fraction is the RUI area without the houses surface; the latter constitutes the denominator. The B fraction represents the area to be protected per unit of housing surface, and measures the surface that must be cleaned yearly by vegetal fuels per unit of housing surface. It is indicative of the efforts that residents in a given RUI type must make to accomplish the annual clearing and maintenance of the surrounding areas of their houses. High values mean that each resident must manage wide areas in which bushes and grasses must be mown, while low values are associated with contexts in which yearly maintenance does not require big resources.

Table 18. Average A and B calculated for all RUI types of Local Scale mapping methodology – option 1, on Alghero territory

RUI category		Surface		Perimeter	Dwellings	Dwellings/ RUI	BCZ/ dwellings	Perimeter/ dwellings
Housing	**A.I.**	(ha)	(%)	(km)	($m^2 \cdot 10^3$)	(%)	($m^2\ m^{-2}$)	($m\ m^{-2}$)
Isolated	0	857.4	3.81	195.5	96.0	1.12	88.3	2.0
Isolated	Low	74.4	0.33	101.4	4.5	0.61	162.9	22.3
Isolated	High	225.4	1.00	140.1	44.0	1.95	50.3	3.2
Scattered	0	1347.3	5.98	272.1	199.6	1.48	66.5	1.4
Scattered	Low	150.0	0.67	201.7	18.5	1.23	80.0	10.9
Scattered	High	508.6	2.26	259.5	169.9	3.34	28.9	1.5
Dense	0	176.8	0.78	29.7	32.3	1.83	53.7	0.9
Dense	Low	16.8	0.07	23.1	3.0	1.78	55.3	7.8
Dense	High	49.1	0.22	31.9	16.2	3.29	29.4	2.0
Very dense	0	40.8	0.18	15.5	16.9	4.14	23.1	0.9
Very dense	Low	13.7	0.06	18.1	4.9	3.60	26.7	3.7
Very dense	High	98.3	0.44	24.4	133.9	13.62	6.3	0.2
RUI		3558.8	15.80	1312.9	739.7	2.08	47.1	1.8
Non-RUI		18965.5	84.20		1718.6	0.91	109.4	
Alghero		**22524.3**			**2458.4**	**1.09**	**90.6**	

Both of them were expected to present high values in low density RUI and, on the contrary, low values in Dense and Very Dense housing type of RUI.

Our results indicate that there is a clear dependence on RUI type of the two quantities since both of them, A and B, vary with the RUI typology. Although data obtained from mapping the North Eastern Sardinia and Alghero differ in absolute values, in both areas the pattern is the same and, as expected, A and B values progressively decrease with housing density from Isolated to Very Dense housing. The two fractions in both areas show the same trend: high differences between Isolated and Scattered Housing, lower difference between Scattered and Dense Housing, and again high difference between Dense and Very Dense housing.

Table 19. Mean value of A and B calculated for RUI types aggregated according to the housing type. Comparison between NE Sardinia and Alghero territory

Housing types	NE Sardinia		Alghero	
	A	**B**	**A**	**B**
Isolated Housing	13,9	245,3	9,2	100,5
Scattered Housing	4,8	87,4	4,6	58,5
Dense Housing	4,3	70,5	3,6	46,1
Very Dense Housing	0,8	13,1	1,6	18,7

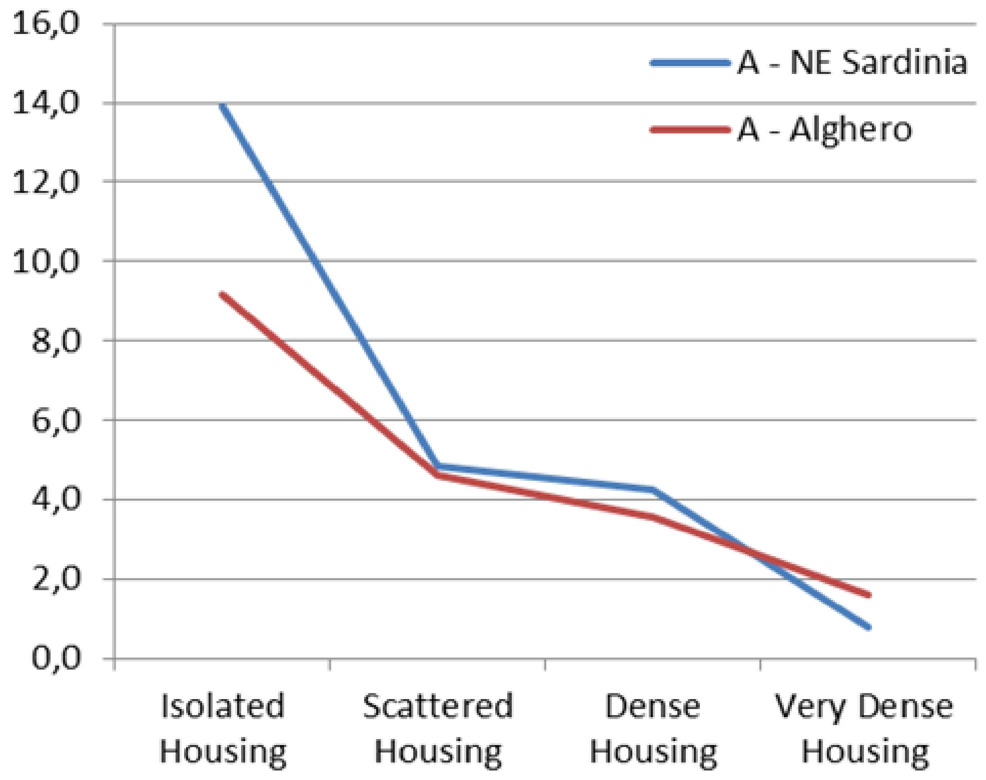

Figure 15. Mean value of A calculated for RUI types aggregated according to the housing type. Comparison between NE Sardinia and Alghero territory.

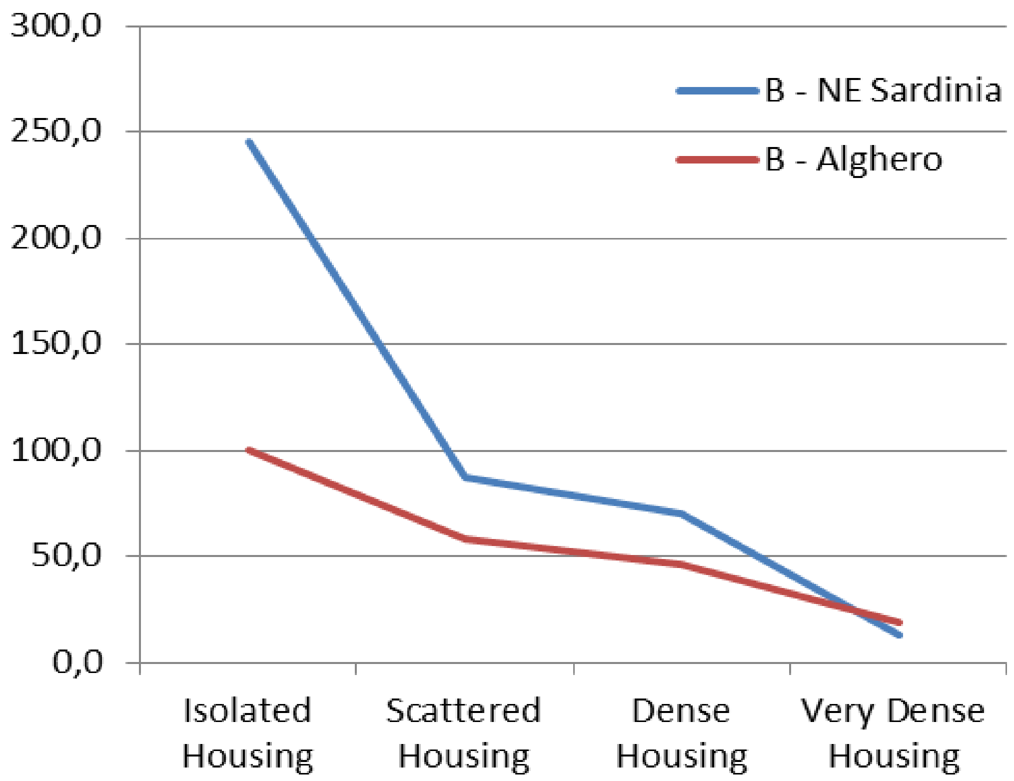

Figure 16. Mean value of B calculated for RUI types aggregated according to the housing type. Comparison between NE Sardinia and Alghero territory.

The results clearly show that, in order to protect values and people living in RUI with low dense housing, a stronger effort must be made, than for protecting RUI with higher density housings. It means that especially people living in Isolated housing incur high costs to protect the safety of themselves and their houses, while Very Dense RUI residents incur the lowest costs for fire prevention per unit of housing surface.

C – studying the relation RUI-fire regime

The RUI maps of Sardinian NE and of Alghero calculated according to the Local Scale mapping methodology option 1 have been used to analyse the relation fire regime/RUI. Like for the Global Scale methodology, we used the same database of *georeferenced ignition points* and of *georeferenced perimeters of burned areas* as descriptors for fire regime. Data were provided by Sardinian Forest Service (Corpo Forestale e di Vigilanza Ambientale), and finally the databases we used are:

1. the GPS georeferenced ignition point (database 2005-2010), and 30-50 m precision georeferenced ignition point for the years 1998-2004;
2. the GPS georeferenced perimeters of burned areas (database 2005-2011).

Table 20. Ignition points recorded from 1998 to 2010 in the NE part of Sardinia and in Alghero territory. Distribution inside/outside RUI and per each RUI type of: number of ignitions, percentage on the total ignitions and ignition density

RUI type		Alghero			NE Sardinia		
Housing	**AI**	**ignitions**	**%**	**ignitions/km^2**	**Ignitions**	**%**	**Ignitions/km^2**
Isolated	Null	20	4.1	2.33	102	4.8	0.90
Isolated	Low	4	0.8	5.38	25	1.2	0.78
Isolated	High	7	1.4	3.11	62	2.9	0.71
Scattered	Null	36	7.4	2.67	125	5.8	1.23
Scattered	Low	7	1.4	4.67	29	1.4	0.80
Scattered	High	19	3.9	3.74	79	3.7	0.89
Dense	Null	9	1.8	5.09	86	4.0	3.33
Dense	Low	2	0.4	11.90	32	1.5	3.94
Dense	High	1	0.2	2.04	50	2.3	2.67
Very dense	Null	9	1.8	22.06	96	4.5	3.49
Very dense	Low	4	0.8	29.20	34	1.6	2.29
Very dense	High	3	0.6	3.05	120	5.6	2.31
RUI		121	24.7	3.40	840	39.2	1.38
Non-RUI		368	75.3	1.94	1304	60.8	0.51
Whole Area		**489**	**100.0**	**2.17**	**2144**	**100.0**	**0.68**

NE Sardinia. In the period 1998-2010, 2144 ignitions were recorded in NE Sardinia (165 per year, on average). Analysing their distribution (Table 20) we find that 39.2% of ignitions were recorded in RUI while the majority (60.8%) were located outside RUI. Nevertheless, accounting for the difference in occupied surfaces, ignition density in RUI is definitely higher than elsewhere (1.38 and 0.51 ignitions/km^2, respectively).

All RUI categories, with no exception, present values above the NE Sardinia average. The 6 maximum density of ignition in RUI are presented by RUI of Dense and Very Dense Housing (showing densities of ignition from ~4.5 to ~7.7 times higher than outside RUI). The other 6 values of ignition density belong to RUI of Isolated and Scattered Housing and they are anywhere from 1.4 to 2.4 times higher than the ignition density recorded in non-RUI areas.

Aggregating data per housing type (Table 21), we can see that the lowest density of ignition is in Isolated Housing (0.81 ignition/km^2) and the highest is recorded in Dense Housing (3.19 ignition/km^2). We can also notice that RUI of Isolated and Scattered Housing on one side and RUI of Dense and Very Dense housing on the other have similar values, but that the two denser classes show values that are at least three times higher than Isolated and Scattered. We can notice that in NE of Sardinia, AI does not appear to be very influent on RUI ignition densities and just a weak decreasing trend of ignition density is recorded with the increase of AI.

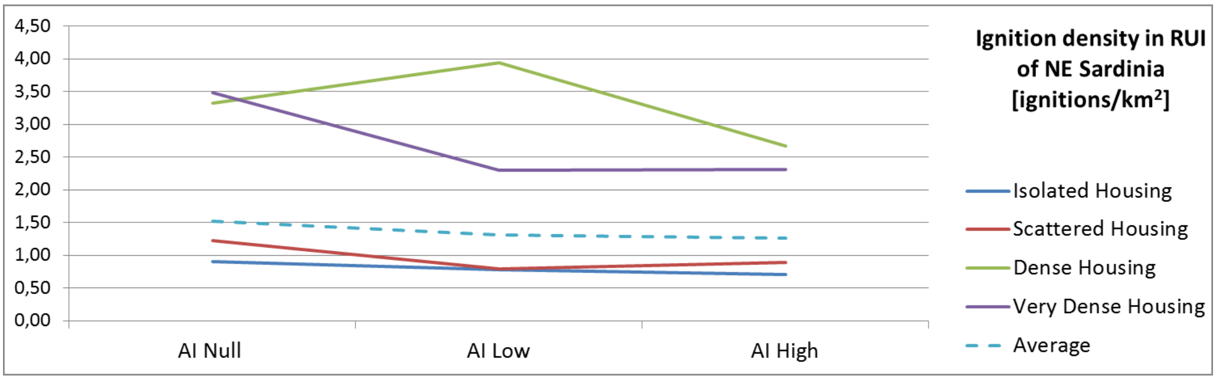

Figure 17. Variation with Aggregation Index of vegetation of ignition density per square kilometer in NE Sardinia.

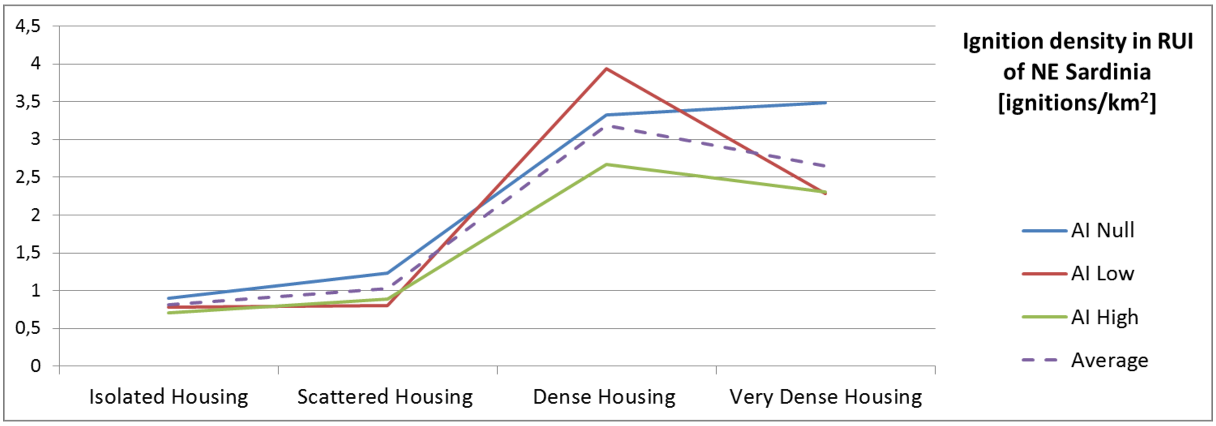

Figure 18.Variation with Housing type of ignition density per square kilometer in NE Sardinia.

Alghero. In the period 1998-2010, 489 ignitions were recorded in Alghero communal territory, 38 per year, on average. Analysing their distribution we found that 24.7% of ignitions were recorded in RUI while the majority (75.3%) were located outside RUI. Nevertheless, being the non-RUI area wider than RUI, ignition density is higher in RUI than elsewhere (in RUI 3.40 ignitions/km^2, outside RUI 1.94 ignitions/km^2).

Table 21. Density of ignition points recorded from 1998 to 2010 in the NE part of Sardinia. Distribution inside/outside RUI and per each RUI category.

NE SARDINIA Density of Ignition [ignitions/km^2]		Housing Types			
		Isolated	Scattered	Dense	Very Dense
AI	Null	0,90	1,23	3,33	3,49
	Low	0,78	0,80	3,94	2,29
	High	0,71	0,89	2,67	2,31

Ignition Density per aggregated Housing Type of RUI and aggregated AI Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	0,81	Null	1,53
Scattered	1,03	Low	1,31
Dense	3,19	High	1,26
Very Dense	2,65		

Figure 19. Variation with Housing type of ignition density per square kilometer in NE Sardinia and Alghero territory.

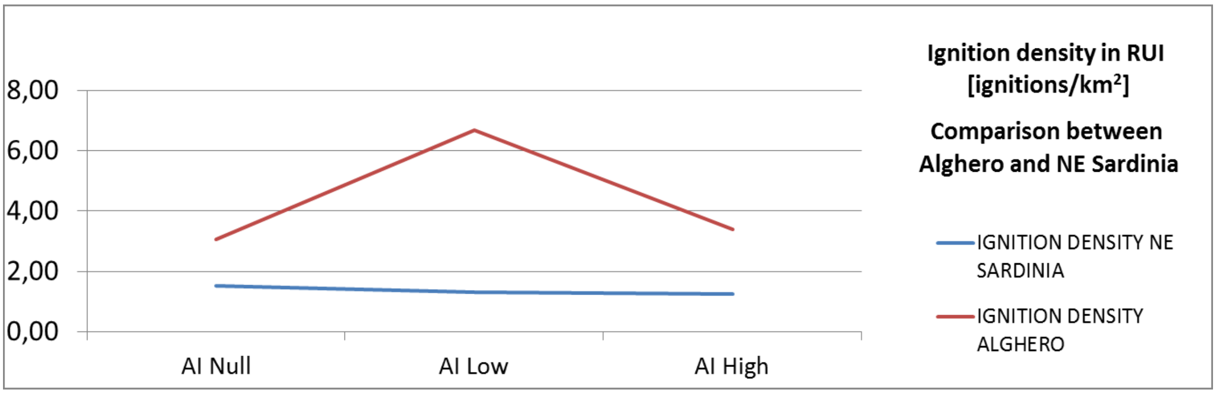

Figure 20. Variation with Aggregation Index of Vegetation of ignition density per square kilometer in NE Sardinia and Alghero territory.

Comparing NE Sardinia and Alghero we can notice:

1. in Alghero the ignition density is much higher than in NE Sardinia (the average on the territories are respectively 2.17 and 0.68 ignitions/km^2, while in RUI they are respectively 3.40 and 1.38 ignitions/km^2); it can be due to a higher population density and a greater diffusion of housing in the territory of Alghero than in NE Sardinia;
2. in both cases, a general increase of ignition density with the density of Housing in RUI is evident, which means that ignition density is higher where also population density presents higher values; the RUI type recording the highest ignition density is Very Dense in Alghero and Dense in NE Sardinia.
3. all categories in Alghero recorded higher values than in NE Sardinia but it is particularly true for RUI of Very Dense Housing, and RUI in AI Low. It can be indicative of differences in the two case studies, with regard to the patterns of urban occupation of the territory.

In Alghero, the highest density of ignition points is recorded in RUI of Very Dense Housing AI Low (29.20 ignitions/km^2), and the second highest value, 22.06 ignitions/km^2, in RUI of Very Dense Housing AI Null. These two values are particularly high since they are respectively 13 and 10 times higher than the average value of Alghero territory (2.17 ignitions/km^2). They can be considered outstanding since they are much higher than all the others values. The two RUI types identify a particularly interesting portion of territory on which energies can be concentrated for prevention purposes: for instance, since they do not occupy very wide areas, they can be considered ideal locations for prescribed burning and Brush-Clearing operations.

In Alghero RUIs, almost all categories present values above the territorial average (2.17 ignitions/km^2), except the category **Dense Housing AI high** (2.04 ignitions/km^2), a peculiar type: in its area (that is not very wide) only 1 fire occurred in the 13 years and it cannot be considered statistically reliable. Considering the same period, if another event was recorded, ignition density would be 4.1 ignitions/km^2, and if one event less happened, then ignition density would be null. For the study of Alghero, the ignition density statistics on the widest RUI categories (where many ignitions are located) are more reliable than the ones calculated on smaller RUI types where less ignitions are recorded. For this reason ignition densities of RUI with Very Dense housing which presents small areas are less reliable. Anyway, especially aggregating RUI classes per housing type and per AI, statistics provide trustworthy data.

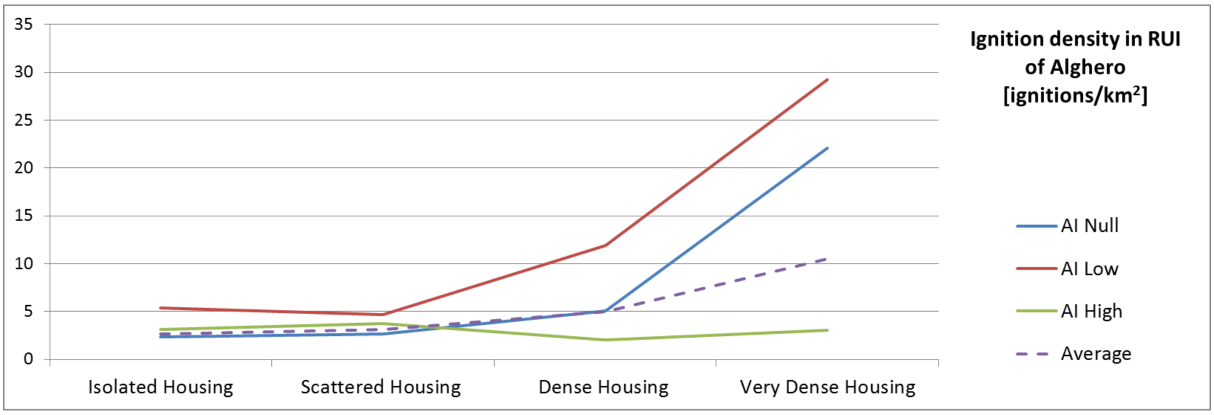

Figure 21. Variation with Housing type of ignition density per square kilometer in Alghero Territory

Aggregating data for housing type, we can see that the lowest density of ignition is in Isolated housing (2.68 ignitions/km^2) and the highest is recorded in Very Dense housing (10.47

ignitions/km²). We can also notice that RUI types in AI High, present almost constant values which are below the average in RUI and are not influenced by housing density.

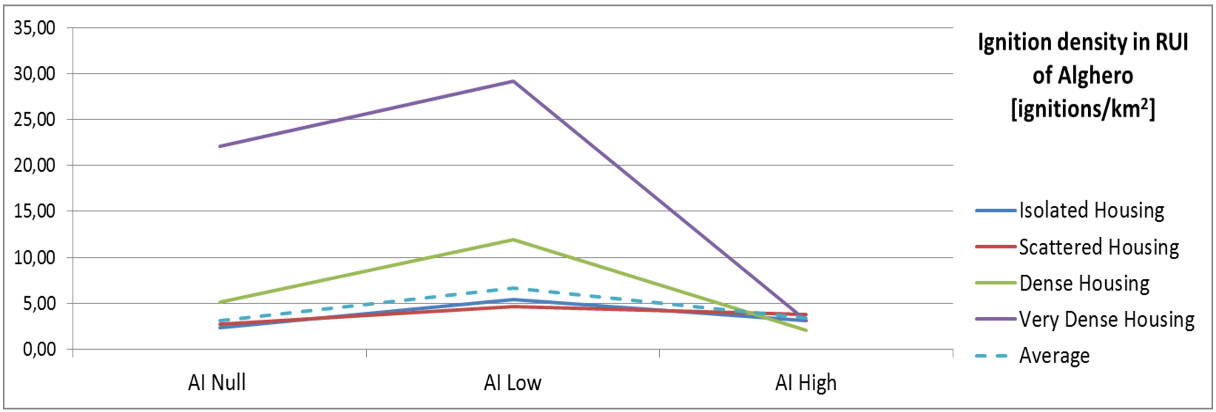

Figure 22.Variation with Aggregation Index of Vegetation of ignition density per square kilometer in Alghero Territory

Table 22. Density of ignition points recorded from 1998 to 2010 in Alghero Territory. Distribution inside/outside RUI and per each RUI typology

ALGHERO Density of Ignition [ignitions/km²]		Housing Types: Isolated	Scattered	Dense	Very Dense
AI	Null	2.33	2.67	5.09	22.06
	Low	5.38	4.67	11.90	29.20
	High	3.11	3.74	2.04	3.05

Ignition Density per aggregated Housing Type of RUI and aggregated Land Cover Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	2.68	Null	3.05
Scattered	3.09	Low	6.67
Dense	4.94	High	3.40
Very Dense	10.47		

As well as RUI defined according to Global Scale methodology, also RUI defined according to Local Scale methodology option 1 seems to strongly influence the ignition point distribution. Although the two cases studied present different values, anyway a common trend of ignition density increase with Housing/population density is recognizable.

Focalizing the attention on RUI areas, means to deal with the zones where the presence of people, goods and belongings is the highest and, simultaneously, where also the ignition density presents the peak values: in NE we found that the 40% of ignitions are located in RUI (which occupies less than 20% of the study area); in Alghero, about 25% of the ignitions are located in that 15% of territory constituting RUI.

In the period 2005-2011 (Table 23), a surface of 77.95 km² was burned in NE Sardinia (an average of about 1114 ha per year). Since just 19.16% of the territory is RUI, as expected, we found that the majority of burned areas were recorded in non-RUI areas (64.33 km² meaning the 82.52%) and just 13.62 km² (= 17.48%) in RUI. If we consider that from 2005 to 2011, 2.46% of NE Sardinia was burned, with percentage of 2.51 % and 2.24% respectively for non-RUI and RUI, we can see that although RUI presents higher ignition density, it burns a little less than elsewhere. It does not seem that there is a big difference between RUI and non-RUI areas; anyway, having a glance to the single categories we can notice that there are differences among RUI type.

Table 23. Distribution of burned areas inside/outside RUI and values/percentage of burned areas per each category of RUI in NE part of Sardinia.

RUI category Housing	AI	RUI Area [ha]	(RUI area/ tot RUI) [%]	Burned Area [ha]	(Burned RUI area/ Burned tot RUI) [%]	(Burned RUI Area/ RUI area) [%]
Isolated	Null	11302.03	18.62	332.15	24.38	2.94
Isolated	Low	3219.88	5.30	66.22	4.86	2.06
Isolated	High	8761.66	14.43	179.13	13.15	2.04
Scattered	Null	10172.99	16.76	255.34	18.74	2.51
Scattered	Low	3644.05	6.00	72.87	5.35	2.00
Scattered	High	8894.71	14.65	185.03	13.58	2.08
Dense	Null	2583.78	4.26	60.94	4.47	2.36
Dense	Low	811.21	1.34	18.72	1.37	2.31
Dense	High	1874.88	3.09	46.56	3.42	2.48
Very Dense	Null	2752.20	4.53	46.19	3.39	1.68
Very Dense	Low	1482.39	2.44	27.33	2.01	1.84
Very Dense	High	5204.20	8.57	71.78	5.27	1.38
RUI areas		60704.00	100.00	1362.27	100.00	2.24
non-RUI areas		256123.56		6433.05		2.51
NE Sardinia		**316827.56**		**7795.32**		**2.46**

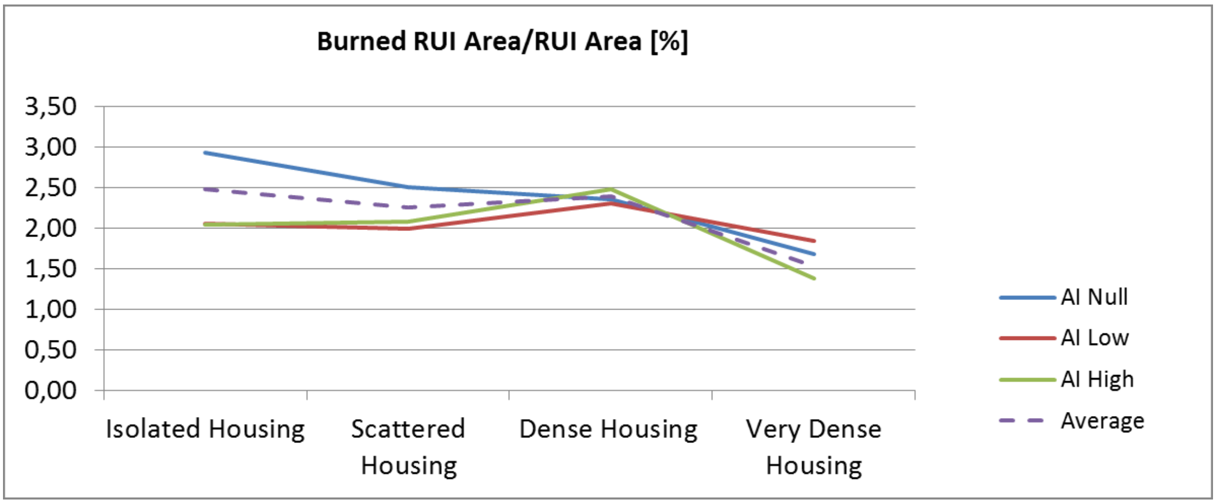

Figure 23. Distribution of burned areas per RUI category in NE Sardinia. Variation with housing type

The majority of RUI categories are below the NE Sardinia average (2.46%) but Isolated Housing AI Null, Scattered Housing AI null and Dense Housing AI High present higher values. The lowest percent value of burned area is recorded in Very Dense Housing AI High, the RUI type which is the most dangerous in case of wildfire.

Aggregating data per AI level and Housing type (Table 24) we notice that Very Dense Housing RUI types have average value significantly lower than the mean value (1.54%) and that in general the percentage of burned area decreases with the density of Housing. We can also point out that RUI with High AI are characterized by lower % of burned area than RUI with Null and Low AI and it means that forested areas are the less burned.

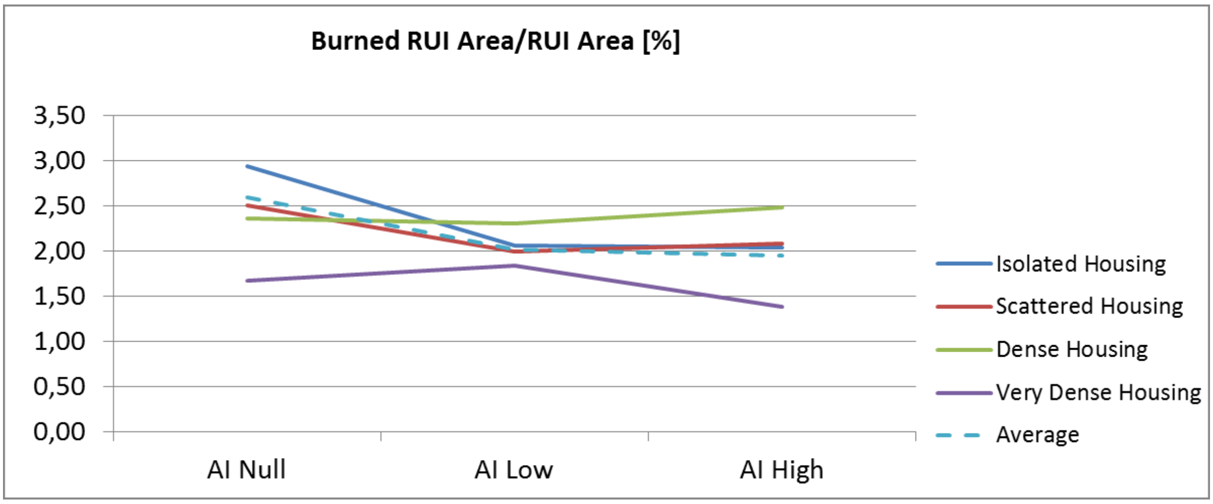

Figure 24. Distribution of burned areas per RUI category in NE Sardinia. Variation with Aggregation Index of Vegetation

NE SARDINIA. In NE Sardinia, RUI of low density housing located in AI null landscapes (which are typical of Agricultural environment) burn more than the territorial average, while in RUI types characterized by denser housing the percentage lessens arriving to score 1.38% in Very Dense Housing AI High.

This difference can be interpreted as the consequence of:

1. quick intervention of numerous residents to protect their goods and strong reaction of firefight forces that activate a robust response in dense housing RUI, also with the use of water supply by aircrafts.
2. Rapidity of fire propagation in low charge thin fuels like grasses typical of agricultural/grazing land, especially in windy days. This kind of wildfire is characterized by high speed and low intensity propagation in less densely populated landscapes; being less damaging the response of firefight is less sharp and the burned areas can be very large.

Burned area is a simple metric that in this situation shows its limit in describing the effects of wildfire because it is incapable of distinguishing among intense fires and weaker ones. Not all fires have the same capacity to damage and so the measure of the burned area is not descriptive of danger and damage. Also firefight responses can be different according to the values at risk.

In NE Sardinia wildfire propagation inside/outside presents little differences, but the RUI types have a strong influence on burning patterns and fire propagation is impeded or slowed down in denser housing RUI Types. It is probably due mainly to quick and strong intervention against wildfire and to fuel fragmentation.

While all the other RUI categories (including Dense housing RUIs) have high percentage of burned areas, Very Dense Housing RUI types show low values, with a weak decreasing trend for higher AI. The highest values among RUI category are recorded in AI null – low density housing RUI (Isolated Housing AI null, Scattered Housing AI null).

Table 24. Percentage of burned area per RUI type and per RUI category aggregated according to AI and Housing type. Data relative to NE Sardinia

NE SARDINIA		Housing Types			
Burned RUI Area/RUI Area [%]		Isolated	Scattered	Dense	Very Dense
	Null	2.94	2.51	2.36	1.68
AI	Low	2.06	2.00	2.31	1.84
	High	2.04	2.08	2.48	1.38

Ignition Density per aggregated Housing Type of RUI and aggregated AI Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	2.48	Null	2.59
Scattered	2.26	Low	2.02
Dense	2.40	High	1.95
Very Dense	1.54		

Table 25. Distribution of burned areas inside/outside RUI and values/percentage of burned areas per each category of RUI in Alghero Territory

RUI category Housing	**AI**	**RUI Area [ha]**	**(RUI area/ tot RUI) [%]**	**Burned Area [ha]**	**(Burned RUI area/ Burned tot RUI) [%]**	**(Burned RUI Area/ RUI area) [%]**
Isolated	Null	857.4	24.09	4.75	18.69	0.55
Isolated	Low	74.4	2.09	1.07	4.22	1.44
Isolated	High	225.4	6.33	2.07	8.14	0.92
Scattered	Null	1347.3	37.86	9.99	39.33	0.74
Scattered	Low	150.0	4.21	1.58	6.20	1.05
Scattered	High	508.6	14.29	4.91	19.34	0.97
Dense	Null	176.8	4.97	0.55	2.15	0.31
Dense	Low	16.8	0.47	0.10	0.41	0.61
Dense	High	49.1	1.38	0.07	0.28	0.14
Very Dense	Null	40.8	1.15	0.32	1.25	0.78
Very Dense	Low	13.7	0.39	0.00	0.00	0.00
Very Dense	High	98.3	2.76	0.00	0.00	0.00
RUI areas		3558.8	100.00	25.41	100.00	0.71
non-RUI areas		18965.5		393.93		2.08
Alghero		**22524.3**		**419.34**		**1.86**

ALGHERO. In the period 2005-2011, a surface of 4.19 km^2 was burned in Alghero (an average of about 60 ha per year). Since just 15.8% of the territory is RUI, as expected, we found that the majority of burned areas were recorded in non-RUI areas (393.93 ha meaning the 94%) and just 25.41 ha (=6%) in RUI. If we consider the period from 2005 to 2011, 1.86% of Alghero Commune was burned, with percentage of 2.08 % and 0.71% respectively for non-RUI and RUI, we can see that although RUI presents higher ignition density, it burns less than elsewhere. The difference looks to be significantly higher than in NE Sardinia. We can also notice that there are very important differences among RUI types.

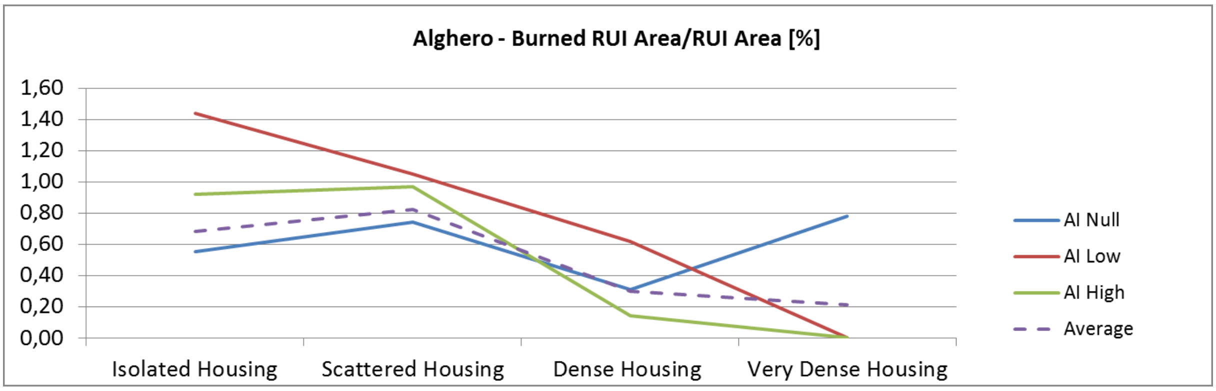

Figure 25. Percentage of burned area per each RUI type in Alghero territory. Variations with housing density

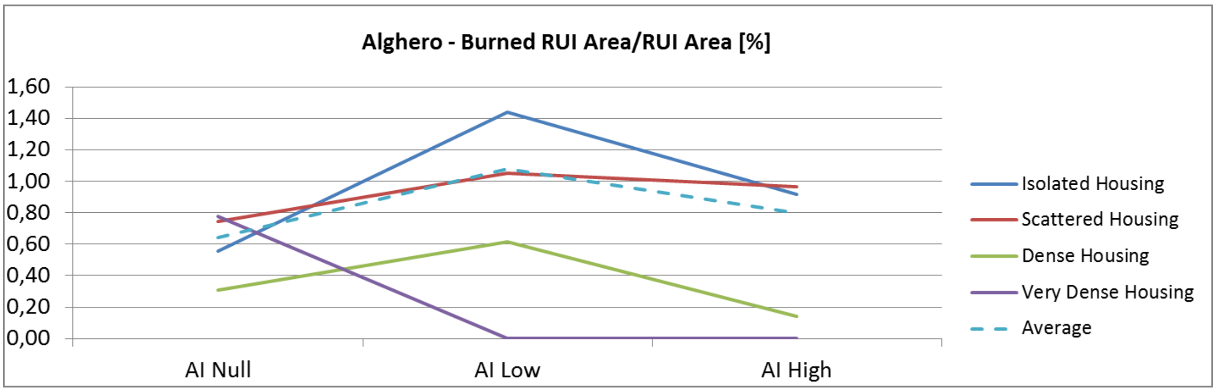

Figure 26. Percentage of burned area per each RUI type in Alghero territory. Variations with Aggregation Index of Vegetation

All RUI categories values are below the territorial average (1.86%) and some categories have not burned at all. Their surfaces are not very wide and the time series is not so long so we must pay attention to their statistical significance. Anyway, they are not the smallest surfaces and it is noticeable that both null values are relative to Very Dense Housing. The three RUI types of Very Dense housing constitute a particular macro-category since it recorded the highest ignition densities and the lowest percentage of burned area.

Aggregating data for housing type and AI (Table 26), values become more reliable, and show a strong decrease of burned area in RUI for high density housing categories.

We can also point out that RUI with Low AI are characterized by higher % of burned area than RUI with Null and High AI and it can be related to the similar pattern presented by ignition point distribution which in Alghero presents a maximum in AI Low RUIs (mainly agricultural environments).

In Alghero, RUI of low density housing located in AI Low landscapes (which are typical of grazing and sparsely vegetated environment) are the categories that present the highest burned area percentage among RUIs.

Unlike in NE Sardinia area, in Alghero, wildfire propagation presents a big difference between RUI and non-RUI areas and the influence of RUI types is not as important. Nevertheless significant variations have been recorded between the different categories and in particular between RUI types of Isolated and Very Dense housing.

Comparing the percentages of burned areas in the two case studies, the differences in absolute value among Alghero territory and NE Sardinia are important and NE Sardinia definitely presents higher values.

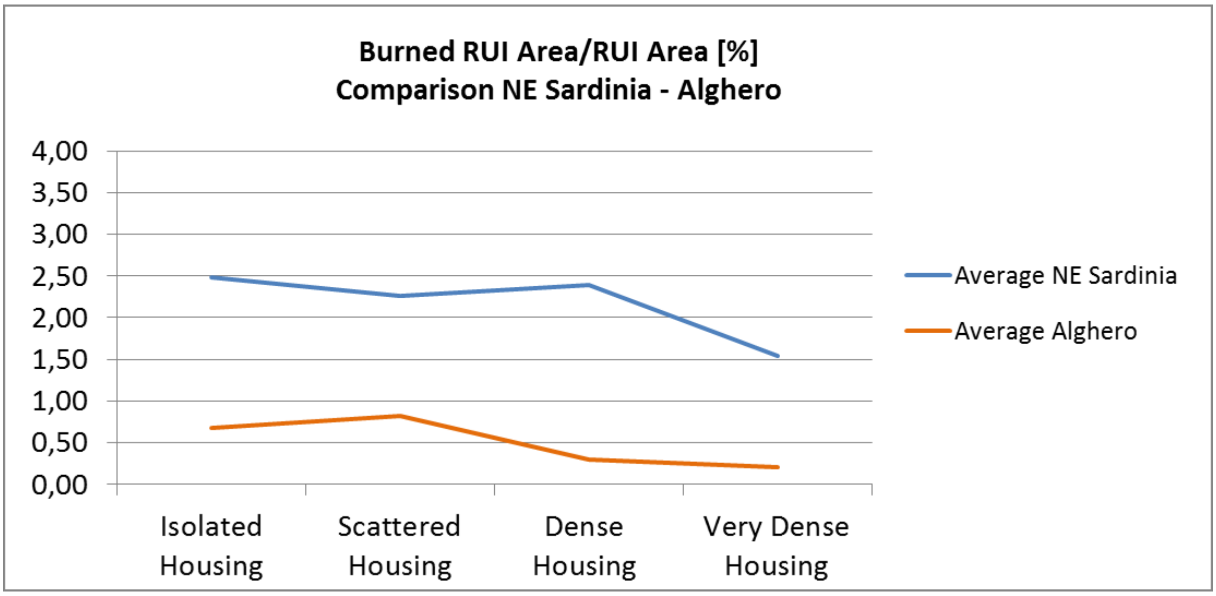

Figure 27. Comparison of percentage of burned area on RUI categories aggregated per housing density in NE Sardinia and Alghero territory

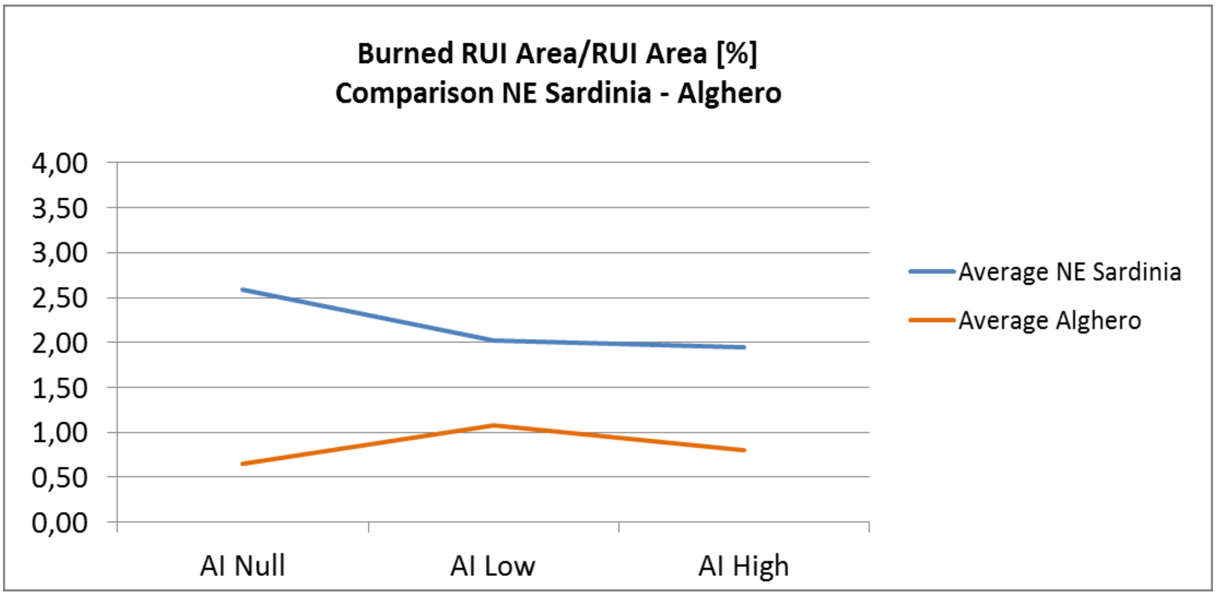

Figure 28. Comparison of percentage of burned area on RUI categories aggregated per Aggregation Index of Vegetation in NE Sardinia and Alghero territory

Alghero presents higher ignition density and lower percentage of burned areas than the NE of Sardinia. It is peculiar how we record the highest ignition densities exactly where we also record the lowest percentage of burned areas.

The apparent paradox that Alghero has an ignition density 2.5 times higher than NE Sardinia, but at the same time presents values of burned areas that are 1/3 in comparison to NE Sardinia can be hypothetically explained by considering the following facts:

1. Alghero is denser populated than the north east;
2. Ignitions are generally related to human activity;
3. Burned areas are inversely proportional to human presence: in particular the more densely populated environments are also characterized by higher fragmentation of fuels and the more diffuse presence of people and goods implies a stronger response of firefighters and residents to wildfire.

The same reasoning can be used to explain the other apparent paradox that with Housing density, ignition points are more common but burned areas lessen their width.

Notwithstanding the differences between the two cases study, some common trends can be noticed:

1. In both territories RUI burns less than outside RUI (in Alghero it is more evident);
2. Inside RUI of the two territories, percentage of burned area decreases with the density of Housing type.

Table 26. Percentage of burned area per RUI type and per RUI category aggregated according to AI and Housing type. Data relative to Alghero Territory

Alghero		Housing Types			
Burned RUI Area/RUI Area [%]		Isolated	Scattered	Dense	Very Dense
	Null	0.55	0.74	0.31	0.78
AI	Low	1.44	1.05	0.61	0.00
	High	0.92	0.97	0.14	0.00

Ignition Density per aggregated Housing Type of RUI and aggregated AI Type of RUI

HOUSING TYPE		VEGETATION AGGREGATION INDEX	
Isolated	0.68	Null	0.64
Scattered	0.82	Low	1.08
Dense	0.30	High	0.80
Very Dense	0.21		

Local Scale mapping – Option 2

A – mapping

In order to generate the input data required for running *RUImap®* tool in configuration Local Scale mapping methodology – option 2 we used the same layers (Land Use Map and a Building Map) as for the option 1. They were downloaded from the official site of Regione Autonoma della Sardegna, and corrected through the use of Coverage Function of Esri ArcGis 9.3, as illustrated for the local methodology option 1.

We used the same study area shape file of Alghero territory that we created for running the tool in option 1. Successively, we made the required preparing operation to obtain inputs:

- We reclassified the Land Use map into the 5 categories: Shrubs and Forests, Water, Agricultural, Urban, Unproductive;
- We added a field to Building layer .dbf file. In this new field, as required, we wrote the string "URB" in each feature corresponding to a house.

Table 27. Input files required by Local Scale mapping methodology option 2

Name	Type	Source
Study area	Polygon Shape file	User (usually Commune administrative borders)
Reclassified Land Use	Polygon Shape file	User (the 5 categories into which the reclassification is operated are fixed but the user chooses in which of the final categories the initial classes will be included)
Building dataset	Polygon Shape file	Regione Autonoma della Sardegna http://www.sardegnageoportale.it/index.php?xsl=1594&s=40&v=9&c=8753&n=10

Once the input files were prepared we run the tool in configuration local option 2 obtaining the RUI map of Alghero territory according to the selected local methodology. The output we obtained are a vector files (polygon shape file):

- Settlement map of Alghero territory;
- RUI Type Map of Alghero territory.

The territory is classified in RUI and non-RUI and RUI is categorized according to the seven theoretical typologies provided by the methodology.

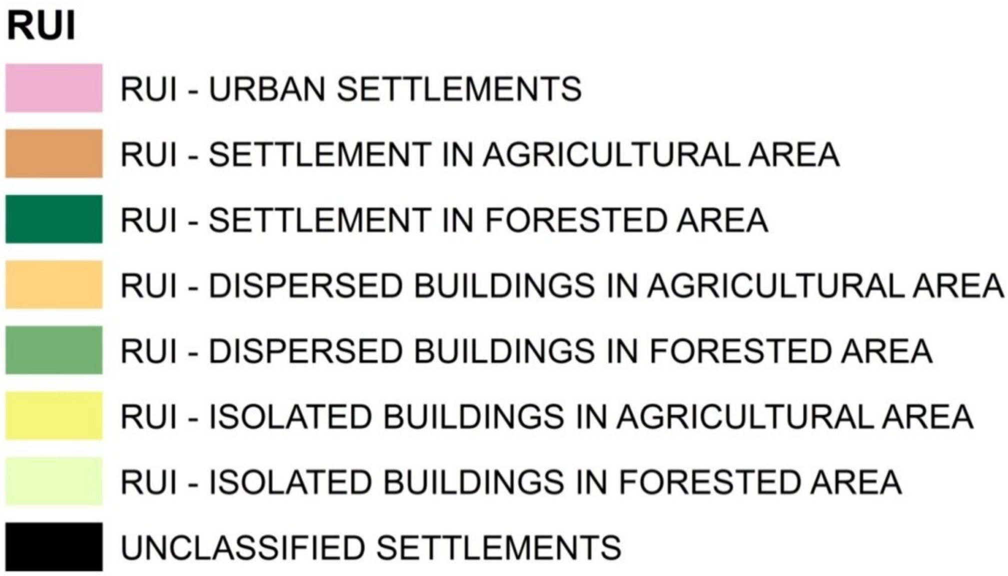

Figure 29. Set of theoretical RUI categories according to Local Scale mapping methodology – option 2

Also the local methodology option 2 provide RUI maps which are suitable means to easily see presence, distribution and type of RUI on the area. Greens have been used for RUI located in Forested Areas, yellow-browns for RUI located in Agricultural Areas, rose for Urban Settlement. RUI housing density can be deduced by the intensity of colours, since stronger tonalities have been applied to denser housing RUIs.

Alghero RUI map obtained with local methodology option 2 shows an extensive diffusion of RUI on the communal territory:

- the countryside is densely populated and RUI are broadly diffused.
- As it was pointed out for the Alghero RUI obtained with local methodology option 1 some RUI spots related to touristic presence are located all along the coastline, but the density of RUI in periurban areas is decidedly higher than in the coasts of the north-western part of Alghero region;
- Only the western coast (and particularly the peninsula which constitute the Regional Park of Porto Conte, a high natural protected area), the urban centre and a central part of the territory which is located far from forested area are devoid of RUI.

We extracted aggregated data from the map.

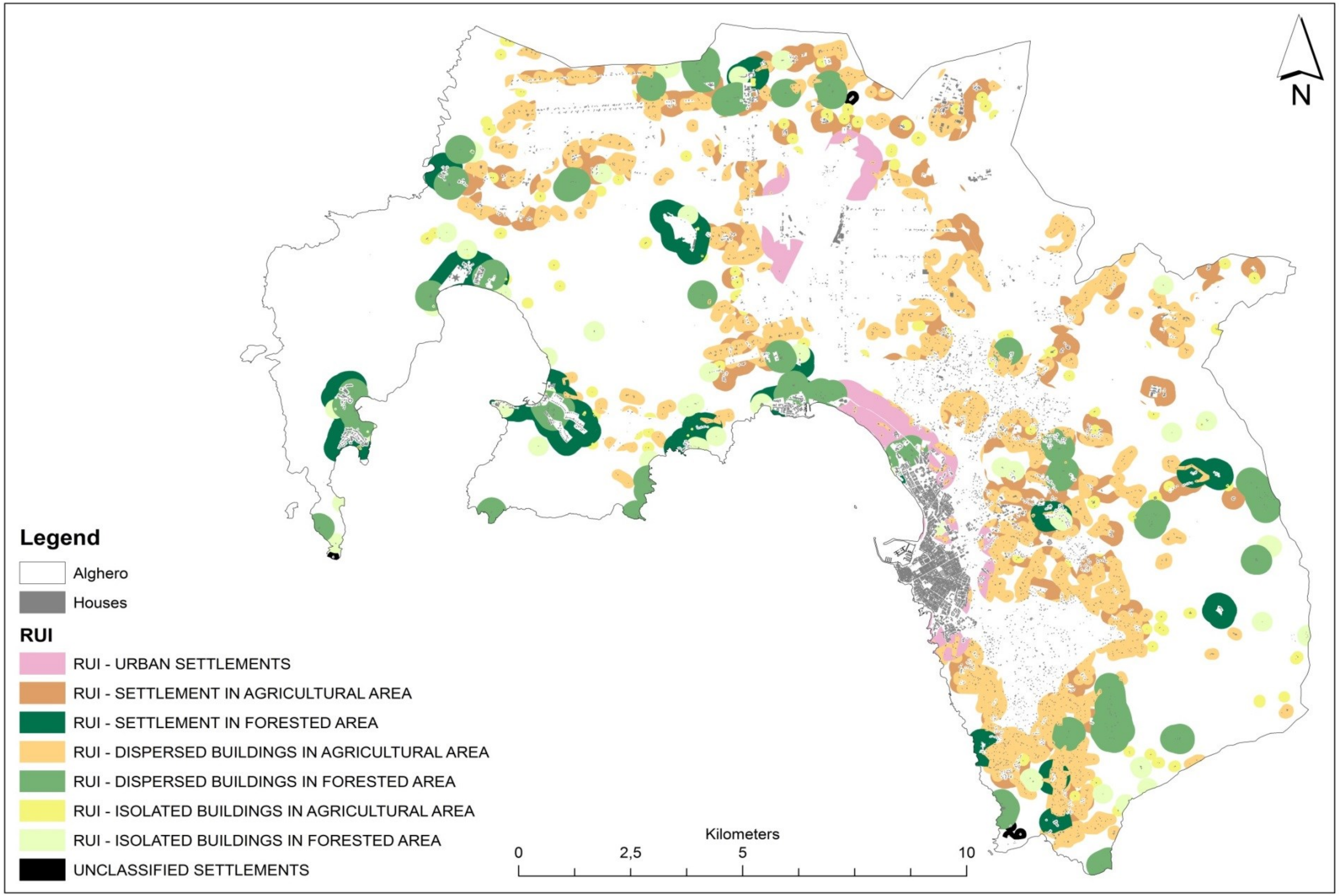

Figure 30. RUI of the Alghero territory calculated using the Local Scale mapping methodology - option 2.

Table 28. Surfaces occupied by each RUI type in Alghero Territory according to Local Scale mapping methodology – option 2

RUI categories	Surface		% of all RUI
	Ha	%	
RUI - URBAN SETTLEMENTS	366.95	1.63	5.18
RUI - SETTLEMENT IN AGRICULTURAL AREA	907.94	4.03	12.83
RUI - SETTLEMENT IN FORESTED AREA	660.96	2.93	9.34
RUI - DISPERSED BUILDINGS IN AGRICULTURAL AREA	2827.11	12.55	39.94
RUI - DISPERSED BUILDINGS IN FORESTED AREA	1356.35	6.02	19.16
RUI - ISOLATED BUILDINGS IN AGRICULTURAL AREA	425.12	1.89	6.01
RUI - ISOLATED BUILDINGS IN FORESTED AREA	534.33	2.37	7.55
RUI areas	7078.76	31.43	100.00
non-RUI areas	15445.57	68.57	
Alghero	**22524.33**		

RUI calculated according to the local methodology option 2, represents the 31.43% of Alghero territory. Although the layer describing the dwelling distribution and land use of Alghero territories were the same, the perimeters of RUI calculated according to the two methodologies differ very much. In particular, the RUI surface classified by local methodology option 2 has a double area if compared with the surface or RUI calculated using local methodology option 1. As already illustrated in the chapter about RUI definition it is not an exceptional fact and it is consistent with other results already published in literature (Stewart et al., 2009)[xxxix], (Rutherford et al., 2010)[xl].

Table 29. Comparison between areas mapped according to the two different Local Scale mapping methodologies on Alghero territory

Area and Percentage of Alghero territory classified as RUI	Area [ha]	% of territory
Areas considered RUI according to Local Scale mapping methodology option 1 and simultaneously non-RUI by Local Scale mapping methodology option 2	879.3	3.90
Areas considered RUI according to Local Scale mapping methodology option 2 and simultaneously non-RUI for Local Scale mapping methodology option 1	4399.3	19.53
Areas considered RUI according to both Local Scale mapping methodologies, option 1 and option 2	2679.5	11.90
Total RUI area according to Local Scale mapping methodology option 2	7078.8	31.43
Total RUI area according to Local Scale mapping methodology option 1	3558.8	15.80
Alghero	**22524.3**	**100.00**

In the Alghero RUI map calculated using Local Scale mapping methodology option 2, the widest RUI areas are occupied by Dispersed Building in Agricultural Areas (almost 40% of RUI surface and 1/8 of all Alghero territory); Dispersed Building in Forested area and Settlement in Agricultural

Area also have a huge diffusion; while both RUI of Isolated Building, Settlement in Forested area and Urban Settlement are the less common RUI types and they occupy little more than ¼ of RUI surface.
Consistently with the Alghero map produced by local methodology option 1 which shows that Dense and Very Dense Housing are not broadly diffused, also with this second approach we find that Dispersed building are much more common than Isolated Buildings and Settlements.

B – studying the geometries of different RUI type to analyse spatial indicators related to fire risk

The local method option 2 does not appear to be suitable for performing the same analysis that was done with maps produced with option 1 on the geometrical parameters A and B that are spatial indicators related to fire risk. Hereafter the definition of A and B is reported:

$$A = \frac{perimeter\ of\ a\ given\ RUI\ class\ polygon}{surface\ of\ houses\ inside\ the\ polygon}$$

$$B = \frac{surface\ of\ a\ given\ RUI\ class\ polygon}{surface\ of\ houses\ inside\ the\ polygon}$$

The Local Scale mapping methodology presents some peculiarities that make it unsuitable for the analysis of the relation between perimeter/surface of RUI and Housing area:

- Houses are not part of RUI which is considered just the buffer surrounding them, and so it is not immediate to be able to simultaneously attribute to one RUI polygon its surface and the housing surface related to the polygon. Besides, when different RUI types buffers overlap each other, one of the two is considered prevalent and because of the different buffer sizes for each type of RUI, sometimes houses are located in the border between two RUI types. Furthermore, sometimes it happens that houses generating a given RUI type are located inside another type and it becomes impossible to univocally attribute it to the right polygon.
- The different buffer sizes defining RUI of each type makes the variables A and B, not very good descriptors for housing exposure (and for difficulty in protecting dwellings against fire). Buffer sizes ranges from 100 to 400 m, but, circles of 100 or 400 m radius are one 16 times bigger than the other (3.14 ha and 50.26 ha respectively since a proportional factor of 4 times in distances becomes its square, 16, for the surfaces). This fact make the methodology not suitable for calculating how much area in the surroundings a house must be managed for the house safety.

  Also if for more complex geometries the proportion lessens the problem of lack of proportionality in RUI surfaces still remains. Taking for instance a single squared house of 10X10 m = 100 m^2, in a case we would have a RUI whose surface would be S_1 = $(\sim 105m)^2 * \pi - 100\ m^2 \approx 3.46$ ha, in the second we would have a RUI whose surface would be $S_2 = (\sim 405m)^2 * \pi - 100\ m^2 \approx 51.53$ ha. Their ratio is not 16 anymore but $S_2/S_1 = 14.9$.

This methodology has not been considered suitable and reliable for this kind of analysis.

C – studying the relation RUI-fire regime

We analyse the fire regime/RUI relation also on RUI of Alghero mapped according to the Local methodology option 2. Like for the Global methodology and the Local methodology option 1, we used the same database of *georeferenced ignition points* and of *georeferenced perimeters of burned areas* as descriptors for fire regime. Data were provided by Sardinian Forest Service (Corpo Forestale e di Vigilanza Ambientale), and the databases we used are:

1. The GPS georeferenced ignition point (database 2005-2010), and 30-50 m precision georeferenced ignition point for the years 1998-2004;
2. The GPS georeferenced perimeters of burned areas (database 2005-2011).

Table 30. Ignition points recorded from 1998 to 2010 in Alghero territory. Distribution inside/outside RUI and per each RUI category of: number of ignitions, percentage on the total number and ignition density

RUI categories	ignitions	%	ignitions/km^2
RUI - URBAN SETTLEMENTS	51	10.43	13.90
RUI - SETTLEMENT IN AGRICULTURAL AREA	30	6.13	3.30
RUI - SETTLEMENT IN FORESTED AREA	30	6.13	4.54
RUI - DISPERSED BUILDINGS IN AGRICULTURAL AREA	56	11.45	1.98
RUI - DISPERSED BUILDINGS IN FORESTED AREA	51	10.43	3.76
RUI - ISOLATED BUILDINGS IN AGRICULTURAL AREA	12	2.45	2.82
RUI - ISOLATED BUILDINGS IN FORESTED AREA	16	3.27	2.99
RUI areas	246	50.31	3.48
non-RUI areas	243	49.69	1.57
Alghero	**489**	**100.00**	**2.17**

RUI Typologies aggregated per Land Use/Land Cover type and Urban Pattern type

Aggregated RUI typologies	ignitions	%	ignitions/km^2
RUI types in Agricultural Area	98.00	20.04	2.36
RUI types in Forested	97.00	19.84	3.80
RUI – Urban Settlement	51.00	10.43	13.90
Settlement RUI types plus Urban Settlement	111.00	22.70	5.73
Settlement RUI types without Urban Settlement	60.00	12.27	3.82
Dispersed Building RUI types	107.00	21.88	2.56
Isolated Building RUI types	28.00	5.73	2.92

In the period 1998-2010, 489 ignitions were recorded in Alghero communal territory, 38 per year, on average.

Analysing their distribution we found that 50.3% has been recorded in RUI while the rest of the territory hosted the remaining 49.7%. Although RUI occupies less than 1/3 of the territory, more than half of the ignition points is located there.

The ignition density is higher in RUI than outside (in RUI 3.47 ignitions/km^2, outside RUI 1.57 ignitions/km^2).

Table 31. Distribution of burned areas inside/outside RUI and values/percentage of burned areas per each category of RUI in Alghero Territory

RUI categories	RUI Area [ha]	Burned Area [ha]	Burned area/ tot burned area [%]	Burned RUI area/ Burned tot RUI [%]	Burned Area/ RUI area [%]
Urban Settlements	366.95	4.33	1.03	4.82	1.18
Settlement in Agricultural Area	907.94	20.13	4.80	22.43	2.22
Settlement in Forested Area	660.96	5.06	1.21	5.64	0.77
Dispersed Buildings in Agricultural Area	2827.11	21.06	5.02	23.47	0.74
Dispersed Buildings in Forested Area	1356.35	18.41	4.39	20.51	1.36
Isolated Buildings in Agricultural Area	425.12	3.89	0.93	4.33	0.92
Isolated Buildings in Forested Area	534.33	16.87	4.02	18.80	3.16
RUI areas	7078.76	89.75	21.40	100.00	1.27
Non-RUI areas	15445.57	329.60	78.60		2.13
Alghero	**22524.33**	**419.34**	**100.00**		**1.86**

RUI Typologies aggregated per Land Use/Land Cover type and Urban Pattern type

Aggregated RUI typologies	Burned Area [ha]	(Burned RUI area/ Burned tot RUI) [%]	(Burned Area/ RUI area) [%]
RUI types in Agricultural Area	45.08	50.23	1.08
RUI types in Forested	40.34	44.95	1.58
RUI – Urban Settlement	4.33	4.82	1.18
Settlement RUI types plus Urban Settlement	29.51	32.88	1.52
Settlement RUI types (no Urban Settlement)	25.19	28.06	1.61
Dispersed Building RUI types	39.47	43.98	0.94
Isolated Building RUI types	20.77	23.14	2.17

Excepting RUI – Dispersed building in Agricultural area (that occupies a very wide surface), all the other categories show values of ignition density that are higher than the territorial average.

Analysing more in detail the differences among categories, we can see that although Urban Settlement is not a very wide area it records the highest ignition density of all RUI categories and one of the highest number of events among all categories. It identifies a particularly interesting portion of territory on which energies and resources can be focalized for prevention purposes; for

instance, not being very wide, it can be the ideal location for prescribed burning or complete underbrush-clearing.
This result appears to be consistent with the exceptionality of RUI type Very Dense Housing with AI Null and Low of maps obtained with local methodology option 1.
Apart from Urban Settlement peculiarity, we can notice that RUI of Settlement types present higher ignition density than Dispersed and Isolated Building, and that RUIs in Forested Areas show a higher density than RUI located in Agricultural Area.
Also maps generated according to the local methodology option 2 are a very good territorial descriptor of Rural Urban Interfaces which are confirmed to be an important phenomenon influencing the ignition point distribution.

In the period 2005-2011, a surface of 4.19 km^2 was burned in Alghero (an average of about 60 ha per year). Since, according to local methodology option 2, 31.43% of the territory is RUI, as expected, we found that the majority of burned areas were recorded in non-RUI areas (329.60 ha meaning 78.6%) and just 89.65 ha (= 21.4%) in RUI. If we consider that from 2005 to 2011, the percentage of burned area for Alghero has been, on an average, 1.86% (2.13 % not in RUI and 1.27% in RUI), we have an ulterior confirmation of what we found in Alghero RUI mapped with local methodology option 1: although RUI has the highest ignition density, fire propagation appear to be less favoured than elsewhere. We must, anyway point out that there are very important differences among RUI types. Settlement in Agricultural Areas and Isolated Building in Forested Area present higher values than the non-RUI areas as much as Isolated Building RUI types when analysing RUI types aggregated per housing macro-categories.
Notwithstanding the RUI type Urban Settlement presents high ignition density, its percentage of burned area is lower than the RUI average.

Also according to this mapping methodology, in Alghero wildfire propagation is higher outside RUI than inside and RUI presence shows to have a strong influence on burned areas. Nevertheless, important differences have been recorded among categories and it is not in all of them that wildfire propagation has very low probability. In particular, consistently with maps realized according to local methodology option 1, RUI of lower density housing (i.e. Isolated Building macro-category) have higher percentage of burned areas.

Table 31. Comparison of ignition density and burned area inside/outside RUI mapped with both Local Scale mapping methodologies, option 1 and 2

	Area [%]		**Ignition density [ignitions/km^2]**		**Burned RUI Area/RUI Area [%]**	
	Option 1	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**
RUI	15.80	31.43	3.40	3.48	0.73	1.27
Non-RUI	84.20	68.57	1.94	1.57	2.07	2.13
Alghero	**100.00**	**100.00**	**2.17**	**2.17**	**1.86**	**1.86**

We found big differences in the sizes of RUI calculated according to the two local methodologies; anyway both of them prove to be able to create maps in which RUI areas record the highest ignition densities and simultaneously a lower percentage of burned areas. If RUI areas are those zones where ignition densities are higher and the presence of people, goods and belonging is conspicuous, it can be crucial for fire prevention to concentrate efforts and resources on these areas and in particular in specific categories of RUI. In Alghero, we found that, mapping the

territory with local methodology option 1, about 25% of the ignitions are located in 15% of the territory constituting RUI, while, mapping the territory with local methodology option 2, more than 50% of ignition points are located in less than 1/3 of the territory.
Categorizing the territory in different way, the use of two methodologies describes the territory in a more complete manner, providing a more accurate knowledge.
They can be used separately, as two valid options to map RUI or they can be used together to obtain a better description of the phenomenon RUI on the territory. They produce consistent results but at the same time each of them adds particular spatial information, and in this sense they can be considered complementary.

Dynamics in RUI – A diachronic analysis on a case study

On Alghero territory, we also performed a diachronic analysis of RUI dynamics at municipality scale to quantitatively assess RUI evolution between 1998 and 2008. The first step was to map the area using both local methodologies option 1 and 2 and creating for each of them, two maps, one relative to year 1998 and another relative to 2008.

Year 1998 Local Scale RUI mapping methodology – option 1	**Year 2008** Local Scale RUI mapping methodology – option 1
Year 1998 Local Scale RUI mapping methodology – option 2	**Year 2008** Local Scale RUI mapping methodology – option 2

RESULTS

This part of the research reports the changes that happened in Alghero RUI area during the ten years 1998-2008.

As already pointed out, since the definitions of RUI in the two methodologies are completely independent, the RUI identified by local methodology option 2 does not correspond to RUI identified with local methodology option 1. Taking a glance at Table 32 and comparing both pairs of maps (relative to 1998 and 2008), it is evident that, the option 2 classifies as RUI a wider part of Alghero territory than the option 1 does (almost the double).

Table 32. Total RUI area in hectares according to the two Local Scale mapping methodologies option 1 and 2 used to map the territory of Alghero

	Local methodology option 1	**Local methodology option 2**	**Ratio (option2/option1)**
1998	2994,30	6459,36	2.16
2008	3558,60	7078,76	1.99

Referring to the following Table 33 and summarising the main results of the trends of RUI area between 1998 and 2008 it can be observed that, with local methodology option 1:

- during the period 1998-2008 the increase of RUI surface has been 18.85%.
- All the RUI categories show an increase in their surface excluding the category Isolated Housing AI Null and Isolated Housing AI High which remained practically stable;
- When typologies are grouped for same Aggregation Index, the relative macro-categories do not show marked differences in the rate of increase (values between 16.89% and 19.64%). But, looking at data grouped for Housing Configuration type, it is evident that there are strong differences among the RUI types with values ranging between 0.31% and 32.43%. In particular, RUIs of Scattered and Dense Housing show the highest expansion rate (see Figures 31 and 32 for details).

Table 33. Dynamics in RUI registered in Alghero territory between 1998 – 2008. RUI calculated according to Local Scale mapping methodology – option 1.

RUI Typologies	Surface 1998 [ha]	Surface 2008 [ha]	Difference 08-98 [ha]	Difference 08-98 [%]
Isolated Housing AI Null	857.42	857.40	-0.02	-0.00
Isolated Housing AI Low	71.01	74.40	3.39	4.77
Isolated Housing AI High	225.15	225.40	0.25	0.11
Scattered Housing AI Null	999.97	1347.30	347.33	34.73
Scattered Housing AI Low	119.94	150.00	30.06	25.06
Scattered Housing AI High	394.72	508.60	113.88	28.85
Dense Housing AI Null	135.85	176.80	40.95	30.15
Dense Housing AI Low	11.37	16.80	5.43	47.71
Dense Housing AI = High	39.58	49.10	9.52	24.07
Very Dense Housing AI Null	31.44	40.80	9.36	29.76
Very Dense Housing AI Low	13.27	13.70	0.43	3.26
Very Dense Housing AI = High	94.58	98.30	3.72	3.93
RUI Typologies aggregated per Land Use/Land Cover type and Urban Pattern type				
RUI in AI Null	2024.68	2422.30	397.62	19.64
RUI in AI Low	215.60	254.90	39.30	18.23
RUI in AI High	754.03	881.40	127.37	16.89
RUI of Isolated Housing	1153.58	1157.20	3.62	0.31
RUI of Scattered housing	1514.63	2005.90	491.27	32.43
RUI of Dense Housing	186.79	242.70	55.91	29.93
RUI of Very Dense Housing	139.29	152.80	13.51	9.70
Total sums				
RUI	2994.30	3558.60	564.30	18.85
Non-RUI	19530.02	18965.73	-564.30	-2.89
ALGHERO	**22524.33**	**22524.33**	**0.00**	**0.00**

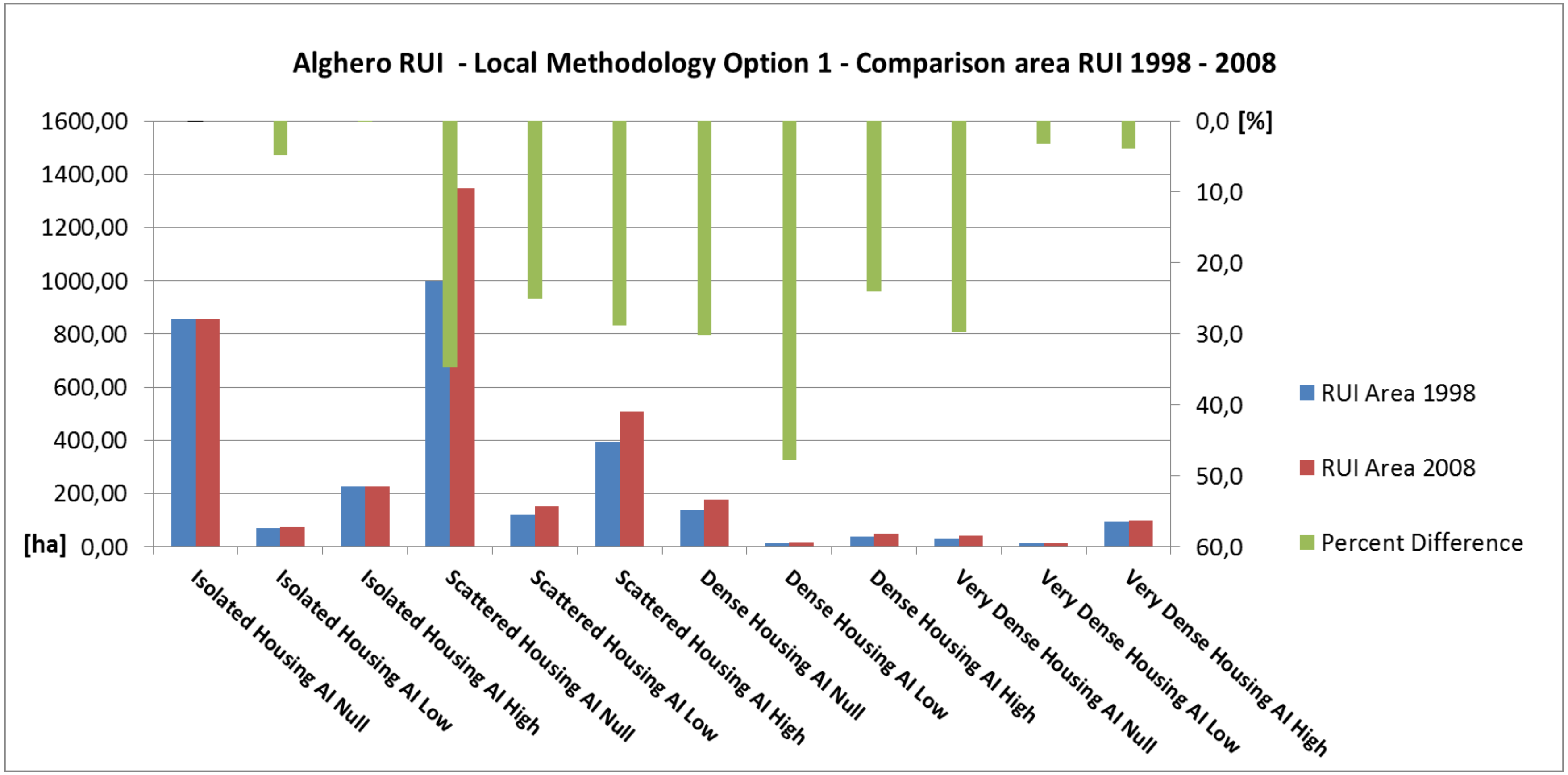

Figure 31. Changes in the RUI surfaces (in hectares) occurred in the Alghero municipality between 1998-2008. RUI is calculated using Local Scale mapping methodology – option 1. In green, the relative differences between 1998 and 2008

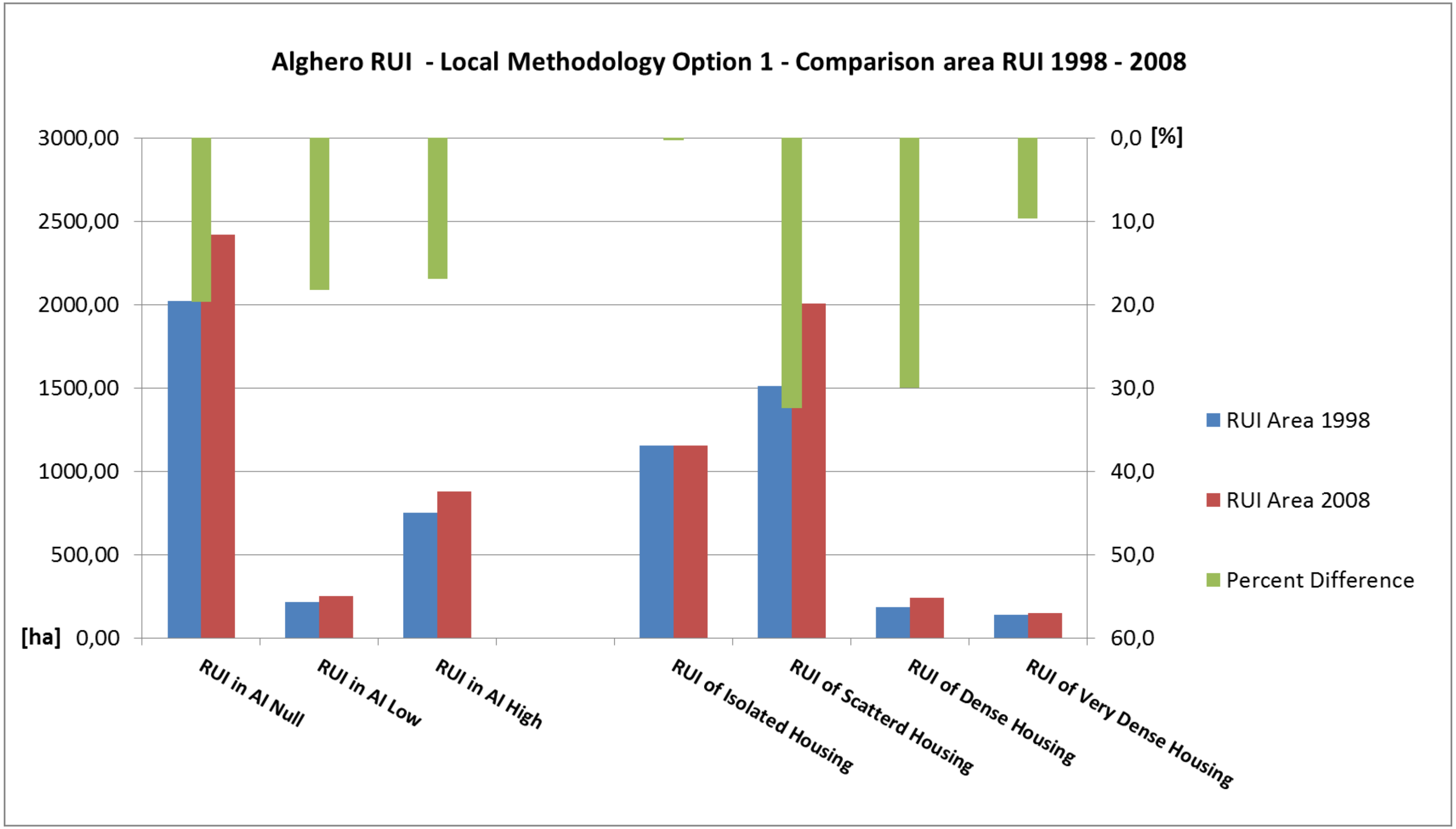

Figure 32. Changes in the RUI surfaces (in hectares) occurred in Alghero municipality during the 1998-2008 period. RUI is calculated using Local Scale mapping methodology – option 1, and RUI types are aggregated per Aggregation Index of Vegetation and per housing density. In green, the relative differences between 1998 and 2008

The same analysis was conducted on the maps produced using the local methodology option 2. Referring to the following Table 34 and to figures number 33 and 34, it can be pointed out that during the ten years 1998-2008 the whole RUI area calculated with local methodology option 2, increased by 9.6%. Illustrating dynamics of single RUI categories, it is easy to notice that:

- RUI Isolated Building in Agricultural Area reduced its surface,
- RUI Isolated Building in Forested Area, Settlements in Forested Area and Urban Settlements, appear to have substantially remained as wide as they were (or show a slight reduction in their surfaces)
- RUI Dispersed Buildings in Forested Area, Dispersed Buildings in Agricultural Area, and Settlement in Agricultural Area increased their surfaces during the examined period.

Aggregating RUI type, data show that while the Isolated Buildings decreased (-8.7%), the Disperse Buildings and the Settlements grew with percentages ranging between 6.6 and 16.4%. Data also reveal that while in Urban context the surfaces of RUIs remained stable, they grew in Agricultural Areas (12.6%) and in Forested Areas (6.4%).

Table 34. RUI dynamics in the Alghero municipality area between 1998 and 2008 observed with the local methodology option 2 mapping

RUI Typology	Area RUI 1998 [ha]	Area RUI 2008 [ha]	Difference 08-98 [ha]	Difference 08-98 [%]
Urban Settlement	367.57	366.95	-0.62	-0.17
Settlement in Agricultural Area	784.29	907.94	123.65	15.77
Settlement in Forested Area	663.91	660.96	-2.95	-0.44
Dispersed Buildings in Agricultural Area	2411.71	2827.11	415.40	17.22
Dispersed Buildings in Forested Area	1181.19	1356.35	175.16	14.83
Isolated Building in Agricultural Area	498.41	425.12	-73.29	-14.70
Isolated Building in Forested Area	552.28	534.33	-17.95	-3.25
RUI Typologies aggregated per Land Use/Land Cover type and Urban Pattern type				
RUI of Isolated Building	1050.69	959.45	-91.24	-8.68
RUI of Dispersed Buildings	3592.90	4183.46	590.56	16.44
RUI of Settlement (no Urban)	1448.20	1568.90	120.70	8.33
RUI of Settlement (with Urban)	1815.77	1935.85	120.08	6.61
RUI in Forested Area	2397.38	2551.64	154.26	6.43
RUI in Agricultural Area	3694.40	4160.17	465.77	12.61
RUI in Urban Area	367.57	366.95	-0.62	-0.17
Total sums				
RUI	6459.36	7078.76	619.40	9.59
Non-RUI	16064.96	15445.57	-619.40	-3.86
ALGHERO	**22524.33**	**22524.33**	**0.00**	**0.00**

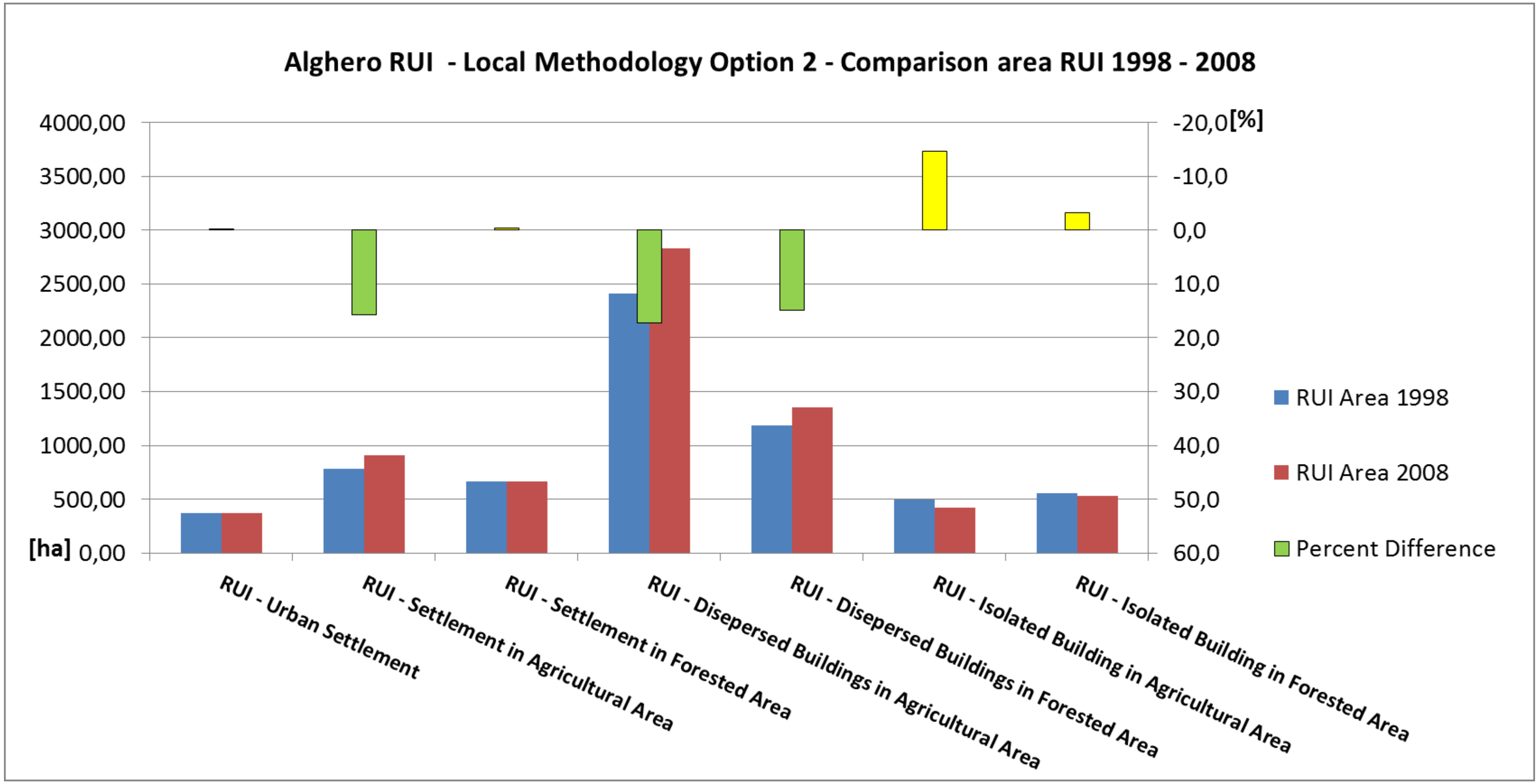

Figure 33. Changes in the RUI surfaces in hectares occurred in the Alghero municipality during the 1998-2008 period. RUI are calculated according to Local Scale mapping methodology – option 2. . In green/yellow, the relative differences between 1998 and 2008

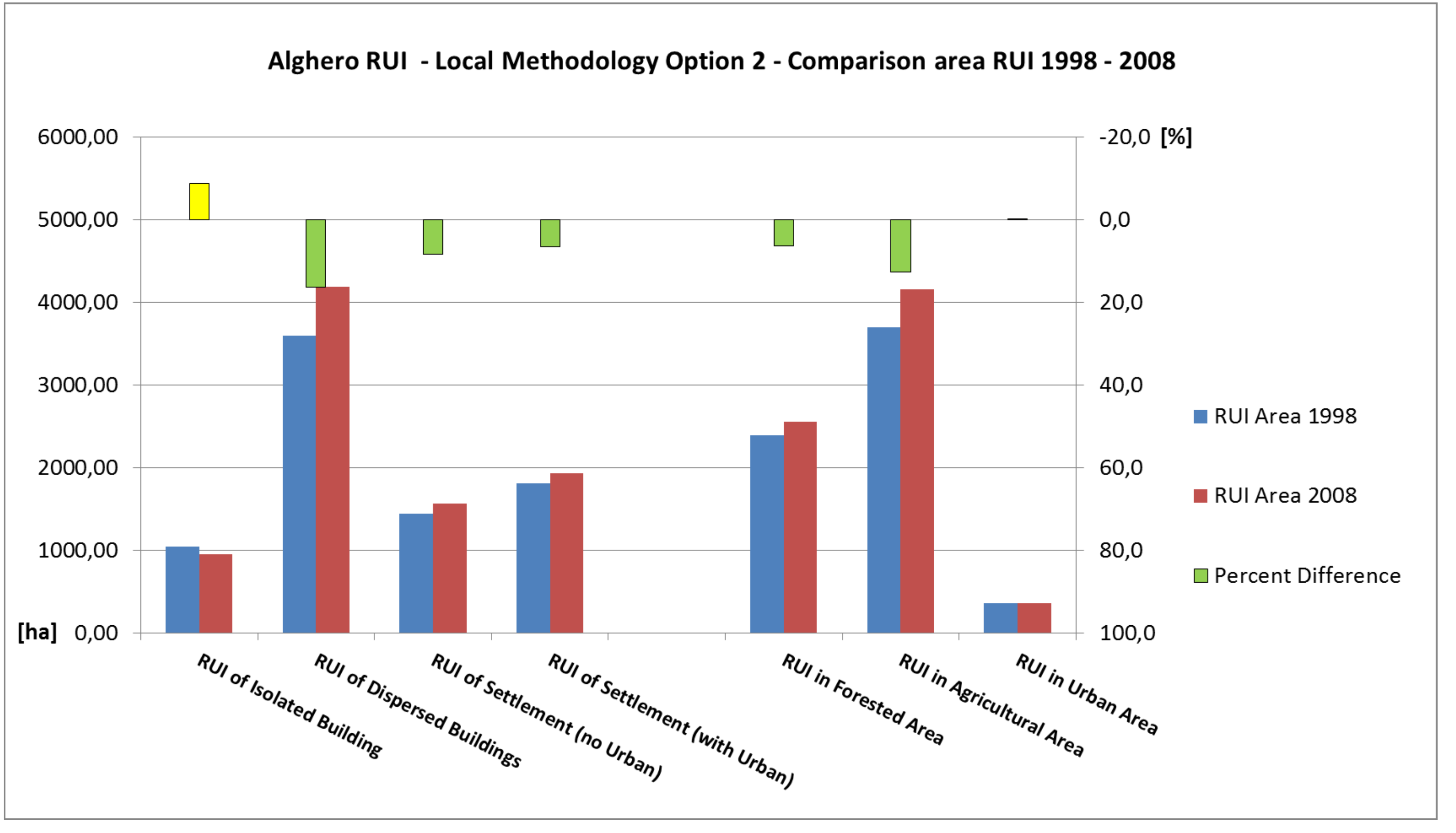

Figure 34. Changes in the RUI surfaces (in hectares) occurred in Alghero municipality during the 1998-2008 period. RUI is calculated using Local Scale mapping methodology – option 2, and RUI types are aggregated per housing type and per environment in which are located. In green/yellow, the relative differences between 1998 and 2008

Part 3: Wildfire Risk Assessment in Rural-Urban Interface

Foreword

Risk, Hazard, Danger, Intensity, Vulnerability – Definitions

The word risk is commonly evocative of fear, damage, and exposure to dangers, and is not a neutral concept because it is, emotively, very intense. To face a risk can, in practice, result in panic and also, to approach the field of risk theoretically, is not easy and emotionally neutral, and it can be difficult to ensure scientific objectiveness.

The story of what the French call "Cindynique", the scientific discipline dealing with risk, has been progressively enriched with theoretical speculation and practical contributions coming from the scientific study of reality. The scientific experience was useful to rigorously define risk from an objective point of view, separating all the emotive resonances and was applied to some calamities like Seveso in Italy (1976) and Bhopal in India (1984), industrial accidents that generated strong debates and contributed towards the development of risk analysis techniques and prevention of damage. Nowadays the approach to risk is objective and rigorous and it has been integrated in almost all national law about risk. A rich law production (for instance, the EU Seveso Directive, received and integrated in all European nations and used as reference point worldwide), rigorously defines what risk is, imposes evaluation and reduction of risks in workplaces, and thanks to it, a general focus on safeness is diffused in all fields. All European countries received the EU directive defining by law the concepts of risk, exposure, risk source, damage, and stating a hierarchy of intervention for risk reduction: firstly, intervention on the risk source, then, protection of the general environment, and finally if no other alternatives are possible, local range protection like wearing individual protection devices.

Not only applied science but also Psychology helped in distinguishing the emotive impact of risk from the objective phenomenon. Psychologists point out that risk is something subjective that is felt and evaluated by people; in particular:

- risks are more tolerable when we voluntarily expose ourselves to them because of the perception of having an internal locus of control and being able to manage the risk (typical example can be considered extreme sports or parachute)
- risk gets more tolerable when we are used to being exposed to them (for example to drive our own car is a typical LowHazard-HighDamage risk)
- risk perception is absolutely not objective: for instance, no person thinks to his/her house as a source of risk, although many people lose their lives and report severe wounds in the kitchen or in the shower. Similarly, surgery is perceived less risky than pesticides while a higher number of people die from surgery than from pesticides. "…Wayne Gretzky principle: our willingness to expose ourselves to danger increases steeply with the potential benefits from the dangerous situation" (Diamond, 2012)[xli].
- Risk perception is strongly influenced by culture. To cross a road with vehicle traffic can be obvious for westerners but can be terrifying for a member of a New Guinean tribe; similarly, for westerners to spend a night alone in the jungle can be perceived as an insurmountably risky situation (Diamond, 2012)[xlii].
- risks are more tolerated when the risk source is completely unmanageable: seismic risk, is more tolerated than flood risk because we are able to forecast meteorological extreme events; wildfires are more tolerated when they are a natural consequence of firestorm and less if they are caused by people; being related to processes completely put up and managed by us, the industrial hazards are less tolerated than natural hazards.

The instinctive emotive reactions to risks are characterized by a binary logic: following our emotions we are driven to consider only the situations in which no negative risky event can happen as positive and safe and, on the contrary, to consider the same happening of the risky event coinciding with the damage itself.

This attitude towards risks loses the possibility of accepting that, although the risk source exists, and a potential negative event occurs, the latter doesn't mean "immediate damage without any possibility of protection" because, actually, the source of risk and the negative event do not coincide with the damage. The emotive approach can hence aim only toward the absence of the risk source. This attitude is particularly common towards wildfires also because the majority of fires are caused by people and, in this sense, the possibility to avoid all fires appears to be achievable.

The duality of this binary logic that thinks in terms of absolutely positive/absolutely negative impedes the description of the real phenomenon and also impedes the ability to cope with the real problem and, finally, it sways from the total powerlessness when the events happen, to the omnipotence of projecting solutions capable of totally avoiding the phenomenon itself. This Boolean attitude is a logic characterized by demonization of wildfires and by total refusal and rejection of them as it was possible to cancel the phenomenon itself; its solution can just be the reduction to zero of wildfire occurrences, which is not a possible solution in real world.

Such a black/white simplified description prevents the reality to present its complexity and its shades of greys about wildfire phenomenon. It is a denial of the naturalness of wildfires that idealizes the total absence of fire (as the only safe condition) and demonizes fires themselves (as if their occurrence is a damage itself). It impedes to deeper understand wildfire as an ecological factor and to cope with the real problems that they can cause.

To consider wildfire as a natural phenomenon and as an ecological factor signifies not to resort to denial; and the fact of not to deny reality, concretely means to do the first step in order to cope with it. The beginning of every solution starts from recognizing wildfires as a real, unavoidable, natural, ecological factor. Once the recognition is given, we can think about how to manage it as a phenomenon inserted in a net of human and natural processes with the goal of reducing damages.

A less instinctive and emotive but richer approach is typical of science and it allowed the scientific community to study fire presence, fire frequency and fire regime evolution (Dubar et al. 1995a)[xliii]. For the Mediterranean basin (Dubar et al. 1995b)[xliv], along the last 10000 years, the presence of fire increased due to agriculture spread, but there is evidence of wildfires (strata of charcoals in soils) since the Miocene. The same existence and diffusion of species like cork oak (Quercus suber), Cistus spp., and serotinous pines demonstrates the influence of fire all along the ecological evolution of fire prone areas.

Although wildfires are dangerous and can cause a lot of damage, they are an unavoidable natural phenomenon. For the last few decades a lot of resources have been invested in wildfire suppression and the surface of burned areas has been reducing. But, at the same time it is becoming more common that suppression crews lose control of a small number of events that then become enormous and unmanageable. It is the effect of fuel accumulation due both to suppression strategies and countryside abandonment. The strategy to avoid all fires finally means just to postpone them because, in the meantime, fuels accumulate and become continuous on the landscape, resulting in more intense and bigger wildfires against which suppression strategies are powerless.

The rejection of fire itself and the idealization of its absence is the root of the diffused distaste against prescribed burning, and tactic fires, of the prohibition law of traditional fire utilization in agriculture/breeding and also of the big investments in air fleet for fire suppression. Similarly, a common idealized conception of nature as “untouched landscape” hinders a rational forestry management based on economic use of forests and reduction of fuels. The deceitful strategy to extinguish all fires comes directly from the instinctive approach of refusing fire and trying to achieve its eradication, but, finally, it is not a successful one.
The occurrence of a fire is not itself a damage, like it can appear if we look at wildfire phenomenon by the Boolean perspective driven by emotive reaction or by the ***all-fire-must-be-extinguished*** paradigm. Fire doesn’t mean *immediate damage* and the absence of fire is not always desired either and above all, is not the only solution to the problem.
The scientific definition of risk helps to think in more complex ways for facing wildfire problems. Its focus is, not only on the risk source (wildfire), but also on goods that are exposed to risk, on their characteristics and on their interaction with the risk source. In this way many strategies to avoid or reduce damage can emerge.

In facts, a more complex definition of risk R applied to wildfire is:

R = P*I*V*W(E)

where :

- R = Risk
- P = Probability of a fire to ignite and propagate
- I = wildfire Intensity
- V = Vulnerability of a good exposed to risk
- W(E) = Value of a good exposed to risk
- (P*I) = H = Hazard

In the present work:

- Hazard is a description of the source of risk in terms of probability and intensity of wildfires.
- Risk is the probable damage that will be suffered by a given good exposed to a given hazard.

The more objective approach to risk offered by science helps to go beyond the unfruitful questions “how can we avoid any risk?”, i.e. “how can we reduce to zero wildfire occurrences”. It is more helpful to ask “how can we act and what can we do to reduce damages?”; and other questions are important if we refer to risk perception and to the economic resources that we must use to face the risks: “how safe is safe enough?”, i.e. “how much can we invest for reducing the risk?”.
The proposed scientific formulation helps in overcoming the Boolean logic that considers the same happening of a wildfire as a fail, as a damage and sees the goodness in its absence. To adopt the scientific formulation of risk means to reason in a more complex way considering the risk as the *possible damage resulting from the interference of the source of risk and the values exposed to it*. What we called “the Boolean logic” considers the risk as the mere probability that a fire arises. In this case the definition of wildfire risk is:
R = P
Risk = probability of a wildfire to ignite and propagate.

This second formulation neglects many of the factors that, on the contrary are taken into account in the first one. To neglect factors like vulnerability of the goods exposed to risk means to hide important parameters on which we can operate to reduce risk and finally means to focus just on fire occurrence aiming to reduce the number of wildfires. Being fire occurrence a parameter on which our influence is limited, if we use the Boolean logic that just focus on avoiding fires ignition and propagation, we are not able to reduce risk and to mitigate the consequences of wildfires. It must be recognized that the real question is not "**if**" a wildfire will happen but "**when**" it is going to happen, and that to extinguish a fire actually means just to postpone it.

The more complex scientific definition as repeated hereafter

R = P*I*V*W(E)

points out many parameters on which we can act having an influence for reducing wildfire risk.
Using this second formulation, it is still true that we can reduce risk acting on the risk source, that is to act on the probability of a wildfire to ignite and propagate; but at the same time it becomes evident that we can also diminish risk by reducing the number of values exposed to wildfire and by increasing their resistance and resilience.
The richness of this formulation of risk concept considers the fire probability as one of its elements, but it also contains other factors including Intensity, Vulnerability and values exposed to risk. It reflects a logic that is more complex than the Boolean one, and through it, the undeniable existence of risks emerges, but at the same time it provides means to study, plan, anticipate and mitigate wildfire consequences. It states the many explicit parameters on which it is possible to really act, getting out of the illusion to cancel the source of risk itself and simultaneously offering possible strategies for defending values and reduce the possible damage in case of wildfire.
The available options for reducing the possible damage caused by wildfire (i.e. the risk of forest fires) can be gathered into six basic groups:

1. Measures acting on the source of risk: we can act on the occurrence P (ignition and propagation probabilities) and on intensity of the event I. Ignition probability can be partially reduced by information/awareness of the population and by penal repression of the arson crime (lightening as a source of wildfire cannot be managed). Propagation can be reduced to some extent by creating fuel brakes (large streets, wide belts of terrain without vegetation or with hydrated vegetation). Forestry techniques and prescribed burning can be used to reduce fuel load and fuel continuity thereby reducing both the propagation probability and the intensity of wildfire and finally containing the severity of damages.
2. Measures aiming to reduce vulnerability V of values at risk; for instance:
   - *Soil*: post-burning immediate intervention or terraced slopes against post-fire soil erosion;
   - *Population*: a network of wide streets with more than one exit allowing evacuation;
   - *Ecosystem*: use of species adapted to fire that are resistant (cork oak) and/or resilient (like re-sprouting broadleaves or serotinous pines that are able to massively reproduce after fire);
   - *Houses*: clearing of first 30 m around the houses, water supply net in case of emergencies, fireproof construction materials.

3. Reduction of the number of elements at risk and of total value exposed to risk W(E); for example the WUI area can be reduced through the densification of settlements;
4. Active extinction techniques: firefighter crews, aircrafts and helicopters;
5. Act on R in order to increase the threshold of acceptable risk by population. Tolerance of risk depends on the awareness of being exposed to it and on the self-involvement in its management which increase the sensation of control on the risky situation (see the fire adapted community experience). In this sense, education and information about wildfire risk and about the inevitability of wildfires on one side and on the other, active involvement of the population in the first-person defence of their property can increase the tolerance to risk and reduce the perception to be at risk, the risk of panic and the feeling of being powerless and can enable the population to be more efficient in facing fires. As learned from psychological analysis, to be involved in the management of the risk that we are exposed to, makes one feel more confident, more efficient and less at risk. It is the principle according to which, during a flight, we are required to fasten the seat belt, to close the little table in front of us and to put the seatback in vertical position. We are required to take those actions that we can do and to participate in our safety. Although they are not the most influential parameters for our safety, it is what we can do in that moment and to accomplish with what we are required to do, reduces the perception to be at risk in that situation and it can sometimes work like an antidote against panic. Similarly, social sciences demonstrate that fire adapted communities feel that they are less at risk and are more effective in defending themselves from the damage that wildfire can cause (Toman et al. 2013)[xlv]. In this sense the policy to completely devolve the defence from wildfire to Civil Protection, aircraft floats and fire-fighters looks to work as an ousting of population from participating in their own safety management, and contributes to create a feeling of powerlessness and resignation in front of an event of fire.
6. Increase the threshold of tolerable residual risk after having done what was reasonably doable to reduce the risk. It can be achieved through a sharing of losses: insurance systems, aid and compensation.

The diffusion of such a conception of risk contributes to its manageability, and in this sense also media can do a lot, for example, by avoiding sentences like “The risk of wildfire occurrence this summer will be high” if what is meant is that the hazard will be high. In such a sentence the conception of risk is merely coincident with the probability of wildfires to happen. It directly locates the audience in that perspective of powerlessness typical of the Boolean logic whose focus is on the risk source and consequently whose only solution is to avoid/demonize all fires. It is because of a simplified conception of risk that to cope with wildfire has progressively meant just to extinguish fires, without an adequate attention on all the other strategies to protect values and increase the resistance in order to reduce damage (i.e. wildfire risk). It is, for instance, different to use the phrase “The risks due to wildfire are high in this area”, in which the definition of risk is not R = P, and hence the conception of risk is not merely the likelihood of fires to happen. In this sentence the word risk means “possible damage” and the focus is not on the risk source but on the values exposed to risk and on the damage they can suffer. There are many more opportunities for protection against the possible damage than against fire occurrence. The concepts of mitigation of risk, defence of exposed values, vulnerability of exposed values and interaction *source-of-risk/value* can be very useful to tackle wildfire problems.

Moreover, going beyond the emotive reaction (i.e. the Boolean logic), it also becomes evident that not all fires are bad fires: low intensity fires (as some natural fires or as prescribed fires conducted in spring), can be easily controlled in case of need, are able to reduce fuel accumulation, to separate canopy and underbrush in a forest, to disconnect landscape patches working as diffused fuel-brakes; they don't damage the seed stock in the soil and can be used as an economic tool to create "passively secured landscapes" preventing the increase of fuel quantity and contiguity.
The number of fires and the burned areas are not good parameters to assess wildfire damage and risk. These descriptors focus on wildfire itself and not on the possible damage that strongly depends on the values exposed to risk. Not all fires are equally damaging and so burned area is a good descriptor of wildfire diffusion but, for sure, wildfire caused damage cannot be modelled using burned areas data. Actually a little fire in WUI can be much more dangerous and detrimental than a bigger one in a grazing area.
According to the scientific risk definition, we must not focus on fire diffusion but, first, we must define what are the values at risk, and then think about their vulnerability, resistance and resilience. Since our possibility to control the hazard itself is limited, we must accept that fires will happen, and if we want to protect a good, we must define it, study its characteristics and its interaction with the source of risk.
Many values are jeopardized by wildfires in RUI: human life (public and firefighters), houses and belongings, economic activities, forests and its products such as economic goods, farms activities (crops, animals).
Although it is not easy to define them and to assess the damage that wildfires cause to them, three other particular elements are exposed to wildfire risk: *soil, ecosystem functionality, atmosphere*.

Soil: the effect of wildfire on soil depends on fire intensity. Wildfires mainly alter the edaphic soil condition, accumulate mineral component reducing the organic one, and expose the soil to direct erosion. The loss of soil mainly depends on the type of soil, on local topographic slope (tilt angle) and on the intensity of first rains immediately after the fire and before that a first grass coverture appears.

Ecosystem functionality: it is difficult to define the health and functionality of an ecosystem and their alterations produced by wildfires. Damage depends on the intensity of wildfire and can vary from the total destruction to the partial alteration of equilibriums and cycles of elements. In general, it can be affirmed that being alive, the ecosystem includes resistance (for instance: vegetal species adapted to fire, or animals – in particular birds – that can escape) and resilience that allows it to recover with time (re-sprouting from coppices after fire, serotinous pines that need fire to open the cones and release the seeds). In living systems, the damage is time-scale dependent since with time they tend to recover, though often with different species.

Atmosphere: the effects of wildfires on the atmosphere are pollution due to smoke and CO_2 release whose consequences are particularly difficult to assess.

Although scientific research has rigorously defined the concept of risk, there is still a lot of confusion in common use of the word risk and about the concept itself. Probably due to the emotive resonance of risk, we commonly register confusion among concepts like hazard, danger, risk, vulnerability, intensity, probability of occurrence, severity and damage.

As mentioned earlier we shall use the word ***hazard*** *to refer to the probabilistic side of wildfire risk, indicating with hazard the probability of a certain event of a given intensity to happen. It can be seen as the characterization of the source of risk. The word* ***risk*** *will be used to designate the probable damage that will be suffered by a given good exposed to a given hazard.*

To define risk we must focus on a given good, on its characteristics (vulnerability, resistance, resilience), and its interaction with the source of risk.
We shall use intensity as an attribute of wildfire (of the source of risk), while severity will be used as an attribute of the damage suffered by goods.
In 1977 USGS defined "geological danger" as every event or process that is potentially able to threaten health, sureness and wellness of a community, while in the UNESCO report Varnes (1984)[xlvi] abandoned the concept of danger and stated for the first time the more objective concept of hazard: hazard describes the source of risk without referring to the concept of damage and loss, that is, without evoking all the emotive negative background associated with it.
This change can be seen as a step towards the objective and rigorous description of risk that does not consider the event immediately as the damage, and that, on the contrary, describes the whole chain of different interactions that connect the cause (the wildfire) to the effect (the damage). Risk is the conjunction of two components: the event on one side (described in terms of probability and intensity) and the good on the other (described in terms of value, vulnerability, resistance, resilience). This innovative (for 1984) approach helped to separate the emotive resonances of damage from the event itself and was the base to realize objective analysis of risk. It can be considered in some way similar to the adoption of the Richter scale instead of the Mercalli scale to assess seismic intensities of earthquakes. The focus of Mercalli scale is on damage and it is through it that the earthquake magnitude is assessed, while the Richter scale directly assesses the magnitude of the seismic event through the measure of the seismic wave amplitude that is strictly bound to the emitted energy.
Although it is still commonly used in literature, we will not utilize the word and the concept of danger because it is not emotionally neutral and in our schema it is located between hazard and damage, and can be confusing after the definition of hazard, appeared in 1984.
Although our formulation of risk is a complete description of the incidental scenario, and permits to clarify the whole chain from the cause (the wildfire) to the effect (the damage), it can be considered a particular mathematical formulation of risk among many possible ones, in which factors can be summed and multiplied and can present different exponents that differentiate the importance of each risk component.
The most used formulation is the arithmetical product of all factors intervening in risk, and only sometimes different exponents are used to stress the importance of some of the factors.
In Italy, it is common to adopt a neutral formulation such as:

$$R = (P*I)*[V*W(E)]^k$$

in which k is equal to 1.
If $k = 1$ the expression defining risk becomes implicitly neutral regarding each of the component of risk. Risk is a simple product of terms with same exponent. This mathematical form assigns the same risk to different kinds of situations: for instance a probable event that is not very damaging can be equivalent to a very damaging but very rare event.
The decision about the value of the exponent is not a technical one, it is exquisitely political: for instance in Holland people tend to consider **high hazard – low damage risks** more tolerable than **low hazard – high damage risks** and, hence, in Dutch laws, $k = 2$. If $k = 2$, the formulation of risk is

not neutral and the risk assigned to high damage risk scenarios is higher than the one assigned to low damage risky situations, notwithstanding the fact that the latter can be more probable.
Using this formulation of risk the focus is on high damaging events however rare they are.
The study of risk is intrinsically multidisciplinary and, as the existence of the French “cindynique science” shows, it is also transdisciplinary:

- technical criteria are used to describe the source of risks;
- the value of goods exposed to risk is assigned through socio-economic methodologies;
- the perception of risk is studied by psycho-social disciplines;
- and finally planning and territorial management is part of the political sphere.

White et al. stated (White et al., 1992)[xlvii]: “Traditionally natural sciences are concerned with the natural environment. Social sciences and applied sciences with the socio-economic environment. In reality these two components of our environment are inseparable; the natural environment cannot be fully understood in isolation from us and our interactions with it”.

The wildfire risk assessment in Rural-Urban Interfaces is particularly complicated because of the high number and of the different kinds of exposed values, because of the extremely various connection patterns of vegetation patches and because of the presence of many local factors (like irrigated gardens, brush-cleaned zones, water supply in case of alarm etc.) that can greatly influence fire propagation but, at the same time, are not easy to be taken into account.
In the present work, the results of the application of three different methodologies for wildfire risk assessment are presented. The three techniques are completely diverse. Each of them has a different focus on the phenomenon and a different approach to it. Their application aims to contribute to get a better evaluation of wildfire risk, through comparisons and integration, and through the evidence of consistencies and dissimilarities.

1. A first one can be defined as a classical ***overlay mapping*** process in which different parameters involved in the phenomenon are mapped and simply summed in a GIS environment. It can be considered an easy approach that takes into account what scientific literature considers the principal risk factors. It produces maps that, according to the definition we just gave, are not rigorously “risk maps”. Nevertheless they can be considered risk maps because they are useful to distinguish among RUI that are likely to report different damage for wildfire.
2. A second approach is a ***Multicriteria*** one, based on formalization of experts’ knowledge about the phenomenon.
3. A third one, we shall call it ***Multi-simulation*** approach, uses a wildfire propagation simulator. Running 100,000 simulations of wildfires we are able to see which pixels are more probable to burn and with what intensity. Through the multi-simulation the hazard (probability and intensity of wildfires) can be evaluated, pixel by pixel. The kind of RUI maps we developed are a combination of two factors: housing/settlement type and descriptors of the environment in which urban structures are located. They present two spatial distributions on the territory: on one side the distribution of values exposed to risk, and on the other the one of the environments in which they are located (forested, agricultural, urban etc.) which can be considered a coarse approximation of the vulnerability of values. Crossing the hazard map obtained with the fire simulator with the RUI maps, we have all the elements taken into account by our definition of risk
R = P*I*V*W(E).

In order to get a better local evaluation of risk, a deeper knowledge of each good exposed to risk must be gathered (constructive material of dwelling, irrigation or emergency water supply, Brush-Clearing of building surroundings etc.).

Part 3: Wildfire Risk Assessment in Rural-Urban Interface

Materials and Methods

Overlay Mapping methodology for wildfire risk assessment

Among the three methodologies that we use to assess wildfire risk in RUI, the Overlay Mapping Methodology can be considered the most intuitive and simple.

The process we used is based on a methodology developed by Tragsatec (Spain) and the proposed spatial analysis approach has been thought to be easy to apply at regional scale. It takes into account those factors that literature considers to be the most important ones in wildfire risk evaluation.

We applied the Overlay Mapping methodology for wildfire risk assessment to Alghero municipality.

In this methodology the final risk is calculated combining the following spatial main components of risk:

- Demographic Risk Factor Map;
- Propagation Risk Factor Map;
- Statistic Risk Factor Map.

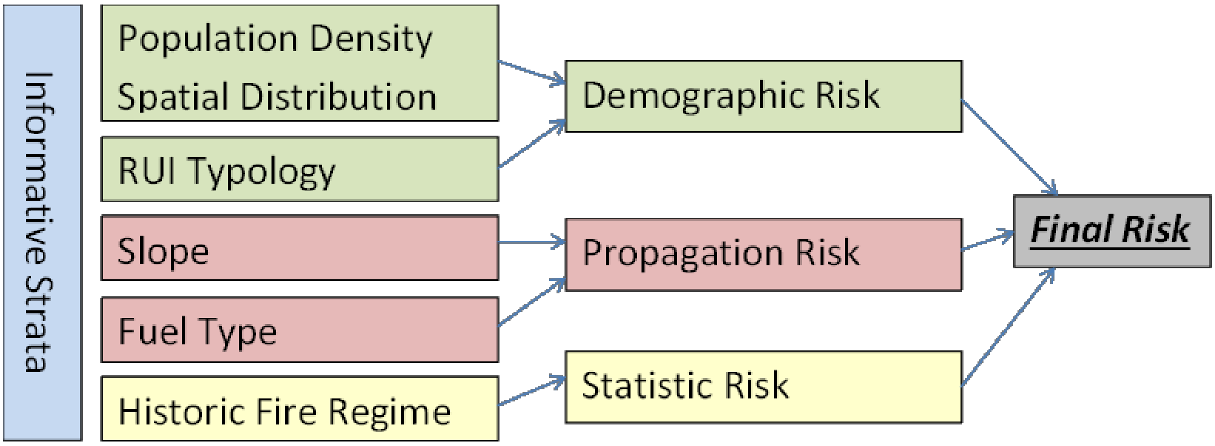

Figure 35. Schematic diagram of flux of wildfire risk assessment according to the Overlay Mapping methodology.

The three components of risk must be calculated according to the schema in the image.

The Statistic Risk Factor Map must be calculated using fire regime data: in particular, we created a raster map in which the value in the pixels was assigned according to how many times they had burned:

- PIXEL VALUE = 1; not burned – low frequency,
- PIXEL VALUE = 2; burned once – medium frequency,
- PIXEL VALUE = 3; burned more than once – high frequency.

Historical forest fires	*Statistical Risk*	*value*
3 or 2 forest fires	HIGH	3
1 forest fire	MODERATE	2
No forest fires	LOW	1

Figure 36. Statistic risk factor. Matrix of risk levels according to the frequency of burning

The Propagation Risk Factor Map is the combination of two other maps, the Fuel Type Risk Factor Map and the Slope Risk Factor Map.
The Fuel Type Risk Factor Map has been calculated through a reclassification of the Land Use Map available at the Official Site of the Regione Autonoma della Sardegna, at the URL
http://www.sardegnageoportale.it/catalogodati/download/
In particular, the land use types were reclassified according to the table in figure 37.

Mixed forest	HIGH	3
Conifer forest	HIGH	3
Shrubs with scattered trees (Transitional woodlands)	HIGH	3
Moors and heathlands	HIGH	3
Sclerophyllous vegetation	HIGH	3
Burnt areas	HIGH	3
Agriculture with natural vegetation	MODERATE	2
Herbaceous vegetation	MODERATE	2
Broadleaves forest	MODERATE	2
Agriculture-crops	LOW	1
Agriculture-trees	LOW	1
Agroforestry	LOW	1
Urban with vegetation	VERY LOW	0
Open spaces	VERY LOW	0
Artificial	VERY LOW	0
Wetlands	VERY LOW	0
Water bodies	VERY LOW	0

Figure 37.Fuel Type risk factor. Matrix of risk levels according to the vegetation type

The Slope Risk Factor Map has been created starting from the DTEM file available at the same URL of the Official Site of Regione Autonoma della Sardegna (http://www.sardegnageoportale.it/catalogodati/download/)
We created a raster whose pixel values 3, 2, 1, have been assigned according to the table reported in figure 38.

Slope	Slope Risk	value
≥ 30%	HIGH	3
16-29%	MODERATE	2
≤ 15%	LOW	1

Figure 38. Slope risk factor. Matrix of risk levels according to the tilt angle

The two latter maps (Slope Map and Fuel Type Map) were then combined to create the Propagation Risk Factor Map according to the matrix reported in figure 39.

Propagation risk	Slope Risk		
Fuel risk	3	2	1
3	3	3	2
2	3	2	2
1	2	2	1
0	2	1	1

Figure 39. Propagation risk factor. Matrix for combining Slope and Fuel Type risk factor values

<u>The Demographic Risk Map</u> is created combining two other maps: RUI Risk Factor Map, and Population Risk Factor Map.

The RUI Risk Factor Map is a reclassification of the RUI map obtained with the Local Scale Mapping Methodology option 2. To reclassify the map the table reported in figure 40 has been used.

RUI type	RUI Risk	value
RUI urban settlement	MODERATE	2
RUI settlement in forested area	HIGH	3
RUI settlement in agricultural area	LOW	1
RUI dispersed buildings in forested area	HIGH	3
RUI dispersed buildings in agricultural area	LOW	1
RUI isolated buildings in forested area	MODERATE	2
RUI isolated buildings in agricultural area	LOW	1

Figure 40. RUI risk factor. Matrix of risk levels according to RUI typology.

The Population Risk Factor Map has been calculated spatialising the numerical data of Official Italian Census (available at the site http://demo.istat.it/pop2012/index3.html) that are available at communal level. Residents' number has been considered to be proportional to the m^2 of built surface, and population density was, hence, spatialised through the use of the housing layer. This intermediate map has been resampled to 100X100 m pixel and reclassified according to the table in figure 41 to obtain the Population Risk Factor Map.

Population	*Population Risk*	*value*
<50	LOW	1
51-500	MODERATE	2
≥ 501	HIGH	3

Figure 41. Population risk factor. Matrix of risk levels according to population density.

Finally the Population Risk Factor Map and the RUI Type Risk Factor Map have been combined to create the Demographic Risk Factor Map according to the matrix in figure 42.

Demographic risk	*Population Risk*		
RUI risk	3	2	1
3	3	3	2
2	3	2	2
1	2	2	1

Figure 42. Demographic risk factor. Matrix for combining Population and RUI type risk factor values

Once we created the three needed maps (Demographic Risk Factor Map, Propagation Risk Factor Map and Statistic Risk Factor Map), we combined them using the table in figure 44 to produce the **Final Risk Map**.

The final output of the process classifies the RUI area into three classes of risk, high, moderate and low.

3	High
2	Moderate
1	Low

Figure 43. Final risk levels

demographic risk	propagation risk	statistical risk	FINAL RISK
3	3	3	3
3	2	3	3
3	3	2	3
3	1	3	3
3	3	1	3
3	2	2	2
3	1	1	1
3	2	1	2
3	1	2	2
2	3	3	3
2	2	3	2
2	3	2	2
2	1	3	2
2	3	1	2
2	2	2	2
2	1	1	1
2	2	1	1
2	1	2	1
1	3	3	3
1	2	3	2
1	3	2	2
1	1	3	1
1	3	1	1
1	2	2	1
1	1	1	1
1	2	1	1
1	1	2	1

Figure 44. Final risk. Matrix for calculating the final risk combining the values of Demographic, Statistic and Propagation risk factors

Although the required inputs were mostly in vector format, we implemented the whole procedure on GIS, using the raster calculator functions and our outputs are in raster format with a resolution of 100X100 m.

Table 35. Input files required by the Overlay Mapping methodology for wildfire risk assessment in RUI

Input	Source	Format
RUI map (Local Scale Mapping Methodology option 2)	Self-created	Vector
Population density and distribution	ISTAT Official Site (http://demo.istat.it/pop2012/index3.html)	Numerical data to be spatialised
Wildfire historic spatial statistics (Burned areas)	Regione Autonoma della Sardegna Official Site (http://www.sardegnageoportale.it/catalogodati/download/)	Vector
Digital Elevation Model	Regione Autonoma della Sardegna Official Site (http://www.sardegnageoportale.it/catalogodati/download/)	Numerical raster
Fuel model from LULC map	Regione Autonoma della Sardegna Official Site (http://www.sardegnageoportale.it/catalogodati/download/)	Vector

The overlay mapping model has been applied on Alghero territory and the results are presented in the corresponding section Results of the Part 3.

Multicriteria methodology for wildfire risk assessment

During the ‘70s of XX° century, Operational Research (at the time it was a recently born Mathematic discipline whose interest is in applying analytic methodologies to better make decisions) was developing new approaches to provide Decision Support Aids (DSA) to decision-makers. Many environmental problems were arising and planners were beginning to feel the necessity to assess simultaneously the benefit of realising a project (a water dam, a thermoelectric power generator etc.) together with its environmental impact. Decision makers often have to choose among different actions that could be operated on a territory and the DSA is a typical resource for Planning, that:

- Details the current situation considered in terms of resources available and probable constraints;
- Lists all possible action describing their technical implementation and their probable consequences on the territorial equilibrium;
- Analyses and defines the desired final situation in terms of aims and possibilities;
- Assesses for each action, its suitability/adequacy to reach the desired situation and its sustainability;
- Describes the processes in course on the territory for assessing how, each of the option can interfere with them.

Roy 1985[xlviii]: *«l'aide à la décision est l'activité de celui qui, prenant appui sur des modèles clairement explicités mais non nécessairement complètement formalisés, aide à obtenir des éléments de réponses aux questions que se pose un intervenant dans un processus de décision, éléments concourant à éclairer la décision et normalement à prescrire, ou simplement à favoriser, un comportement de nature à accroître la cohérence entre l'évolution du processus d'une part, les objectifs et le système de valeurs au service desquels cet intervenant se trouve placé d'autre part»*. *[the translation is mine: the decision support is the activity of the one who, using models clearly explained but not necessarily completely formalized, helps to obtain elements for answering to issues that a player in a decision process has to face. Elements contribute to inform the decision and usually also to prescribe (or simply to promote), a kind of behaviour aiming to improve the coherence between the evolution of the process on one hand, and, on the other, the objectives and the system of values in which the actor is placed].*

Decision Support Aids contribute to objective knowledge and awareness of all players in a decision process.

For complex decisions, typically, the possible actions have a set of positive and negative consequences on many different fields; many point of view are possible and the decision depends on the territorial “systems of values” according to which the inhabitants of the territory rank differently the various consequences. In this condition the decision is particularly difficult and it becomes merely political. The planner is required to be aware and to make explicit a schema of:

- The system of natural processes in the territory;
- The positive and negative important factors to be taken into account for assessing the options;
- Expectations of people, stakeholders, administrator and all actors involved in the decision process.

Interviews to population and administrators, stakeholders and all actors of the decision context, must be conducted to model the preferences, the system of values, the future situation as desired by the territory.
The Multicriteria Methodology has been developed for such a complex decisions in the last seventies of XX° century.
According to P. Vincke (1989)[xlix], Multi-Criteria Decision Analysis aims to provide, to decision makers, supports capable to make them advancing in solving the decision problem where several points of view, often contradictory ones, must be taken into account.
Typically, the usefulness of DSA like Multicriteria Methodology aims to clarify three levels for simplifying the decision and provides:

- a deep knowledge of the territory and of natural/social processes acting in it;
- an analysis of the possible positive and negative consequences of each option, its costs, its benefices;
- a description of all actors' expectations (population, stakeholders, administrators etc.), their preferences about the future, their system of values and priorities.

Usually the present situation is described putting on evidence resources and constraints, while the future is modelled in terms of aims, expectation of stakeholders and possibilities offered by the context.

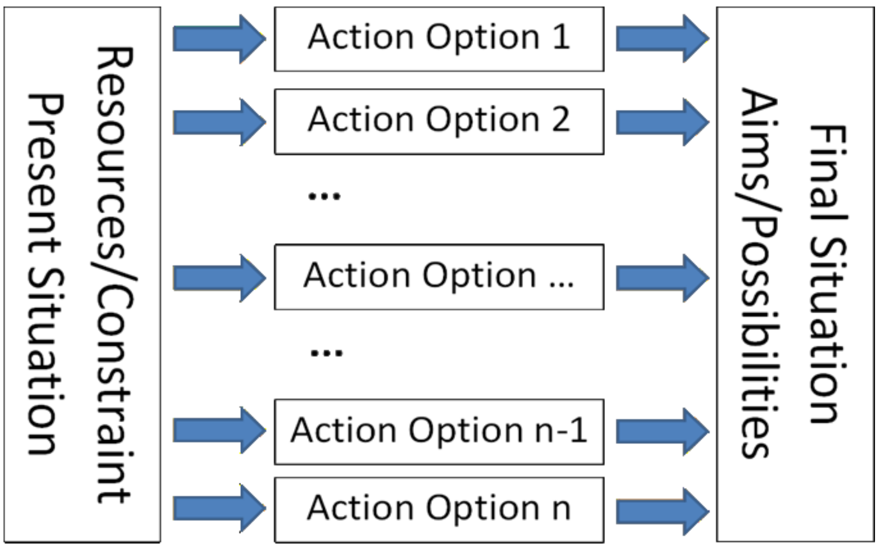

Figure 45. Schematic representation of the context in which a Decision Support Aid is typically used

The various planning choices, including the option "zero" (not to do anything), are studied relatively to the possible consequences on the specific territory. All the effects on the net of on-going processes in the territory are analysed. According to the relative importance that population (or stakeholders) gives to the various factor on which the project will impact, it is then possible to rank the options.
A very useful methodology to take into account the expectation of population, to detail the knowledge of all the possible alternatives and to describe their effect on the territory is the Analytic Hierarchy Process (AHP), a strictly analytic methodology that creates a hierarchy of criteria and sub-criteria suitable for describing the territory as a system and for assessing the options and their consequences.
AHP was developed by T. L. Saaty[l], and it is also known as Saaty method.

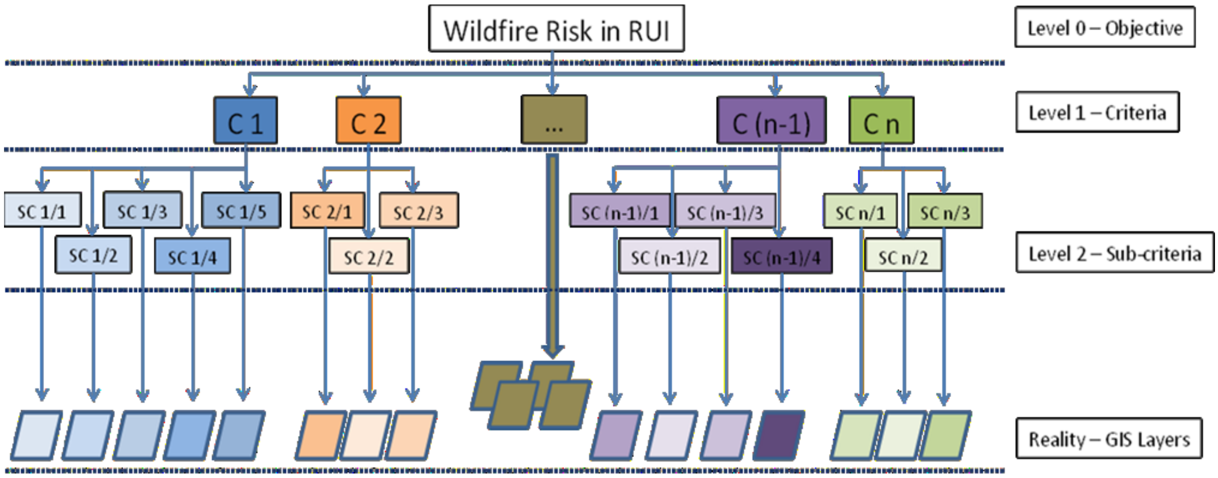

Figure 46. Organization into criteria and sub-criteria of the factors influencing wildfire risk in RUI

Its popularity is due to many aspects:

- It can manage qualitative and quantitative, relative and absolute variables;
- Its hierarchic structure permits to sub-divide the process into components that are easier to handle, understand and judge;
- It provides a complete structure through which the territory (i.e. each pixel) can be assessed, getting to a value for each portion of the territory;
- It provides a value of importance of criteria and of sub-criteria relatively to criteria. The provided value is called "weight of the criteria";
- Its suitability for many kind of decision problems and modelling.

The use of AHP in Territorial Planning is hence useful for:

- Identifying the relevant factors capable to describe the natural/socio-economic functionality of the territory and to organize them into a schema in which each of them corresponds to a criteria (or sub-criteria); actually the factors work as criteria upon which the decision is made;
- Describing the expectation of population and stakeholders on the territory and defining of the system of values in the local culture;
- Detailing the positive/negative consequences that each of the proposed action will have on the territory and inform the decision.

If, for instance, we must decide about the construction of a wind farm of N electric generators, we must take into account many factors. Among the criteria for describing the situation and informing the decision there will be:

- The visual impact (with sub-criteria that take into account colours, number of propeller blade, distance from the ridge, size);
- The impact on aquifers of the foundation (with sub-criteria taking into account depth, width, distance between two generators);
- The productivity (with sub-criteria taking into account, the yield of each generator, the total productivity of the farm, the income for the local population);
- and many other issues involving positive or negative consequences to be detailed with the sub-criteria.

Imagining the concrete situation, we can be required to compare three different projects and the option zero (not to do any wind farm). In the various concrete projects, number, height, distance, exposition, visibility, productivity etc. of the wind generators can be different and, according to economic/ecologic orientation of the local system of values and expectation, a project can be judged better than another.

AHP is capable to describe the factors that the population considers the most important, to describe the processes in the territory and the interactions that each proposed action on the territory would have. The resources that AHP uses to get to the assessment of each action consequence on each factor/criteria are: **reasoned flowchart** of criteria and subcriteria describing territorial functionality, **interview** to population and stakeholders to rank the importance of each factor/criteria, **mathematic treatment of the information** gathered through the interviews to get to the importance of factors.

It finally assigns a score (or a judgment) to all the action for each of the criteria and sub-criteria and, through this procedure, it is possible not only to better describe the matter of decision but also to select the best option.

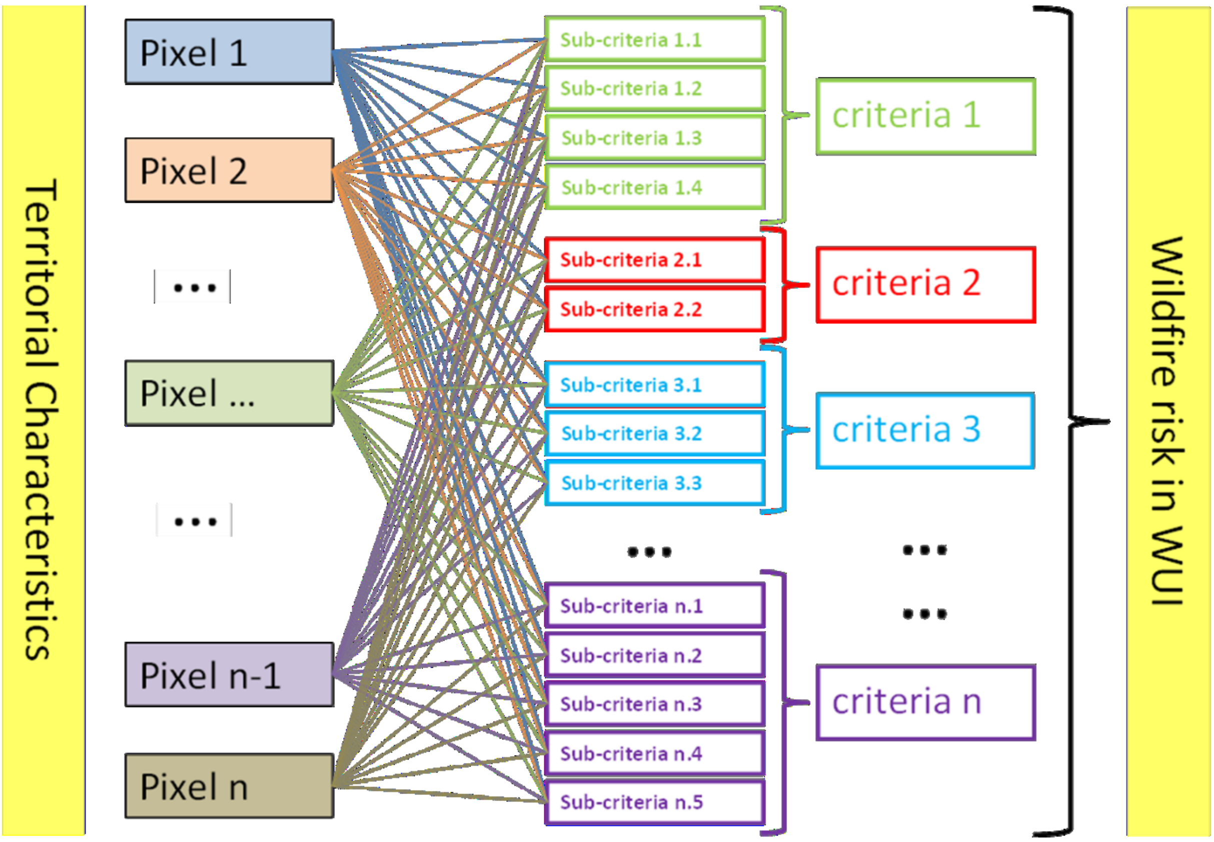

Figure 47. Schematic representation of the theoretical structure that AHP details to get to Wildfire Risk Assessment.

In facts, Multicriteria Decision Analysis can be oriented to:

1. Describe the choices, presenting a systematic and formalized description of alternatives and their consequences aiming to improve knowledge and awareness of the decision maker;
2. Evaluate all different choices and categorize all of them as “certainly good”, “probably satisfying”, and “surely bad”;
3. Rank the choices giving an order of preference/usefulness;
4. Put on evidence just the definitely best choice.

Excepting the first one, the other three points require quantitative/numerical approach and many methodologies were developed (especially matrix calculation methods), to quantitatively treat the information acquired with the interviews, and to, finally, get to a quantitative system of evaluation by which the different possible actions can be judged.

Historically, matrix calculation for quantitative approach in multicriteria decision support, and interview to experts have been main innovations in Operational Research field. After having been developed, they have been recognized to be not only useful for optimizing the decision processes, but also in other fields, for example for modelling various phenomena. Multicriteria approach can, hence, be considered very useful also for our purposes since it helps us to create a model to assess the wildfire risk on the land.

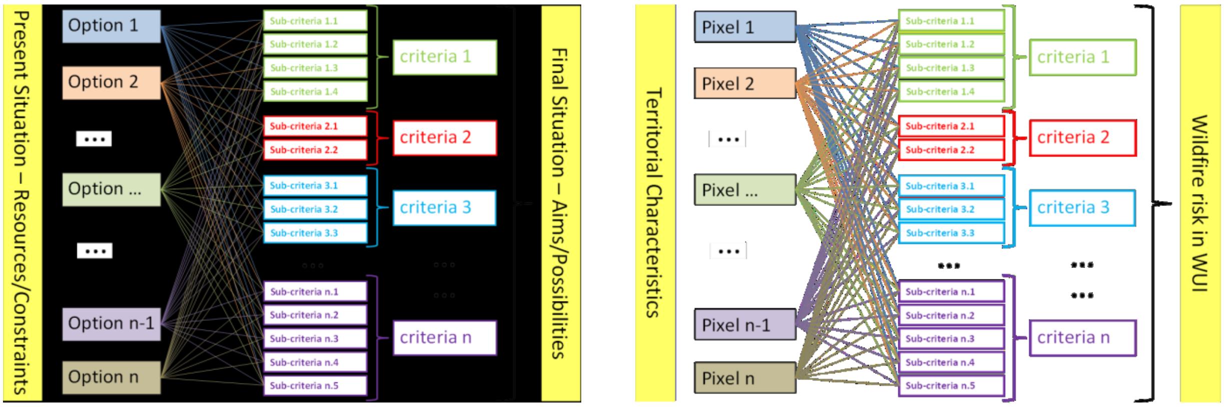

Figure 48. Comparison of the schematic flow charts of two uses of AHP: in Planning for the choice among different possible options and in our case for Wildfire Risk Assessment in RUI

Table 36. schematic comparison between two uses of Analytic Hierarchy Process

DSA	Wildfire risk assessment in RUI
Projects of possible actions on the territory	Pixel
Project characteristics evaluated using the identified criteria	Pixel values for each the relevant factors for wildfire phenomenon
Criteria and sub-criteria according to which the projects are assessed	Risk factors involved in wildfire phenomenon in RUI and used to evaluate the pixels
Interviews to model the relative importance of each criteria taken into account to evaluate the possible actions on the territory	Interviews to expert to assign a relative importance to the factors involved in wildfire phenomenon in RUI environment
Mathematical treatment of the information gathered through interviews (analysis of judgment coherence, definition of the relative weights etc.)	Mathematical techniques for the treatment of the information gathered through the interviews are exactly the same

The figure 48 and the table 36 illustrate the similarities that are presented by the application of AHP in Planning as DSA and in our case of multicriteria modelling for wildfire risk assessment. What, in the DSA schema, are the options to be assessed (the different proposed projects), in our schema are the pixels: both of them will receive a value that in the first case will be a score for the project while in our case will be the value of the local risk. Pixels are portions of territory whose local characteristics are different and can be described, represented and managed through the

use of a GIS. Each pixel is characterized by different configuration (a certain slope, density of ignition, exposition, density of population, presence of houses etc.). The effects on risk of its characteristics can be assessed thanks to the AHP construction of a hierarchy of criteria and sub-criteria corresponding to a model for the factors involved in wildfire phenomenon, factors that must be taken into account for wildfire risk assessment in WUI.
Once that the territorial model is structured into a schema that organizes all factors into criteria and sub-criteria, the technique prescribes to determine their weighs through interview to population that is required to express judgments of preference in all presented comparisons between two criteria (or sub-criteria).
Similarly, once that wildfire risk in RUI is modelled into a schema that organizes all involved factors into criteria and sub-criteria, the technique prescribes to determine their weighs through interview to experts, who are required to express judgments of preference in all presented comparisons between two criteria (or sub-criteria).
In the case of Decision Support Aids (DSA), the interviews are used to formalize the knowledge about the territorial expectation and the "system of values", and hence to assign an importance to each of the selected factors that we are using to evaluate the different options. In our case, interviews conducted with experts on Wildfire Risk in RUI are used to assign a value to each criteria and sub-criteria taken into account as wildfire risk factor.
In the first case interviews permit to formalize the system of values of population while in our case they are used to formalize the intuitive practical knowledge that the experts have about wildfire risk in RUI by their experience. Through interviews and mathematical treatment of the information we are able to model their untaught knowledge, their heuristics, and their practical patrimony of praxis selected by experience.
The same mathematical techniques that were developed to assign a weight to each factor of the DSA model, in our case, are used to assign a weight to each of the various factor of risk. This way, we are able to fully determine the model of wildfire risk assessment and to have a complete model with weighted criteria that can be used to evaluate local riskiness of each pixel on the territory.
The techniques developed for planning decision support (interviews and mathematical treatment of information) are actually useful to create a model for wildfire risk assessment in RUI. The final schema is a theoretical construction which models the representation of the phenomenon that experts have. It can hence be considered an "indirect" way to model the wildfire risk in RUI because it is mediate by experts' representation of the phenomenon.

Using the Analytic Hierarchy Process (AHP), we first created a coherent model organized into criteria and sub-criteria, then, by conducting interviews and by mathematical treating of the gathered information, we defined the weights for refining the model.
Many kind of composition of criteria are possible to get to the objective, but the most frequent one is the weighted sum which permits to produce an extensive, consistent, not redundant and coherent description.
The weighted sum methodology for composing the sub-criteria into criteria and the criteria into the risk value, is integrated into AHP process and is organized into four step:

1. Creation of the schematic model in which criteria and sub-criteria are made explicit and are organized;

2. Interview to experts to gather information on criteria and sub-criteria importance (they are asked to express judgment of preference for all possible direct comparisons between two criteria/sub-criteria);
3. Analysis of coherence of gathered judgments;
4. Quantification of criteria and sub-criteria weights through matrix calculation.

We actually proceeded according to the four points:
In the first phase, through a reasoned top-down process, we started from "Wildfire Risk in RUI" considered as the level 0, and we detailed the level 1 in which we defined 6 criteria involved in the phenomenon:

1. topographic factors,
2. fuel/vegetation factors,
3. meteo-climatic factors,
4. urban-RUI factors,
5. historic-socio-economic factors,
6. single building factors.

Then, searching on the available literature on the topic, reasoning and speaking with experts, we listed the sub-criteria. Step by step, we finally get to the following organization of the variables. We aimed to build a structure of criteria and sub-criteria that were exhaustive, consistent and not redundant.

Table 37. The organization of criteria and sub-criteria for wildfire risk assessment

Level 0	Level 1	Level 2
Objective	**Criteria**	**Sub-criteria**
Wildfire risk in RUI	Topographic Factors	Altitude above sea level
		Slope
		Aspect
		Geomorphological features
	Vegetation Factors	Vegetation Species
		Fuel type
		Horizontal structure
		Vertical structure
		Fuel moisture
	Meteo-climatic Factors	Temperature
		Relative Humidity
		Wind
		Precipitation
	Urban-RUI Factors	Accesses to the RUI
		Street width in RUI
		Water supply in RUI
		Brush-clearing of RUI
		Emergency plan

		RUI Type
		Distance from water source for aircrafts
		Distance from firefight crew
	Historic-socio-economic Factors	Wildfire statistics
		Work division
		Unemployment
		Education level and richness
	Single House Factors	Residents in the house
		Economic capacity for yearly maintenance
		Accessibility to the house
		Fuels in the surroundings
		Vegetation maintenance of the surroundings
		Water supply for emergencies
		Constructing material
		Roof maintenance

A brief description of sub-criteria and of the methodology is presented in table 38.

Table 38. Brief description of all subcriteria

Sub-criteria	Influence on wildfire risk of:
Altitude above sea level	**the altitude** with which wildfire phenomenon can change.
Slope	**The Inclination of the terrain** with which the wildfire propagation characteristics change.
Aspect	**The Exposure to the sun** that can locally dry fuels and rise the temperature.
Geomorphological features	**The shapes and conformation of the relief** that can favour particularly severe condition of propagation.
Vegetation species	**The vegetation species**: conifers, broadleaf, maquis species have different behaviour in fire propagation and post fire recovery.
Fuel type	**Fuel type** which refers to the different fraction of thin/thick, live/dead combustibles.
Horizontal structure	**Horizontal continuity** of vegetation which allow wildfire propagation.
Vertical structure	**Vertical structure** which refers to the difference between environments where canopy is detached from underbrush and where on the contrary they are in contact.
Fuel moisture	**The water content of vegetation.**
Temperature	**Air temperature, Relative Humidity, Wind and Rains** which are the principal meteo-climatic variable involved in wildfire propagation.
Relative Humidity	
Wind	
Precipitation	
Accesses to the RUI	**The presence of just one exit or more**, their practicality in case of fire.

Street width in RUI	**Street width**, which refers to the presence of Firebreaks and wide streets able to interrupt fuel spatial continuity.
Water supply in RUI	**The presence of an emergency water supply** in case of wildfire.
Brush-clearing of RUI	**Annual brush-clearing of the RUI**, of some meters along the roads, works of pruning, and other maintenance works.
Emergency plan	**Presence and annual review of the emergency plan** in case of wildfire for RUI.
RUI Type	**Type of RUI** according to the proposed classifications.
Distance from water source for aircraft	**Distance of the RUI from the sea or from big lakes** that allow aircraft for firefight to charge water easily and increase the frequency of water launching.
Distance from firefight crew	**Distance from the closest firefight crew** which means possibility of fast intervention.
Wildfire statistics	**Historic statistics of distribution of ignition point and burned areas.**
Work division	**% of population working on primary, secondary and tertiary sectors.**
Unemployment	**Socio-economic variable** measuring the disadvantages that looks to influence fire regime.
Education level and richness	
Residents in the house	**Number and Type of resident** (owner, tenant, on holiday), age, sex, mobility problems.
Economic capacity for yearly maintenance	**Economic capacity for yearly maintenance.**
Accessibility to the house	**Wide/narrow, single/double access** to the house, usefulness in case of wildfire for evacuation and for allowing firefighters to arrive.
Fuels in the surroundings	**Fence, firewood stocks, gas tanks, secondary wooden construction, accumulated vegetation.**
Vegetation maintenance of the surroundings	**Doing or don't the annual brush-clearing** at least in the immediate surroundings of the house.
Water supply for emergencies	**Presence of swimming pool, water net distribution** which can be very useful for extinguishing the flames
Constructing material	**The construction material**: bricks, stones and concrete are much safer than wood because are incombustible.
Roof maintenance	**The clearing of the roof.**

Then for each of the 33 subcriteria we set a procedure allowing to directly translate the pixel value on that factor into a level of risk: we defined a suitable descriptor and how to measure it, and we specify how to assess pixel values effect on wildfire risk in WUI by stating thresholds. For instance considering the subcriteria slope, we identified the "% inclination" as the indicator and we statue that from 0% to 15% its impact on wildfire risk in RUI was low, from 15% to 30% it was moderate, and that above 30% it was high.

In particular, if the importance of the subcriteria "slope" for wildfire risk in RUI is the 5% of the total risk, all the pixels with an inclination higher than 30% will have the full risk value 5%, while the pixels in moderate slopes (30% < tilt angle < 15%) will have a reduced risk due to the tilt angle and the pixels with slope <15% a still lower value of risk. We used the factor 0.6 for the moderate slopes (5%*0.6 = 3% will be the value of risk assigned to the pixels with slopes between 15 and

30%) and the factor 0.2 for the slopes with lowest inclination (5%*0.2 = 1% will be the value of wildfire risk due to slope for the pixels in which slope is < 15%). In the following table a schema of all the procedures we adopted for each subcriteria is illustrated.

Table 39. Descriptors, procedures and thresholds adopted for each subcriteria to quantify the effect on risk.

Sub-criteria	Coefficient of reduction of criteria weight
Altitude above sea level	0-600m → 1; 600-1100m → 0.9; >1100m → 0.7
Slope	>30% → 1; 15-30% → 0.6; 0-15% → 0.2
Aspect	135-255° → 1; 255-315° and 45-135° → 0.8; 315-45° → 0.6
Geomorphological features	Localization on GIS environment of the geomorphological features capable to favour extreme fires (eruptive fire behaviours in canyons → 1), very difficult situation to be defended such as long mountain sides in which aspect and exposure to wind could create a synergy (→0.8), small Islands (→ 0.6), short mountain sides in which the exposure to dominant wind could create a synergy (→0.3)
Vegetation species	Conifers → 1; broadleaf and high/dense maquis → 0.9; low maquis and bushes → 0.6; grasses → 0.4
Fuel type	High fuel charge → 1; moderate fuel charge with thin component → 0.8; low fuel charge with thin component → 0.6
Horizontal structure	Aggregation Index (AI) >95% → 1; 0%>AI≥95% → 0.8; AI=0 → 0.3
Vertical structure	Canopy and underbrush in contact in forested areas → 1; just canopy without underbrush (or detached canopy-underbrush) in forested areas → 0.7; no vertical structure (canopies attached to the ground or bush or grasses) → 0.2
Fuel moisture	The perspective of territorial planning considers a time scale of several years and the worst situation (maximum dehydration of fuels) must be taken into account because it is likely to occur (→ 1)
Temperature	The perspective of territorial planning considers a time scale of several years and the worst meteo-climatic situations (strong wind, very low relative humidity, high temperature and long absence of rains) must be considered as likely to occur. (→ 1). Local variation can be stated
Relative Humidity	
Wind	
Precipitation	
Accesses to the RUI	Just one exit → 1; more than one exit → 0
Street width in RUI	Narrow street and no fire break → 1; wide street and no fire break or narrow street with presence of fire break → 0.7; wide street and presence of fire break → 0.4; very wide street (dual carriageway) → 0
Water supply in RUI	Absence →1; presence → 0
Brush-clearing of RUI	No → 1; yes → 0
Emergency plan	Absence →1; presence → 0
RUI Type	Very Dense AI high, Very Dense AI low, Dense AI high → 1; Dense AI low, Scattered AI high, Very Dense AI null → 0,8; Dense AI null, Scattered AI low, Isolated AI high → 0,7; Scattered AI null, Isolated AI low, Isolated AI null → 0,5

Distance from water source for aircraft	>40 km → 1; 20-40 km → 0.6; <20 km → 0.2
Distance from firefight crew	>15' → 1; 7-15' → 0.8; <7' → 0.5
Wildfire statistics	more than 1 fire recorded or one fire recorded but high ignition density → 1; no fire recorded and high ignition density or one fire recorded and low ignition density → 0.5; no fire recorded and low ignition density → 0.2
Work division	Low per cent of primary sector → 1; moderate per cent of primary sector → 0.8; high per cent of primary sector → 0.6
Unemployment	High per cent → 1; moderate per cent → 0.7; low per cent → 0.4
Education level and richness	Low education level and wealth → 1; moderate education level and wealth → 0.7; high education level and health → 0.3
Residents in the house	High number and not-autonomous (old, handicapped) → 1; moderate number, normal people → 0.8; low number, young people that can also help in extinguishing the fire → 0.6
Economic capacity for yearly maintenance	Low economic capacity (no maintenance) → 1; moderate economic capacity (clearing of the immediate surroundings) → 0.7; high capacity (full brush-clearing) → 0.3
Accessibility to the house	Just one narrow access → 1; more than one or just one but wide access → 0.5; two or more wide accesses → 0
Fuels in the surroundings	Presence within the first 10 m → 1; presence at a distance longer than 10 m → 0.7; absence or at distance longer than 30 m → 0
Vegetation maintenance of the surroundings	No maintenance → 1; just few meters or not completely brush-cleared → 0.8; 10m completely brush-cleared → 0.5; first 30 m completely brush-cleared → 0
Water supply for emergencies	No → 1 ; yes → 0
Constructing material	Wood and burnable materials → 1; structure in concrete or not-burnable materials and roof or complementary building in wood or burnable materials → 0.7; the whole building and its complementary structures are in concrete and not-burnable materials → 0
Roof maintenance	No → 1; yes → 0.2

In the second phase we conducted 30 interviews to selected experts belonging to the structures that in Sardinia operate in wildfire fight: Ente Foreste della Regione Sardegna (15 experts), Protezione Civile Regione Sardegna (13 experts), Corpo Forestale e di Vigilanza Ambientale (1 expert), Vigili del Fuoco (1 expert).

The interview consisted in asking the expert to express judgment of preference in all possible pairwise comparison between two criteria or sub-criteria. The preference had to be expressed according to the table 40.

The pairwise comparisons were organised in levels: all sub-criteria of a given criteria were directly compared each other in a complete series of pairwise. After having asked to express all the judgment of preference for the six series of sub-criteria corresponding to six the criteria, the criteria themselves were compared into pairwise.

Table 40. Fundamental Scale of Pairwise Comparison

Intensity of importance	Definition	Explanation
1	Equal importance	Equal contribution to the objective
3	Moderately more important	Experience and judgment slightly indicate one element as more important
5	Strongly more important	Experience and judgment strongly favour one element over the other
7	Very strongly more important	One element is strongly more important than the other and experience demonstrate the dominance
9	Extremely more important	One element is absolutely more influent than the other without any exception and doubt
Intensities of 2, 4, 6, 8 can be used to express intermediate values. Also 1.1, 1.2, 1.3, … , 8.8, 8.9, can be used in case of need to refine the judgment.		

We obtained from each of the 30 experts 7 matrixes of judgement corresponding to

- criteria 1: topographic factors
- criteria 2: vegetation factors
- criteria 3: meteo-climatic factors
- criteria 4: urban-RUI factors
- criteria 5: historic-socio-economic factors
- criteria 6: single dwelling factors
- comparison of criteria

For clarity, in table 41, an example of pairwise comparisons relative to topographic factors and in table 42, the relative matrix of preference are reported.

Table 41. Example of pairwise comparison relative to topographic subcriteria

TOPOGRAPHIC FACTORS																
Altitude								**vs**	**Slope**							
9	8	7	6	5	4	3	2	1	2	3	4	X	6	7	8	9
Altitude								**vs**	**Aspect**							
9	8	7	6	5	4	3	2	1	2	3	X	5	6	7	8	9
Altitude								**vs**	**Geomorphology**							
9	8	7	6	5	4	3	2	1	2	X	4	5	6	7	8	9
Slope								**vs**	**Aspect**							
9	8	7	6	5	4	3	X	1	2	3	4	5	6	7	8	9
Slope								**Vs**	**Geomorphology**							
9	8	7	6	5	X	3	2	1	2	3	4	5	6	7	8	9
Aspect								**vs**	**Geomorphology**							
9	8	7	6	5	4	X	2	1	2	3	4	5	6	7	8	9

The corresponding square matrix of preference is reported in table 42, in which, line by line, is reported the comparison between the two sub-criteria row-column. In the matrix of preference we find just a series of 1 in the principal diagonal (comparison of the criterion with itself); the matrix can be considered a triangular matrix since the values in one triangle are the reciprocal of their symmetric values on the opposite triangle.

Reading, for instance, the III° row of the matrix, we find that regarding wildfire risk, Aspect is 4 times more important than Altitude a.s.l.; Aspect is less important than Slope which scored a double value and, finally, that Aspect is three times more important for wildfire risk than Geomorphology.

Table 42. Matrix of preferences calculated for data of table 41

	Altitude	Slope	Aspect	Geomorphology
Altitude	1	0,2	0,25	0,333333333
Slope	5	1	2	4
Aspect	4	0,5	1	3
Geomorphology	3	0,25	0,333333333	1

During an interview, if a judgment is not consistent, it is possible to point out the incongruity to the expert who can modify all the judgments to get to a more harmonic description.

For example, a circular reference is not acceptable: it happens if, in the direct comparisons, Slope is judged more important than Altitude, Altitude more important than Aspect, and Aspect more important than Slope.

Similarly, we neither can accept incoherent judgment like: Slope is judged 9 times more important than Aspect and 2 times more important than Geomorphology while, in the direct comparison, Aspect is judged more important than Geomorphology. This kind of judgment make impossible to coherently rank the factors in a scale of importance. Many contradictions can arise during the interviews and we are able to solve many but not all of them.

For this reason, **in the third phase**, we performed the analysis of judgments coherence as prescribed by the methodology. The mathematical process is able to point out the incoherence of judgments, and it has been applied to all the 210 matrixes we collected.

The square matrix of preference A = $[a_{ij}]_n$ is a matrix of order N characterized by being reciprocal (a_{ii} = 1 for all I, and $a_{ij} = 1/a_{ji}$ for all i, j). If the pairwise comparisons respect the transitive property, it can be considered consistent, i.e. $a_{ik} = a_{ij}a_{jk}$ for all i, j, and k. This mathematical property, actually, ensures the absence of the circular references and the incoherent judgments that we illustrate above.

Our matrix has n vectors ω of order N such that $[A][\omega] = \lambda\omega$; their name is eigenvectors. As the definition states, this vectors have the property of maintaining the direction in the product [matrix]X[vector]. If we apply an affine transformation (rototranslation) to the matrix of preferences, referring it to its eigenvectors, we obtain the diagonal matrix of eigenvalues. This matrix summarises the same information of matrix A and is characterized by having a single value for each line-column (that is for each factor). The trace of the matrices is invariant in all system of reference linearly transformed and, since our original matrix in the diagonal has just the number 1, the trace of all rototranlated matrixes must be N*1 = n. Then, the sum of eigenvalues must necessarily be n as well.

With Geoff Coyle (2004): "For matrices involving human judgement, the condition $a_{ik} = a_{ij}a_{jk}$ does not hold, as human judgements are inconsistent to a greater or lesser degree" [li]. In such a case the sum of eigenvalues E satisfies the condition $E \geq n$.
The difference between E and n indicates an inconsistency of the judgments. If E = n the matrix is perfectly coherent and consistent. Finally, a Consistency Index (CI) can be calculated from
CI = (E-n)/(n-1).
Again with Geoff Coyle (2004): "The CI has been assessed against judgments made completely at random and Saaty has calculated large samples of random matrices of increasing order and the CI of those matrices. A true Consistency Ratio (CR) is, then, calculated by dividing our matrix CI by the CI of the random matrix of the same order N. Saaty suggests that if that ratio exceeds 0.1 the set of judgments may be too inconsistent to be reliable. [...] A CR of 0 would mean that the judgments are perfectly consistent"[lii].
Since the matrixes usually are not 100% coherent we use the diagonal matrix of eigenvalues to assess the coherence but it is impossible to proceed through it to assign the weights to criteria. For each criteria or sub-criteria, the importance is calculated using the geometric average of the scores that it has reported in the pairwise comparison normalized to the sum of all values. Then the thirty values that each criteria scored in the thirty interviews are used to calculate the weight of each criteria. Finally we express it in per-cent.

subcriteria	altitude	slope	aspect	geomorphology	geometric av.	% geometric av.	Trace (or E)
altitude	1	0,2	0,25	0,333333333	0,359	6,98	4,0953
slope	5	1	2	4	2,515	48,87	
aspect	4	0,5	1	3	1,565	30,41	
geomorphology	3	0,25	0,333333333	1	0,707	13,74	

Figure 49. Calculation of geometric average, calculation of per-cent importance of each of the four factors, calculation of the trace of the diagonal matrix of eigenvalues (last column).

Analysis of Coherence	
Trace (or E)	4,0953
CI_{random} (for N=4)	0.9
CI = (E-n)/(n-1)	0,0318
$CR = CI/CI_{random}$	0,0353

Figure 50. Analysis of Coherence of judgment through the comparison of the trace of the matrix of judgment (that is 4 as it can be easily calculated summing the yellow cells in figure 49) and of the sum of the eigenvalues (4.0953)

The example in figures 49 and 50 illustrates the mathematical procedure to get to the weights of criteria: the calculation of the geometric average, its expression in percentage, the calculation of the trace of the matrix of preferences to be compared with the number n (in this case 4) to assess the coherence of the judgments.

According to the AHP methodology, the matrix in the example can be accepted because the value CR is lower than 0.1. It means that the matrix of preferences in the example is very different from a random one and, hence, it is accepted as sufficiently consistent and reliable.
We conducted the analysis of judgment coherence on all the 210 matrixes and finally we calculated the mean value of importance for each subcriteria and criteria. The results are

presented in the relative section together with an application to the territory of the commune of Alghero.

Multisimulation methodology for wildfire risk assessment

A third methodology based on the use of wildfire simulators has been utilized to assess wildfire risk. Wildfire simulators are software capable to simulate fire spread and behaviour through the calculation of spatially and temporally explicit evolution of fire front according to a mathematic model of the phenomenon.

Remembering our definition of risk

R = P*I*V*W

P = local probability of a wildfire to occur;
I = local intensity of the wildfire;
V = vulnerability of the value exposed to the risk;
W = value of the good exposed to the risk,

we use the concept of Hazard = H = P*I to describe the source of risk in terms of probability of a wildfire characterized by a given intensity to occur at a given site. Wildfire Hazard distribution on the land, pixel by pixel, is a spatial representation of the source of risk to which houses and people are exposed.
Moreover, the two terms V and W account for the goods exposed to the source of risk. The goods are described in terms of values involved (W) and of response to the exposure at the local risk source (V).
To get to the evaluation of all the terms of risk we must be able to quantify the hazard, to describe the vulnerability of goods exposed and to account for their value.
Usually burned area data are not as abundant as we would need to create reliable statistics of burn probability pixel by pixel. Similarly, we don't have measures of the intensity of fire front pixel by pixel and it is, hence, impossible to measure the Hazard.
The basic logic of the methodology here presented consists in using:

- A wildfire simulator to assess the hazard;
- RUI maps to assess the distribution on the territory of the values and of the vulnerability of the goods.

We can evaluate the fire intensity through one of the outputs of the simulators (like the flame length FL expressed in m), and we can run many simulations to record, pixel by pixel, how many fires run over it for deducing the local burn probability. Calculating on each pixel the quantity

$$\boldsymbol{F} = \frac{nuber\ of\ simulated\ fires\ that\ burned\ the\ pixel}{total\ number\ of\ simulated\ fires}$$

we will have the local frequency of burning $\boldsymbol{F}$ and, if the number of simulations is sufficient, $\boldsymbol{F}$ can be considered a simulated measure of the burn probability calculated pixel by pixel.
Once evaluated the hazard, we can use the maps of RUI to assess the other arithmetical factors of the risk formula. The RUI maps, which classify RUI into different typologies, are obtained using

1. The spatial disposition of the houses on the territory;
2. The maps of vegetation.

All the mapping methodologies take into account (and are capable to distinguish between) different urban densities and different vegetation/environments in which houses are immersed.

The density of houses – the first layer taken into account in RUI maps. It indicates pixel by pixel the local amount of values exposed to wildfire risk. We can easily argue that, being proportional to the values exposed, risk is higher where there are more people and more houses. We can, hence, use the RUI maps as indicators of values presence.

The vegetation layer – the second layer taken into account in RUI maps. In order to define the vulnerability of the single house, the system of relations house-environment-hazard should be carefully studied. Actually, as the researches of J. Cohen broadly demonstrated, the immediate surroundings of a house is a very important space for wildfire risk: a house with the first 30 m completely brush-cleared and without any fuel can be considered very safe also if it is immersed in a forested environment; on the contrary, a house located in a low fuel charge grassland can have underbrush and pines in its immediate surroundings, and canopy can, for instance, be in contact with a wooden roof. The second situation can be considered very risky.

At supra-communal scale we cannot analyse all the houses and we cannot note for each of them all the parameters involved in vulnerability to wildfire of each dwelling (like the presence of water supply, the distances of the canopies from the roof, the annual maintenance of the immediate surroundings of the house, the presence of gas tank or firewood immediately close to the house etc.). We cannot, then, assess house by house the vulnerability but, in the RUI maps, we have information not only about house presence but also about the environment in which they are located because RUI maps distinguish between RUI located in areas with high/low fuel charge (or in continuous/discontinuous vegetation). At the scale we chose to work, it can be statistically considered more vulnerable a house immersed in forested area than another one located in areas where the vegetation is merely constituted by grasses. We can hence consider that the distinction operated by the RUI typologies according to the aggregation index or to the forested/agricultural environment can be useful to roughly differentiate the vulnerability of RUIs and we can use RUI maps to recognize the context in which the houses are located.

Finally, we can quantify the four risk factors and produce risk maps, by assessing pixel by pixel

- The hazard through the use of a fire simulator;
- Vulnerability and the exposed values through the use of RUI maps.

In particular, our work was conducted on the whole Sardinia using:

- The results of a previous work carried out by Salis et al. and already published for Hazard assessment (Salis et al., 2012)[liii];
- The RUI maps obtained with the Global Scale mapping methodology for evaluating V and W (see figure 51).

The work on Sardinia global mapping has already been illustrated. Hereafter we present the work done to assess P and I.

The burn probability and the intensity of fire were computed using a command-line version of the fire simulator “FlamMap”, called Randig, which utilises the MTT – Minimum Travel Time fire spread algorithm (Finney, 2002[liv]).

As Farsite, FlamMap and other wildfire simulators, Randig requires various inputs, in particular:

- Three topographic layers (slope, aspect, altitude);
- Fuel model and fuel moisture;
- Meteorological conditions (wind, temperature, relative humidity).

The whole work was executed using raster datasets whose resolution was 250 m.

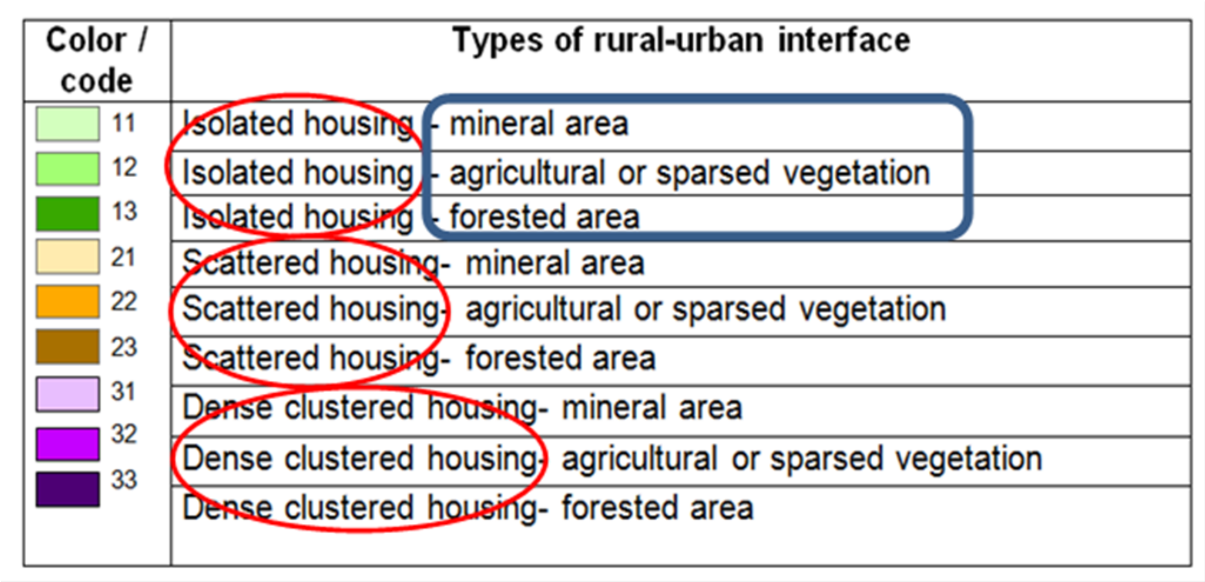

Figure 51. Global Scale mapping methodology types. We put on evidence:

- **The house density (in the red circles) that is considered proportional to value presence on the territory;**
- **The environment in which houses belonging to RUI are located (the blue frame). The contexts where houses lay are characterized by different fuel charge and, on a supra-communal scale, it can be considered an approximation of house vulnerability**

The topographical inputs were created using 90 m resolution digital elevation data available at http://srtm.csi.cgiar.org/.
The fuel models were created using the Corine Land Cover map (EEA 2002) and in particular its 44 classes were used to model fuels and were transformed into 11 fuel types modelling surface and canopy fuels (table 43).

Table 43. Vegetation types and respective fuel models used for the wildfire simulations

Vegetation type	**Incidence (%)**	**Fuel model**
Broadleaf	8.9	TL6 (Scott and Burgan 2005)[lv]
Conifer	2.8	TL3 (Scott and Burgan 2005)
Broadleaf–conifer mix	3.5	TU1 (Scott and Burgan 2005)
Mediterranean maquis	24.2	CM28 (Arca et al. 2009)[lvi]
Garigue	3.2	CM29 (Arca et al. 2009)
Pastures	5.7	CM27 (Arca et al. 2009)
Grass–agricultural lands	44.7	Mod 1 (Anderson 1982)[lvii]
Tree crops	2.9	Mod 2 (Anderson 1982)
Sands and rocks	0.5	Mod 1 (fuel load reduced 50%)
Urban areas	2.4	NB1 (Scott and Burgan 2005)
Water (lakes, rivers, etc.)	1.2	NB8 (Scott and Burgan 2005)

Statistics on wind speed and direction for the fire modelling, were calculated utilizing the Sardinian Forest Service databases and refining the results with observed weather data during escaped fires larger than 100 ha. For each simulation the direction of the wind is randomly selected according to the frequency distribution developed.

Similarly, the ignition location is randomly chosen by the simulator according to the density of ignition calculated using the Inverse Distance Weighting (IDW of Spatial Analyst tool by Esri ArcGis, 5000 m radius) from historic data.

All specifics about:

- crown bulk density,
- crown base height
- stand height of the wooded areas
- fuel moisture content (FMC) calculation

can be directly found in Salis et al. 2012[lviii].

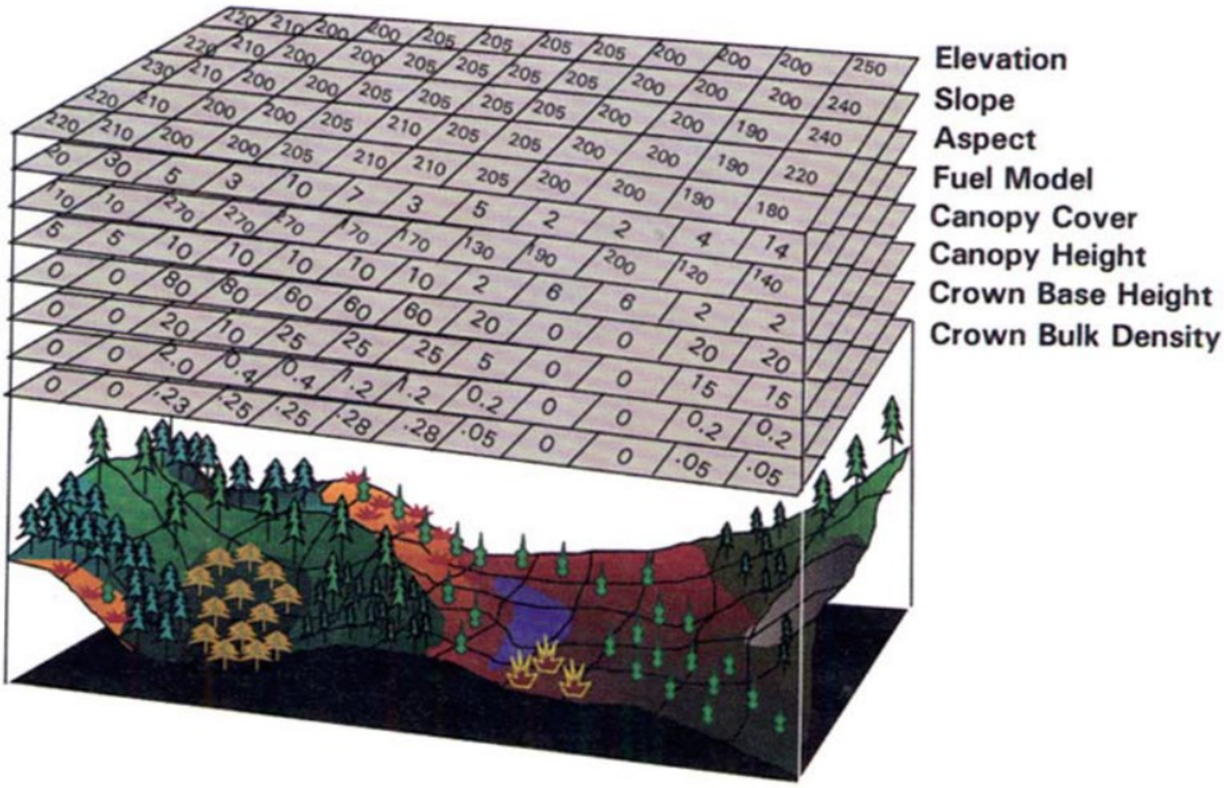

Figure 52. Schematic representation of the different layers used by the simulator each one modeling pixel by pixel a characteristic of the territory

100,000 simulations were run on the whole Sardinia surface. The resulting total burned area is almost 12 times bigger than the study area, with an average burning of ≈12 times per pixel. The number of simulations is considered sufficient to generate reliable frequency distribution by which assessing the burn probability pixel by pixel.

Randig calculates the conditional burn probability (CBP), i.e. (citing directly Salis et al. 2012) the chance that a pixel has "to burn at a given flame length interval, considering one ignition in the whole study area under the assumed weather conditions. It is defined as:

$BP_{xy} = (F_{xy}/n_{tot})$

where F_{xy} is the number of times that pixel xy burns and n_{tot} is the total number of simulated fires (100,000)."[lix]

Fire intensity varies with fuel charge, type and moisture, with wind, slope and aspect but it also depends on the direction of fire front. The heading front develops the highest intensities, the back of the fire the lowest while on the flanks the intensity is intermediate (Finney 2002)[lx].
For this reason, Randig calculates for each pixel the conditional flame length (CFL), a quantity expressed in meters that is a weighted average intensity that can take into account how fire intensity varies on the different directions of fire front propagation.
The outputs of Randig cover the whole Sardinia. We, then, extracted a mask corresponding to Sardinian RUI areas calculated according to the Global Scale mapping methodology.

The first step of the methodology we used to calculate the final risk is a simple reclassification in which each of the four parameters (P, I, V, W) was divided into three levels.
For P and I, we ordered the database in growing values, and then we divided the records of the database in three groups of same number of pixels. We assigned the number 1 to the first third of pixels characterized by the lowest values; we assigned the number 2 to the second third of pixels with intermediate values and, the number 3 was assigned to the last third (highest values pixels).
For V, we used the value 1 for RUI located in mineral areas, 2 for RUI located in agricultural or sparse vegetated areas and 3 for RUI located in forested areas.
For W, we assigned 1 to Isolated housing, 2 to scattered housing and 3 to dense housing.
In table 44 we illustrate the reclassification of parameters into the three levels.

Table 44. Reclassification of the four factors of Risk definition into three levels

Risk component		Low	Intermediate	High
P	Burn probability	1 (lowest values)	2 (intermediate values)	3 (highest values)
I	Fire intensity	1 (lowest values)	2 (intermediate values)	3 (highest values)
V	Vulnerability	1 (mineral area)	2 (agric/sparse vegetat.)	3 (forested areas)
W	Goods values	1 (Isolated housing)	2 (scattered housing)	3 (dense housing)

Then, according to the arithmetical formulation of risk that we chose, we simply perform the multiplication of the four factors for each pixel in GIS environment, obtaining a map in which higher values are associated to more risky situations.
We choose to present the map of risk reclassifying the final map in 5 risk categories: very low, low, moderate, high, very high.
Between the minimum and maximum theoretical values which are respectively 1^4=1 and 3^4 = 81, there are 15 possible values of risk. The five categories of risk were obtained dividing the 15 possible values of risk into five categories of three values each, as it is shown in table 45.

Table 45. List of all possible values of risk according to the formulation R=P*I*V*W when all factors range between 1 and 3. The five classes of risk corresponding to the values

1	2	3	4	6	8	9	12	16	18	24	27	36	54	81
Very Low			Low			Moderate			High			Very High		

The formulation of risk that we chose is not able to distinguish different kinds of risk: high-damage/low-hazard or moderate-damage/moderate-hazard or low-damage/high-hazard risks can result in a similar value. In particular lowest values of risk require low values of all factors and can reliably be associated with low risk situation characterized by low hazard (i.e. low probability and intensity) and by not conspicuous damage (i.e. low vulnerability, few values exposed). The highest

values of risk require high values of all factors, and can be reliably associated with high risk situation characterized by high hazard (high probability and high intensity) and big damage (high vulnerability and plenty of values exposed to risk).
It is hence for the intermediate values that we can find different kinds of risk with the same risk value and we are not able to distinguish just by the risk value if we have a high-damage/low-hazard or a moderate-damage/moderate-hazard or low-damage/high-hazard risk.

Part 3: Wildfire Risk Assessment in Rural-Urban Interface

Results

Overlay Mapping methodology for wildfire risk assessment

We applied the methodology to the Communal territory of Alghero, the little town located in NW Sardinia Island, on which we had already created the RUI maps using the Local Scale Mapping Methodology option 2 available in *RUImap®* tool.

The basic data for our model inputs were:

- The certified Land Use vector map of Sardinia available at the URL http://www.sardegnageoportale.it/catalogodati/download/ which was used to create the Fuel Type Risk Factor Map;
- The certified DTEM of Sardinia, available at the same URL http://www.sardegnageoportale.it/catalogodati/download/ that was utilized to produce the Slope Risk Factor Map;
- The numerical data on Alghero population available at ISTAT Official Site at the URL http://demo.istat.it/pop2012/index3.html and the Building Layer available at the URL http://www.sardegnageoportale.it/catalogodati/download/. They were used to spatialise the Alghero population density on its territory, and create the Population Risk Factor Map;
- The RUI map of Alghero that we had produced in the mapping phase of the present work which was used to create the RUI Type Risk Factor Map;
- Finally the GPS survey perimeters of burned areas available at the URL http://www.sardegnageoportale.it/catalogodati/download/ that were used to create the Statistic Risk Factor Map.

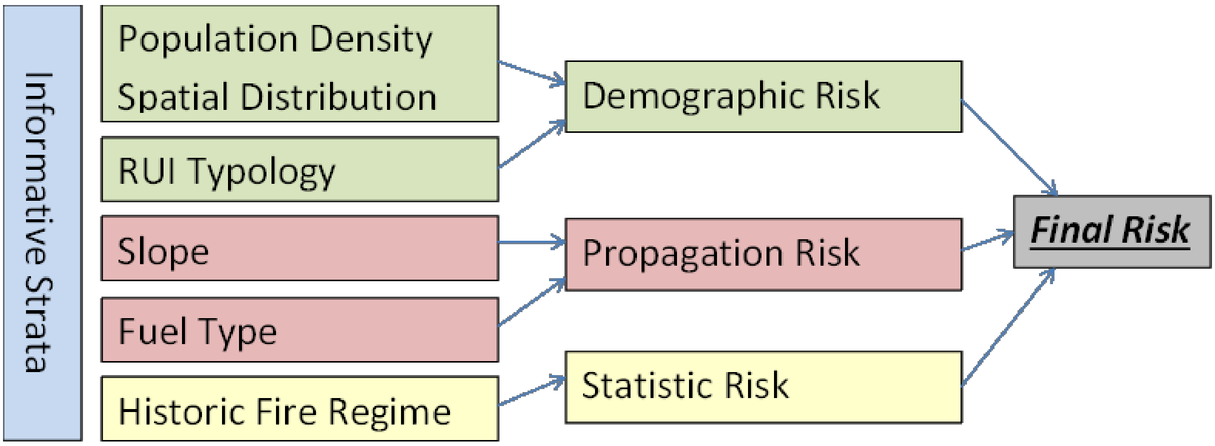

Figure 53. Schematic diagram of flux of Overlay Mapping methodology for wildfire risk assessment.

According to the methodology, we combined the RUI Type Risk Factor Map with the Population Risk Factor Map obtaining the Demographic Risk Factors Map, and we combined the Slope Risk Factor Map and the Fuel Type Risk Factor Map to get to the Propagation Risk Factors Map.
The map of Risk of the territory was then obtained through the combination of the three maps:

- Statistic Risk Factor Map,
- Demographic Risk Factor Map,
- Propagation Risk Factor Map.

Hereafter the intermediate layers and the final result of the methodology obtained in Alghero territory are presented.

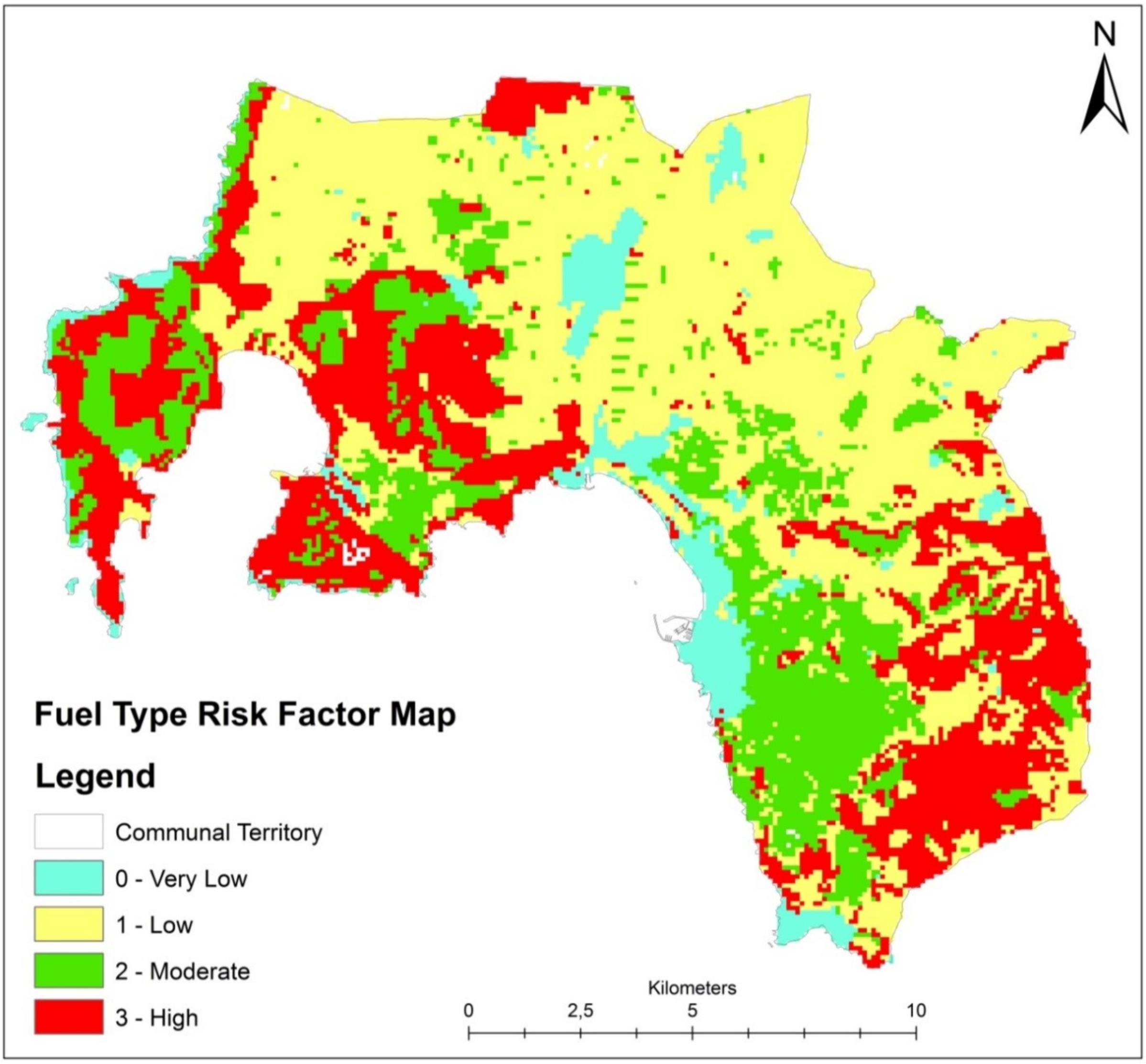

Figure 54. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the fuel type risk factor map calculated on the whole Alghero territory. The fuel type risk factor map must be composed with the slope risk factor map to obtain the propagation risk factor map

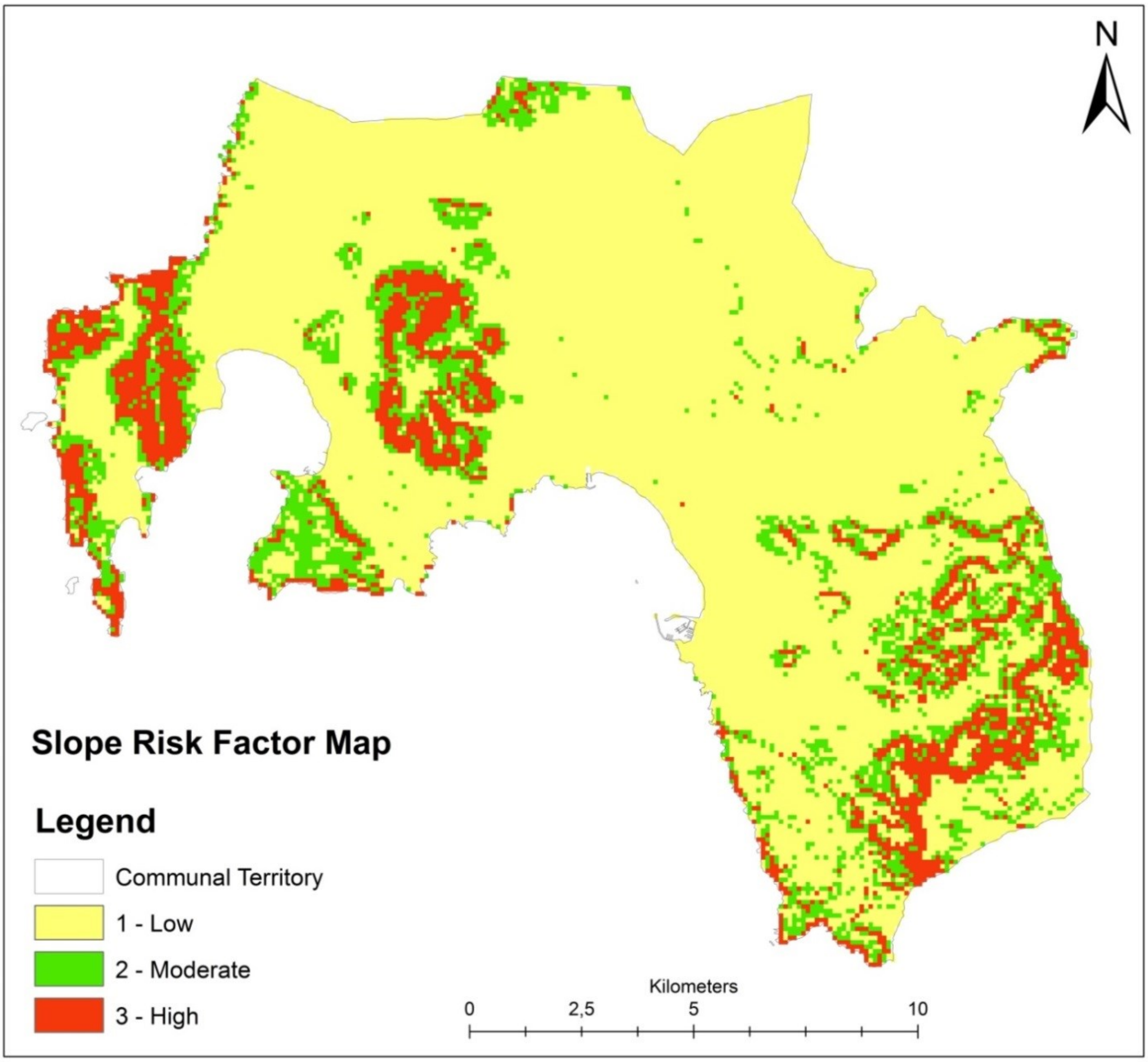

Figure 55. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the slope risk factor map calculated on the whole Alghero territory. The slope risk factor map must be composed with the fuel type risk factor map to obtain the propagation risk factor map

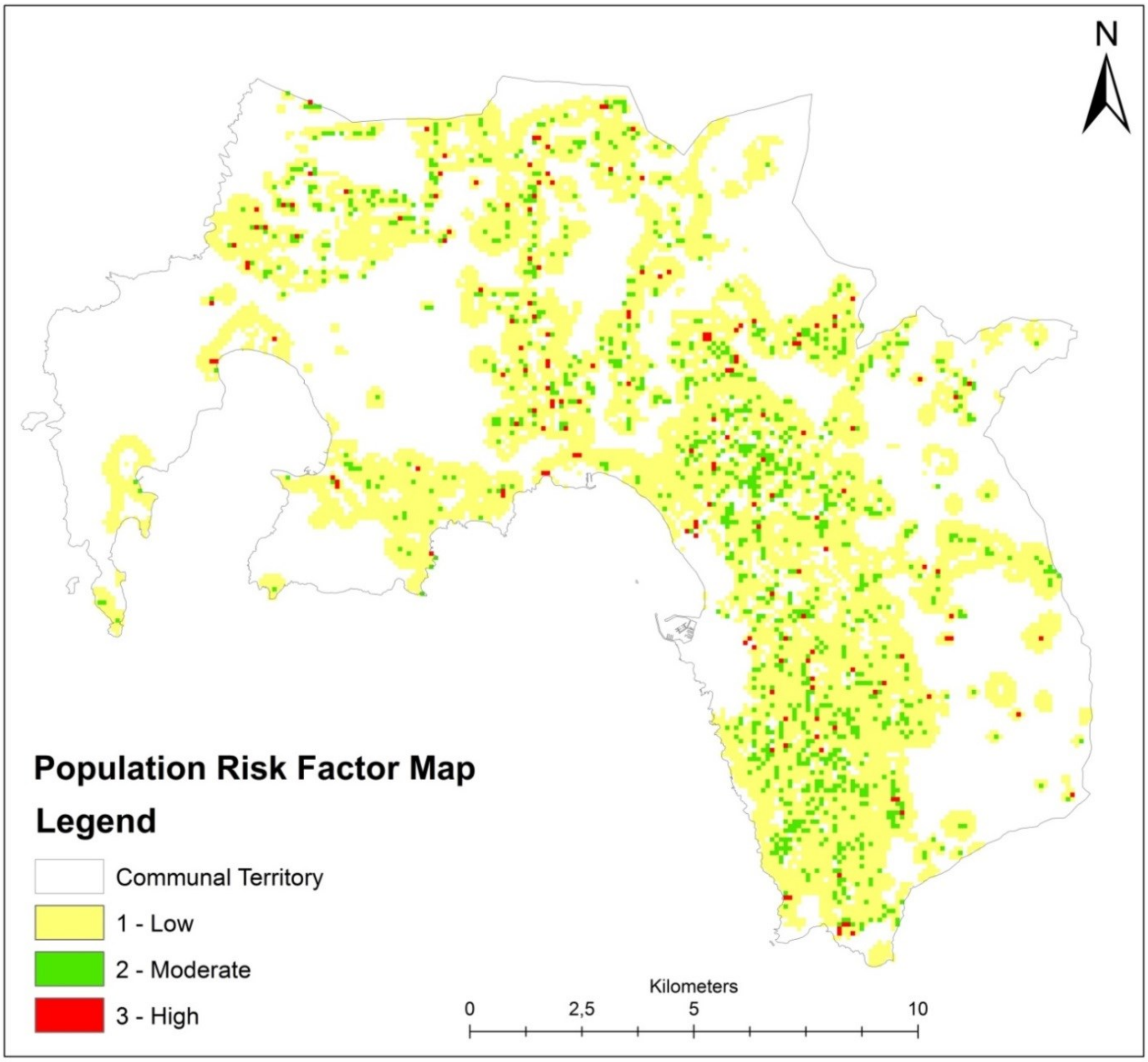

Figure 56. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the population risk factor map calculated on all housing of Alghero territory excepting the mere urban center. The population risk factor map must be composed with the RUI type risk factor map to obtain the demographic risk factor map

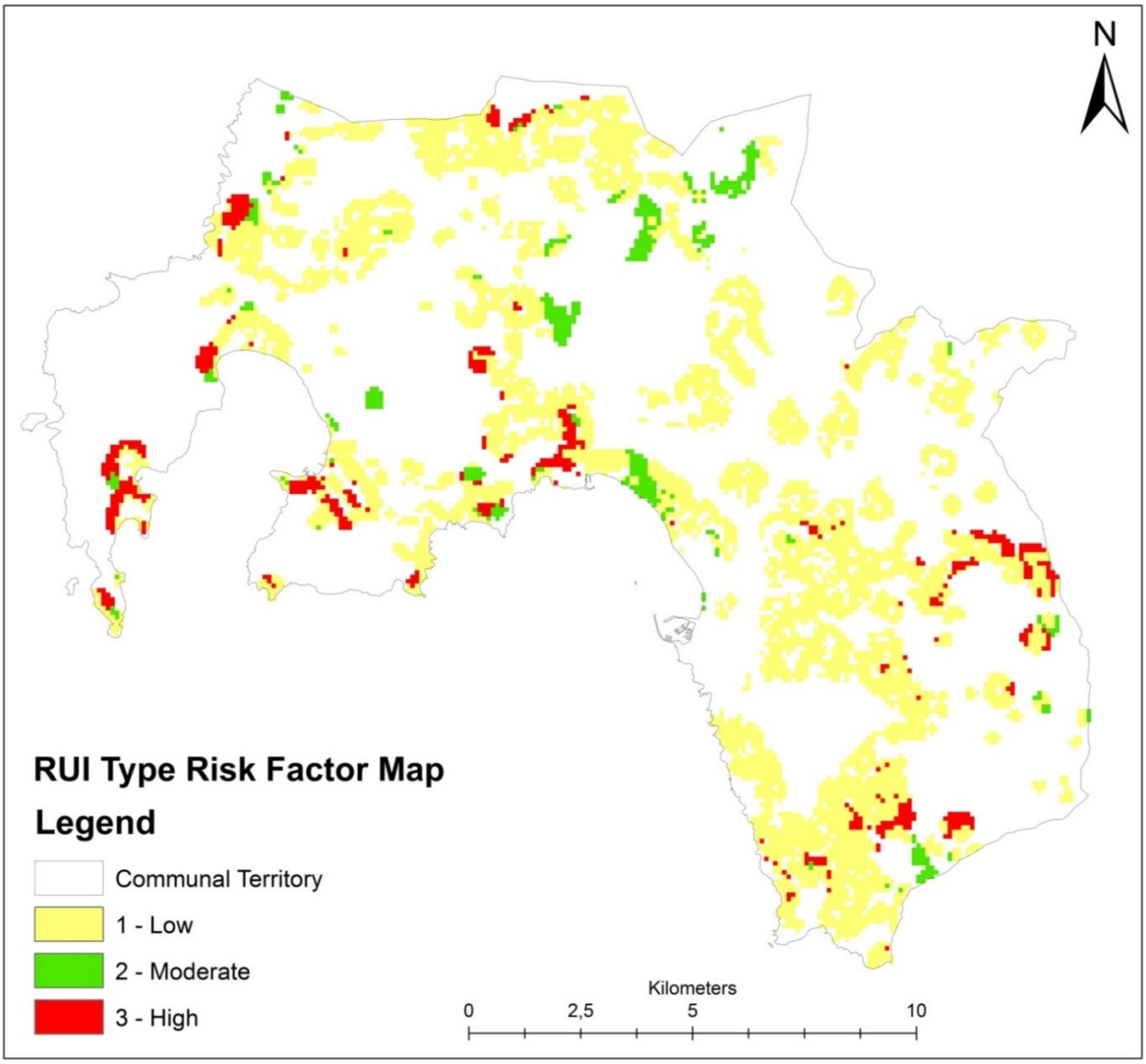

Figure 57.Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the RUI type risk factor map calculated on RUI areas of Alghero territory (Local Scale mapping methodology option 2). The RUI type risk factor map must be composed with the population risk factor map to obtain the demographic risk factor map

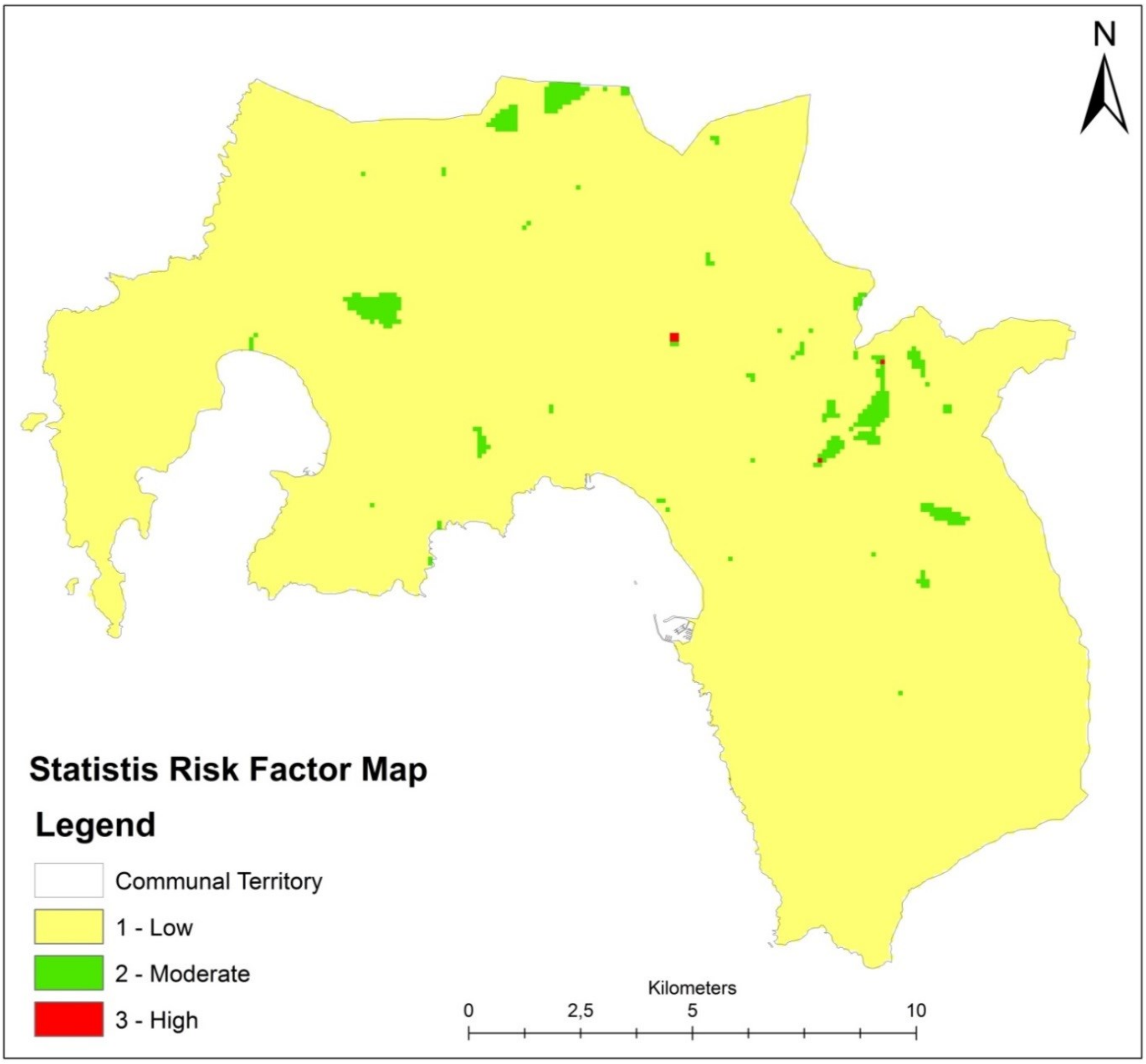

Figure 58. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the statistic risk factor map calculated on the whole Alghero territory

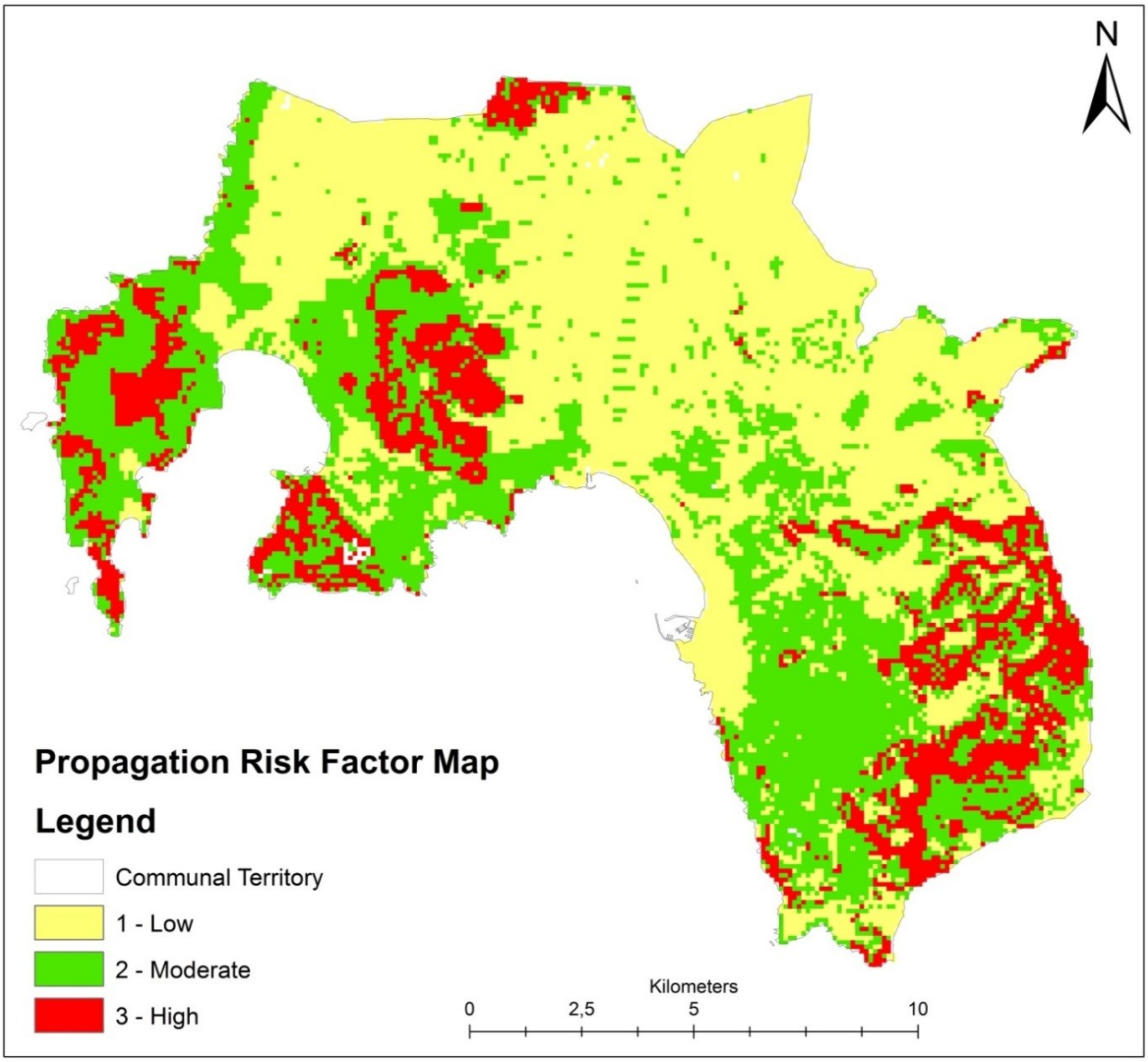

Figure 59. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the propagation risk factor map calculated on the whole Alghero territory through the composition of slope and fuel type risk factor maps

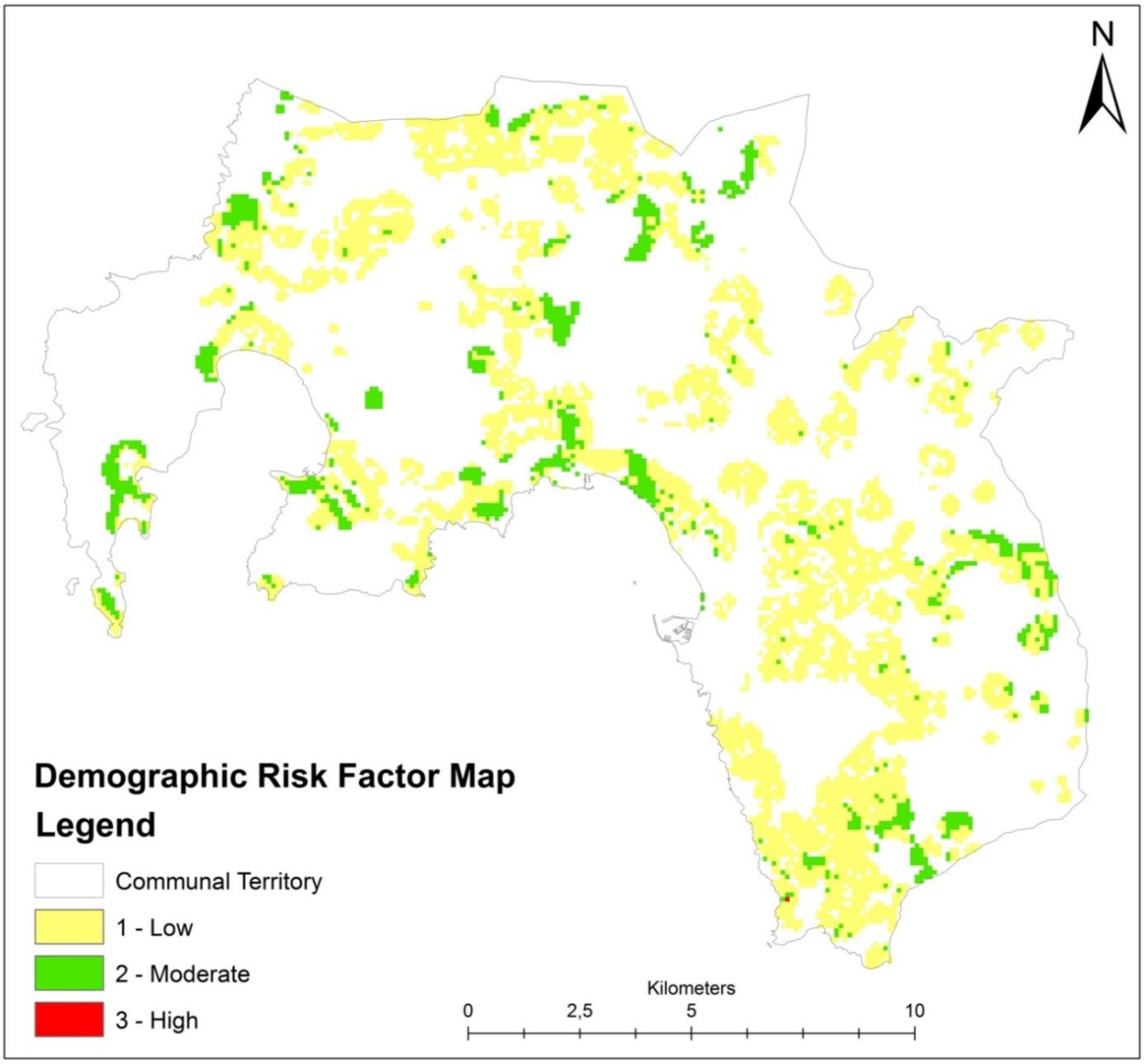

Figure 60. Overlay Mapping methodology for wildfire risk assessment in RUI. One of the inputs: the demographic risk factor map calculated on RUI areas of Alghero territory through the composition of population and RUI type risk factor maps

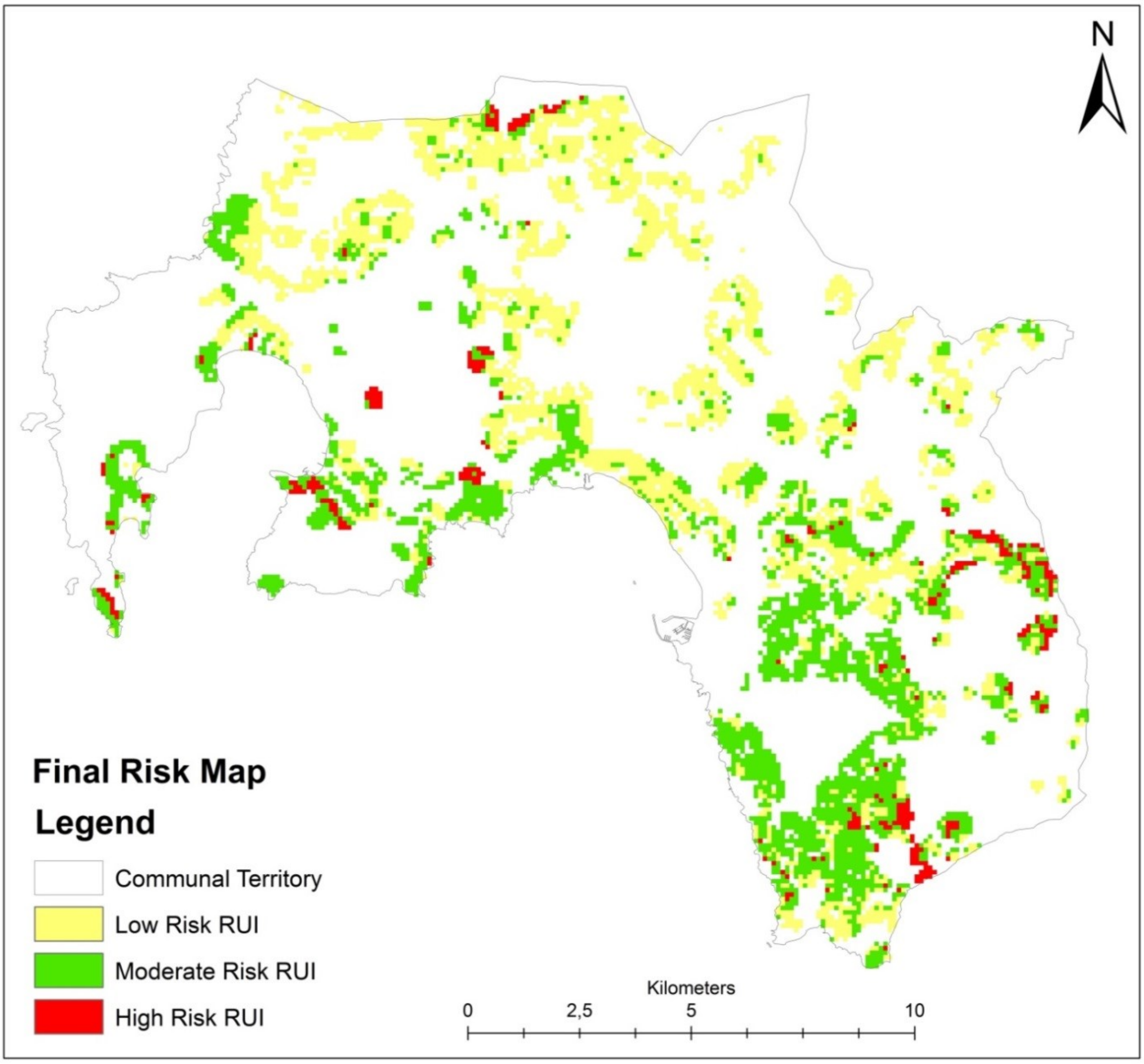

Figure 61. Output of the Overlay Mapping methodology for wildfire risk assessment in RUI. The final risk map calculated for RUI areas of Alghero territory obtained through the composition of demographic, statistic and propagation risk factor maps

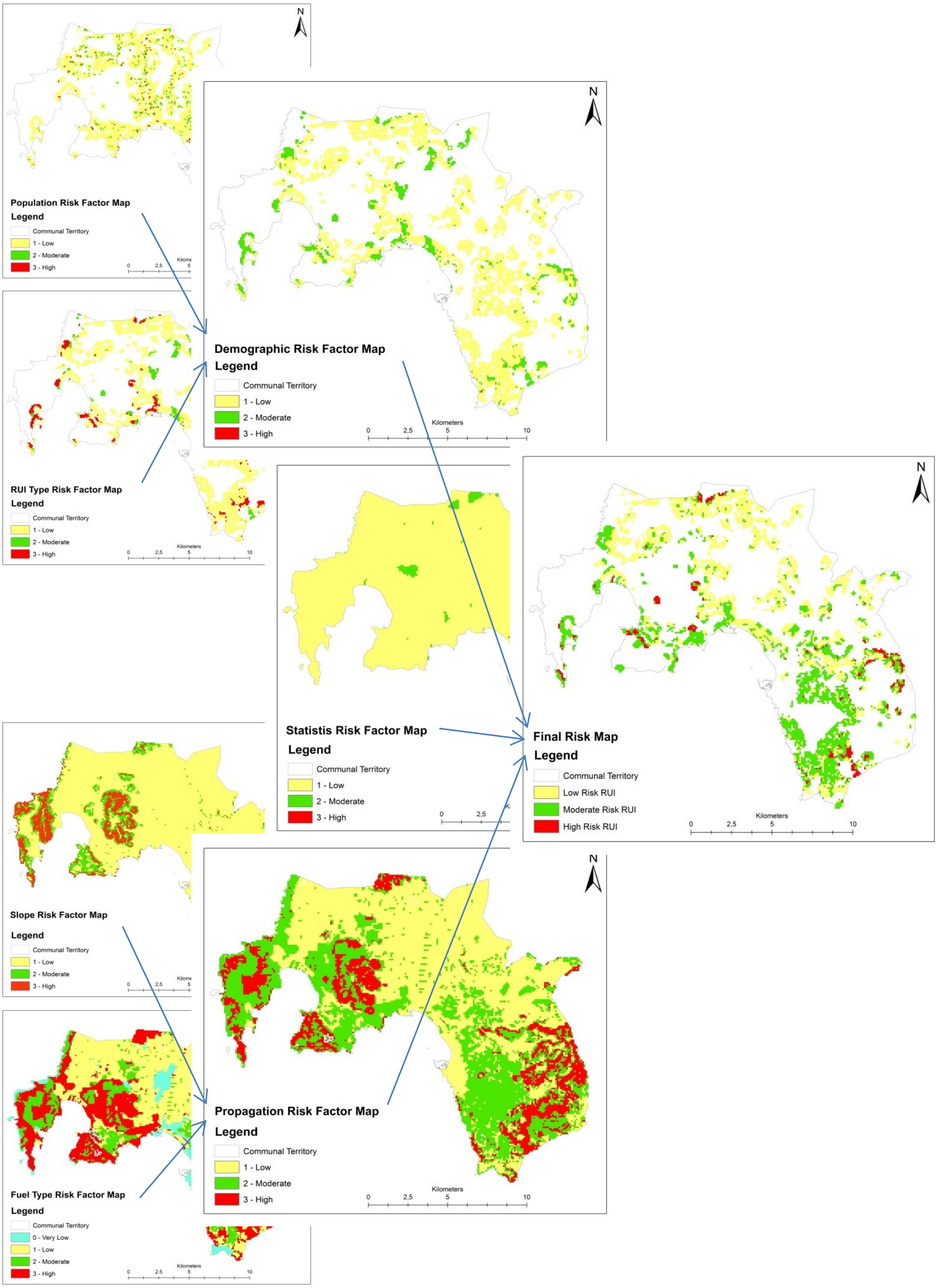

Figure 62. Schematic representation of progressive composition of inputs as prescribed by the Overlay Mapping methodology for wildfire risk assessment in RUI to finally obtain, as output, the final risk map

The spatial representation of Risk in RUI offered by the map is an optimum help for planners for focusing attention and prevention actions (e.g. prescribed burning).

Nevertheless, we also extracted aggregated data from the map and we found that 378 pixels, (meaning 378 Ha since the resolution is 100X100m and corresponding to the 5% of RUI areas) can be considered at high risk according to the Overlay Mapping methodology.

In table 46 it can be seen that, while the 42% of RUI surface is in a condition of moderate risk, more than the half of it (the 53 %) is in low risky conditions.

Table 46. Area of the RUI surfaces at different risk level

Risk level in RUI	Area [ha]	Area [%]
Low	3734	52,7
Moderate	2967	41,9
High	378	5,3
Total area	7079	100,0

Each of the thirty interviews we conducted produced 7 matrices of preferences: one for each set of subcriteria corresponding to the six criteria and one for the pairwise comparisons between criteria. The majority of them (around 95%) could be considered coherent since the CR index was, in general, less than 0.1.

In particular, the difficulty in expressing coherent judgments grew with the number of pairwise comparisons. For instance for the criteria "urban factors" and "single dwelling factors", we had 8 subcriteria each and the corresponding pairwise comparisons were 28. For these criteria experts had more difficulties in producing coherent judgments. In the table 47 we can find the number of incoherent matrixes per each of the seven set of judgments.

Table 47. Coherence of the judgments that we gathered through the interviews

Matrixes of judgment	(N° matrices with CR > 0.1) / tot matrices
Topographic factors matrices	1/30
Fuel factors matrices	1/30
Meteo-climatic factors matrices	0/30
Urban factors matrices	5/30
Historic-socio-economic factors matrices	1/30
Single dwelling factors matrices	2/30
Criteria comparisons matrices	1/30
Total	11/210

Considering the coherent matrices of preferences (and neglecting the not coherent ones) we calculated the average of the scores of each criteria and we expressed it in per cent, obtaining the values presented in table 48.

Table 48. Mean value of the 29 scores that the six criteria received by each of the 29 experts who produced a coherent judgment

Criteria	Weights [%]
Topographic factors	12.66
Fuel factors	14.92
Meteo-climatic factors	32.48
Urban factors	18.16
Historic-socio-economic factors	9.63
Single dwelling factors	12.15
Total	**100**

Then we repeated the same calculation for the matrixes of preferences of subcriteria and we obtained the results presented in the tables 49-54.

Table 49. Mean value of the 29 scores that the subcriteria detailing the criteria "topographic factors" received by each of the 29 experts who produced coherent judgments

Subcriteria – topographic factors	Weights [%]
Altitude	5.34
Slope	32.54
Aspect	16.13
Geomorphology	45.99
Total	**100**

Table 50. Mean value of the 29 scores that the subcriteria detailing the criteria "fuel factors" received by each of the 29 experts who produced coherent judgments

Subcriteria – fuel factors	Weights [%]
Vegetation Species	15.56
Fuel type	15.86
Horizontal structure	16.90
Vertical structure	10.62
Fuel moisture	41.07
Total	**100**

Table 51. Mean value of the 30 scores that the subcriteria detailing the criteria "meteo-climatic factors" received by each of the 30 experts (all of them produced coherent judgments on this criteria)

Subcriteria – meteo-climatic factors	Weights [%]
Temperature	16.91
Relative Humidity	11.83
Wind	44.52
Precipitation	26.74
Total	**100**

Table 52. Mean value of the 25 scores that the subcriteria detailing the criteria "urban RUI factors" received by each of the 25 experts who produced coherent judgments

Subcriteria – Urban-RUI factors	Weights [%]
Accesses to the RUI	13.80
Street width in RUI	14.11
Water supply in RUI	8.28
Brush-clearing of RUI	22.62
Emergency plan	11.56
RUI Type	12.39
Distance from water source for aircraft	5.58
Distance from firefight crew	11.66
Total	**100**

Table 53. Mean value of the 29 scores that the subcriteria detailing the criteria "historic socio economic factors" received by each of the 29 experts who produced coherent judgments

Subcriteria – historic-socio-economic factors	Weights [%]
Wildfire statistics	36.84
Work division	22.12
Unemployment	22.46
Education level and richness	18.59
Total	**100**

Table 54. Mean value of the 28 scores that the subcriteria detailing the criteria "single dwelling factors" received by each of the 28 experts who produced coherent judgments

Subcriteria – single dwelling factors	Weights [%]
Residents in the house	7.61
Economic capacity for yearly maintenance	7.36
Accessibility to the house	7.95
Fuels in the surroundings	15.78
Vegetation maintenance of the surroundings	26.41
Water supply for emergencies	13.31
Constructing material	14.72
Roof maintenance	6.86
Total	**100**

We finally calculated the definitive weight of each subcriteria by multiplying the per-cent value of the subcriteria for the per-cent value of the criteria (and dividing it for 100 to get a new per cent value). For instance: if "fuel moisture" has the 41.07% of the importance among the subcriteria constituting the criteria "vegetation factors", and the criteria itself contributes to wildfire risk in RUI for the 14.92% then the product

(41.07*14.92) / 100 = 6.13%

measures the direct importance of "fuel moisture" on Wildfire Risk in RUI and 6.13% is the weight of the subcriteria "fuel moisture".
All the weights of the final model are reported in the table 55.

After having fully determined the model by assigning the weights to each subcriteria we applied it to the territory of Alghero on which we had already produced the RUI maps.
The list of subcriteria has been thought to be generally useful at different scales, from the small neighbourhoods to the supra-communal. Some of the subcriteria (like the ones detailing the single dwelling characteristics) are important on a very local scale while others (like for instance education level) present differences only between communes and have not the spatial distribution pixel by pixel.
We chose to apply the model to the communal scale that, for a planning approach, looked to be the right compromise. In the figures 63-97 we illustrate inputs and results of the model applied to the Alghero territory.

Table 55. The weights of all the subcriteria

Level 0	Level 1	Level 2	Weights [%]
Objective	Criteria	Sub-criteria	
Wildfire risk in RUI	Topographic Factors (12.66%)	Altitude above sea level	0.68
		Slope	4.12
		Aspect	2.04
		Geomorphological features	5.82
	Vegetation Factors (14.92%)	Vegetation Species	2.32
		Fuel type	2.37
		Horizontal structure	2.52
		Vertical structure	1.58
		Fuel moisture	6.13
	Meteo-climatic Factors (32.48%)	Temperature	5.49
		Relative Humidity	3.84
		Wind	14.46
		Precipitation	8.69
	Urban-RUI Factors (18.16%)	Accesses to the RUI	2.51
		Street width in RUI	2.56
		Water supply in RUI	1.50
		Brush-clearing of RUI	4.11
		Emergency plan	2.10
		RUI Type	2.25
		Distance from water source for aircraft	1.01
		Distance from firefight crew	2.12
	Historic-socio-economic Factors (9.63%)	Wildfire statistics	3.55
		Work division	2.13
		Unemployment	2.16
		Education level and richness	1.79
	Single House Factors (12.15%)	Residents in the house	0.92
		Economic capacity for yearly maintenance	0.89
		Accessibility to the house	0.97
		Fuels in the surroundings	1.92
		Vegetation maintenance of the surroundings	3.21
		Water supply for emergencies	1.62
		Constructing material	1.79
		Roof maintenance	0.83

Regarding the single dwelling factors we could not consider it at communal scale. The Alghero housing layer that we used as input for Local Scale mapping methodology has 13,000 features each of which corresponds to a house. Many of them are in the urban centre and not in RUI but, at this scale on so many dwellings, is anyway impossible to consider the 8 sub-criteria detailing the single house conditions. Then, we produced two maps: in the first we considered the worst conditions and the maximum value of risk due to this criteria (12.15%), in the second one we considered the best possible conditions and the minimum value of risk due to this criteria (0.985%). The table 56 reports the calculation that was done for comparing the two different conditions and see the effect on final risk.

Table 56. Criteria "single dwelling factors". Comparison of risk values due to the criteria in the best and worst conditions

Subcriteria	Ideal situation	Worst situation
Residents in the house	low number, young people that can also help in extinguishing the fire → 0.92%*0.6 = 0.552%	High number and not-autonomous people (old, handicapped) → 0.92%
Economic capacity for yearly maintenance	high capacity → 0.89%*0.3 = 0.267%	Low economic capacity → 0.89%
Accessibility to the house	more than one wide accesses → 0%	Just one narrow access → 0.97%
Fuels in the surroundings	absence or at more than 30 m → 0%	Presence within the first 10 m → 1.92%
Vegetation maintenance of the surroundings	first 30 m completely brush-cleared → 0%	No maintenance → 3.21%
Water supply for emergencies	yes → 0%	No → 1.62%
Constructing material	building and complementary structures in concrete or not-burnable materials → 0%	building and complementary structures in wood and burnable materials → 1.79%
Roof maintenance	yes → 0.83%*0.2 = 0.166%	No → 0.83%
TOTAL – CRITERIA	**0.985%**	**12.15%**

The difference in risk value due to the criteria "single dwelling factors" is

12.15% – 0 .985% = 11.165%.

If we consider that risk values on Alghero territory (calculated using 12.15% for criteria "single

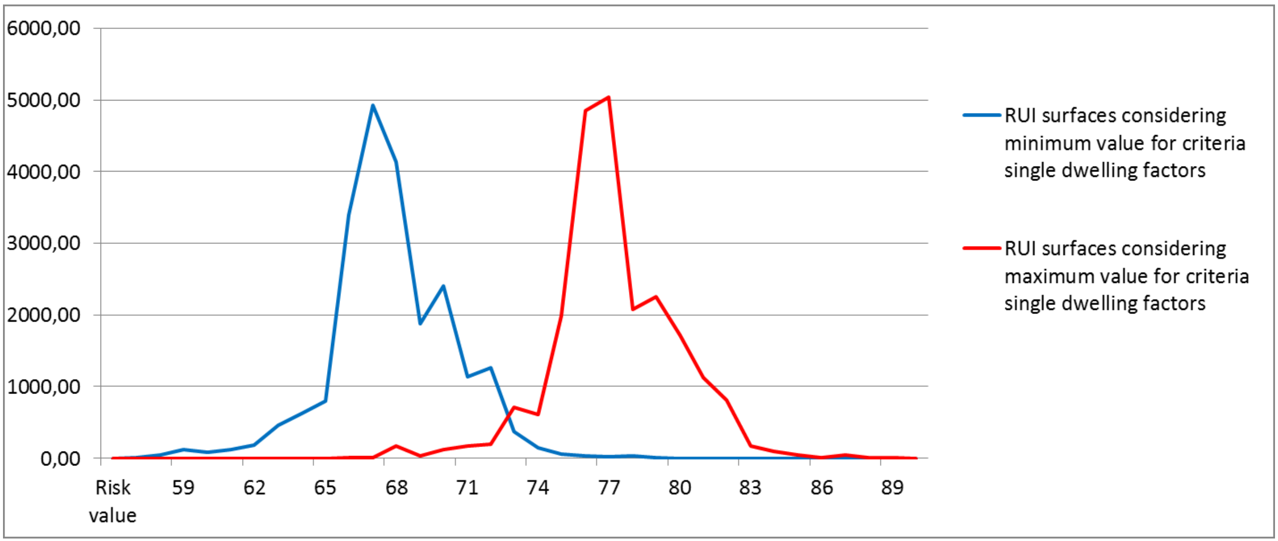

Figure 63. Distribution of RUI surfaces at different risk value considering the maximum and the minimum value for criteria "single dwelling factors". An important shift towards higher values is recorded when we consider the situation in which the value is maximum (12.15%).

dwelling factors") range between 90.6% and 66.2% (range is 24.4%) and that the criteria "single dwelling factors" can add/subtract 11.165% of risk, we can appreciate how influent are the single dwelling characteristics on wildfire risk.
In table 57 and in figure 63 there is the comparison of surfaces with different risk values, when considering the minimum and the maximum value for the criteria "single dwelling factors". The shift of RUI surfaces towards high risk classes is evident.

Table 57. Distribution of RUI surfaces in different classes of risk when considering the maximum (worst situation) and the minimum value (ideal situation) for the Criteria "single dwelling factors"

Risk level	Risk value	Minimum value for Criteria "single dwelling factors" (0.985%)	Maximum value for Criteria "single dwelling factors" (12.15%)
class	**[%]**	**surface [ha]**	**surface [ha]**
very low	57-63	560,95	0
low	64-70	16215,96	204,25
moderate	71-77	5430,51	8651,35
high	78-84	58,79	13195,77
very high	85-91	0	214,84
Total RUI surface		**22266,21**	**22266,21**

Figure 64. Map of Alghero territory representing the risk level relative to the subcriteria "altitude above sea level". The risk is high on the whole territory because none of the pixels has a value above 600 m which is the threshold between high and moderate risk. The per-cent value of risk related to the subcriteria is 0.68% and it is considered the same on the whole territory.

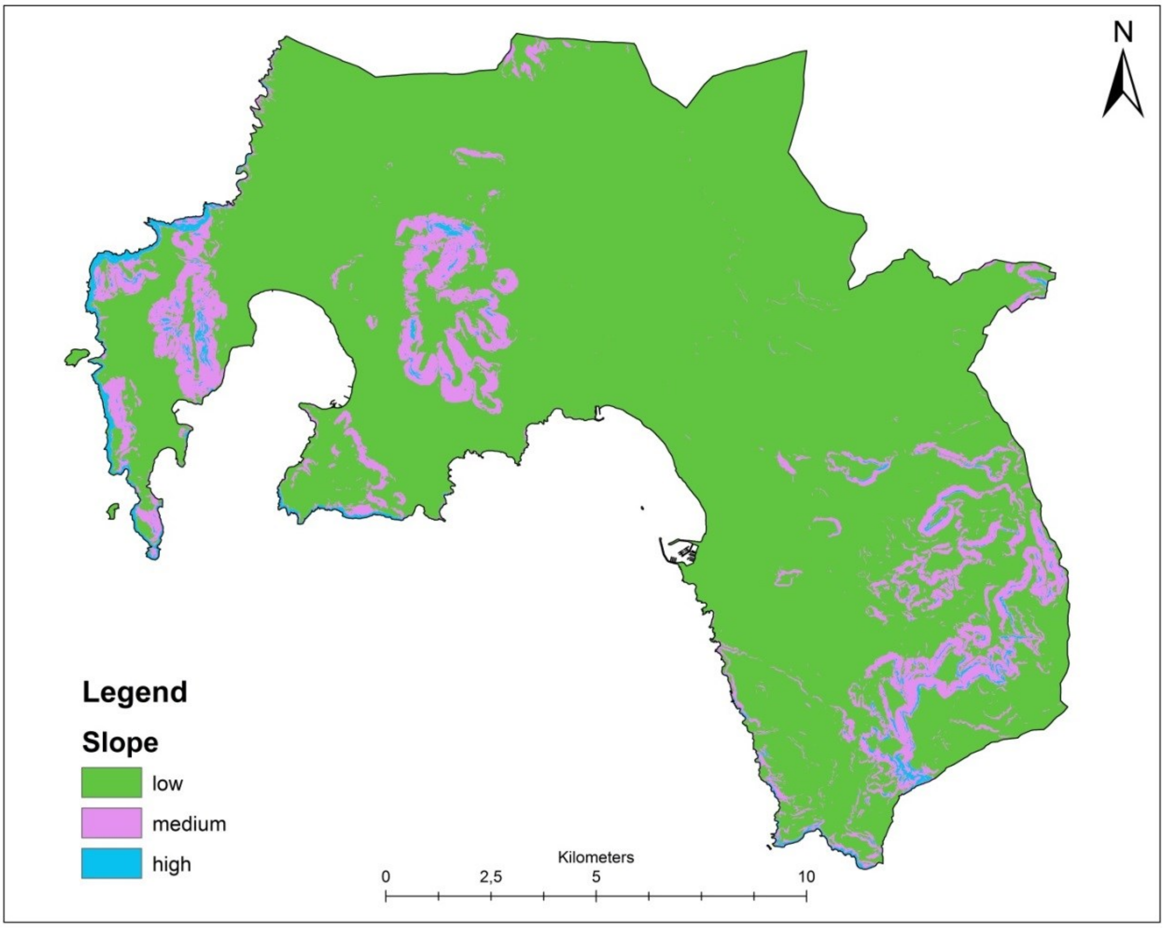

Figure 65. Map of Alghero territory representing the risk level relative to the subcriteria "slope". The risk is low (green) on the plans (inclination below 15%), moderate (violet) where inclination is between 15 and 30% and is high for inclinations higher than 30%. The value 4.12% corresponding to the importance of the subcriteria relatively to final risk, is fully considered for the blue areas, is reduced of a factor 0.6 on violet areas (4.12%*0.6 = 2.472%) and is reduced of a factor 0.2 on the green areas (4.12%*0.2 = 0.824%)

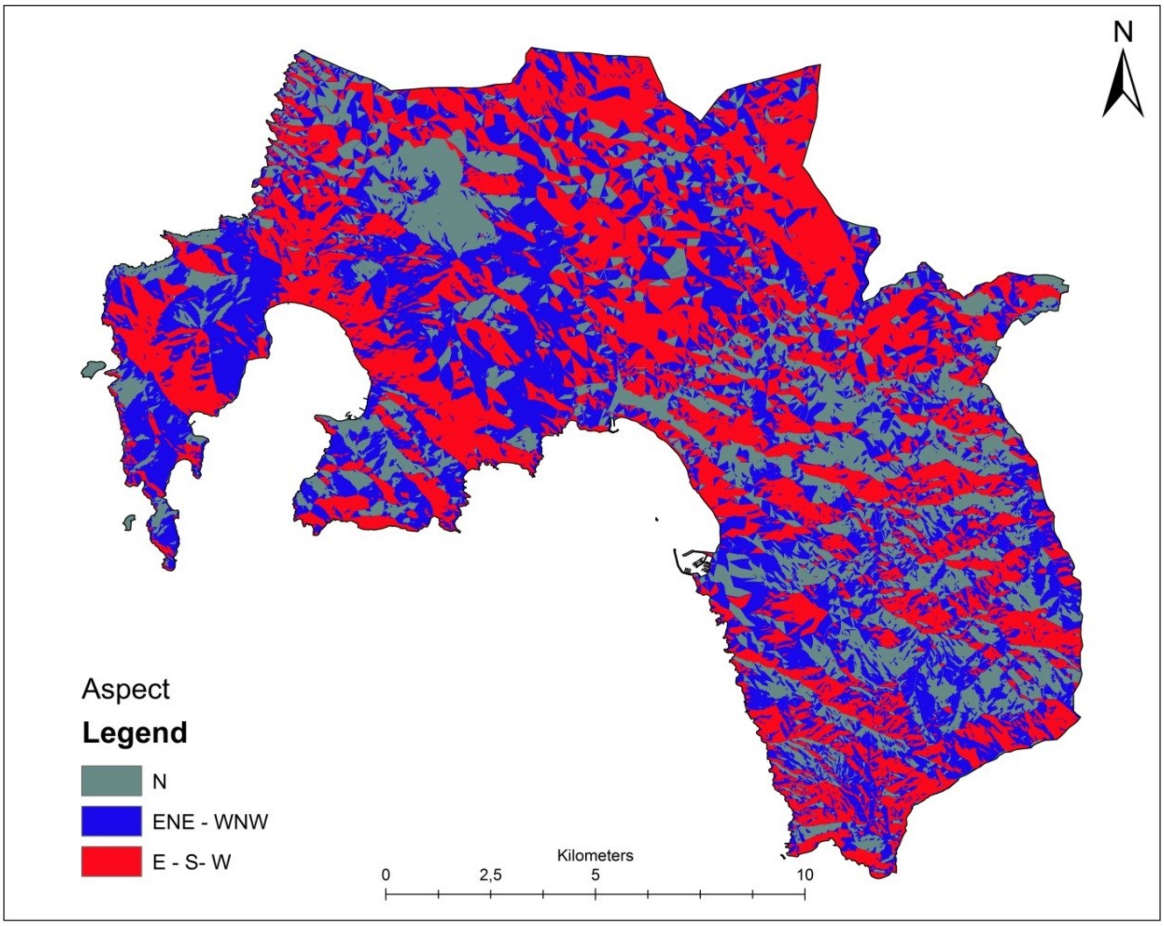

Figure 66. Map of Alghero territory representing the risk level relative to the subcriteria "aspect". The risk is low (grey) on the north oriented slopes (315-360° and 0-45°), moderate (blue) where orientation is towards east and west (255-315° and 45-135°) and is high (red) for slopes oriented towards south (135-255°). The value 2.04% corresponding to the subcriteria importance with respect to total risk is fully considered for red areas while is reduced of a factor 0.8 on blue areas (1.632%) and of a factor 0.6 on the grey areas (1.224%).

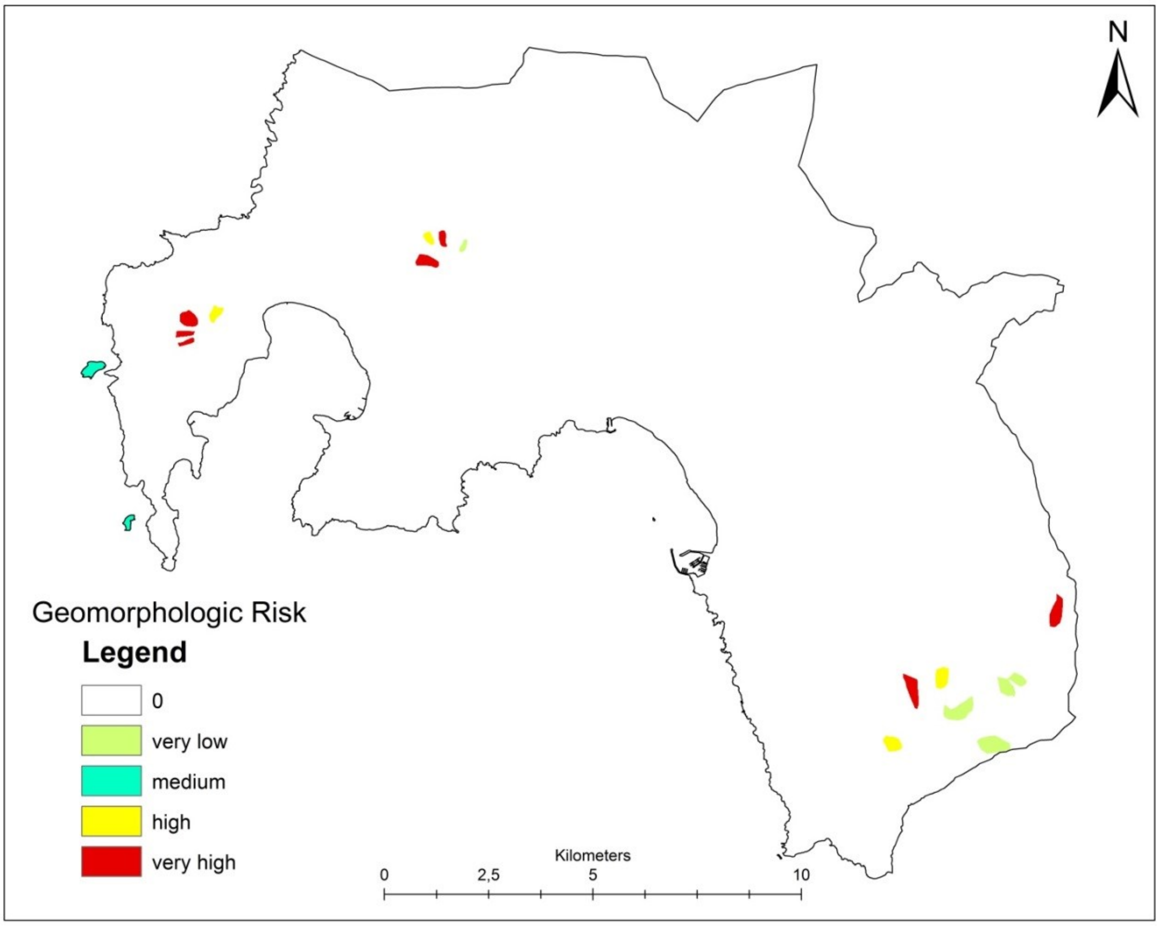

Figure 67. Map of Alghero territory representing the risk level relative to the subcriteria "geomorphological features". The map has been manually created by considering many parameters. The risk is very high (red) on the long and narrow slopes oriented along the more frequent wind (mistral) where it is possible an extreme behaviour of wildfires. In red areas the value 5.82% representing the subcriteria importance with respect to the total risk, is fully considered. The risk is high (yellow) on long but opened slopes oriented mainly towards W where it is possible a synergy of factors (wind, slope, aspect) influencing fire propagation. In the yellow areas the value is reduced of the factor 0.8 and becomes 4.656%. The risk is moderate on the little islands where, although usually no fire occurs, there would be many complication for extinguishing the fire. Here the value is reduced of the factor 0.6 and it is 3.492%. Finally, the green areas where the risk connected to geomorphology is very low, correspond to the short mountain sides in which the exposure to dominant wind could create some synergy. In this case the reduction factor is 0.3 and the value is 1.746%. On the rest of the territory the risk connected to geomorphological features has been considered null

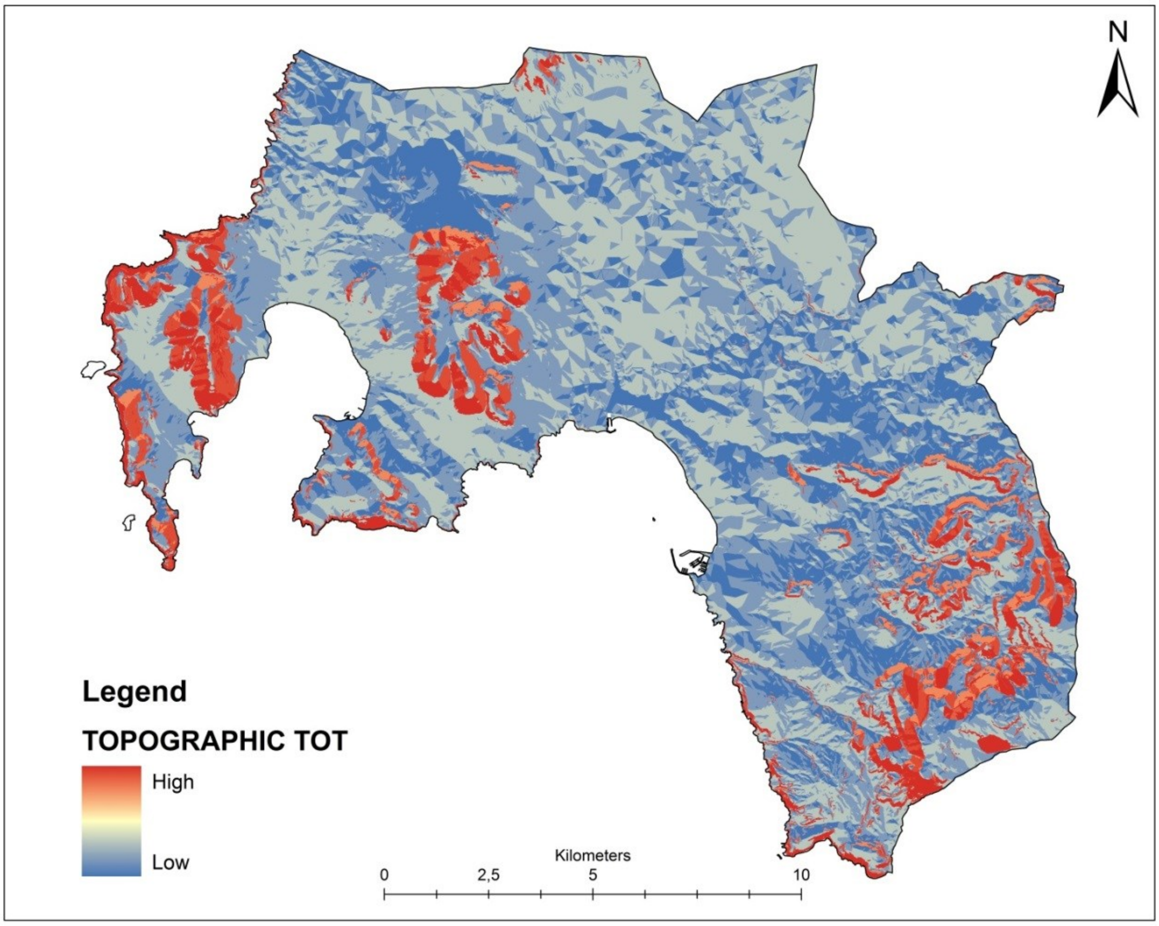

Figure 68. Map of Alghero territory representing the risk level relative to the criteria "topographic factors". It is obtained through the composition of the four subcriteria maps; each pixel value is the sum of the four values of the corresponding pixels in the subcriteria maps.

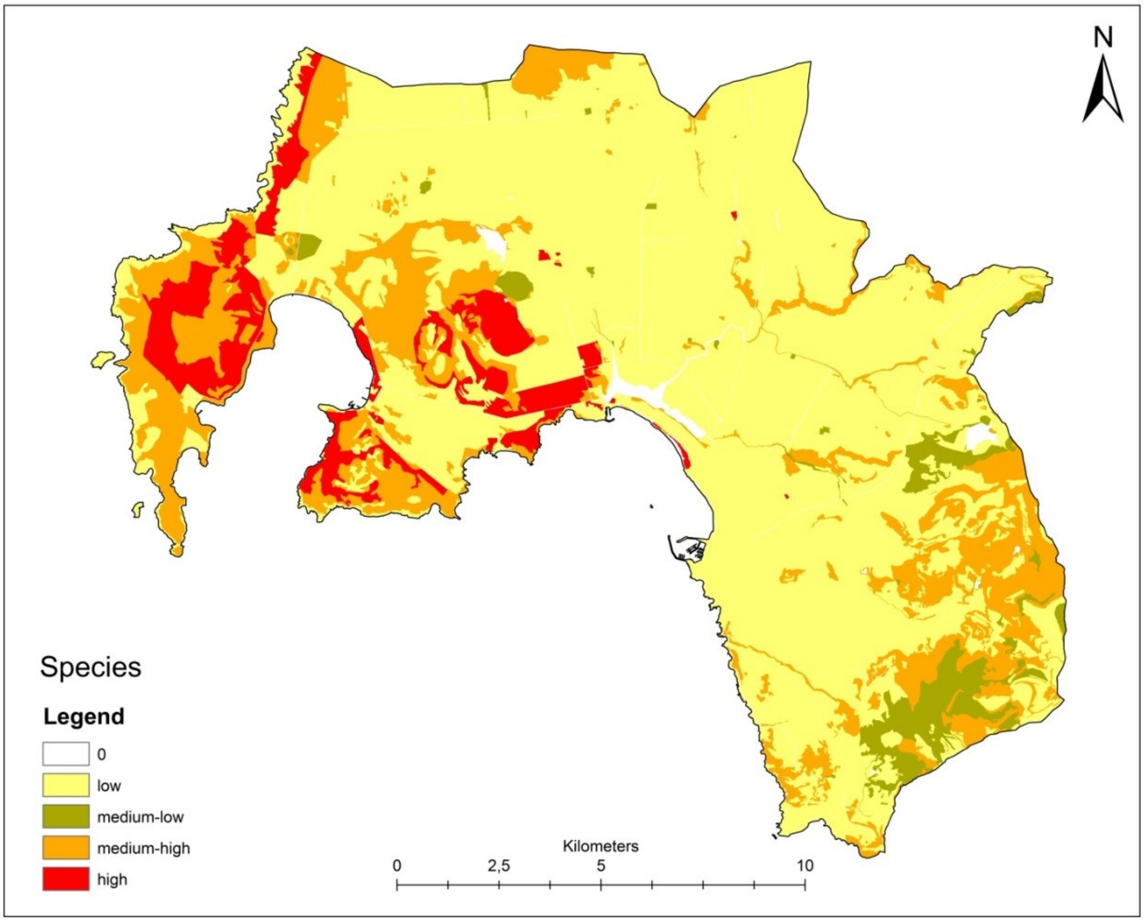

Figure 69. Map of Alghero territory representing the risk level relative to the subcriteria "vegetation species". The risk is low (yellow) on grasses and low bushes with a value of 2.32%*0.4 = 0.928%. The risk is moderate (green) in low maquis with a value of 2.32%*0.6 = 1.392%. The risk is moderately high (orange) in broadleaf forests and high/dense maquis with a value of 2.32%*0.9 = 2.088%, while in conifers (red) the value 2.32% has been fully considered. The value 0 (white) has been assigned to lakes and waters

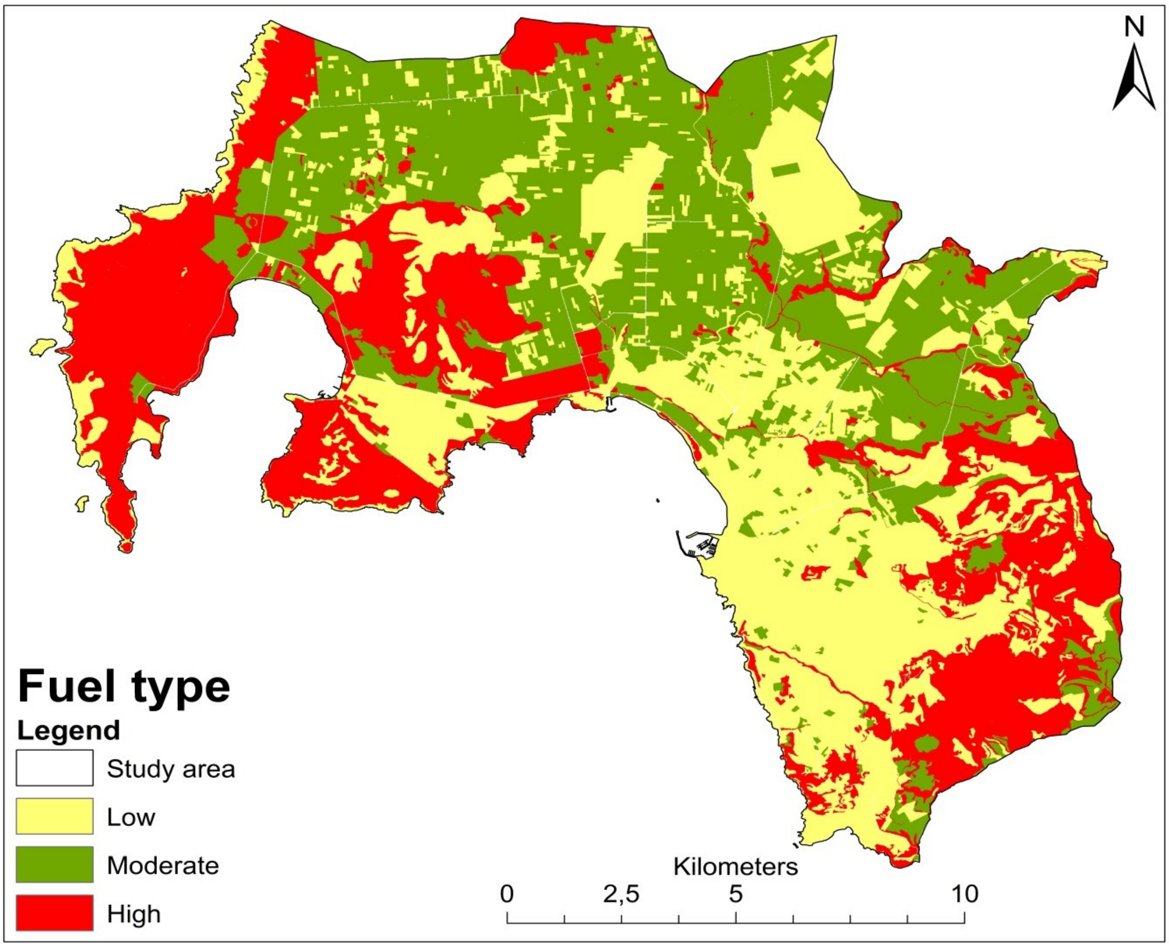

Figure 70. Map of Alghero territory representing the risk level relative to the subcriteria "fuel type". The risk is low (yellow) on low fuel charge with thin component with a value of 2.37%*0.6 = 1.422%. The risk is moderate (green) on fuel types with mean fuel charge values and presence of thin component with a value of 2.37%*0.8 = 1.896%. The risk is high for high fuel charge types and the value is 2.37%

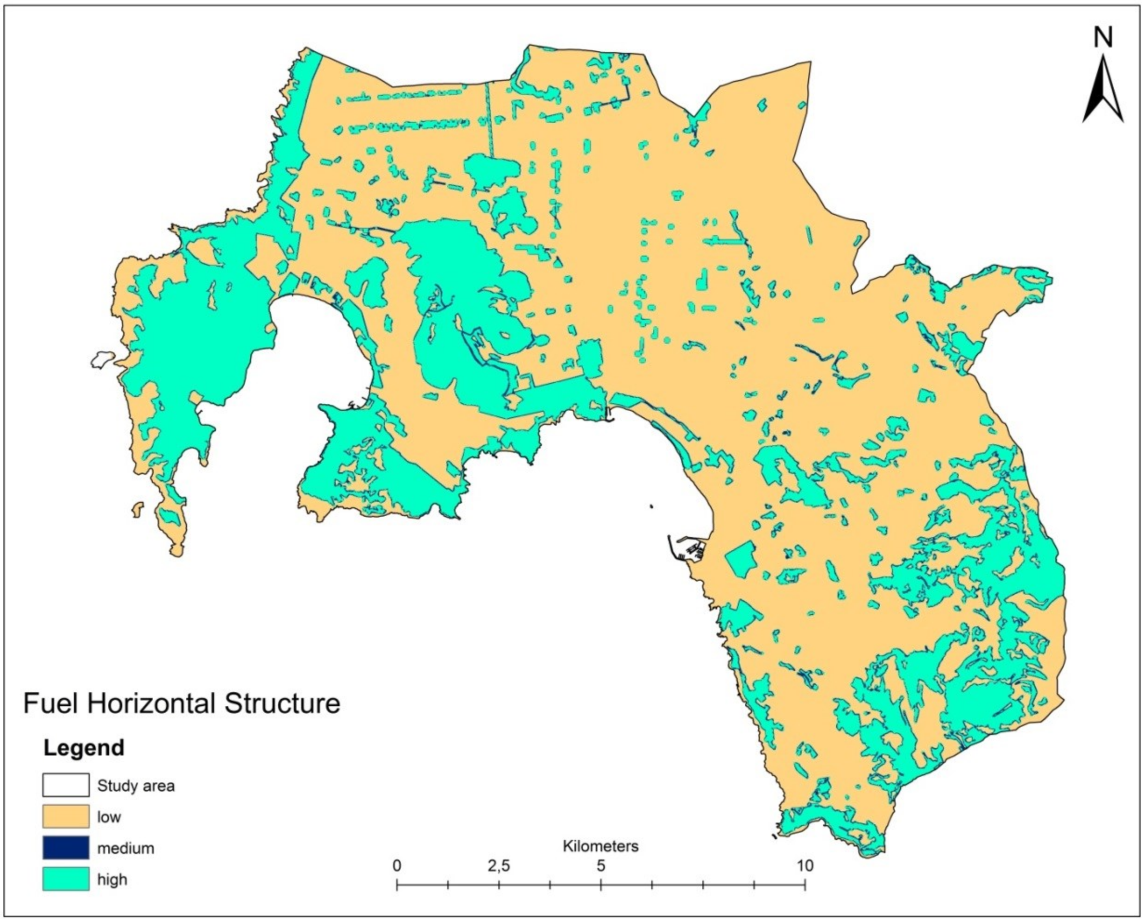

Figure 71. Map of Alghero territory representing the risk level relative to the subcriteria "fuel horizontal structure". The risk is low (clear brown) where the Vegetation Aggregation Index is null. The value of risk to be computed for these areas is 2.52%*0.3 = 0.756%. The risk is moderate on dark blue areas where the AI value is between 0 and 95%. On these areas the risk value is 2.52%*0.8 = 2.016%. The water-blue areas are the ones in which AI is higher than 95% and the risk value is 2.52%

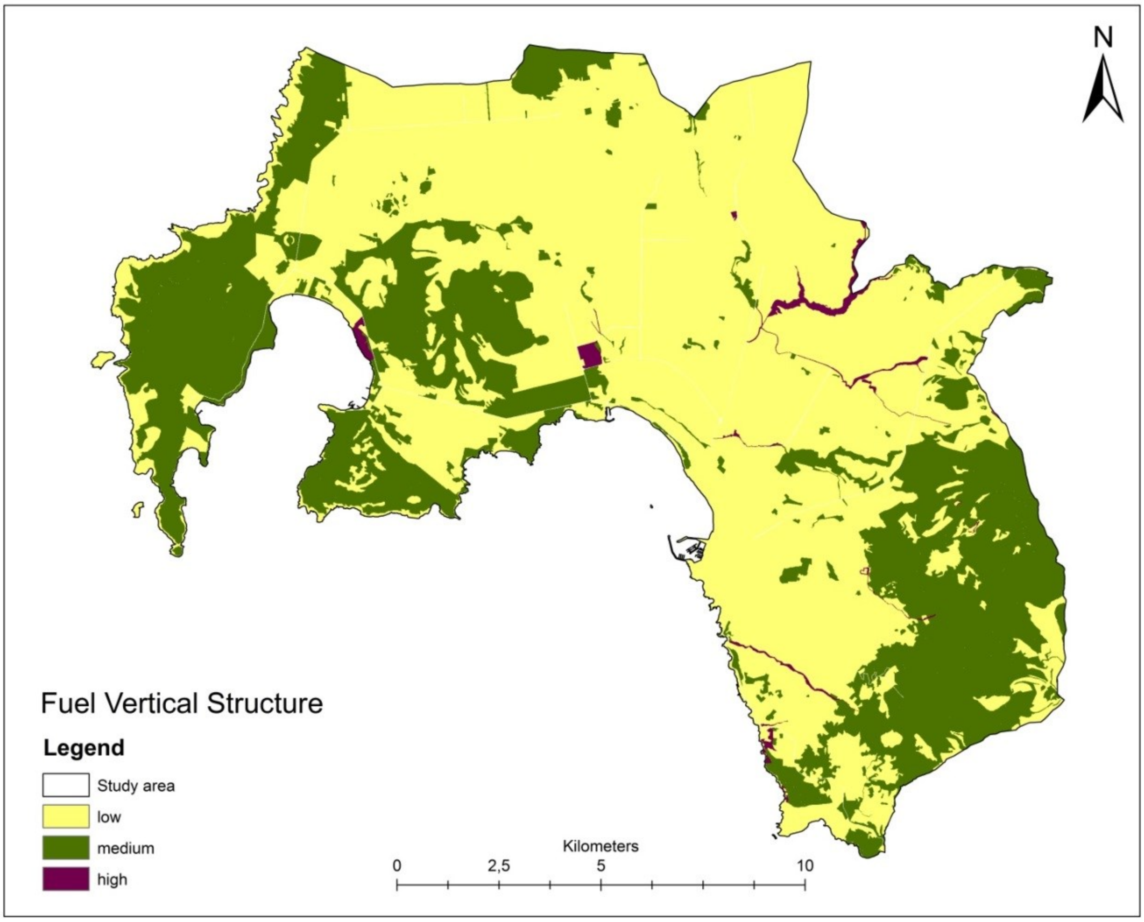

Figure 72. Map of Alghero territory representing the risk level relative to the subcriteria "fuel vertical structure". The risk is low (yellow) where there is no vertical structure (grasses and bushes with canopy touching the ground). In these areas the risk value to be computed is 1.58%*0.2 = 0.316%. The risk is moderate on green areas where forested areas present just canopy without underbrush (or detached canopy-underbrush). On these areas the risk value is 1.58%*0.7 = 1.106%. The dark violet areas are the forested areas where canopy and underbrush are in contact and the risk value to be applied is 1.58%

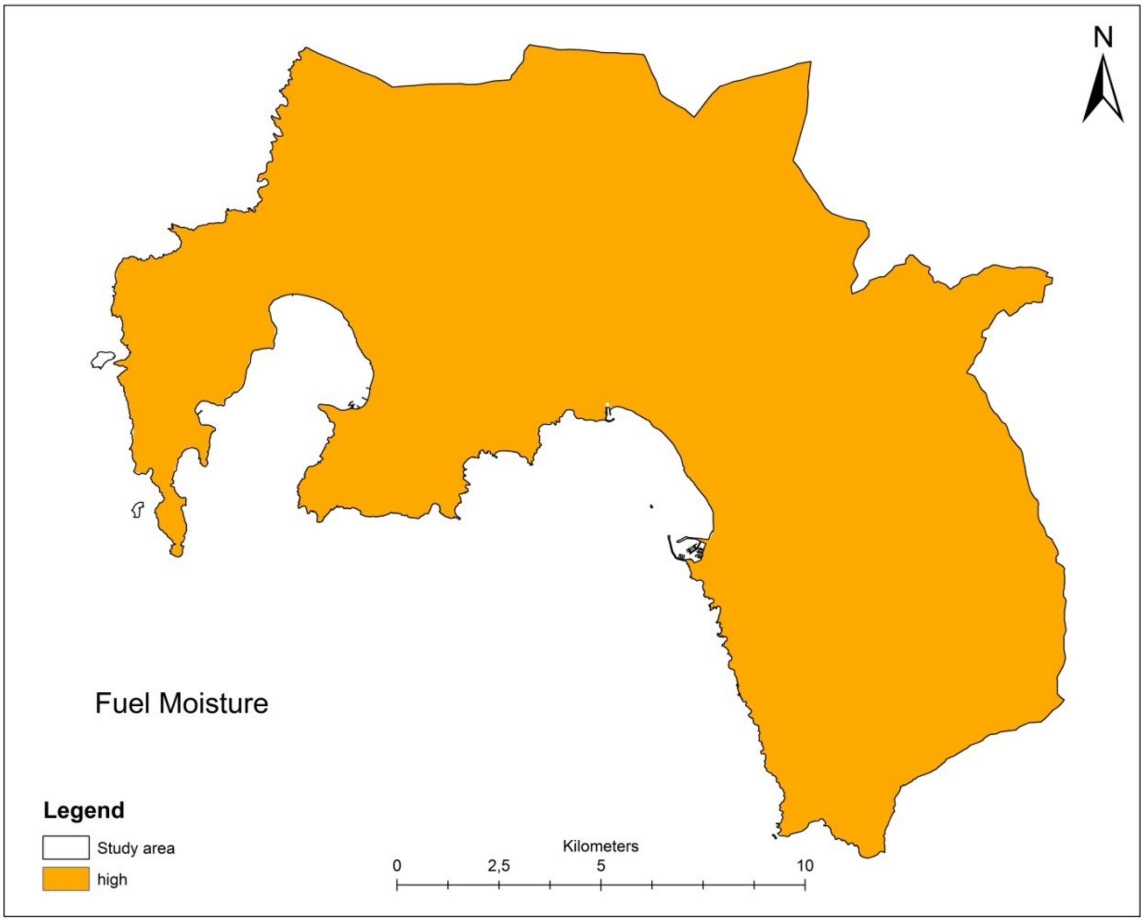

Figure 73. Map of Alghero territory representing the risk level relative to the subcriteria "fuel moisture". The whole territory has been considered at high risk because Alghero statistically has a warm and dry climate during summertime. It is a parameter whose usefulness can emerge in comparing distant areas or whenever we detail the risk assessment using weather data (daily or hourly R.H. data). The value to be considered is 6.13%

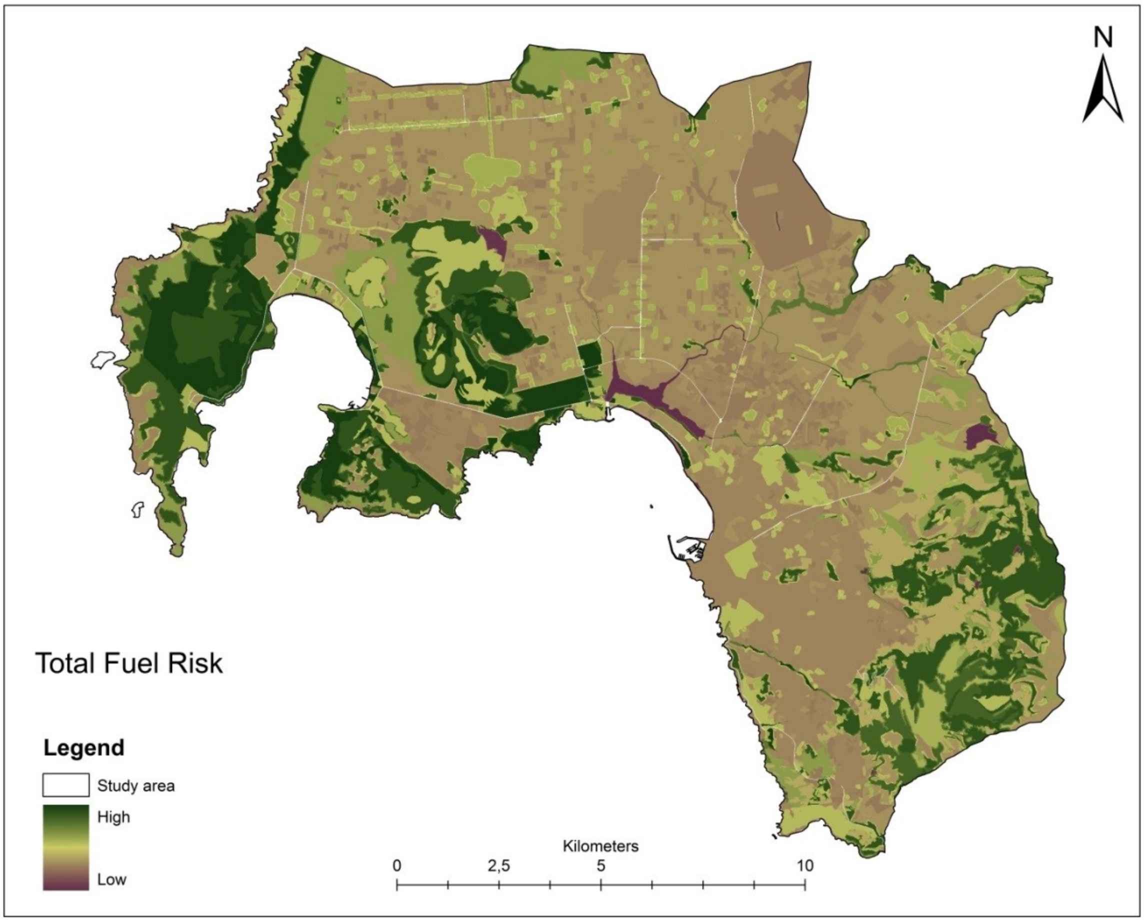

Figure 74. Map of Alghero territory representing the risk level relative to the criteria "fuel factors". It is obtained through the composition of the five subcriteria maps; each pixel value is the sum of the five values of the corresponding pixels in the subcriteria maps

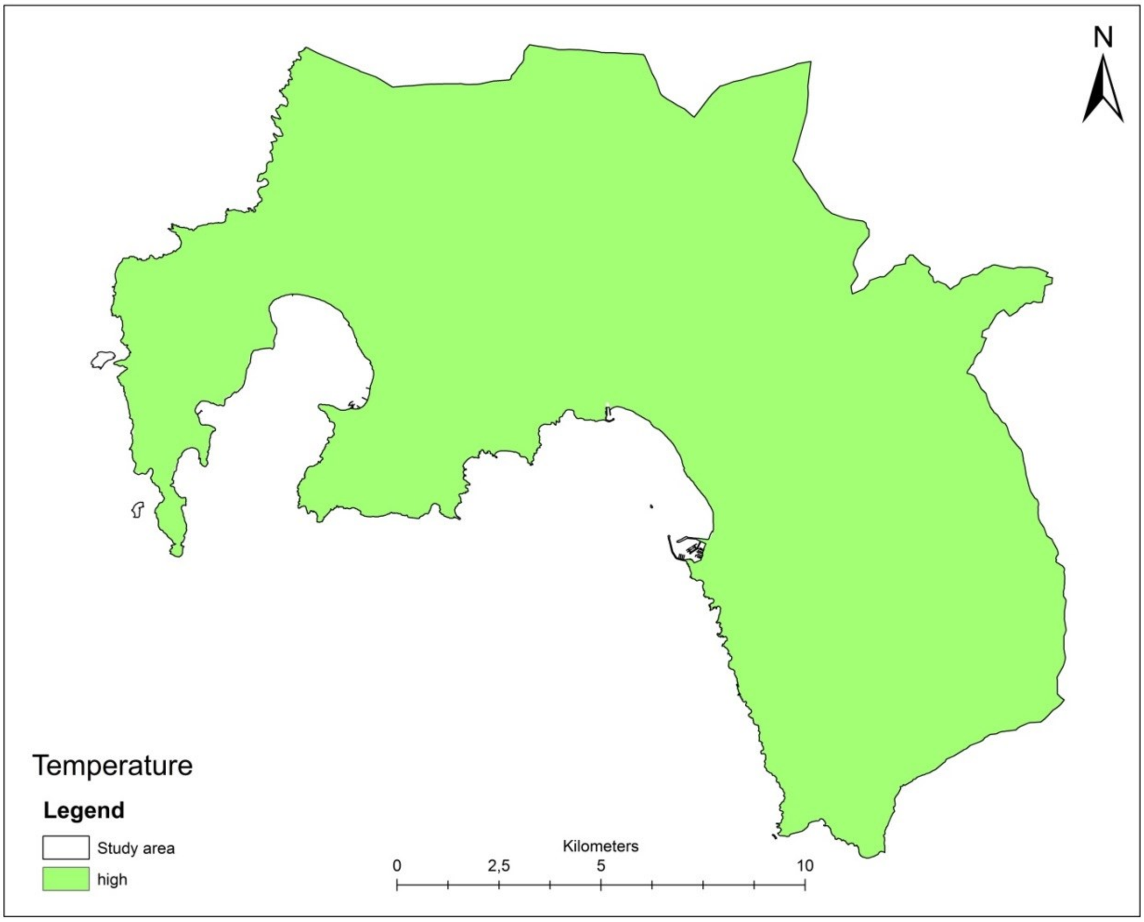

Figure 75. Map of Alghero territory representing the risk level relative to the subcriteria "temperature". The whole territory has been considered at high risk because Alghero statistically has a warm and dry climate during summertime. It is a parameter whose usefulness can emerge in comparing distant areas or whenever we detail the risk assessment using weather data (daily or hourly temperatures). The value to be considered is 5.49%

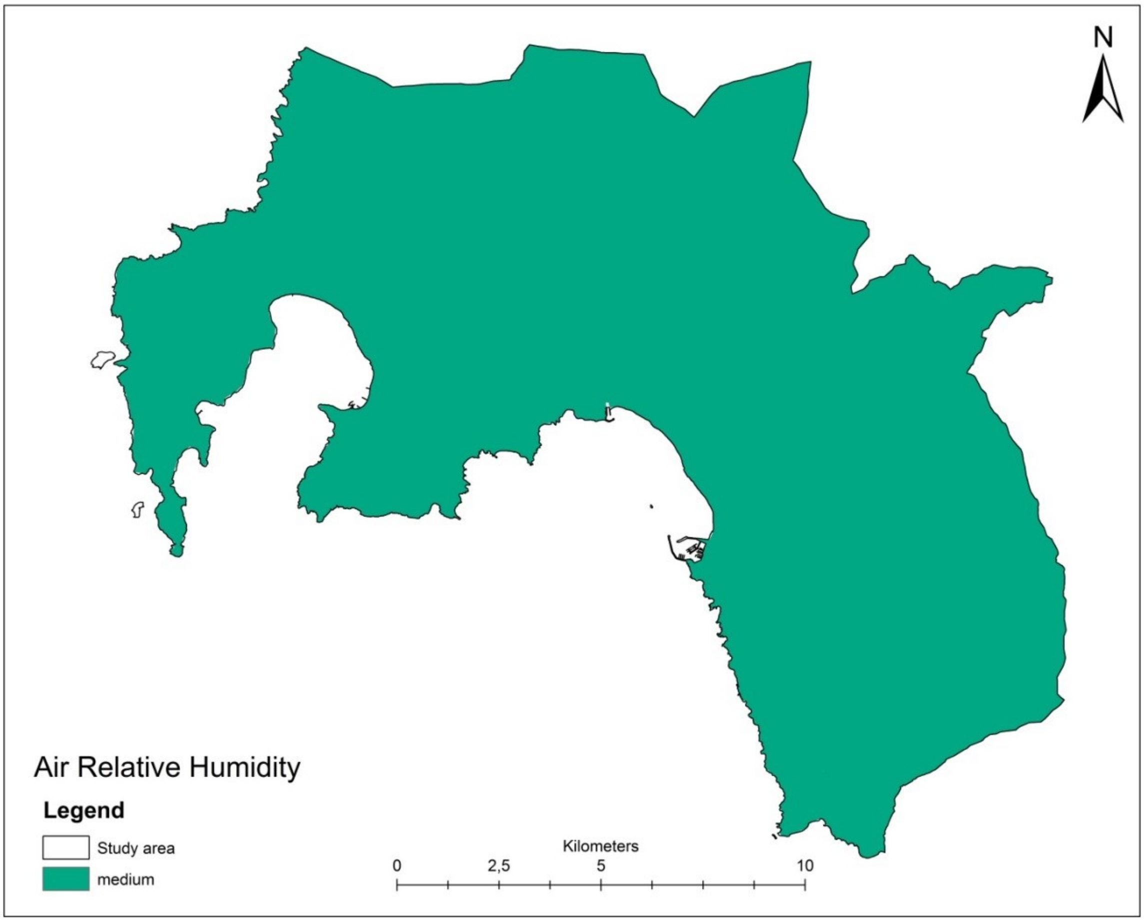

Figure 76. Map of Alghero territory representing the risk level relative to the subcriteria "air relative humidity". The whole territory has been considered at moderate risk because Alghero statistically has a warm climate during summertime but, being located close to the coast line, relative humidity is not very low. It is a parameter whose usefulness can emerge in comparing distant areas or whenever we detail the risk assessment using weather data (daily or hourly R.H.). The value we considered is 3.84%*0.8 = 3.072%

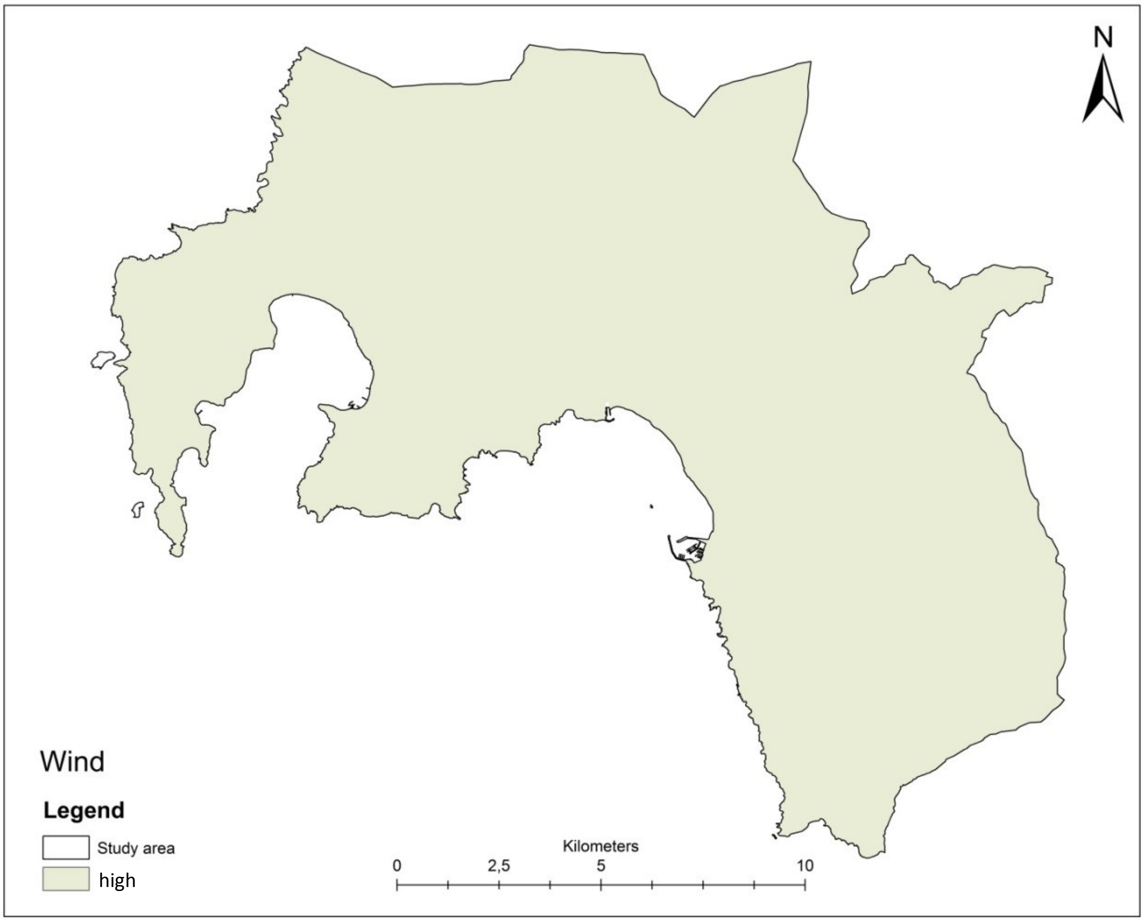

Figure 77. Map of Alghero territory representing the risk level relative to the subcriteria "wind". The whole territory has been considered at high risk because Alghero statistically has a windy climate during summertime (diurnal nocturnal breezes and frequent mistral). As for other meteo-climatic subcriteria the usefulness of this parameter can emerge in comparing distant areas or whenever we detail the risk assessment using weather data (daily or hourly wind speed). The value to be considered is 14.46%

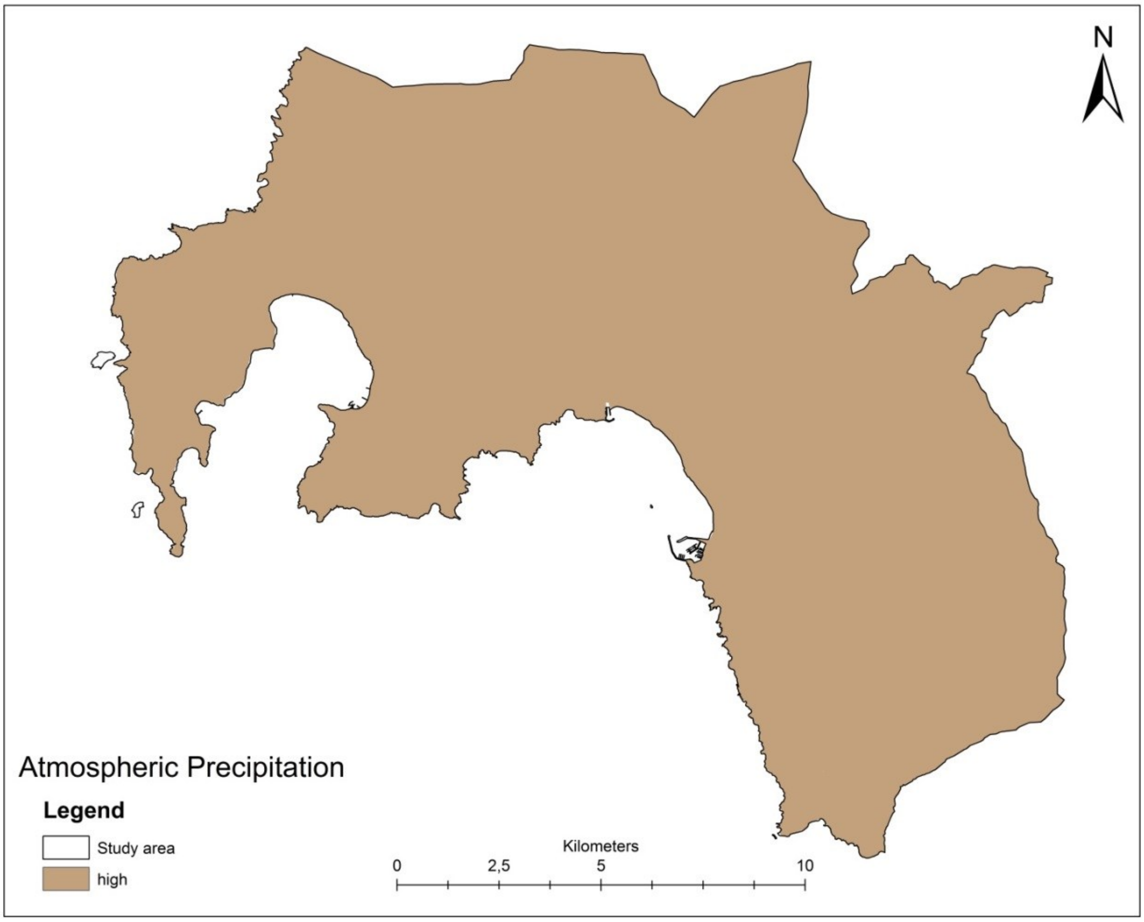

Figure 78. Map of Alghero territory representing the risk level relative to the subcriteria "atmospheric precipitation". The whole territory has been considered at high risk because Alghero statistically has very few days of rain during summertime. As other meteo-climatic subcriteria this one is a parameter whose usefulness can emerge in comparing distant areas or whenever we detail the risk assessment using weather data on rains. The value to be considered is 8.69%

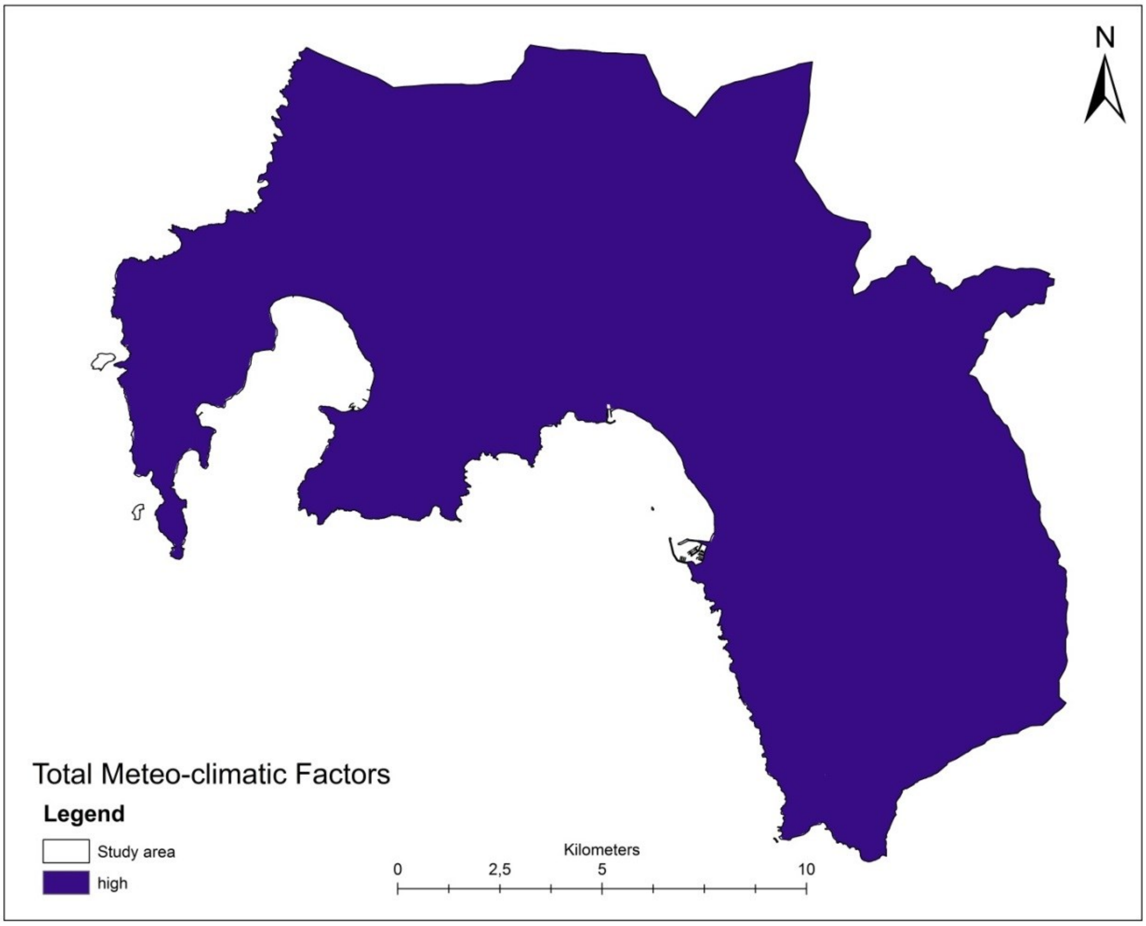

Figure 79. Map of Alghero territory representing the risk level relative to the criteria "meteo-climatic factors". It is obtained through the composition of the four subcriteria maps; each pixel value is the sum of the four values of the corresponding pixels in the subcriteria maps

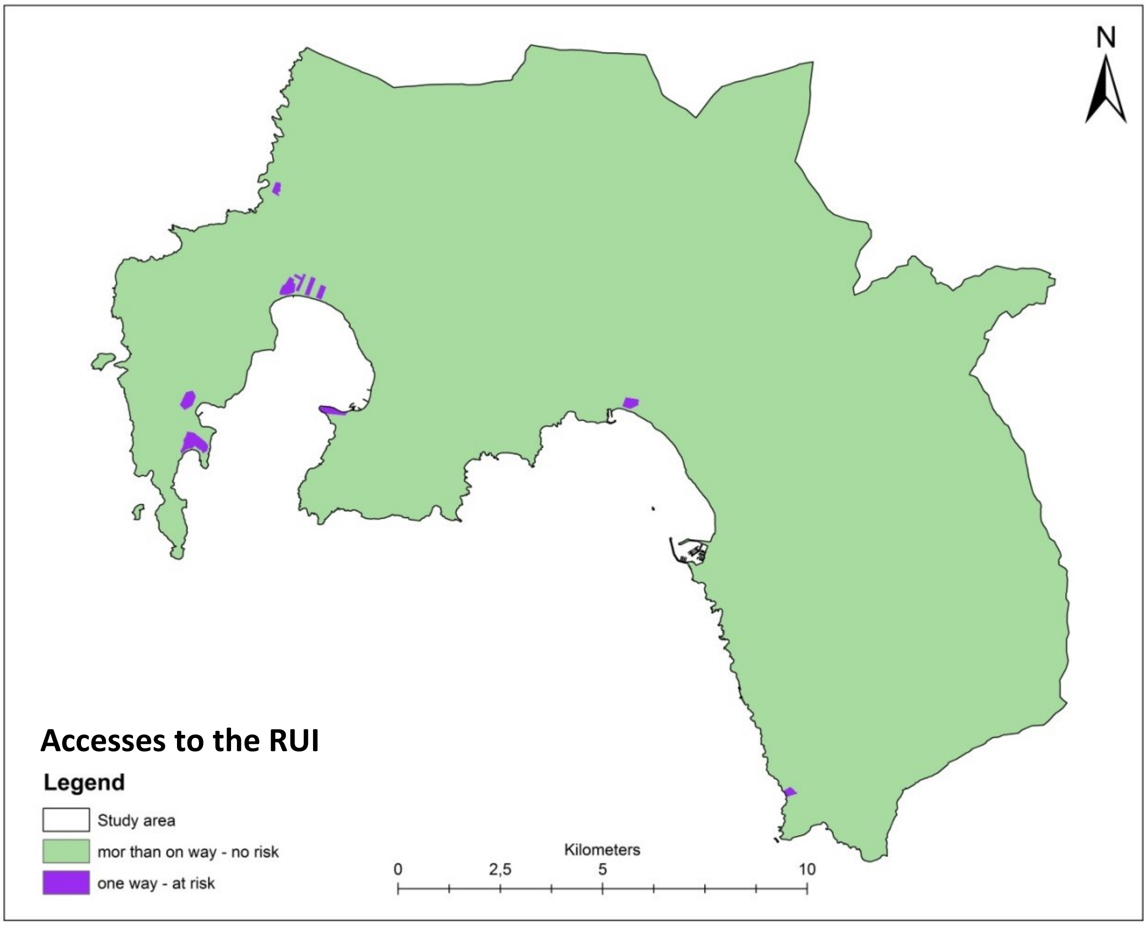

Figure 80. Map of Alghero territory representing the risk level relative to the subcriteria "accesses to the RUI". The risk is 0% on green areas because there are more accesses to the RUI while it is 2.51% on violet areas which are RUI with just one access

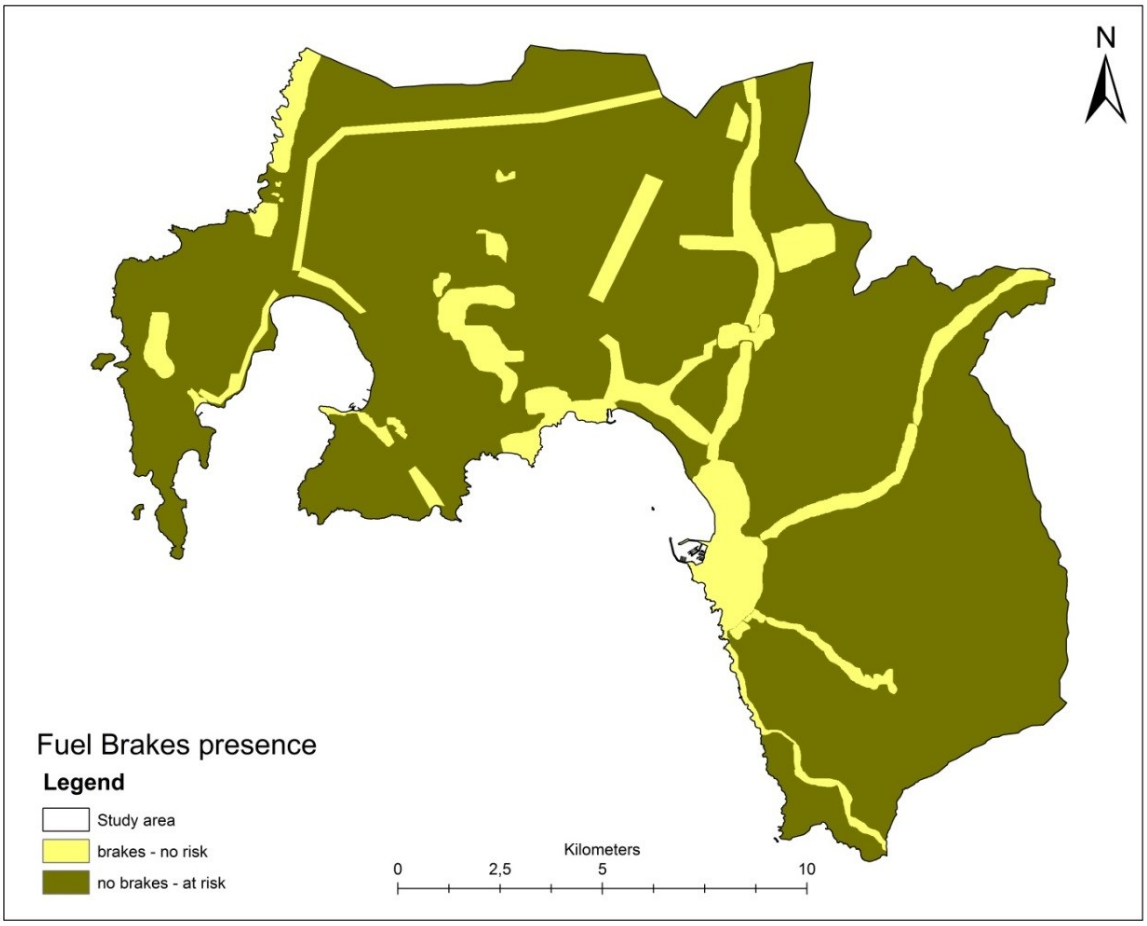

Figure 81. Map of Alghero territory representing the risk level relative to the subcriteria "street width in RUI". The risk is 0% on yellow areas because fuels are interrupted while it is 2.56% on green areas in which no wide street or fuel brake interrupts fuel continuity

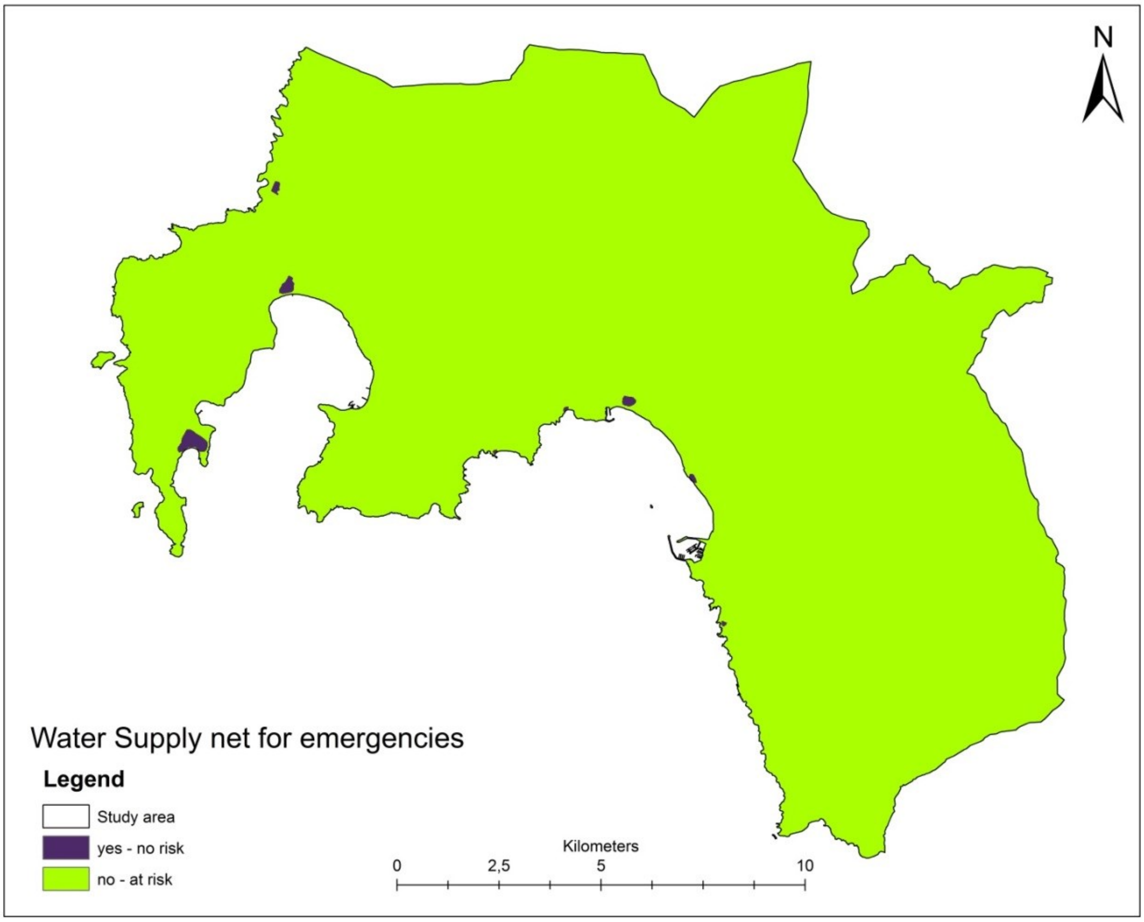

Figure 82. Map of Alghero territory representing the risk level relative to the subcriteria "water supply in RUI". The risk is 0% on violet areas because those RUIs are touristic villages in which there is a water supply net for emergency. On green areas there is no water supply and the risk value is 1.50%

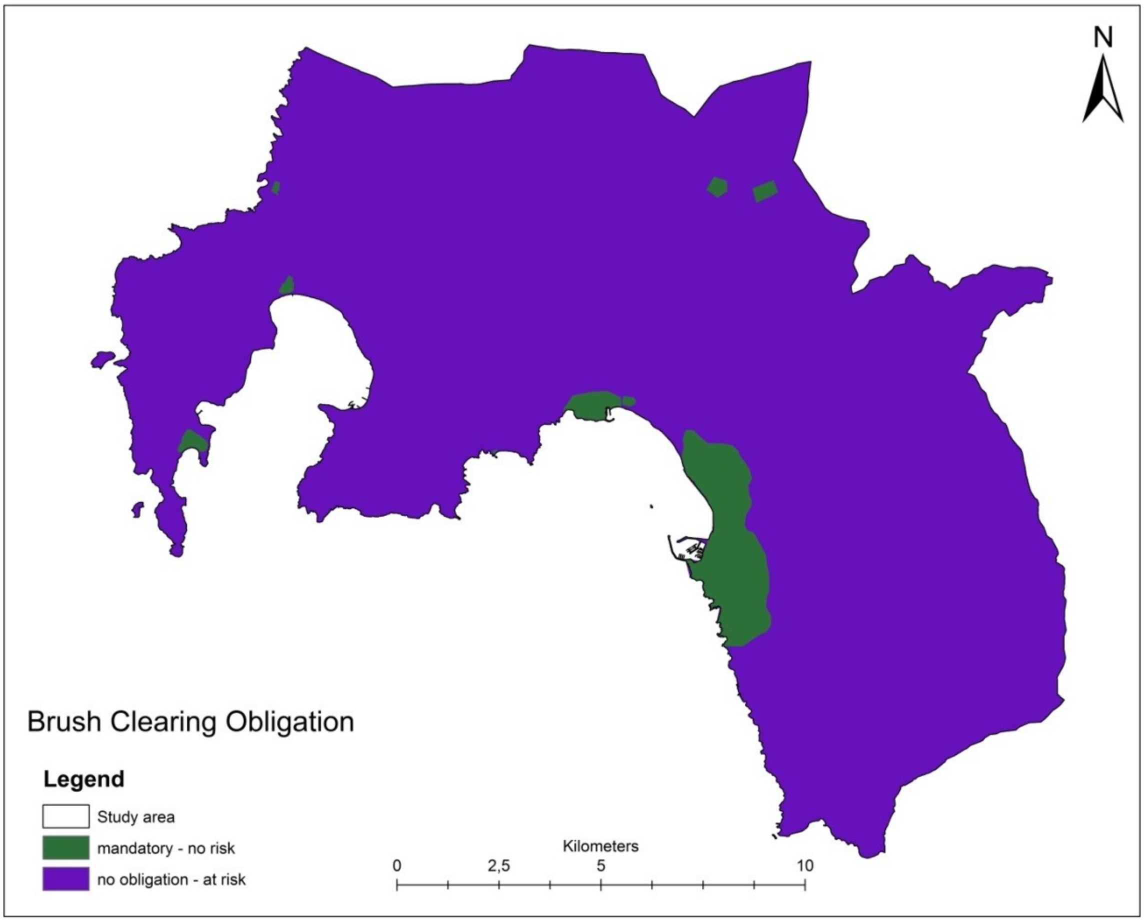

Figure 83. Map of Alghero territory representing the risk level relative to the subcriteria "brushclearing in RUI". The risk is 0% on green areas because the municipality of Alghero prescribes brush-clearing in those areas while in violet areas there is not the obligation to brush-clear the RUI and in this case the risk value is 4.11%

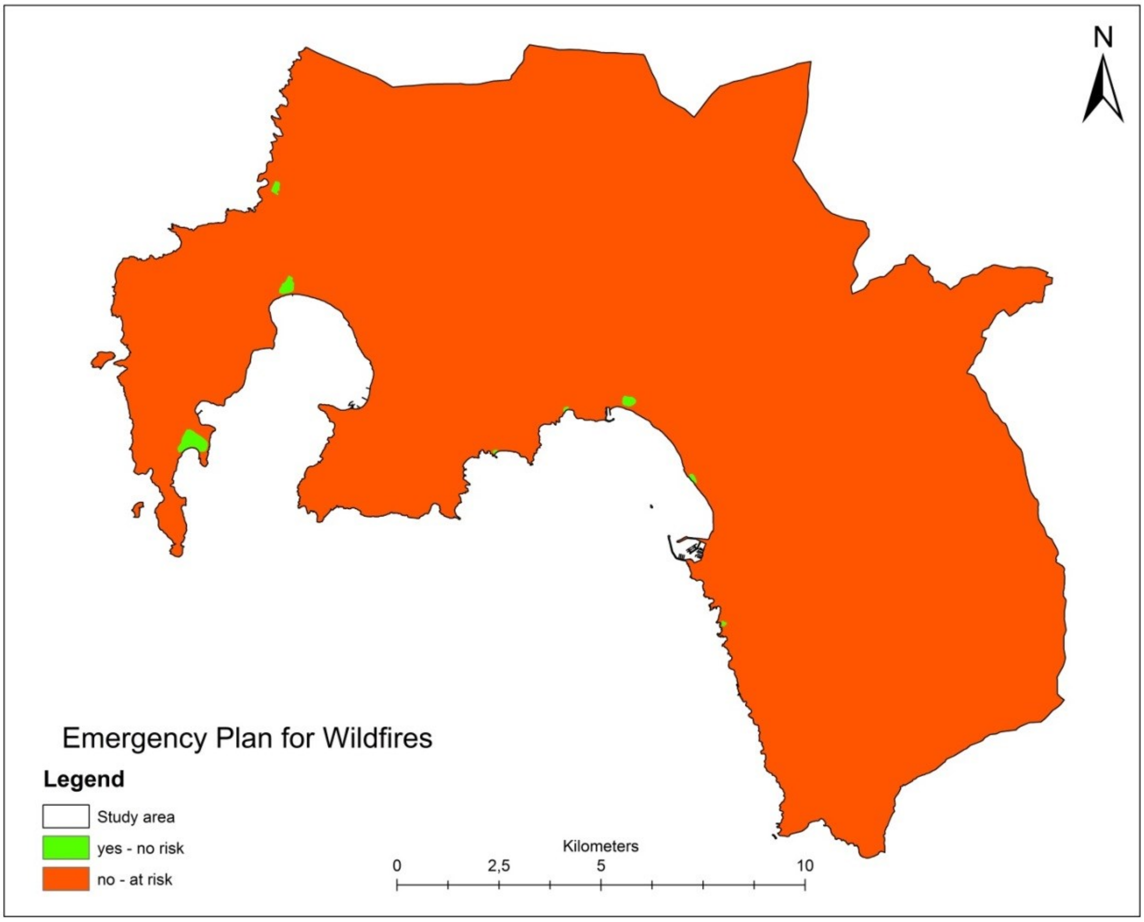

Figure 84. Map of Alghero territory representing the risk level relative to the subcriteria "emergency plan". The risk is 0% on green areas because those RUIs are touristic villages in which there is the plan for emergencies while on red areas there is no emergency plan and the risk value is 2.10%

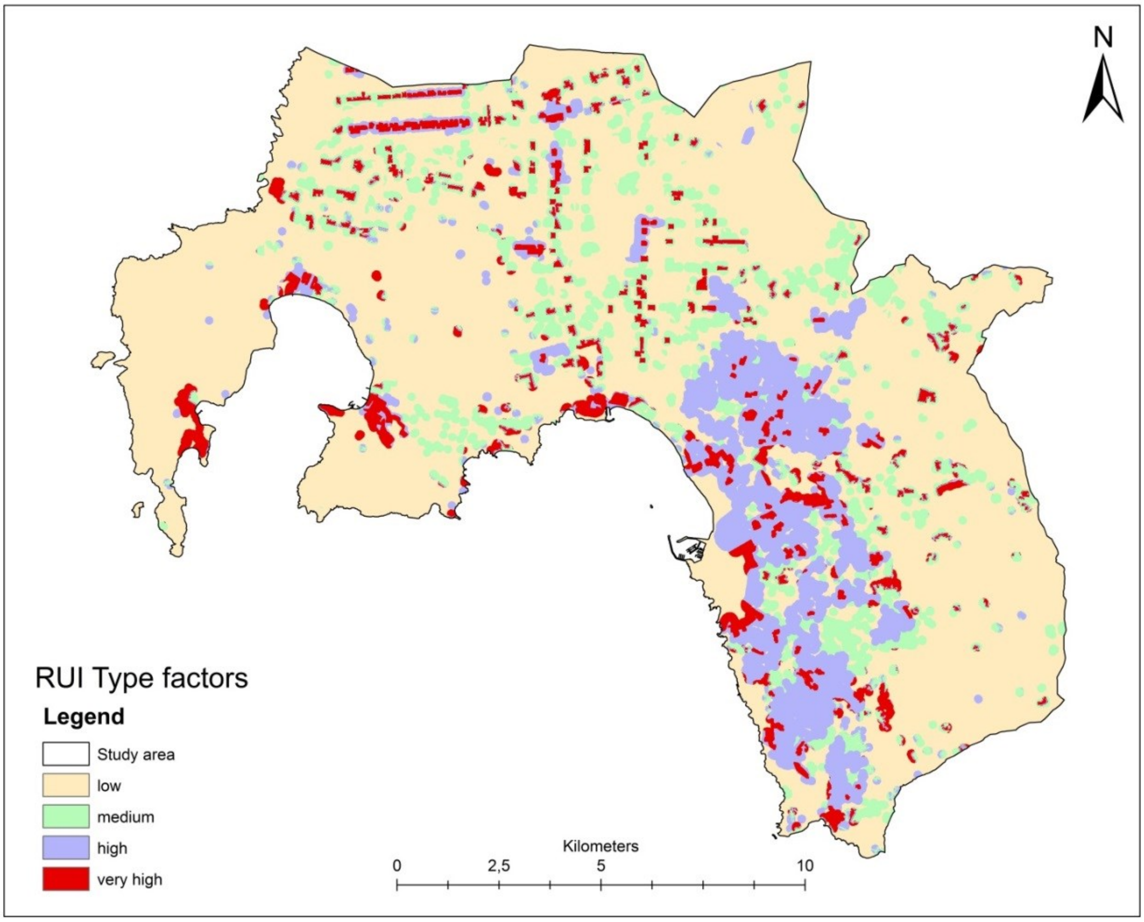

Figure 85. Map of Alghero territory representing the risk level relative to the subcriteria "RUI type". The risk is low (yellow) for the RUI types: Scattered AI null, Isolated AI low, Isolated AI null and the value of risk is reduced of the factor 0.5 and hence it is 2.25%*0.5 = 1.125%. The risk is moderate (green) for the RUI types: Dense AI null, Scattered AI low, Isolated AI high and the value of risk is reduced of the factor 0.7. the value to be computed is 2.25%*0.7 = 1.575%. The risk is high (violet) for the RUI types: Dense AI low, Scattered AI high, Very Dense AI null in which the risk value is reduced of a factor 0.8 becoming 1.80%. Finally, red areas corresponding to RUI types: Very Dense AI high, Very Dense AI low, Dense AI high, are considered at very high risk and the value of risk 2.25% of the subcriteria is fully considered on these areas

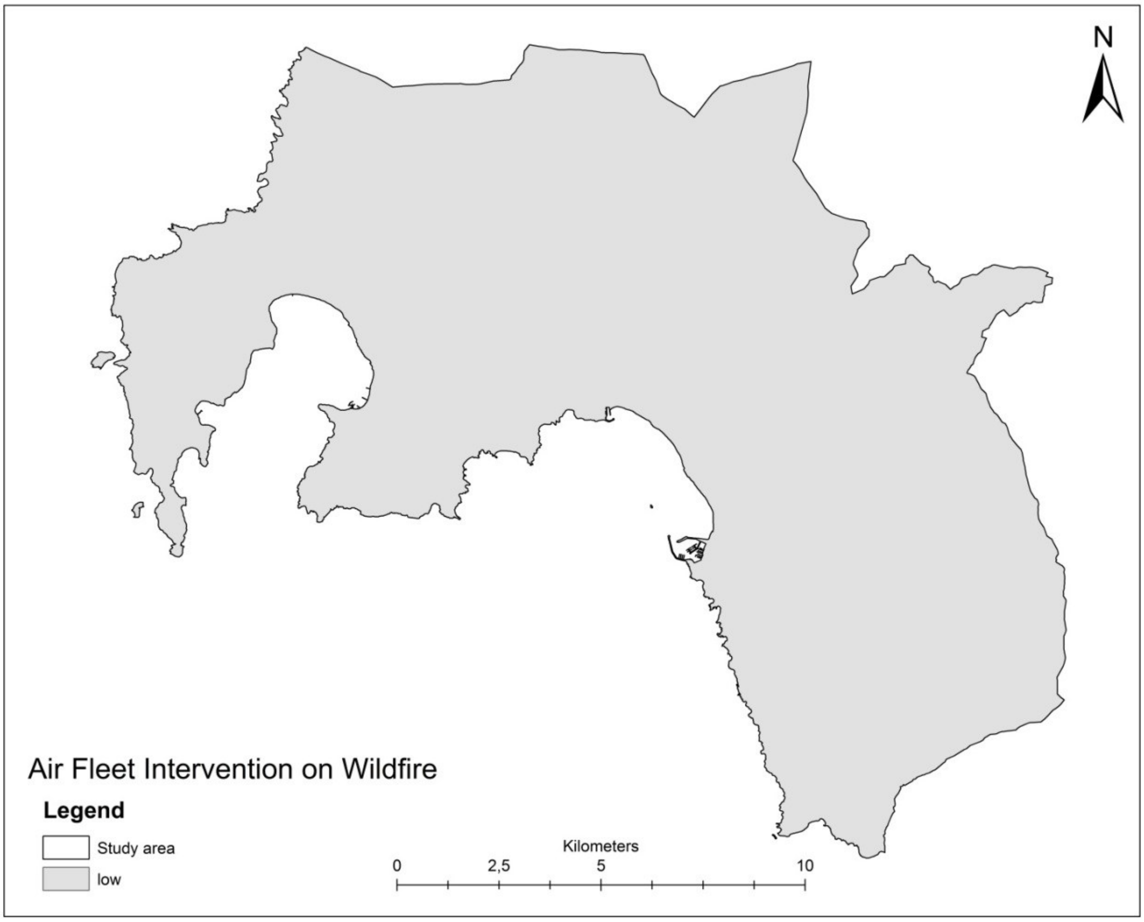

Figure 86. Map of Alghero territory representing the risk level relative to the subcriteria "distance from water source for aircraft". The whole territory has been considered at low risk because Alghero is on the coast line and aircrafts have immediate access to water recharge. It is a parameter whose usefulness can emerge at supra-communal level when comparing areas whose distance from water source for aircraft recharge is different. The value to be considered is 1.01%*0.2 = 0.202%

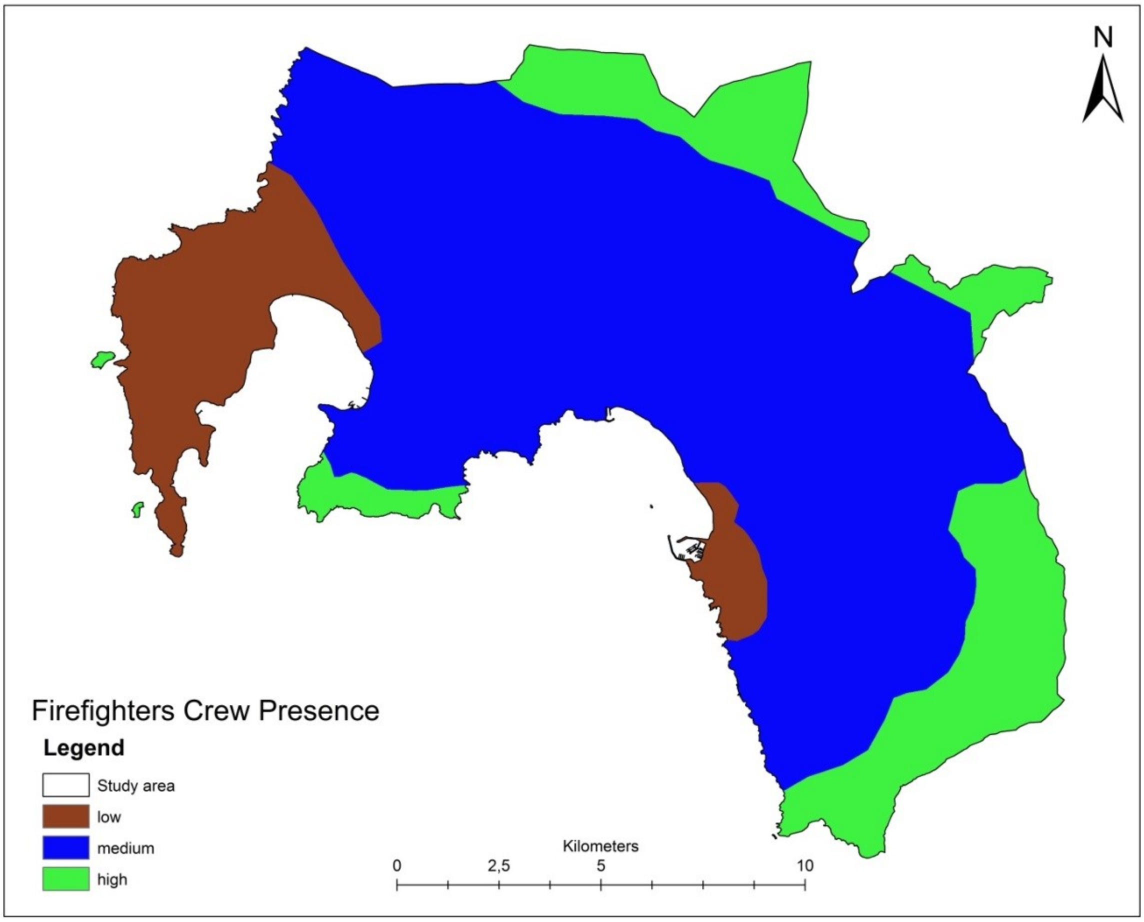

Figure 87. Map of Alghero territory representing the risk level relative to the subcriteria "distance from firefight crew". The risk is low (brown) for the areas where the crew is very close and we can have an intervention on fire in at least 7'. In these case the risk value is reduced of 0.5 and the value is 2.12%*0.5 = 1.06%. The risk is moderate on blue areas where the lapse time of intervention is between 7' and 15'. In this case the risk is reduced of 0.8 and the risk is 2.12%*0.8 = 1.696%. The distance from intervention crews of green areas is higher and the time required before the intervention is longer than 15'. The risk value in this case is 2.12%

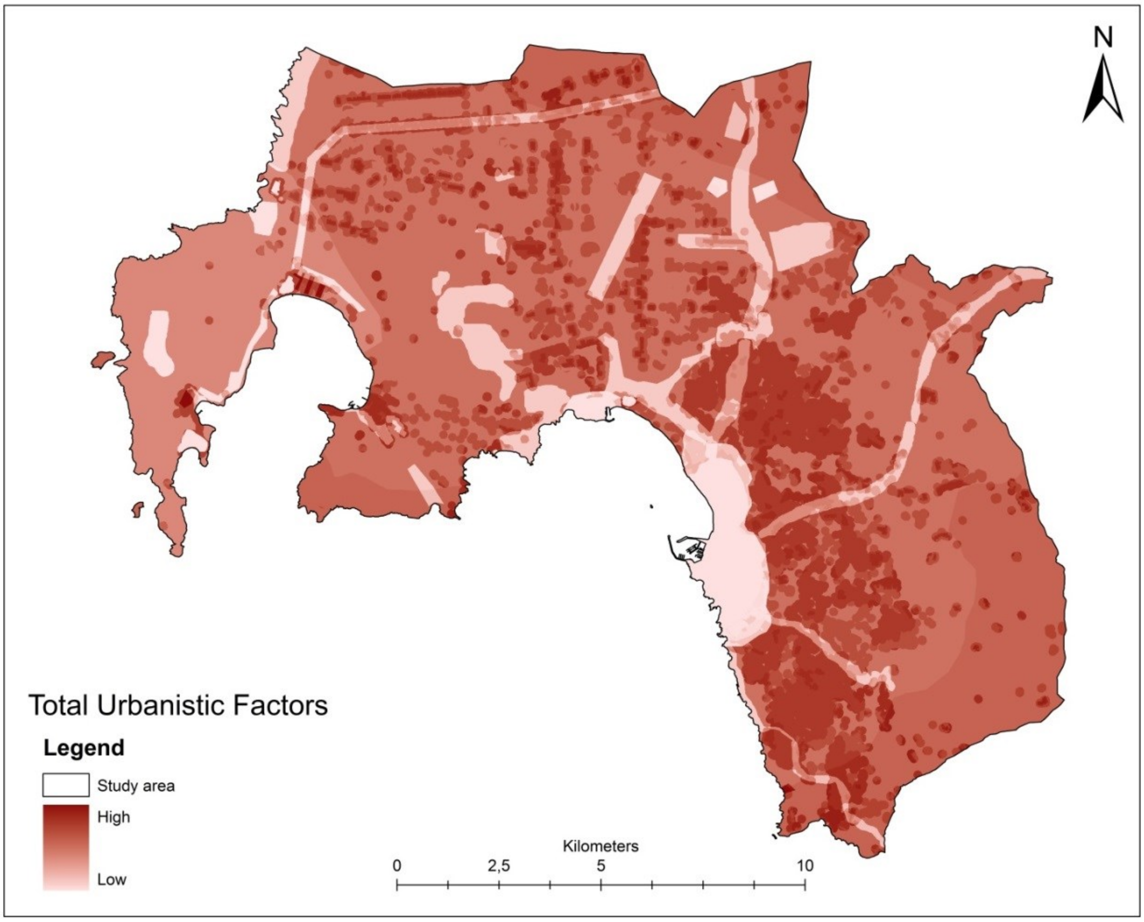

Figure 88. Map of Alghero territory representing the risk level relative to the criteria “urban-RUI factors”. It is obtained through the composition of the eight subcriteria maps; each pixel value is the sum of the eight values of the corresponding pixels in the subcriteria maps

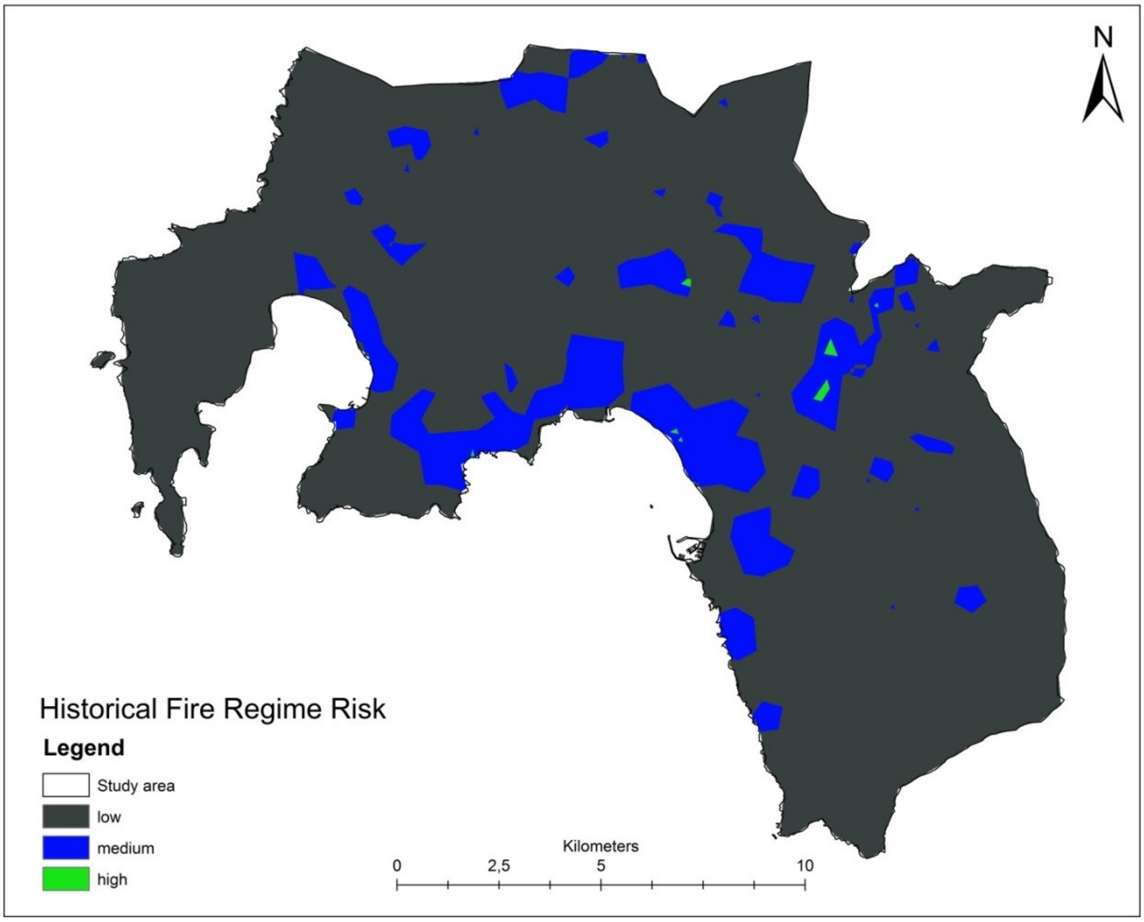

Figure 89. Map of Alghero territory representing the risk level relative to the subcriteria “wildfire statistics”. The risk is low (dark grey) for the areas where no fire was recorded in the last years and the ignition density is low. In these case the risk value is reduced of a factor 0.2 and the value is 3.55%*0.2 =0.71%. The risk is moderate on blue areas where no fire was recorded but the ignition density is high or alternatively one fire was recorded although the ignition density is low. In this case the risk is reduced of 0.5 and the risk is 3.55%*0.5 = 1.775%. The green areas are the ones that burned more than 1 time or alternatively burned just one time but the local ignition density is high. In this case the risk value is 3.55%

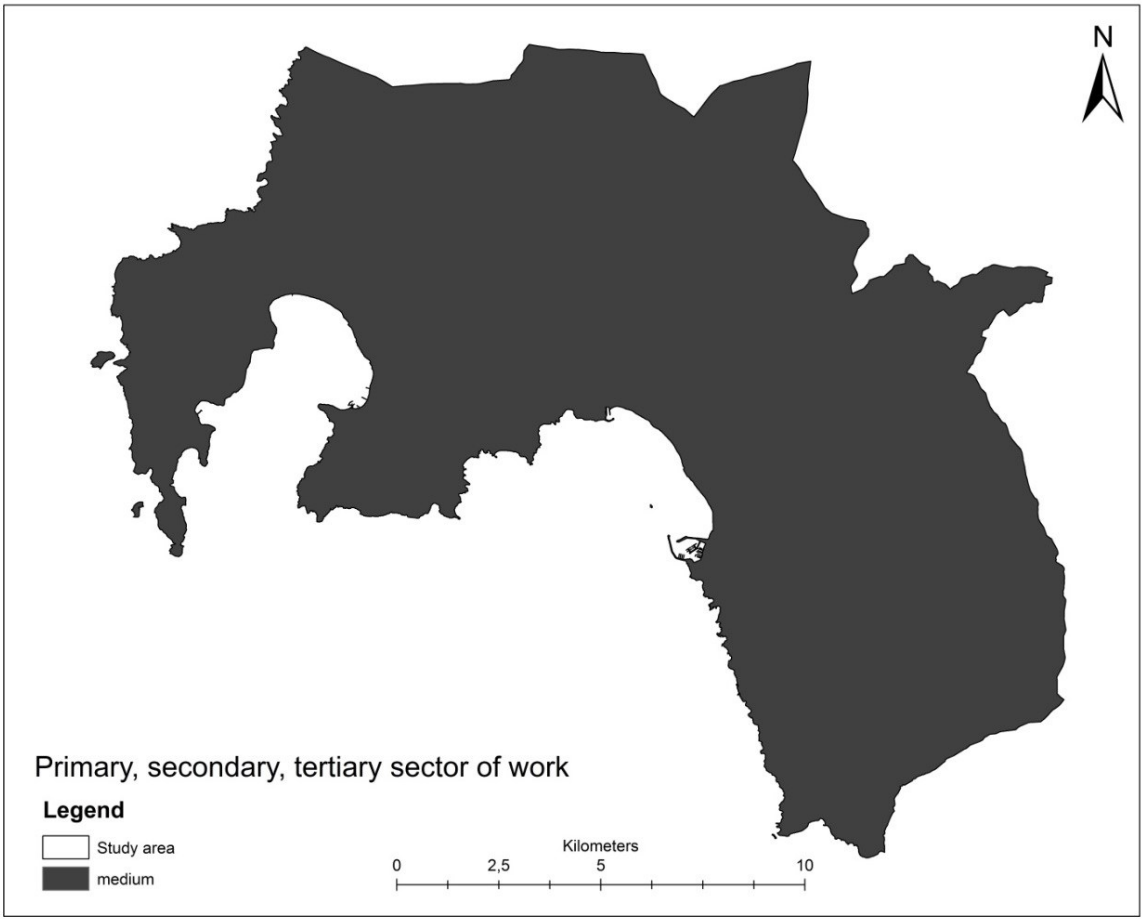

Figure 90. Map of Alghero territory representing the risk level relative to the subcriteria "division of work force". It is a parameter whose usefulness can emerge at supra-communal level since data are given at communal scale. Alghero is a little town with all service and one of the main activities is tourism. Nevertheless there are many agricultural activities on its countryside, and for this reason the risk due to this subcriteria has been considered moderate. The value to be considered is 2.13%*0.8 = 1.704%

Figure 91. Map of Alghero territory representing the risk level relative to the subcriteria "unemployment". It is a parameter whose usefulness can emerge at supra-communal level since data are given at communal scale. Alghero economy, especially during summer with tourism is very active and it doesn't suffer a high percentage of unemployment and, hence, the risk due to this subcriteria has been considered low. The value to be considered is 2.16%*0.4 = 0.864%

Figure 92. Map of Alghero territory representing the risk level relative to the subcriteria "education level and wealth". It is a parameter whose usefulness can emerge at supra-communal level since data are given at communal scale. Alghero economy is relatively rich and, the education level is above Sardinian averages. The risk due to this subcriteria has been considered low. The value to be considered is 1.79%*0.3 = 0.537%

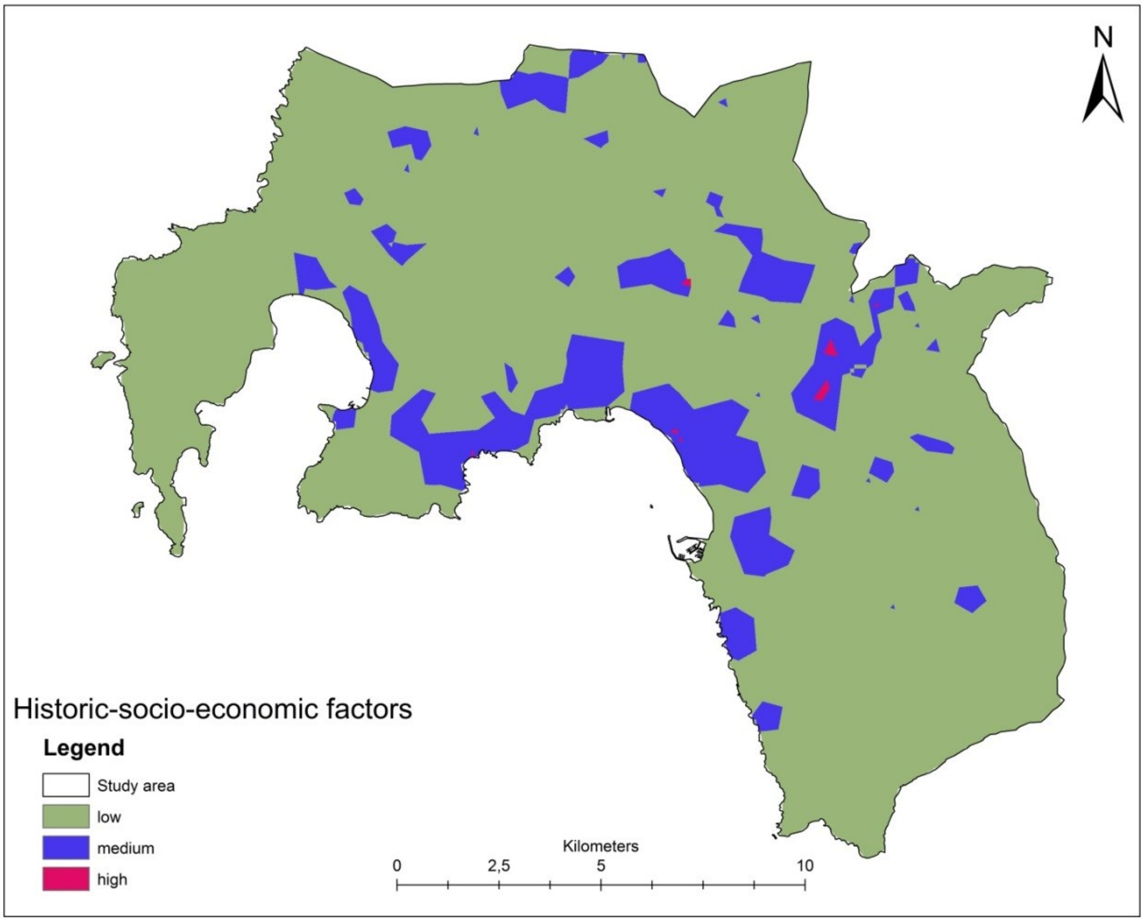

Figure 93. Map of Alghero territory representing the risk level relative to the criteria "historic-socio-economic factors". It is obtained through the composition of the four subcriteria maps; each pixel value is the sum of the four values of the corresponding pixels in the subcriteria map

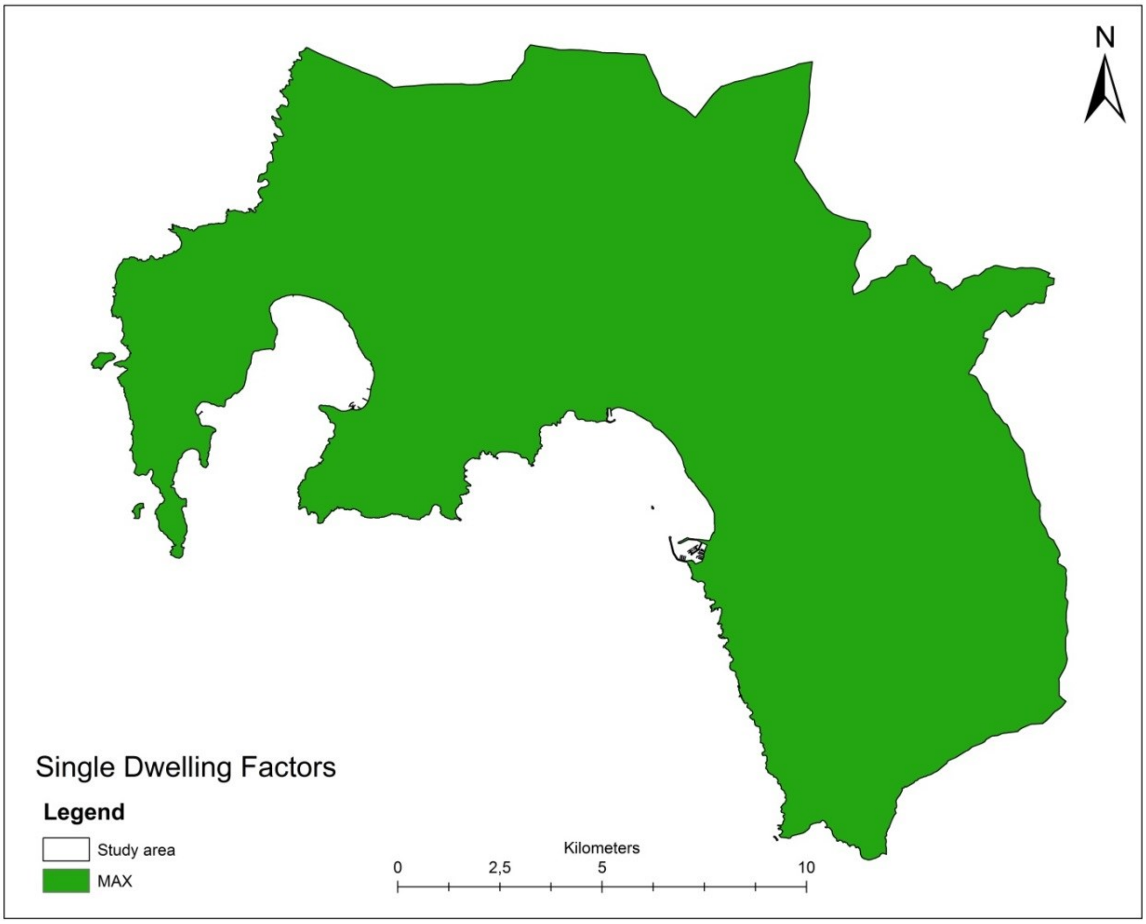

Figure 94. Map of Alghero territory representing the risk level relative to the criteria "single dwelling factors". The evaluation of single dwelling situation cannot be conducted at communal level: the housing layer that we used as input of Alghero Local Scale mapping methodologies has 13,000 features each one corresponding to a house. Many of them are not in RUI environment but in town, but it is anyway impossible to detail the situation of each house of Alghero RUI. The model has been thought to be used at different scales and the single dwelling factors has been included because at neighborhood scale they are very useful. For this criteria, in this figure 94, we consider the maximum possible value (12.15%) of risk, corresponding to the worst situation. In figure 95, on the contrary we consider the minimum possible value of risk due to this criteria corresponding to the ideal situation (0.985%). We produced two maps of final risk and we compared the differences of risk in RUI when brushclearing, roof cleaning, are done, construction material are fire-resistant, there is a water supply, the house has two accesses etc.

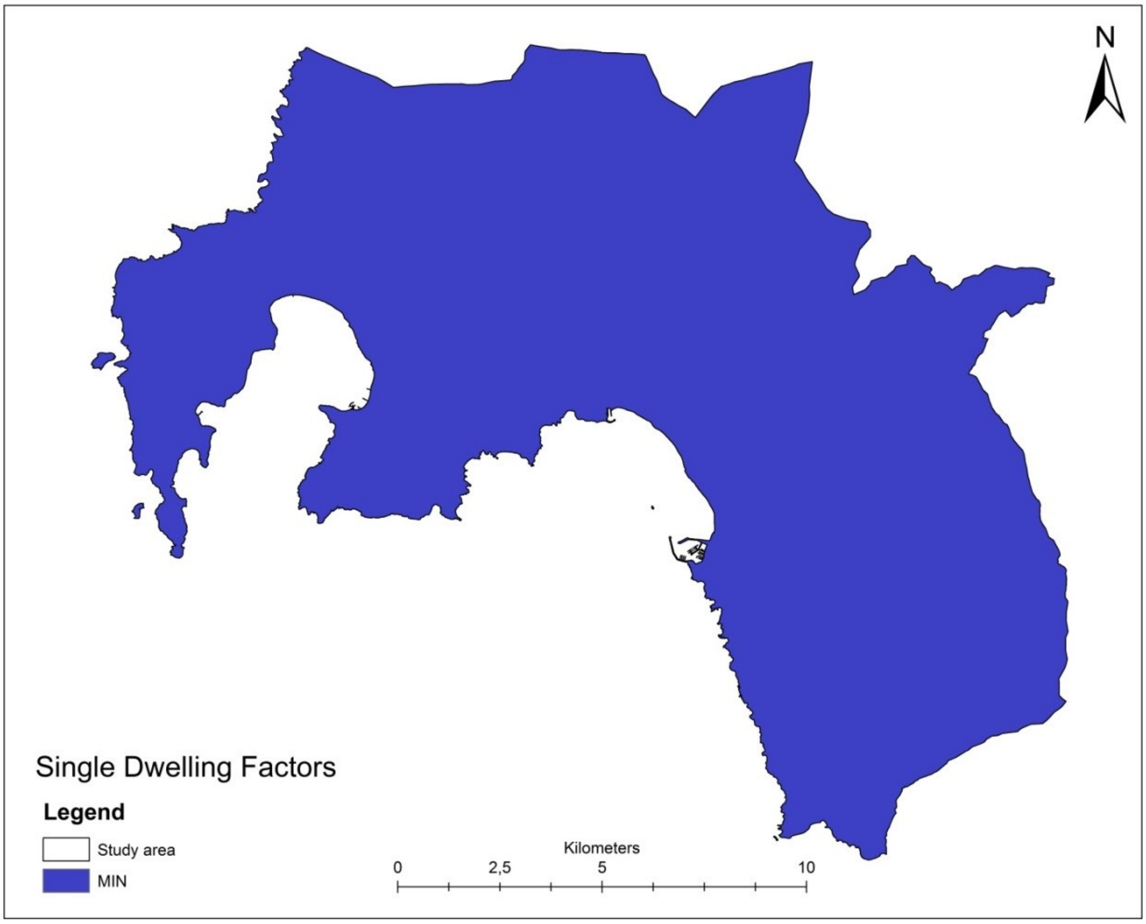

Figure 95. Map of Alghero territory representing the risk level relative to the criteria “single dwelling factors”. The evaluation of single dwelling situation cannot be conducted at communal level: the housing layer that we used as input of Alghero Local Scale mapping methodologies has 13,000 features each one corresponding to a house. Many of them are not in RUI environment but in town, but it is anyway impossible to detail the situation of each house of Alghero RUI. The model has been thought to be used at different scales and the single dwelling factors has been included because at neighborhood scale they are very useful. For this criteria, in this figure 95, we consider the minimum possible value of risk due to this criteria corresponding to the ideal situation (0.985%). In figure 94 we consider the maximum possible value (12.15%) of risk, corresponding to the worst situation. We produced two maps of final risk and we compared the differences of risk in RUI when brushclearing, roof cleaning, are done (or not), construction material are fire-resistant (or not), there is a water supply (or there is not), the house has two accesses (or not) etc.

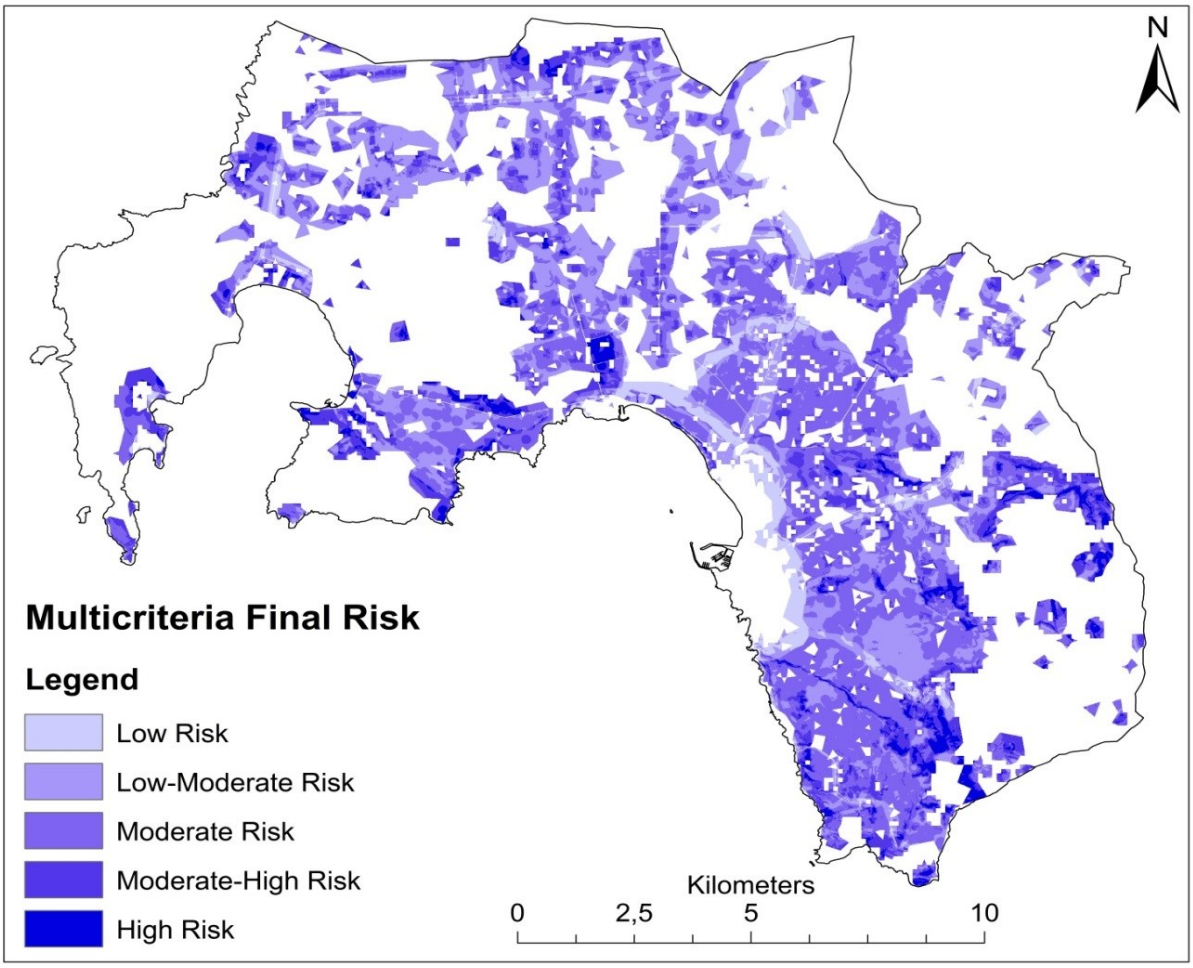

Figure 96. Map of final risk calculated according to multicriteria methodology on RUI areas. It is obtained through the composition of the six maps of criteria; each pixel value is the sum of the six values of the corresponding pixels in each criterion map. In this map the risk connected with the criterion "single dwelling factors" has been considered maximum.

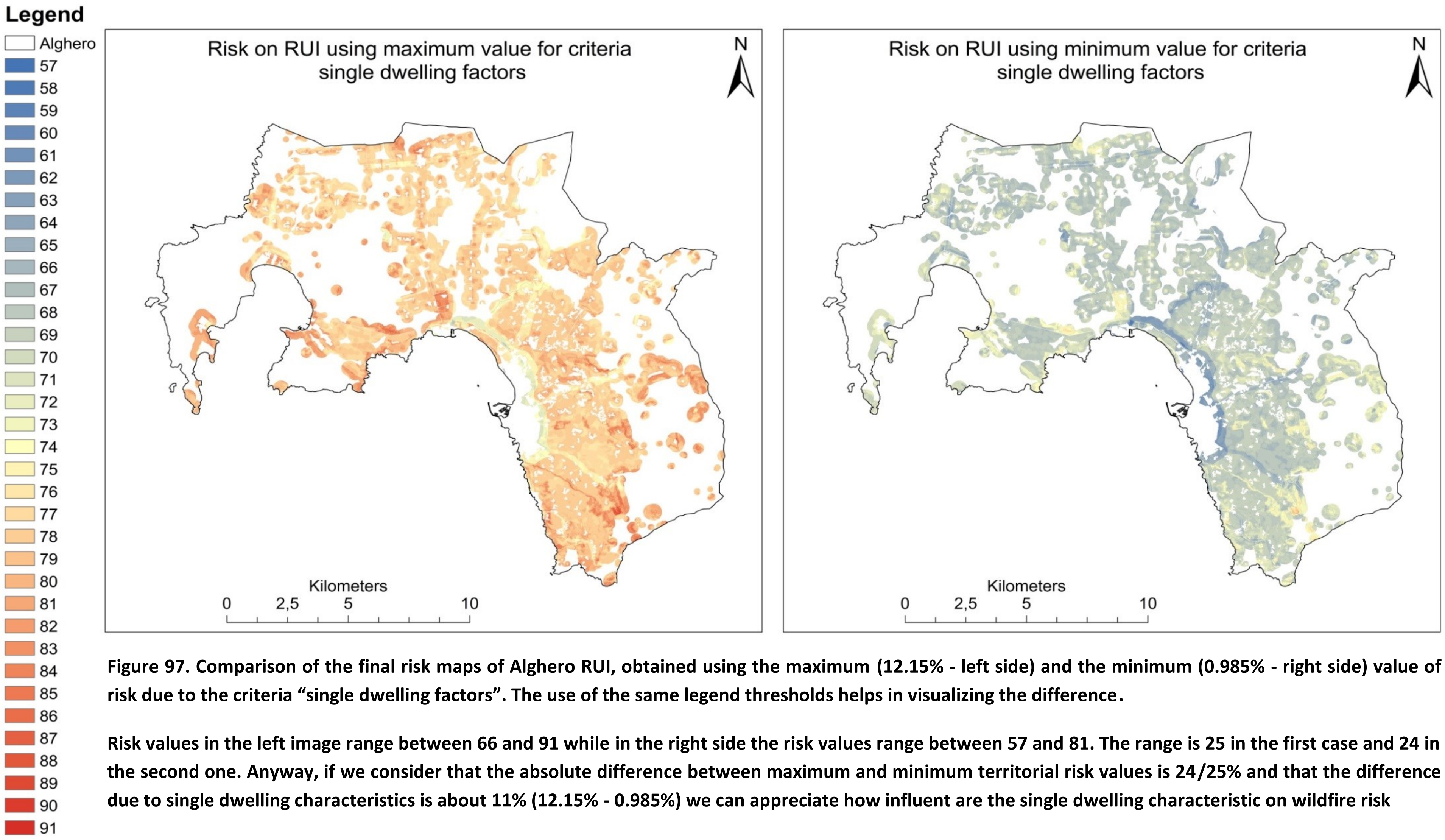

Figure 97. Comparison of the final risk maps of Alghero RUI, obtained using the maximum (12.15% - left side) and the minimum (0.985% - right side) value of risk due to the criteria "single dwelling factors". The use of the same legend thresholds helps in visualizing the difference.

Risk values in the left image range between 66 and 91 while in the right side the risk values range between 57 and 81. The range is 25 in the first case and 24 in the second one. Anyway, if we consider that the absolute difference between maximum and minimum territorial risk values is 24/25% and that the difference due to single dwelling characteristics is about 11% (12.15% - 0.985%) we can appreciate how influent are the single dwelling characteristic on wildfire risk

Multisimulation methodology for wildfire risk assessment

The risk assessment we performed through the use of Randig and of the RUI map of the whole Sardinia (Global Scale mapping methodology), produced a map of wildfire risk on RUI.
The arithmetical multiplication of the four factors of our risk definition was done pixel by pixel in GIS environment, and it put on evidence the areas at different level of risk. The final map was reclassified into the 5 risk categories, very low, low, moderate, high, and very high.

We also extract aggregated data of the average values of risk calculated using all pixels belonging to a given WUI type. They are presented in the table 58 and in figures 98 and 99.

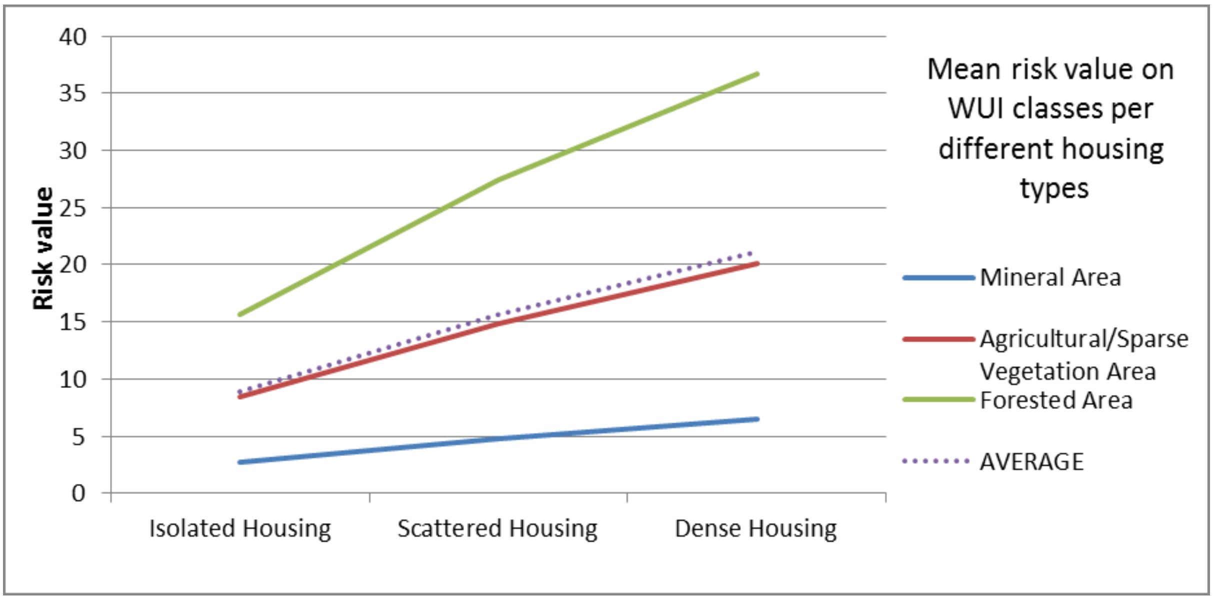

Figure 98. Mean risk value variation with housing type for WUI types located in different environments.

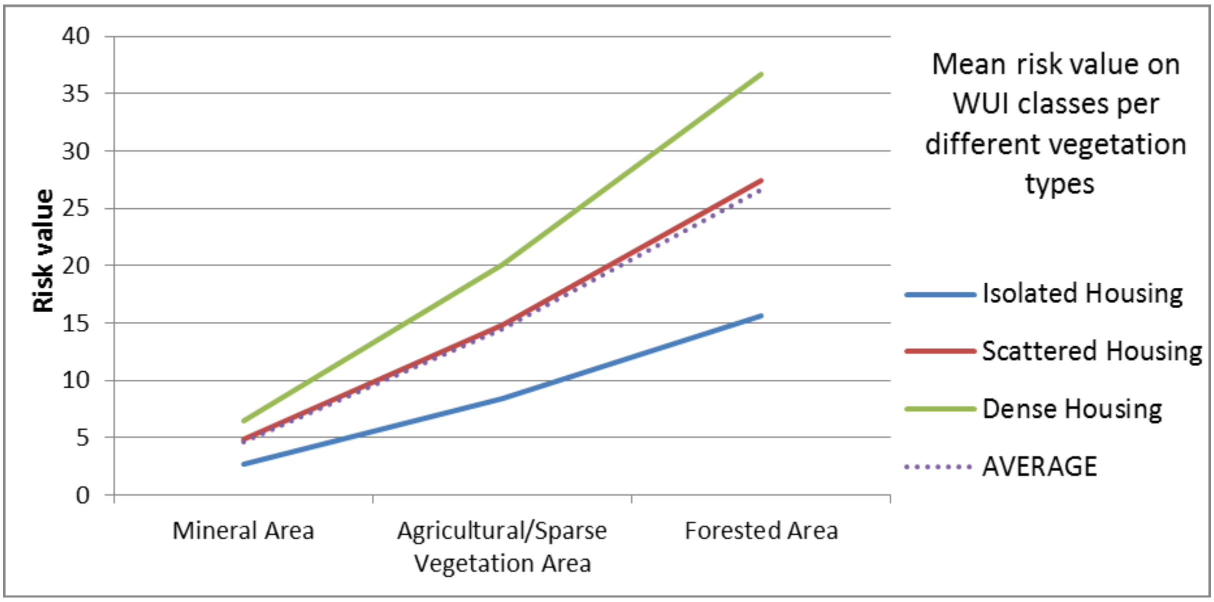

Figure 99. Mean risk value variation with vegetation types for different WUI housing.

As expected, the most risky categories are the ones located in the forested area and the ones in which there are more values at risk. The highest risk value is indeed reported by the WUI type Dense Housing in Forested Area.

Table 58. Average value of risk for each WUI type. They are calculated using the value of all pixels belonging to a given WUI type

Mean risk value per WUI type	Mineral Area	Agricultural/Sparse Vegetation Area	Forested Area	Average per Vegetation
Isolated Housing	2.72	8.39	15.60	8.90
Scattered Housing	4.83	14.84	27.42	15.69
Dense Housing	6.50	20.12	36.67	21.09
Average per Housing	4.68	14.45	26.56	14.45

As already pointed out, the mathematical form we chose for calculating risk is not able to make the distinction between HighHazard-LowDamage and LowHazard-HighDamage risks.

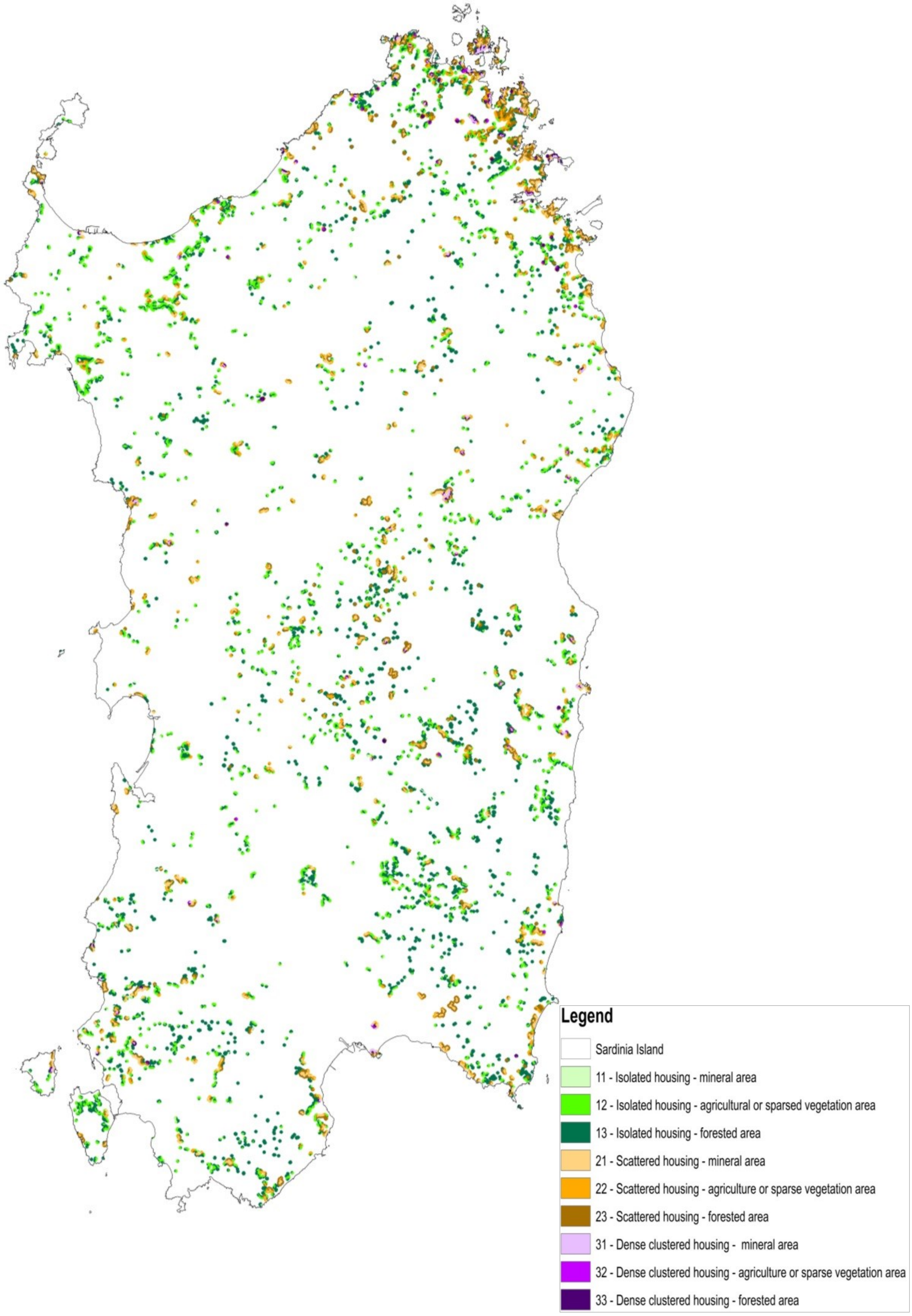

Figure 100. Global Scale mapping methodology output for Sardinia Island. It has been used as input for the multi-simulation based risk model in particular for vulnerability (V) and values at risk (W).

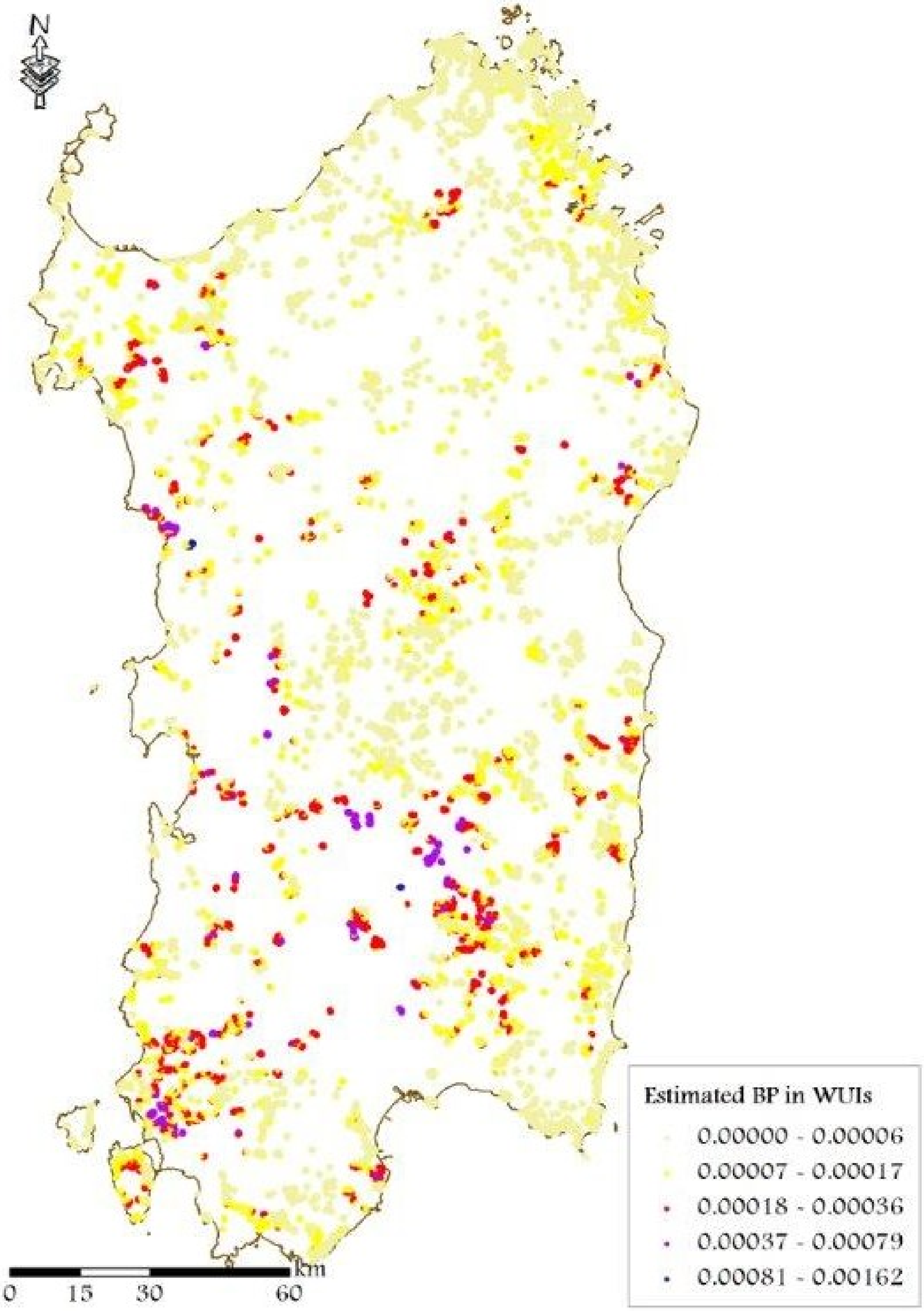

Figure 101. Burn probability calculated by Randig on Sardinia. Extraction of values relative to WUI areas identified according to the Global Scale mapping methodology.

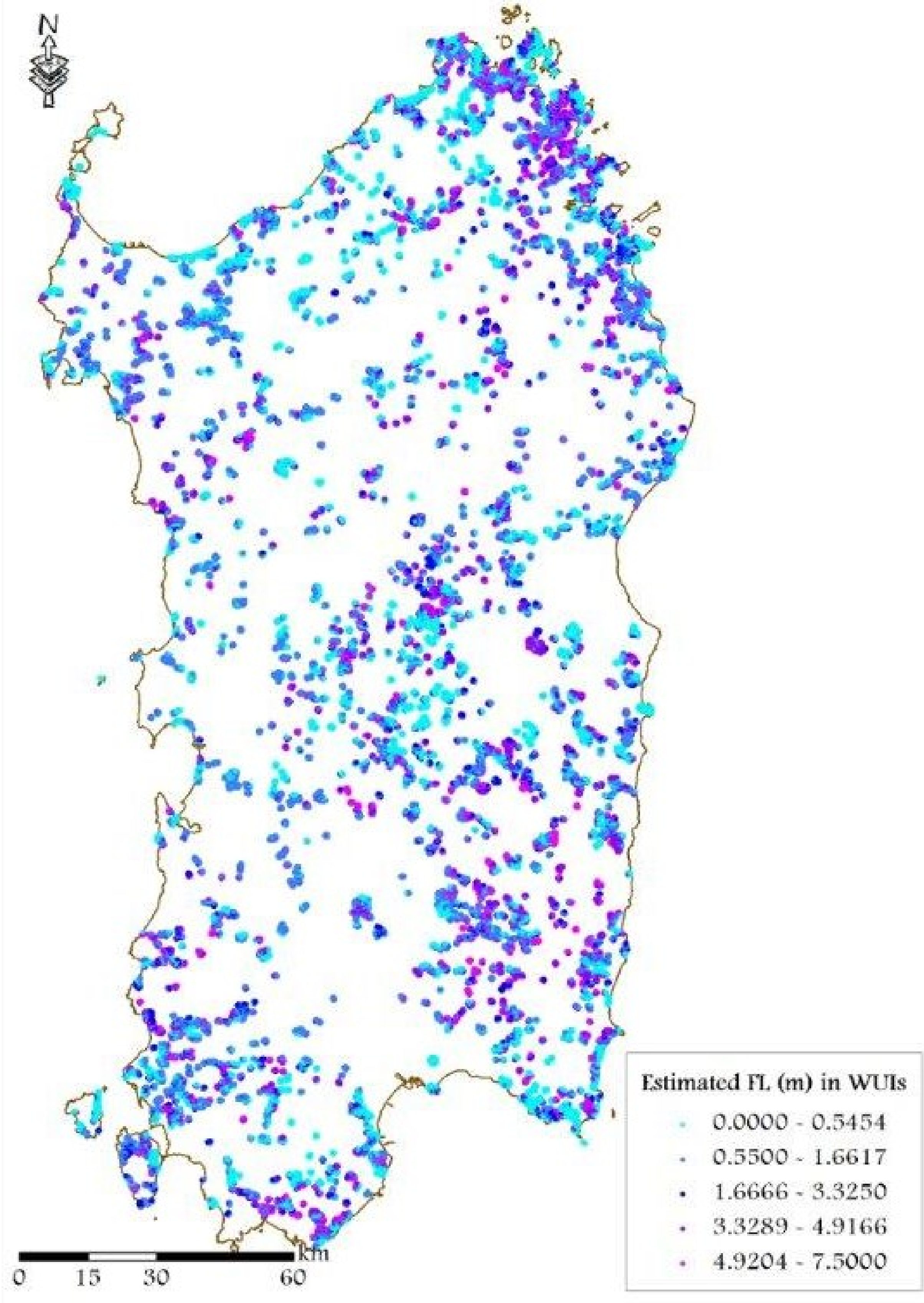

Figure 102. Conditional Flame Length calculated by Randig on Sardinia. Extraction of values relative to WUI areas identified according to the Global Scale mapping methodology.

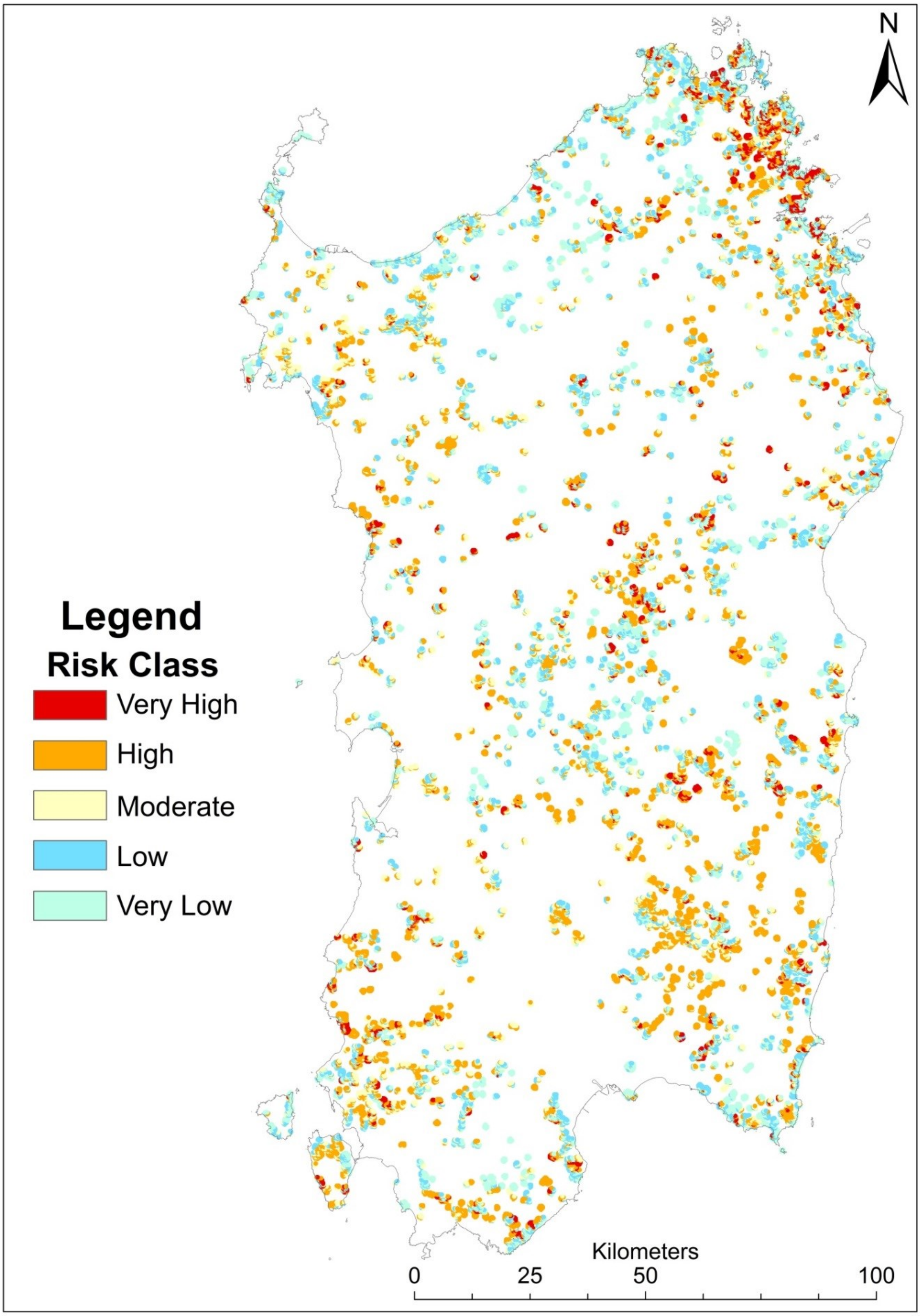

Figure 103. Map of wildfire risk calculated with the Multisimulation methodology on Sardinian global WUI.

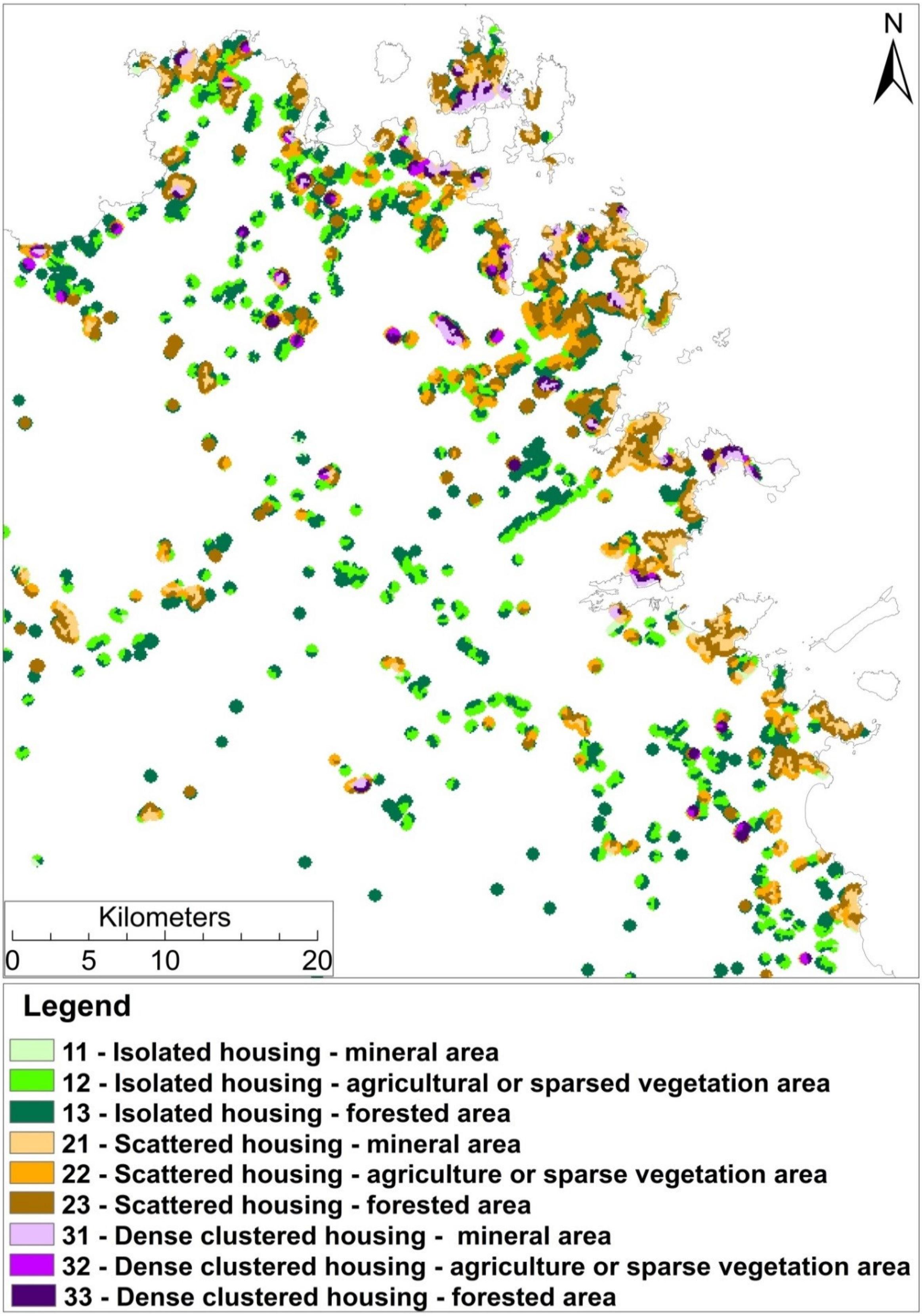

Figure 104. WUI calculated according to Global Scale mapping methodology. Extraction of Northeastern part of Sardinian WUI.

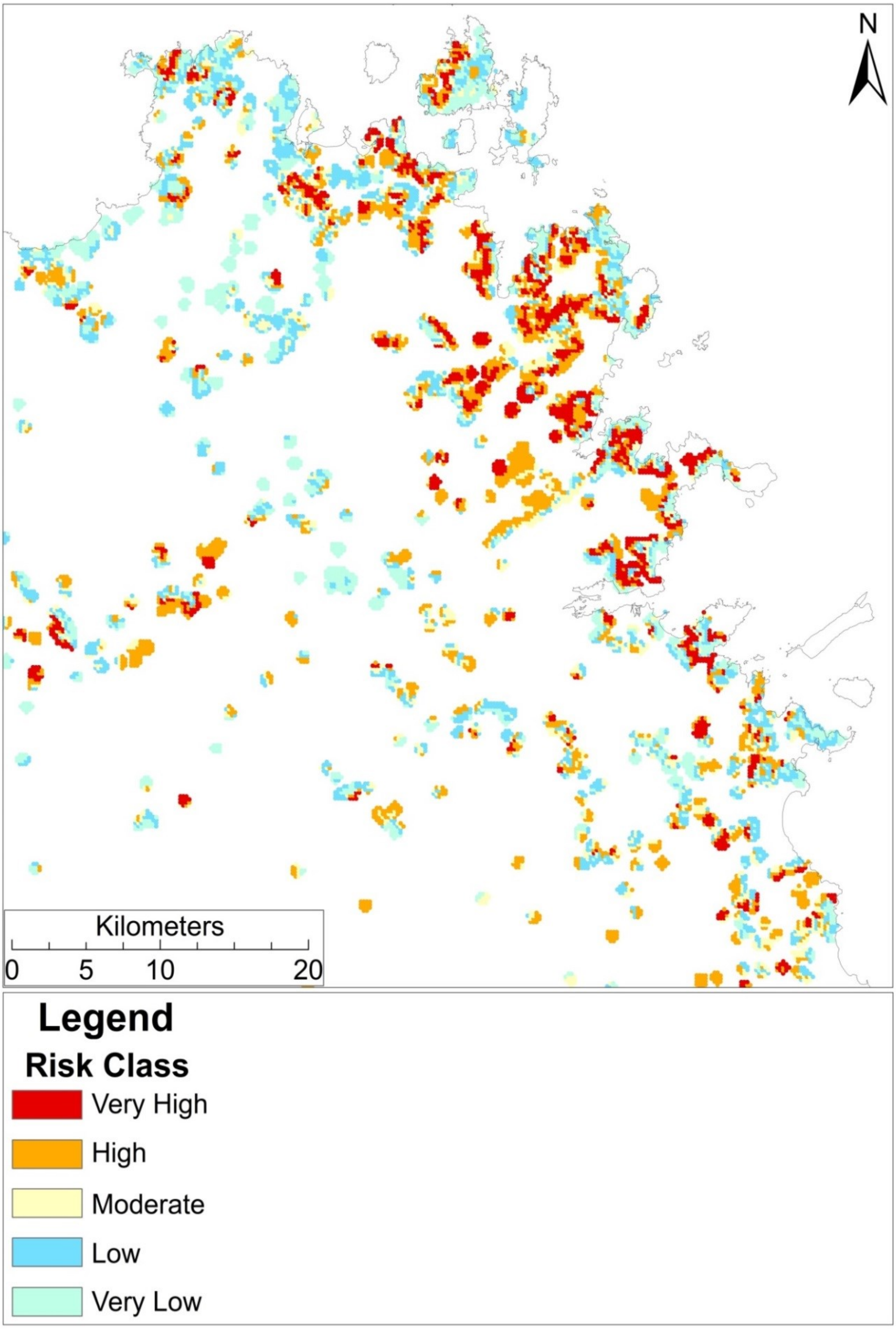

Figure 105. Map of wildfire risk calculated with the Multisimulation methodology on Sardinian north-east global WUI.

We also worked on Randig output for better describing the hazard to which houses located in RUI are exposed. The concept of hazard describes the source of risk itself, in terms of local intensity and local probability of a wildfire. The assessment of the hazard produces a map on the whole area.
The concept of "exposure" is closely related to "hazard". The exposure describes in terms of probability and intensity the likelihood of a wildfire to invest a specific value at risk; in this thesis it is considered an attribute of the good exposed to the source of risk. From the perspective of the source of risk we use the concept of hazard while, from the perspective of the single good exposed to risk, we speak of its exposure to the source of risk. It can be considered a different view on the same phenomenon and the switching from a perspective to the other is just a change of point of view.

We created a graphic representation on the Cartesian plan of the average value of BP and CFL of RUI classes. As it can be noticed in figure 106 their disposition on the BP-CFL plan is very regular.

1) As expected, along the CFL axe we find that the mineral area RUI are characterized by the smaller flames, the agricultural/sparse vegetation classes of RUI present an intermediate value of flame length, while the more intense fires happen in forested areas RUI
2) Along the BP axe we find that the burn probability decreases with the housing density. Although the ignition density for the simulation has been taken from real data that clearly show that ignition density is higher inside RUI than elsewhere, the results of simulation are consistent with the experimental data which show that burned area inside RUI is smaller than outside and decreases with house density.
3) The difference of burn probability from Dense Housing classes to Isolated Housing classes varies with the vegetation categories: as expected the mineral area RUI classes cannot reach very high BP while for agricultural/sparse vegetation and forested area the continuity of fuels is higher and they are characterized by higher BP.
4) Although wildfire simulation and RUI mapping have different backgrounds and theoretical premises, and although they produced two kind of software that were thought separately and were born with different philosophies and purposes, the regularity of the grid in which the category are orderly disposed like in a chessboard, suggests that their theoretical structures and logics are robust and consistent.
5) while CFL varies primarily with vegetation type, BP variation is mainly related to Housing density by which, ignition and propagation are strongly conditioned.

It can be noticed that, if on average each pixel of Sardinia was burned 12 times, the average on WUI is 7.2. Simulation results are then consistent with measured burned area that shows a difference inside/outside RUI, and in particular a percentage of burn area inside RUI smaller than outside. The 5.49% of Sardinia area was burned in the years 2005-2012. In RUI calculated with the Global Scale methodology we measured that just the 3.93% of the surface was burned in the same period.
In tables 59 and 60, and in figures 107-110 it can be noticed how CFL depends practically just on vegetation type and not on housing type, and that BP strongly decreases with housing density while its variation on vegetation type is not so important excepting the fact that in mineral area fire propagation is slowed down or impeded.

Table 59. Hazard characterization in terms of Conditional Flame Length [m] for all WUI types. Average values are calculated taking into account the different areas of each category

CFL per WUI type [m]	Mineral Area	Agricultural/Sparse Vegetation Area	Forested Area	Average on Vegetation
Isolated Housing	0.66	1.14	2.36	1.83
Scattered Housing	0.67	1.09	2.18	1.48
Dense Housing	0.68	0.99	2.06	1.30
Average on Housing	0.67	1.13	2.3	1.71

Table 60. Hazard characterization in terms of Burn Probability (BP) for all WUI types. The reported values are the average number of times that pixels burned during the 100,000 simulations. They are calculated using all pixels belonging to a given WUI type and the averages take into account the different areas occupied by the categories

BP per WUI type	Mineral Area	Agricultural/Sparse Vegetation Area	Forested Area	Average per Vegetation
Isolated Housing	5.07	8.11	8.41	8.22
Scattered Housing	3.28	6.35	6.19	5.48
Dense Housing	2.03	3.68	4.13	3.20
Average per Housing	3.33	7.61	7.72	7.22

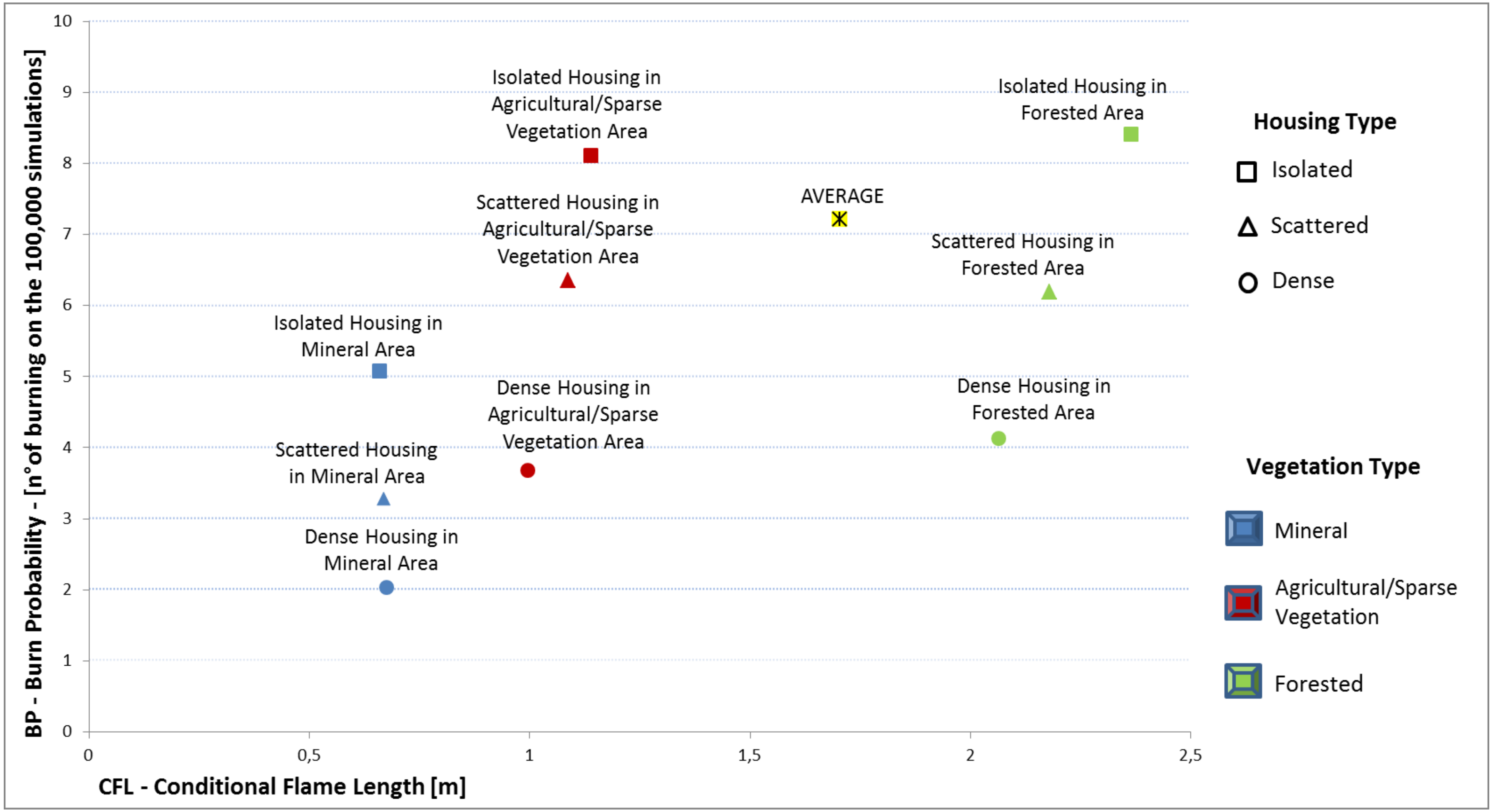

Figure 106. Exposure characterization: representation on CFL – BP Cartesian plan of WUI types. WUI are calculated according to Global Scale mapping methodology

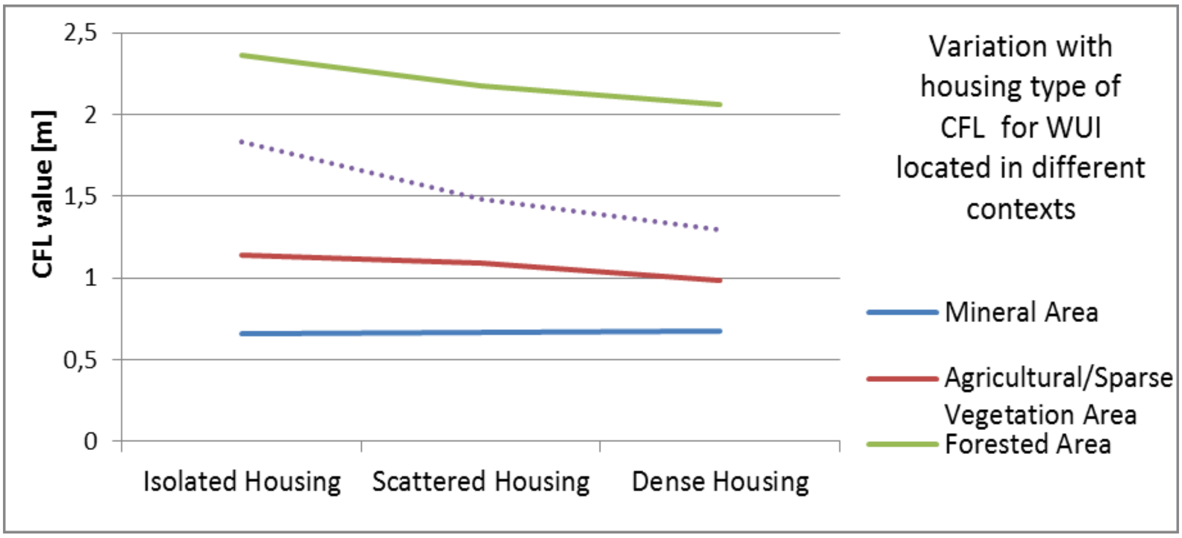

Figure 107. Variation with housing type of Conditional Flame Length on WUI located in different vegetation contexts. WUI are calculated according to Global Scale mapping methodology

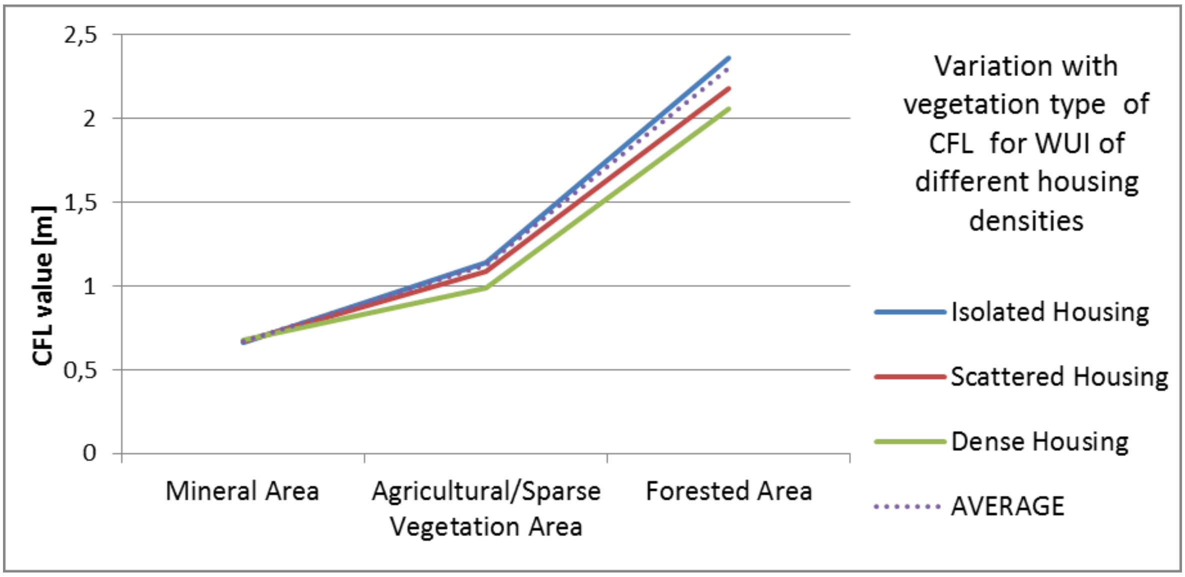

Figure 108. Variation with vegetation types of Conditional Flame Length on different WUI housing types. WUI are calculated according to Global Scale mapping methodology

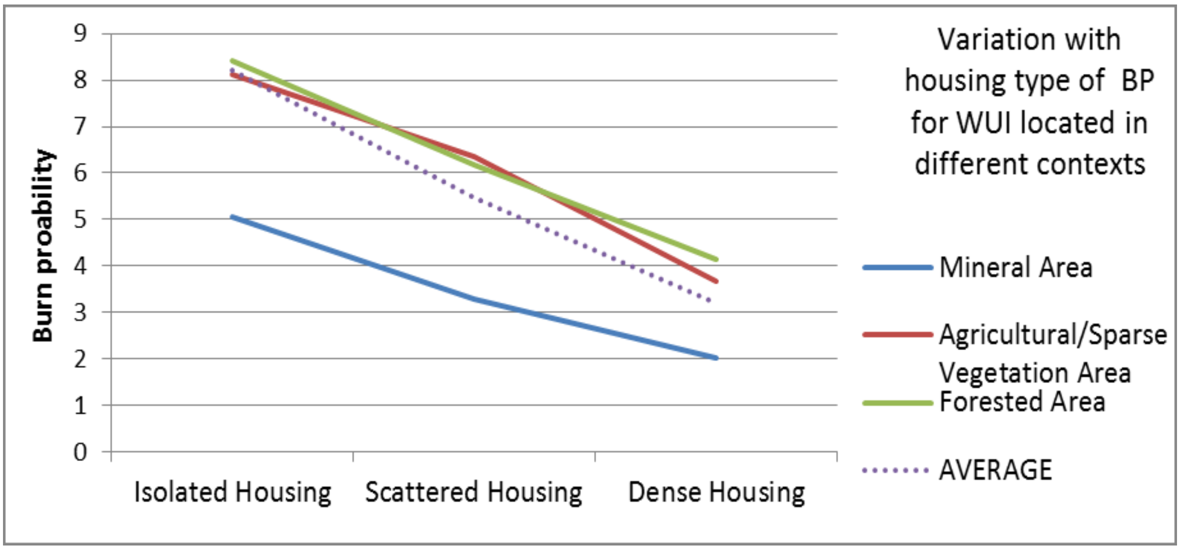

Figure 109. Variation with vegetation types of Burn Probability on different WUI housing types. WUI are calculated according to Global Scale mapping methodology

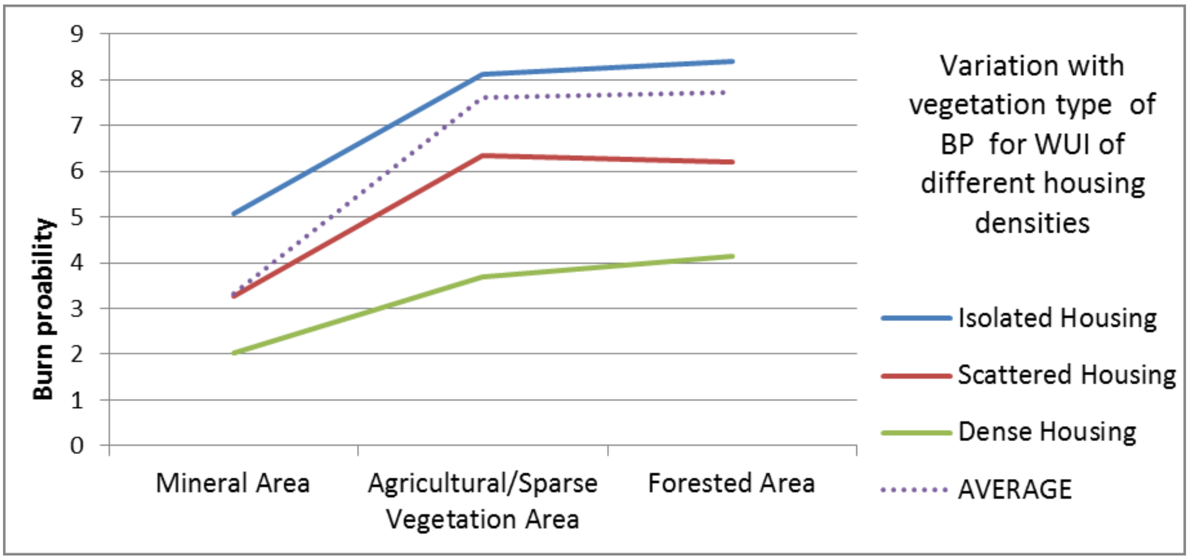

Figure 110. Variation with WUI housing types of Burn Probability on WUI located in different vegetation contexts. WUI are calculated according to Global Scale mapping methodology

Conclusions and perspectives

The wildfire risk assessment in RUI is a very important topic that, dealing with two concepts, RUI and risk which are peculiar, implies many methodological difficulties in the planning of scientific research, difficulties which had to be taken into account when we planned the development of the present thesis.
Whereas the idea of RUI is clear, its operational definition is not immediate. The concrete definition is very influent on the same object of study which depends very much on the arbitrary decisions that the researchers must take in order to create an operational definition of RUI about distances, house/vegetation densities, buffers area surrounding houses or forested areas etc.
The general idea of fuel-houses coexistence, can result in very different operational definitions of RUI implemented by the researcher. All the approaches are legitimate and none of them can *a priori* be considered the right one, but at the same time all of them recognise as RUI different surfaces, classify RUI in different categories, and the choice of one of the approaches has deep influence on the results of the scientific work. Actually, there is a lack of separation observer/observed which complicates the epistemology of research, requiring additional carefulness and caution in defining the set of research. A certain degree of awareness of our influence on what we are studying is required to responsibly carry out the research, to select the different ways for mapping RUI, to evaluate usefulness, consistency and complementariness of different approaches, and also to assess the influence of each definition we chose on the results that we obtained.

In the present work we chose to go beyond the definition of RUI perimeter and the logic of inside/outside RUI. We were not only interested in finding the general perimeter of RUI area but also in distinguishing among RUIs with different characteristics. We consider very valuable the classification of RUI into different typologies, especially if typologies are conceived as already oriented to wildfire risk assessment.
We used three different RUI mapping methodologies, each of which implements the general concept of RUI in a different way. They are available in the software *RUImap®* and they are called Global Methodology, Local Methodology Option 1, Local Methodology Option 2. Each of them

- was conceived with a different philosophy and logic;
- classifies RUI into a different set of classes (9 for the Global, 12 for the Local Option 1, 7 for the Local Option 2);
- is thought to be useful for different purposes;
- has different resolution and is valuable for working at a certain scale and not likewise at another scale;
- has different internal implementation (different programming language, different diagram of flux, different inputs and outputs, GIS vector/raster functions etc.).

The three different way we used to map the interface reflect the complexity of those environments. None of them can be considered a “best choice” and is capable to perfectly describe RUIs summarising all the knowledge on RUI environment. The methodologies look to be complementary and to contribute for a better representation and understanding of the concrete local RUI configuration.
Depending on data availability, scale at which we are working, purposes of the mapping work, one of them can show to be the most suitable but, if we use together more than one of them, the integrating information that they can provide becomes a better way to locally describe the RUI phenomenon.

The Global methodology provides raster maps whose resolution is 100X100m and has been found very interesting and helpful:

- to quantify RUI presence on wide scales;
- to put on evidence at a glance, which areas need to be more carefully mapped by the use of one of the local methodologies;
- to compare presence, diffusion, typologies, in areas adopting different definition of RUI (i.e. different European nations);
- to more carefully plan the placement of firefight forces at regional scale taking into account also the regional diffusion of RUI.

The two local options classify RUI in different ways and provide two kinds of detailed maps of RUI, classified according to two different sets of RUI theoretical classes. They recognize as RUI different portions of territory, and in our concrete case study in Alghero, the surface of RUI according to the Local Methodology Option 2 has been about the double of RUI areas calculated according to the Local Methodology Option 1. Which definition is then the best? Which is the definition we must trust and prefer? We cannot answer this question directly in this form, nevertheless we can visualise and accept the underlying necessity that it expresses to have just one definition. We can respond to this need that the best way to map RUI must be chosen each time we need to do it, because the best choice depends on the concrete situation and in particular on the scale we are working, on data availability, on the purposes of the work.
Regarding the interaction RUI – fire regime (in terms of ignitions and burned area) the results we obtained using the three methods are consistent and all the methodology point out that although ignition density is higher in RUI, the burned areas we record in RUI are smaller than elsewhere.

Further difficulties emerged dealing with the concept of risk. Being particularly complex, it can be taken on from many points of view and there is no universal agreement on its definition and on the definition of its components.
The formulation we chose is sufficiently well-structured to hold and manage the various definitions of risk components and to work like a shared common code capable to host different definitions and different approaches that deal with the problem of risk. We clearly defined risk, hazard, exposure , probability and intensity, the vulnerability function and the concept of values at risk. We ignored the concept of danger which focuses on predisposing factors and neglects the determinant ones (i.e. ignitions) and we also decided not to use the concept of severity and objective risk, and finally not to deal with risk perception.
Like for mapping RUI, also for wildfire risk assessment in RUI, we used three approaches. They are characterized by different theoretical frameworks, resource requirements (input data, time consumption), scales at which they can be applied, levels of complexity.
The methodologies were thought to be useful both for planning and civil protection operations; all of them look to have been capable to produce risk maps by which we have a spatial indication of the local wildfire risk in RUI, and to have been able to recognise different levels of risks on the territory.
The more complex approaches lie on more robust theoretical basis and look to be more trustworthy and accurate but on the other side they requires many input data and showed also to be more time-consuming.
The results can be judged consistent: in particular the two application on Alghero territory (overlay mapping methodology and multicriteria methodology) were able to identify same areas

as high risk ones, and similar patterns in the risk maps. Their acuity in classifying the landscape is different and the multicriteria methodology which takes into account many more parameters and inputs looks to be more accurate in creating wildfire risk maps of RUI.
The Multisimulation approach for spatially assessing hazard on the territory produced results that are strictly consistent with fire regime in RUI whose peculiarity is to have higher ignition density and smaller burned area than elsewhere. Acquiring the distribution of values at risk and their Vulnerability from RUI maps (Global Scale mapping methodology), and combining simulated hazard with them, we finally get to the maps of risk, according to our definition R = P*I*V*W.
For further developments, it could be worthwhile to investigate the usefulness of the Multisimulation methodology for assessing wildfire hazard, when combined with a more accurate mapping of RUI, like, for instance, one of the Local Scale mapping methodologies. It would require a different resolution for wildfire simulation (for instance 50X50-30X30 m). We theoretically would expect the output to be more detailed, accurate and reliable in particular because at local scale, on smaller surfaces, we can integrate a more precise modelling of the real vulnerability of goods. But it has not been tested yet to verify our expectations, and there is a lot to do for projecting a Multisimulation local methodology for assessing wildfire risk in RUI.

Appendixes

Appendix A – Global Scale mapping methodology.

In the global methodology RUI are defined as the whole area within a 400 m radius around those houses that are located at less than 200 m from forested or shrubland zones. The implementation of this definition available in the tool works on four logic steps:

- Select forested/Shrubland areas plus a 200 m radius;
- Analyse house presence in this area and select pixels with housing;
- Create a buffer of 400 m surrounding the selected pixel containing houses, identifying RUI area;
- Define pixel by pixel to which RUI category it belongs.

The flow chart of the real process is reported in the following figure.

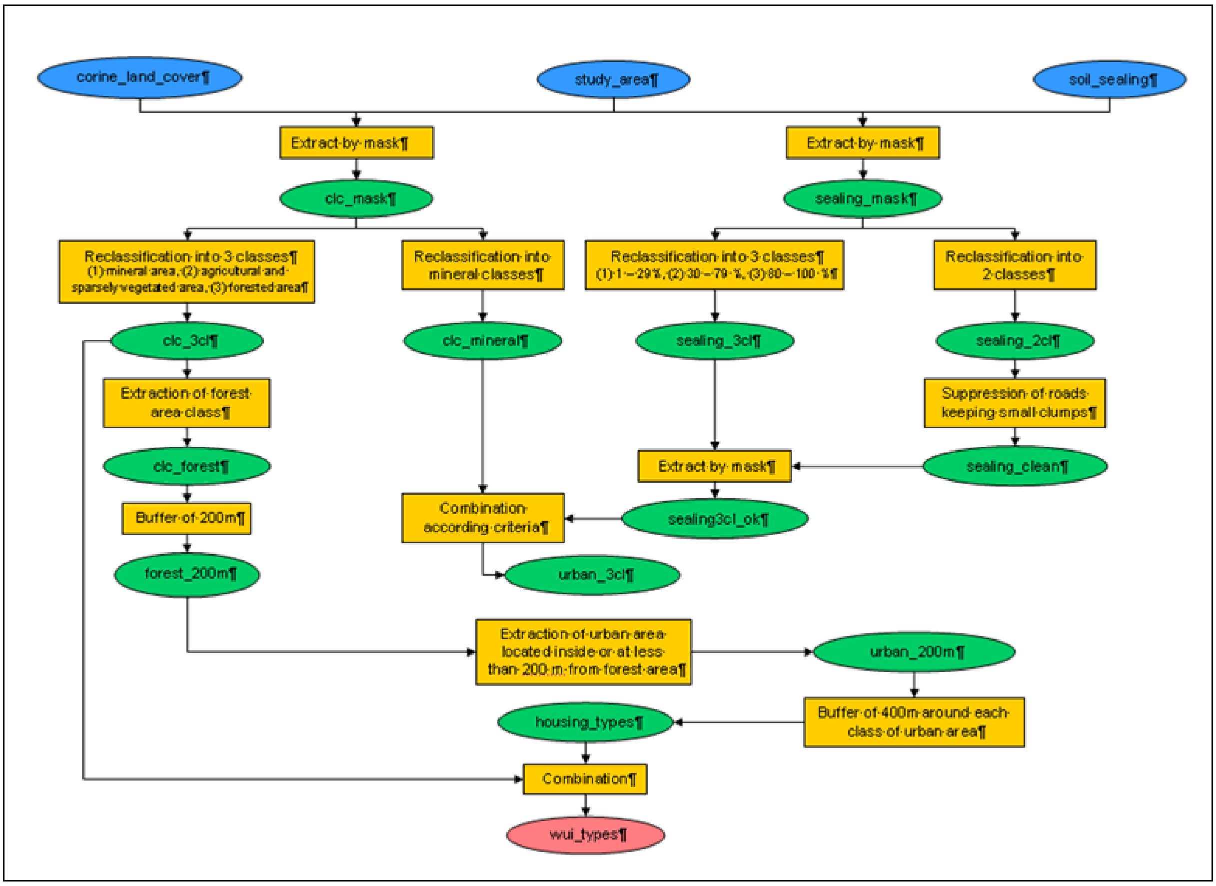

Figure 111. Schematic flow chart complete of input and output of the Global Scale mapping methodology process implemented in *RUImap*

The real process operates according to the following steps:

1) reclassification of Corine Land Cover raster dataset into three classes (mineral area, agricultural and sparse vegetation area, forested area) and creation of the layer CLC_3cl which merges the original CLC classes according to the table 60.

Table 60. Corine Land Cover raster dataset reclassification

CLC CODE	CLC LABEL	SPARSE VEGETATION, AGRICULTURE	FORESTS, MAQUIS, SHRUBLANDS	BARE SOIL, WATERS, DENSE URBAN
111	Continuous urban fabric			X
112	Discontinuous urban fabric			X
121	Industrial or commercial units			X
122	Road and rail networks and associated land			X
123	Port areas			X
124	Airports			X
131	Mineral extraction sites			X
132	Dump sites			X
133	Construction sites			X
141	Green urban areas		X	
142	Sport and leisure facilities		X	
211	Non-irrigated arable land		X	
212	Permanently irrigated land		X	
213	Rice fields		X	
221	Vineyards		X	
222	Fruit trees and berry plantations		X	
223	Olive groves		X	
231	Pastures		X	
241	Annual crops associated with permanent crops		X	
242	Complex cultivation patterns		X	
243	Land principally occupied by agriculture, with significant areas of natural vegetation		X	
244	Agro-forestry areas		X	
311	Broad-leaved forest	X		
312	Coniferous forest	X		
313	Mixed forest	X		
321	Natural grasslands		X	

322	Moors and heathland	X		
323	Sclerophyllous vegetation	X		
324	Transitional woodland-shrub	X		
331	Beaches, dunes, sands			X
332	Bare rocks			X
333	Sparsely vegetated areas		X	
334	Burnt areas	X		
335	Glaciers and perpetual snow			X
411	Inland marshes			X
412	Peat bogs			X
421	Salt marshes			X
422	Salines			X
423	Intertidal flats			X
511	Water courses			X
512	Water bodies			X
521	Coastal lagoons			X
522	Estuaries			X
523	Sea and ocean	NODATA	NODATA	NODATA

2) extraction of forested area into the new layer clc_forest;
3) creation of a third layer, forest_200, in which a 200 m buffer is added to forested areas to have the area where RUI can be found;
4) reclassification of Soil Sealing layer into 2 classes (sealing_2cl) merging all values of soil sealing above 0% into a single class;
5) neighbourhood analyses on sealing_2cl to remove linear clusters corresponding to little roads without removing small clusters corresponding to isolate housing;
6) reclassification of Soil Sealing layer into 3 classes (sealing_3cl): values of SS dataset between 0 and 29% are reclassified into a single class 1 corresponding to isolated housing; values of SS dataset between 30 and 79% (threshold compatible to ceiling of CLC class 1.1.2) are reclassified into a single class 2 corresponding to scattered housing; values of SS dataset between 80 and 100% (threshold compatible to ceiling of CLC class 1.1.1) are reclassified into a single class 3 corresponding to dense clustered housing. Soil sealing reclassifications are made according to the table 61.

Table 61. Integration of Soil Sealing and Corine Land Cover information for crating the SEALING_3CL layer

LUT VALUES	EEA CODE	EEA DESCRIPTION	SEALING _2CL	SEALING _3CL
0%	0	-	0	NODATA
1 – 29%	1	-	1	1
30 – 49%	2	30% threshold is compatible to lower limit of CLC class 1.1.2; 49% threshold is a median of CLC class 1.1.2	1	2
50 – 79%	3	79% threshold is compatible to ceiling of CLC class 1.1.2	1	2
80 – 99%	4	80% threshold is compatible to CLC class 1.1.1	1	3
100%	5	-	1	3

7) extraction of mineral area from the reclassified CLC_3cl and creation of the new layer clc_mineral.
8) clc_mineral is used to complete the reclassified SS (sealing_3cl) and to create the layer urban_3cl. During this part of the process, continuous urban fabric (CLC class 111) and discontinuous urban fabrics (CLC class 112) are compared and integrated respectively in dense clustered housing (class 3 of reclassified SS) and scattered housing (class 2 of reclassified SS).
9) forest_200m and urban_3cl are crossed to create the layer urban_200m.
10) Buffer of 400m to the layer urban_200m and creation of the layer housing_type that reports the housing configuration into the three classes.
11) Crossing of housing_type with CLC_3cl to obtain the final output of 3X3 classes according to the classification of the methodology. The final combination of the two layers (reclassified Corine Land Cover map and the reclassified, integrated and clipped Soil Sealing map) allows classifying the rural urban interface, according to global methodology, into the 9 classes.

All the processes described above are implemented in a customized application written in Python language that, after having been tested, has been integrated in the *RUImap®* tool.

Appendix B – Local Scale mapping methodology option 1.

Before running the tool, the layers that it uses as input must be prepared:

1. Study area Polygon shape file
2. Brush-Clearing Zone shape file (forested areas plus 200m buffer)
3. Houses Polygon shape file (each feature is a building)
4. Aggregation Index Raster dataset file.

To get the four required strata, we must have a detailed map of houses and of vegetation (or land cover).

- First, **the study area layer** must be created. It simply means to generate a polygon shape file in which the user defines the study area as a single feature or various features in the same file.
- Second step is to create **the Brush-Clearing Zone** polygon shape file (BCZ). It is obtained through a simple buffer of 200m around the areas that in our informative stratum of vegetation (or land cover) are coded as forest or similar (maquis, densely vegetated Shrubland etc.)
- The third step is to correct the geometry and the topology of **House Polygon shape file** that can present null geometries or disconnected features that prevent the GIS function to run out to completion.
- the **Aggregation Index layer (AI)**, (Turner, 1990)[lxi], which can be mapped using *FRAGSTAT© S3.3©* software (McGarigal & Marks, 1994 [lxii]; Robbez-Masson et al., 1999[lxiii]). Coherently with the philosophy that the necessary condition for a wild fire to spread is vegetation presence and that the focus must be on BCZ, the local methodology ideated by IRSTEA, maps the structure of vegetation emphasizing its horizontal connections and the contiguity of vegetated patches on the landscape. Actually the possibility of a uninterrupted fire propagation depends on fuel spatial continuity. The AI is hence considered more useful than the characterization of vegetation into fuel types which is a more suitable classification for wildfire simulators and for fire intensity descriptions.

Landscape ecology includes numerous metrics describing the characteristics of landscape composition and structure. Among the existing ones, the most appropriate index to measure fragmentation/aggregation of spatial patterns is, indeed, the AI.

As a spatial metric, it is a "configurations descriptor" which refers to the spatial arrangement and agglomeration of pixels of the same kind on a raster layer of vegetation and it provides information about the frequency of connections between the pixels. The first step is to determine the width of the window to be studied, and usually it size is from 5 to 11 pixels (corresponding to a radius of 2-5 pixels on both sides of the central one).

The general formula defining the aggregation index for a generic i-class vegetation is:

$$AI = \left[\frac{g_{ii}}{\max g_{ii}} \right] (100)$$

Where

- $\mathbf{g_{ii}}$ = number of contacts between pixels belonging to class i located inside the window

- **max g_{ii}** = maximal possible contacts between i-class pixels in the window (corresponding to the situation in which all pixels belong to the i-class and, clearly, there is the maximum of contacts among them).

Fragstat© can calculate the Aggregation Index of any kind of patches in the landscape: agricultural, conifers, bare soil, forested, sand, water etc. We are, clearly, just interested in the vegetated pixel connexions. The vegetation layer is, hence, reclassified into two classes "vegetated" and "not vegetated" and through the use of Fragstat© we study the connection among vegetated-forested pixels. So, the AI that we refer to is the Aggregation Index of Vegetation.
Fragstat© works using a moving window with a radius of 2-5 pixels around the central one. In this window it calculates the connections among vegetated pixels and after having divided for the maximum possible number of connections that we could have recorded in that window and after having multiplied for 100, it records the value in the central pixel of the window before moving to the following one. The AI values increase with the spatial continuity and compactness of the pixels as illustrated in Fig. 112.

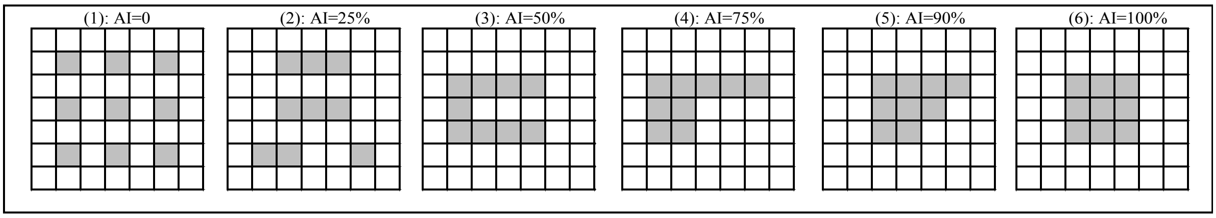

Figure 112. Evolution of aggregation index from the arrangement of 9 grey pixels (taken from Lampin et al. 2006)

Its calculation produces a tiff raster map (.tif file) with values from 0% to 100%, and this is the input that the tool requires.

After having accomplished with input preparation the tool can be run.
Housing configuration: the tool first rung consists in classifying each house inside Brush-Clearing Zone according to the method developed by Lampin-Maillet et al. (2009), into one of the four housing configuration types: Isolated, Scattered, Dense, and Very Dense housing.
To perform the classification, the tool operations are based on the distance between houses. First, a 50m buffer is applied to each building and then the buffers are dissolved into simpler features. Then the tool separates the different features generated by the buffering operation into classes of housing density according to the following rules:

- Isolated: buffer feature containing 1 to 3 buildings;
- Scattered: buffer features containing 3 to 50 buildings;
- Grouped: buffer features containing more than 50 buildings.

A following step divides the features of Grouped Class into two new classes according to a distance rule between houses. If, analysing each feature, we can find more than 10 buildings being less distant than 30m, the feature belonging to Grouped is reclassified as Very Dense, while if we can find only from 1 to 10 buildings being distant less than 30m then the feature is reclassified as Dense.
The resulting vector layer is converted into raster format and the final output is a tiff file (*.tif*) whose default name is "housing configuration type" and whose default resolution is 2.5X2.5m (it can be adjusted operating on the source code).

<u>AI reclassification</u>: In a second rung the tool, automatically, reclassifies AI layer input into three classes according to the following thresholds:

- Aggregation Index = 0 corresponds to land covers different from vegetation (urban centres, bare soil, waters etc.) or to completely detached patches;
- 0 < Aggregation Index ≤ 95% corresponding to discontinuous, sparse vegetation or edges;
- Aggregation Index > 95% which corresponds to dense and continuous vegetation.

The resulting raster layer presents just three classes:

- AI = 0 - no vegetation aggregation,
- 0 < AI ≤ 95% - low vegetation aggregation,
- AI> 95% - high vegetation aggregation.

<u>RUI type</u>: finally the tool combines the two layers (Reclassified AI and Housing Configuration) producing a third raster file called "RUI type" whose default resolution is 2.5X2.5m (it can be adjusted operating on the source code). A raster calculator function reads pixel by pixel the Housing Configuration and the AI layers producing a raster layer called by default "RUI Type" in which the territory is classified in 12 classes of RUI plus the class NO_RUI. The 12 types come out by crossing the 4 housing configuration types and the three Vegetation Aggregation Index classes.

Table 62. RUI typologies : codes and names

AI		1 - null	2 – Low	3 - high
Housing	1 – Isolated Housing	11	12	13
	2 – Dispersed Housing	21	22	23
	3 – Dense Housing	31	32	33
	4 – Very Dense Housing	41	42	43
RUI types				
11	Isolated Housing – Aggregation Index null			
12	Isolated Housing – Aggregation Index low			
13	Isolated Housing – Aggregation Index high			
21	Dispersed Housing – Aggregation Index null			
22	Dispersed Housing – Aggregation Index low			
23	Dispersed Housing – Aggregation Index high			
31	Dense Housing – Aggregation Index null			
32	Dense Housing – Aggregation Index low			
33	Dense Housing – Aggregation Index high			
41	Very Dense Housing – Aggregation Index null			
42	Very Dense Housing – Aggregation Index low			
43	Very Dense Housing – Aggregation Index high			

The tool is organized in modules and if detailed vegetation data are not available it can also be executed just the first step calculating only the Housing Configuration. It provides the urban patterns on the territory and, although it is not a map of RUI, it can be crossed with coarse vegetation maps obtaining a rough RUI characterization.

In the first theoretical definition of the method, only building used as residence where people live permanently, temporarily or seasonally, were taken into account for mapping, while, agricultural, industrial, commercial and public buildings were not included. They can anyway be added by the user to better define the shape of RUI and include all kind of goods in RUI, not merely the houses.
This conceptual model of the entire mapping process was developed using MERISE, a general-purpose modelling methodology in the field of information system development, software engineering and project management. First introduced in the early 1980s, it has been widely used in France and continuously developed and refined. Many large French governmental, commercial and industrial organizations had adopted it as their standard methodology.
The conceptual model of the process was transferred in a global flow chart taking into account all calculations and relationships pointed out using MERISE. The definitive flow charts were created using ModelBuider® developed by ESRI®. They were, finally, tested in order to optimize the final model.
The tests consisted in using as input:

- study areas of different sizes;
- different spatial distributions of houses;
- different Aggregation Index layers created using Vegetation raster with resolution varying from 0.5 m to 20 m (with this tests it was demonstrated that the resolution of vegetation raster layers for calculating useful AI must be 10X10m or more defined and absolutely not more than 20X20m[lxiv], a threshold upon which AI is completely useless)
- and finally in applying the process with missing data.

After the tests some of the rules were tuned. Then the final tested model was implemented in Python language (open source) to create the fully functioning application.

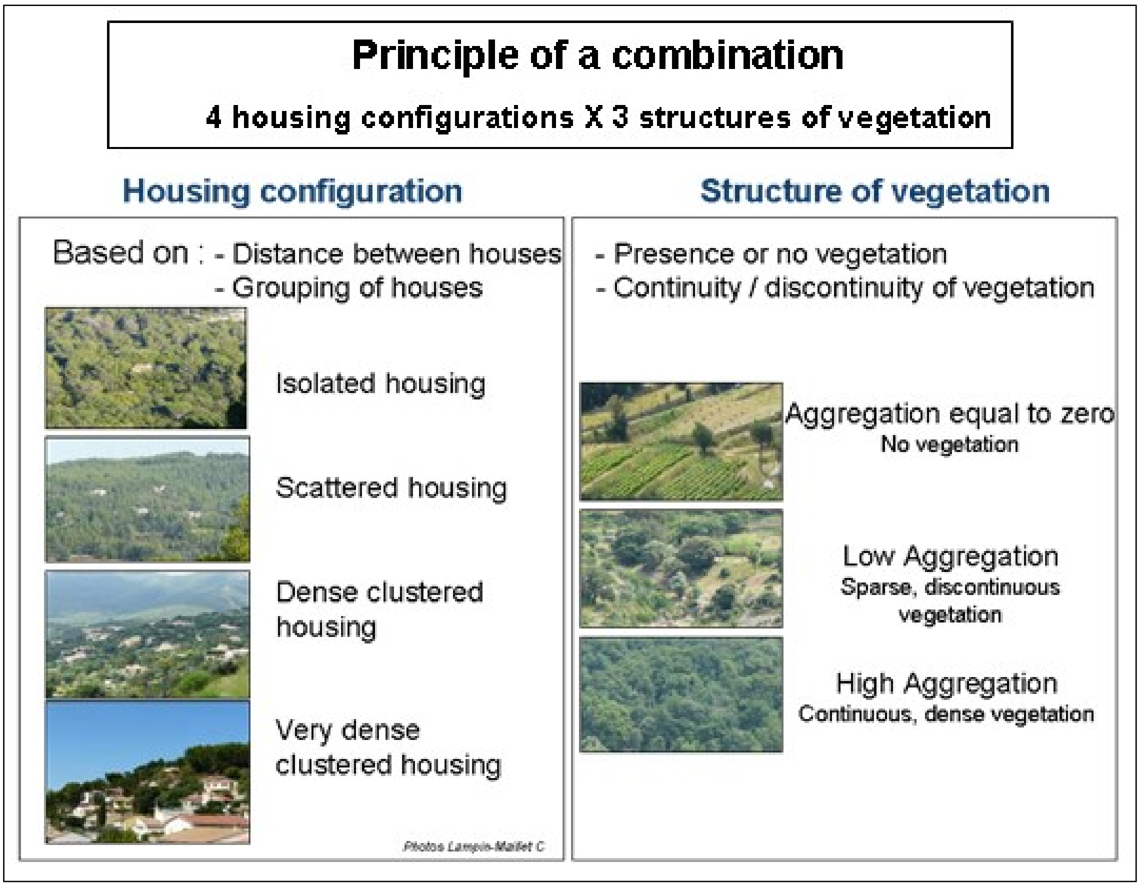

Figure 113. Combination of housing configuration with the structure of vegetation

The Python code uses the existing function of ESRI ArcGis and it is required the version 9.3 (or further). It can be installed or run directly without any installation.

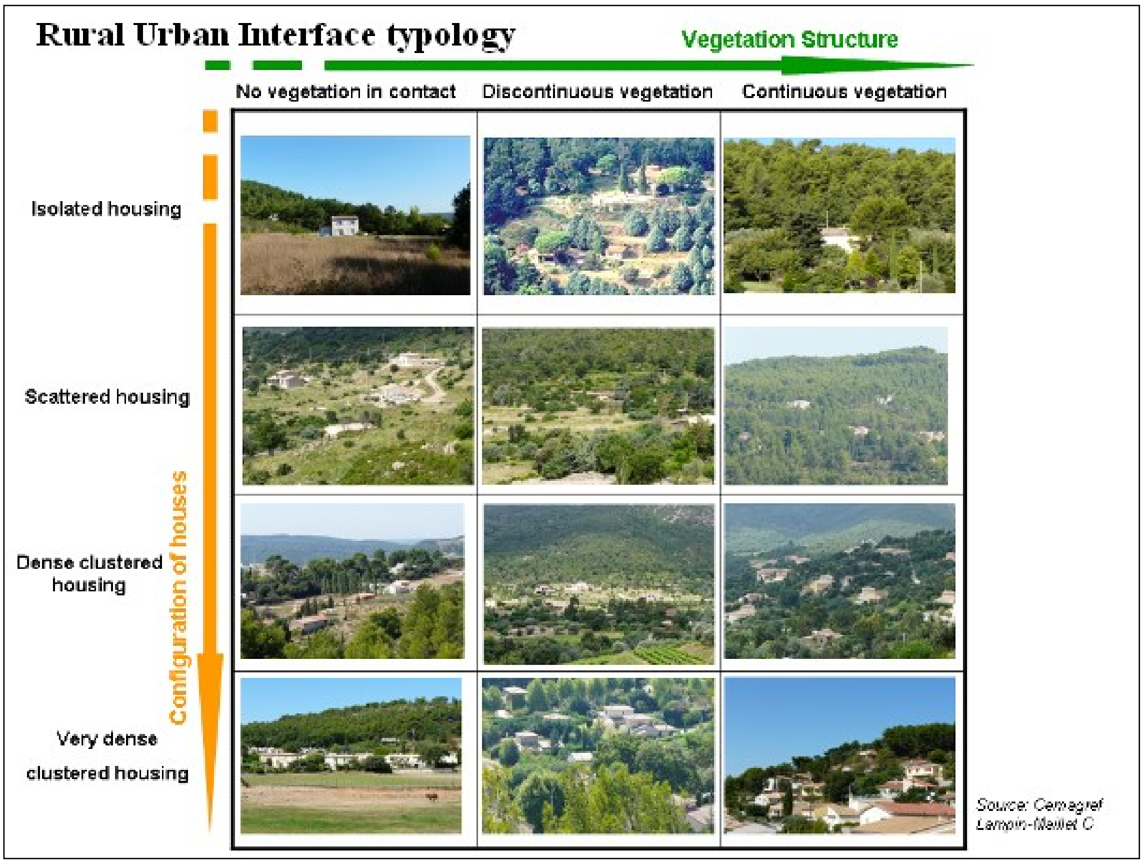

Figure 114. Typology of Rural-Urban interfaces

Appendix C – Local Scale mapping methodology option 2

The methodology implementation is realized into two different VBA applications that must be run sequentially because the first produces the input for the second.

The first one is called Settlements Type and creates a polygon shape file in which each feature encompasses various houses. It classifies all houses in "urban unities" through a series of operations according to rules about dimension of the created features, number of houses and distances and precisely:

1) it creates a 25m buffer around houses and dissolves them eliminating "the holes", little areas inside the polygon but not belonging to it. If the surface of the hole is more than 1000 m^2, it is not deleted.
2) According to the area of each of these new polygons we can have:
   - Features whose surface is > 50 ha: they are coded as URBAN SETTLEMENT
   - Features whose surface is between 1 ha and 50 ha: they are coded as SETTLEMENTS IN AGRICULTURAL AREA/FORESTED AREA
   - Features whose surface is less than 1 ha are coded as DISPERSED/ISOLATED BUILDING IN AGRICULTURAL/FORESTED AREA.
3) The features whose surface is less than 1 ha are deeper analysed to determine if they contain dispersed buildings or Isolated buildings or if they are little settlements:
   - if they contain more than 5 houses they are re-coded as SETTLEMENTS IN AGRICULTURAL AREA/FORESTED AREA
   - if they contain less than 5 houses a new buffer of 100m is drawn around houses and the buffers are dissolved (eliminating holes of less than 1000m^2 areas) obtaining a new polygon shape file.
4) The new features are investigated to distinguish among Dispersed buildings and Isolated buildings:
   - If the new features contain 3 or more houses, they are coded as DISPERSED BUILDING IN AGRICULTURAL AREA/FORESTED AREA
   - If the new features contain less than 3 houses (1 or 2) they are coded as ISOLATED BUILDING IN AGRICULTURAL AREA/FORESTED AREA
5) In order to see if the housing types that have been classified are located in Agricultural or in Forested area, around all housing polygons except Urban Settlement a 1m buffer is created.
   - If the area of the buffer drown around the polygons is forested for 30% or more, then the polygon is coded as forested (SETTLEMENT IN FORESTED AREA, DISPERSED BUILDING IN FORESTED AREA, ISOLATED BUILDING IN FORESTED AREA),
   - If the area of the buffer drown around the polygons is forested for less than 30%, then the polygon is coded as agricultural (SETTLEMENT IN AGRICULTURAL AREA, DISPERSED BUILDING IN AGRICULTURAL AREA, ISOLATED BUILDING IN AGRICULTURAL AREA).
6) Now that the tool has assigned one of the 7 classes to each polygon a buffer is created around each feature using a radius that depends on the class according to the table 63.

Table 63. buffer size according to settlement type and location

SETTLEMENT TYPE & SURROUNDING ENVIRONMENT	Buffer size [m]
Urban settlement	400
Settlement in forested area	300
Settlement in agricultural area	200
Dispersed buildings in forested area	300
Dispersed buildings in agricultural area	100
Isolated buildings in forested area	200
Isolated buildings in agricultural area	100

Rural Urban Interface according to the TRAGSATEC methodology is the area included in this last buffer.

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