Geographical Research

Development of a Methodology for the Assessment of Vulnerability Related to Wildland Fires Using a Multi-Criteria Evaluation

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Abstract
In the geography of risk, vulnerability may be defined as a physical characteristic that describes the tendency of a territory to suffer damage as a result of the occurrence of certain phenomena. According to this synthetic definition, there are two main components of vulnerability in the context of wildland fires. The first is internal, and is related to the effects of fires on the value of the affected assets affected and their capacity for recovery. The second is external, and is related to the characteristics of fires and the ability of society to deal with the hazards of wildland fires. The aim of the present study is to develop an assessment of spatial vulnerability in the context of wildland fires, at a scale appropriate for planning (1/25 000), in a mountainous region of the Spanish Mediterranean coast (Sierra Calderona). The proposed methodology entailed the definition of a synthetic index associated with the management of the risk of wildland fires, which was made up of significant factors such as the difficulty of extinction, the need for forest defence, the need for civil protection, and territorial value. To define and calculate the factors, variables and indicators that reflected aspects of the components of vulnerability (such as exposure, sensitivity, and the capacity to fight fires) were used. These were combined in a hierarchical structure, each having its own cartographical representation. Geographical information systems and multi-criteria evaluation were then used to provide a successful framework for the analysis of vulnerability in relation to wildland fires. The cartographical outputs of the various components of the index are of particular interest to the planning of certain activities (e.g. forest, wildland fire, and civil protection), all of which are directly involved in the management of risk. In turn, the final synthetic index provides comprehensive spatial information that is useful for spatial planning and also enables the assessment of potential future land use in view of its usefulness in simulations.

KEY WORDS *cartography; hazards; forest management; land use planning; risk assessment; wildland urban interface; Sierra Calderona (Spain)*

Introduction

In environmental science, the term 'vulnerability' has never been clearly defined nor is it widely accepted as a term either by the scientific community as a whole or by technicians with responsibilities for territorial management. Its meaning,

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understood to be the tendency of goods and people to suffer damage when exposed to a hazard (Coburn *et al.*, 1994), was first established within the field of risk assessment and management. The term was later adopted by researchers in many disciplines (such as in economics, psychology, anthropology, engineering, and ecology) whose objectives are remote from one other. This has led to a number of interpretations of the term, with a final result that has somewhat different meanings across disciplines (e.g. the negative effects of climate change on the socioecological system or the poverty and marginalisation that affect certain social groups; Adger, 2006). A broad debate has resulted from this expansion in the range of meanings and approximations, which has progressively changed from a theoretical and conceptual discussion to one relating to problems that arise from its practical application.

The current conceptualisation of vulnerability dates back to studies by White (1945) of flooding and to his criticism therein of the reductionism of the technocratic approach with regard to risk management (Smith, 2004; Montz and Tobin, 2010). White challenged the simplicity of applying technical approaches alone to the problem of risk assessment, which expressed vulnerability as the percentage loss that results from the effects of a particular event, in accordance with a simple causal scheme. From this perspective, the analyses focused on the nature of the events that led to a succession of damages or effects. To White, from his conception of geography as human ecology, the key research factors with respect to risk are human perception and behaviour.

As a result of the influence of White on risk geography, not only have those situations capable of generating negative effects now received some attention, but so have the characteristics of the social groups and places likely to be affected by the events involved. There has been an evolution within this field that has developed from an interest in finding differences in the physical elements to the need to include human structural factors to explain vulnerability. The final result is a conceptualisation of vulnerability in connection with resource availability and mobilisation (Blaikie *et al.*, 1994; Cutter, 2003).

The analyses carried out from this viewpoint have begun to show how the economic, political, and social characteristics of a particular location can change over time in ways that lead to unsafe conditions. The simple causal scheme has become more complex, and vulnerability is now defined to be the variable in the relationship between hazard and damage, which is key to understanding the processes of risk generation and the consequences of these. At this stage, the focus of attention is no longer the event itself but the conditions of the human beings and/or communities that are theoretically exposed to the potential calamities. To Hewitt (1997), these conditions have two basic dimensions: social and physical. Factors such as age, education, or income certainly have an influence but so do the biophysical characteristics (e.g. vegetation, altitude, and slope) of the various spaces affected by these phenomena (Ribas and Saurí, 2006).

Vulnerability, understood as a social product, is becoming established as part of the formula for risk (in which risk = hazard × vulnerability), and more and more researchers are now focusing on the causes of the unsafe situations that affect certain populations. From the perspective of political economics, the close relationship between the impact of natural disasters and the socioeconomic and environmental conditions in developing countries has previously been demonstrated (Ribas and Saurí, 2006). Researchers in other disciplines have investigated the concept more thoroughly and have used, as generators of spatial vulnerability, parameters such as the deficient perception of risk as the main factor that explains increased loss, levels of institutional development, which explain the extent to which a society is ready to deal with hazardous situations, or the effects of poor planning. (Fleischhauer *et al.*, 2007).

From the viewpoint of the management of risk, the largest contribution to the analysis of vulnerability has been from ecology through the incorporation of the concept of resilience (and in connection, the ability to adapt). The most recent research into vulnerability and resilience in socioecological systems showed the convergence and complementarity of both approaches (De Lange *et al.*, 2009). There has thus emerged the science of vulnerability, the purpose of which is to understand the circumstances that expose people and places to risk and to determine the conditions that could reduce the capacity to respond to environmental challenges (Cutter, 2003).

All these conceptual changes have resulted in the need to broaden and revise the design of assessments of vulnerability (Turner *et al.*, 2003). To a large extent, the challenge lies in the application of the significant number of concepts involved to the understanding of hazards and their effects in a local sense (Cutter, 2003) and in the consideration of vulnerability as an element that depends on the type of hazard involved. In this connection, different models of interpretation have been defined that have implicitly or explicitly incorporated vulnerability into the risk formula and which have progressively adjusted to an increasingly complex and broad understanding of the term (Turner *et al*., 2003).

The aim of the present work is to obtain an assessment of spatial vulnerability in connection with the hazard of wildland fires in a mountainous area of the Spanish Mediterranean coast (Sierra Calderona). Vulnerability in this case is understood to be a physical characteristic that explains the tendency of the territory to suffer damage as a consequence of a particular phenomenon. In line with this synthetic definition, there are two main components of vulnerability: an internal one, related to the effects of wildland fires on the value of the assets affected and their capacity for recovery, and an external one, related to the characteristics of the fire and the ability of society to manage the hazard of wildland fires. To obtain an assessment of spatial vulnerability, a procedure is herein defined that enables us to assess the factors involved in the calculation of vulnerability, both by synthetic means and by breaking down the vulnerability into its component parts.

It is hoped that the methodological approach used herein to assess vulnerability will eventually become established as a useful tool for the management of spatial risk and must therefore adapt to the complex nature of the object of analysis as well as to the requirements of planning. The large number of parameters that define vulnerability can not be reduced to one simple measure (Alwang *et al*., 2001, *cit.* Adger, 2006). On the contrary, the assessment must incorporate and reflect the great number of relevant variables involved in the calculation of a value for vulnerability. The selection of the appropriate thematic organisation, hierarchical structure, and weight of these variables, both quantitatively and qualitatively, is one of the cornerstones of the proposed method. It is also necessary to quantify and map the various tangible aspects of vulnerability on which the mitigation and management of risk must be based (Coburn *et al*., 1994).

Study area

The area selected for this study was the natural resource planning area of the natural protected area of Sierra Calderona (Valencia, Spain). The social, economic, and ecological conditions in Sierra Calderona are similar to those found in other mountain areas along the Spanish Mediterranean coast. These mountainous regions are subject to intense spatial pressures that resulted in profound changes in their functions, spatial organisation, and landscapes (Burriel and Salom, 2002; Pascual, 2003; 2004).

These areas can be understood to be transitional in that there is currently a growth in the degree of suburbanisation, a general increase in the abandonment of traditional rural lifestyles, a reduction in traditional agrarian activities, and an increase in the cultivation of new crops. In addition, secondary natural vegetation is advancing, and large forest fires have had a powerful impact on the landscape. The impact of these changes has translated into an increased risk from forest fires due to an increase in the number of wildland–urban interfaces (WUIs) and a greater continuity and availability of fuel in forest areas (Figure 1).

Materials and methods

The understanding of vulnerability as a spatial characteristic of the socioecological system requires an analysis of the elements of an enclosed system at a particular scale. Furthermore, the thematic and hierarchical cartographic output must enable us not only to approach the problem as a whole but also to break it down into its main constituent factors in order that these can be mapped. The definition of these factors is a central issue and must be carried out according to the adequacy of the factors when determining measures for the prevention and extinction of wildland fires. Likewise, the need to quantify the different components that make up these factors, as well as the difficulty involved, is resolved to a great extent by means of the indicators used to feed the interpretation model.

Geographical information systems (GIS) and multi-criteria evaluation (MCE) provide an excellent framework for the analysis of the vulnerability related to wildland fires because it is considered to be an attribute of the territory and therefore has a spatial dimension and is formed by various elements or criteria that need to be merged into a single indicator. In fact, both techniques have previously been applied to forest management and issues related to wildland fires, such as forest conservation (De Oliveira Averna and Vettorazzi, 2008), management and biodiversity (Næsset, 1997), and the risk assessment of fire (Martínez *et al*., 2009; Chuvieco *et al*., 2010).

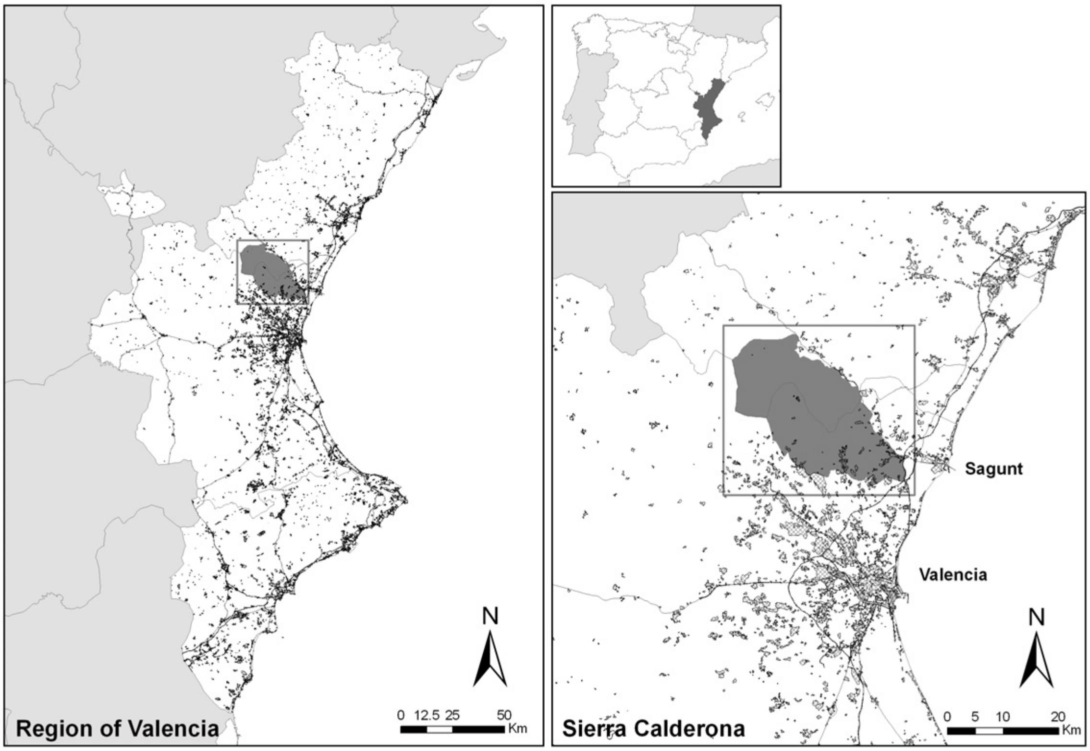

Figure 1 Location of the area of study (Sierra Calderona, Spain).

The calculation of a synthetic index and its components

The proposed methodology for the spatial assessment of vulnerability, at an adequate scale for planning (1/25 000), resulted in the definition of a synthetic index, which we broke down into its significant factors from the perspective of the management of risk of wildland fires (including the difficulty of their extinction, the need for the defence of forests, for civil protection, and the value attached to the territory). In order to define and calculate these factors, we have used variables and indicators that reflect various aspects of vulnerability (such as exposure, sensitivity, and the capacity for anticipation of a fire). These factors were combined in a hierarchical structure of variables, each having its own cartographical representation. The final product was therefore a cartographical series composed of a synthesis map as well as partial maps for each variable (Figure 2).

An MCE method supported by a GIS was used to obtain an index of vulnerability based on different spatial variables structured at various levels. Given that these variables were divided into different levels, each of them formed by the aggregation of other variables, this method was an iterative process, through the different levels of the hierarchical structure, of standardisation into a common scale and weighing and aggregation through the Analytical Hierarchy Process (AHP) (Saaty, 1980).

The AHP is an additive method that is composed of a process of aggregation based on the calculation of the weights of the variables by means of a pairwise comparison matrix using the relative importance of the values of the variables and a weighted linear combination of these values using the weights obtained from the pairwise comparison matrix. In order to aggregate the variables using AHP, the values must be standardised into a common scale. Given that the variables were not all assessed quantitatively because of their nature and that those that were quantitatively assessed had very different ranges, the values of all the variables have been reclassified into a semi-quantitative scale of values from 1–5. The values were reclassified by considering a direct or inverse relationship with the variable into which they were aggregated. The values that

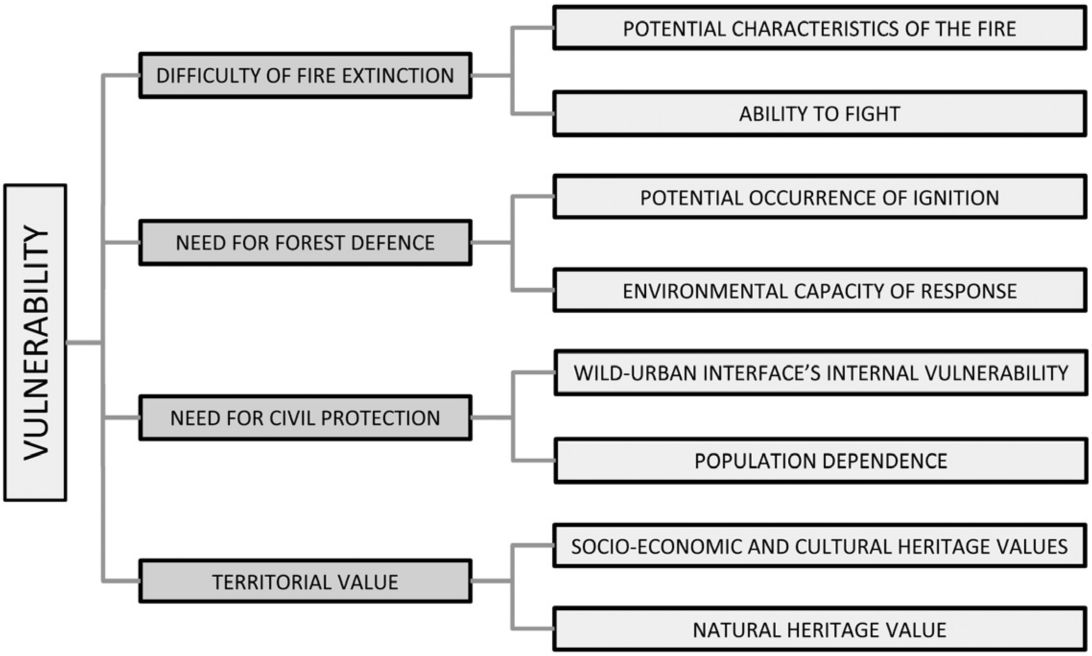

Figure 2 Hierarchical structure of the main components of the synthetic index for the vulnerability to wildland fires.

fell within each of the classes depended on the variable being reclassified because the values in each case were different and also depended on the range of these values because this varies for different studies or scales of approach. The final intervals used generally depend on the preference of the user for a specific area by considering in each case the subject that is being measured and the variable to which it will be aggregated.

The weighting of variables was an important part of the development of this index of vulnerability with regard to wildland fires because of the number and complex structure of the variables considered. Here, our calculation was made using two kinds of information, namely consultation with experts and an analysis of the database for wildland fires (1989–2007).

The consultation with experts was carried out through personal contact with the individuals responsible for the prevention and extinction of wildland fires in the study area. Each expert was questioned by means of a semi-structured interview, the aim of which was to obtain first-hand knowledge of the factors and conditions that led to vulnerability. They also completed a standardised questionnaire that required a quantitative assessment of the relative importance of each variable. The results of the questionnaires were used to calculate and quantify the relative importance of the variables necessary to calculate the pairwise comparison matrix needed for the AHP. The subsequent analysis of the database (1989–2007)[1] enabled us to assess various aspects related to exposure (such as frequency, magnitude, and the main causes), as well as data required for the determination of some of the weights of the variables and the capacity to fight fires (response time).

After all the variables had been quantified, standardised into a common scale, and weighted, the MCE was run once for each level of the structure of variables of vulnerability until values for the four final components were obtained. The final index was calculated by the addition of these four components, thereby producing a result that ranged from 3 to 20 because each component could vary from 1 to 5 (with the exception of the need for civil protection, which could be zero). In order to obtain a more logical scale, this result was reduced to a value between 0 and 1. The result of adding the four main components was standardised using the following equation in order to ensure that the lowest value remained as the minimum and the highest value as the maximum of the standardised scale while not maintaining the original proportionality (Barba-Romero and Pomerol, 1997, *cit*. Gómez and Barredo, 2005):

$$mi = (xi - min\ xi)/(max\ xi - min\ xi)$$

where *mi* is the standardised value, *xi* is the original value, and *min xi* / *max xi* is the ratio of the minimum and maximum values that are being standardised.

The proposed index of vulnerability was defined using the four main components of the difficulty of extinction, the need for forest defence, the need for civil protection, and territorial value. These components were then further subcategorised into variables.[2]

The difficulty of fire extinction is a variable that indicates the spatial distribution of the degree of difficulty involved in the control and extinction of a wildland fire by the available firefighting personnel. Two factors that varied according to the spatial context were linked in order to calculate this component, namely the potential characteristics of the wildland fire and the ability to fight it. The first represents one of the manifestations of the exposure to hazard and was established by analysis of several indicators for the intensity that a fire could reach. The second is an assessment of the capacity for anticipation made through an analysis of the experience of fire extinction that is the accumulation of the experience of recent years, as well as of the existing structures for the prevention of fires (Figures 2 and 3).

The need for forest defence is defined to be the extent to which natural elements in the forest require protection against wildland fires. The spatial distribution of this factor is directly proportional to the probability of the occurrence of the phenomenon. However, schemes that must be in place in particularly sensitive forested areas, known as priority actions, were been taken into account.

This component is determined by the following: the potential occurrence of ignition and therefore the possibility of a certain area being hit by a wildland fire; and the environmental capacity of the response, i.e. the level of resistance of the natural environment against degradation after the occurrence of a hazardous event in a particular area (Figure 4).

The need for civil protection represents the influence that a human presence in the territory has on the vulnerability, expressed in terms of a higher or lower need for protection. The social homogeneity of the area in this study did not require the introduction of elements of social vulnerability related to socio-economic status (Gaither *et al*., 2011). This component is mainly determined by the density of the population and the demographic structure, as well as by the characteristics of the human settlements (Figure 5).

The territorial value reflects the potential impact of fire on the territory and depends on the

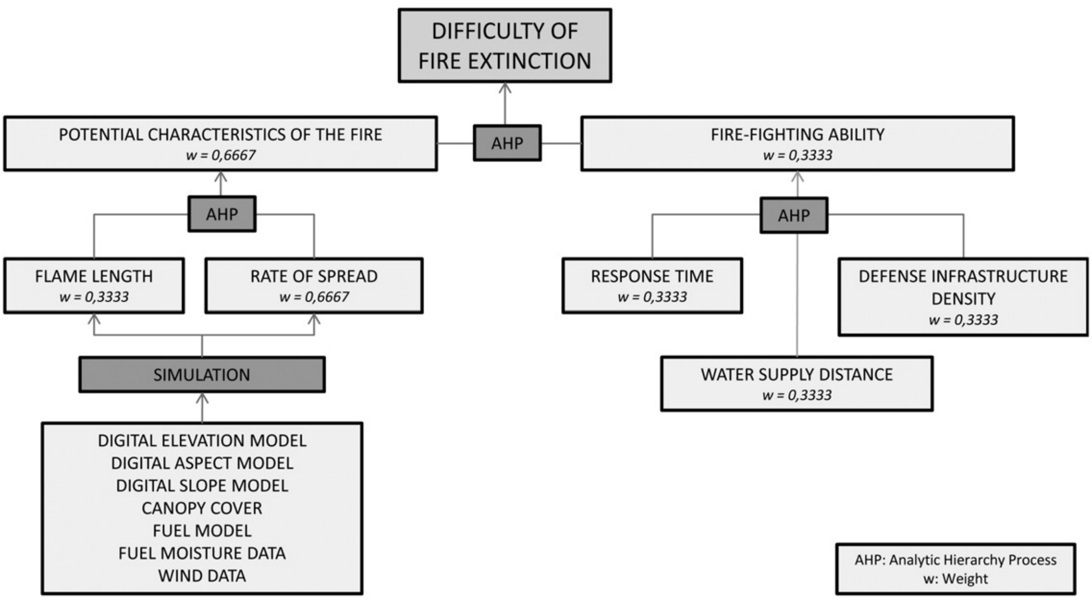

Figure 3 Wildland fire vulnerability index component: difficulty of fire extinction. Elements involved, calculation process, and variable weighting.

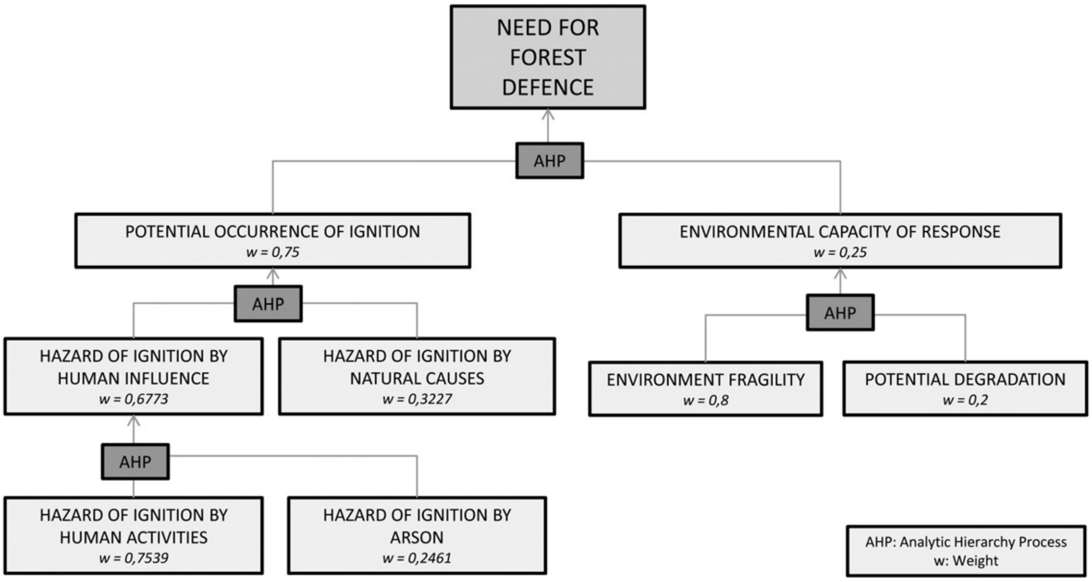

Figure 4 Wildland fire vulnerability index component: need for forest defence. Elements involved, calculation process, and variable weighting.

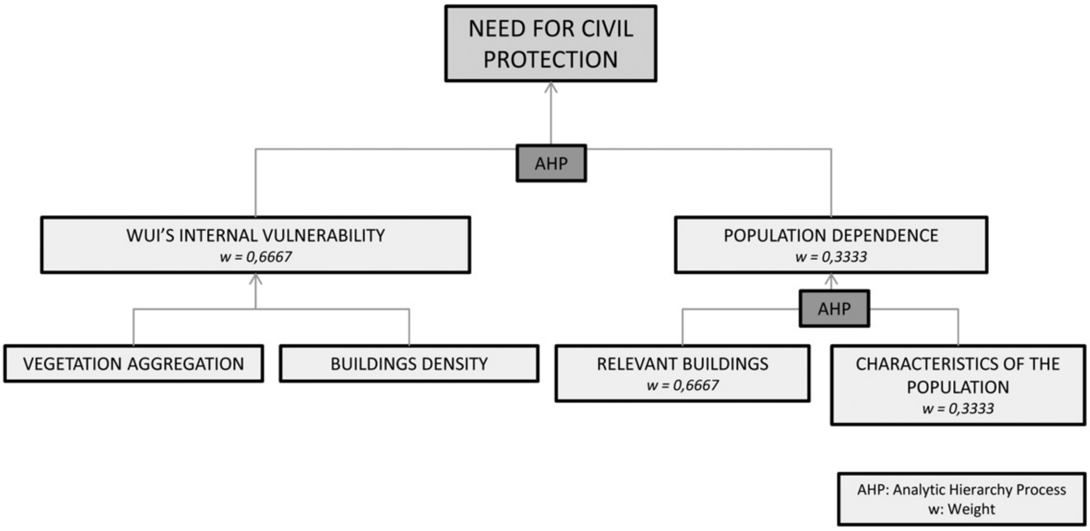

Figure 5 Wildland fire vulnerability index component: need for civil protection. Elements involved, calculation process, and variable weighting.

natural, cultural, and economic assets affected (Figure 6).

Results and discussion

The assessment of vulnerability herein undertaken took the form of a synthetic index that represented the spatial distribution of this variable in the territory. In order to reflect the complex nature of this concept, the various components involved in the calculation of the index are also considered later. These components have been defined according to their operational significance in strategies for the prevention and extinction of fires and were calculated using indicators related to exposure, sensitivity, and the capacity for anticipation. By means of these

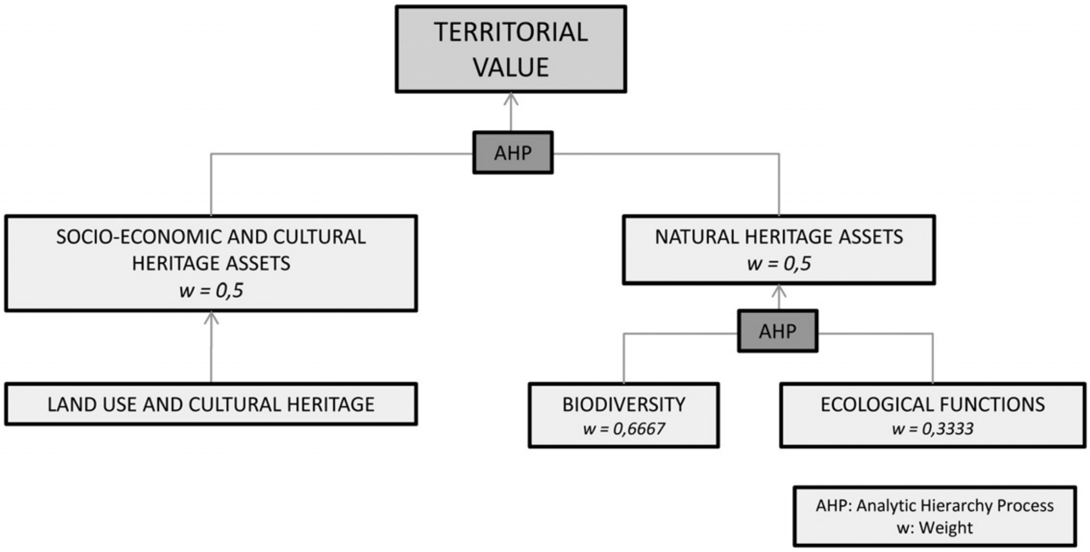

Figure 6 Wildland fire vulnerability index component: territorial value. Elements involved, calculation process, and variable weighting.

intermediate concepts, it was possible to express the essential characteristics that define the hazards of wildland fires and the resultant predictable effects and consequences.

The components of spatial vulnerability in wildland fires

As previously mentioned, the spatial vulnerability of land to wildfires may be broken down into four components, namely the difficulty of extinction, the need for a mechanism of forest defence, the need for civil protection, and a territorial value.

The assessment of difficulty of extinction began with an evaluation of the magnitude of the scale that fires could attain, as well as the capacity of local systems to anticipate these events.

To determine the kinds of conditions that might occur, specialised simulation software was used to calculate the length of the flame (an indicator of intensity) and the rate of spread (an indicator of area). Both variables were obtained from FlamMap 3.0 (OSKAR, Missoula Fire Sciences Laboratory, Missoula, MT, USA) fire simulation software (Finney *et al*., 2006). In our study, the worst-case scenario was simulated by the use of values for temperature and relative humidity that established the highest level of fire alert.

An immediacy of action is of great importance in preventing the development of significant fires following an initial outbreak. Much of the effort in firefighting is focused on minimising the time required for a response. For this reason, the response time was used to assess the ability to fight fires. The response time of the personnel engaged in firefighting documented in the database corresponded only to specific locations. In order to obtain a continuous range of data, these specific points were therefore interpolated into a surface by use of the inverse distance weighted algorithm.

In order to assess fully the ability to fight wildland fires, the density of infrastructure with access to the area at risk, as well as existing sources of water, were also taken into account. The distance to the nearest water supply was calculated by measuring the Euclidean distance to the closest source of water using the spatial capabilities of the GIS, while the density of the defence infrastructure was measured by calculating of the density of firebreaks, paths, and tracks using kernel density and a search radius of 500 metres.

The area did not show significant internal differences from the perspective of the planning of the prevention and extinction of fires so no indicator was introduced to reflect this variable (Figure 7).

The spatial representation of the difficulty of extinction clearly shows a topographical gradient in which a longer response time is correlated with a lower density of the infrastructure for defence in those areas that have a highly varied

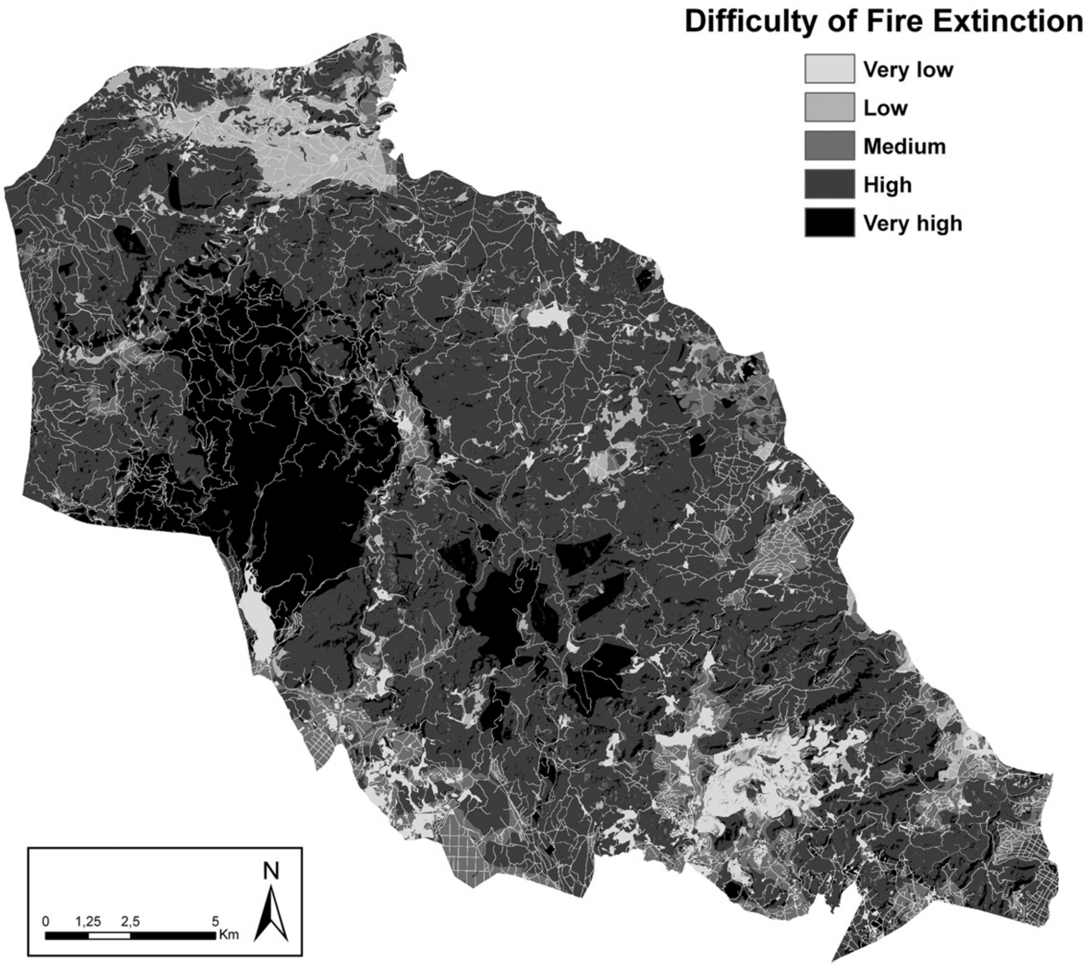

Figure 7 Difficulty of fire extinction.

topography. The difficulty of extinction also coincides with those sectors where the vertical continuity of vegetation is greater, resulting in the potential for a higher intensity of fires when compared with those areas with a more gentle topography, where the development of agriculture and/or urban areas favours the occurrence of a land use 'mosaic' and therefore has a lower propensity for the propagation of fires.

The probability of occurrence of wildland fires, in connection with the different spatial incidences of the various causes, is the factor that most directly determines the need for forest defence. The potential for ignition is influenced by two main factors, namely the hazard of ignition due to human influence and that due to natural causes.

Ignition caused by human activity may be subcategorised into two different causes, namely that caused by normal human activities and that caused by arson. The hazard of ignition caused by normal human activities was herein calculated by the addition of the areas under influence from the various different human activities considered here. The area under the influence of each activity included the area itself as well as a buffer zone of 100 m around it. The activities considered were roads, railroads, buildings, power lines, agricultural areas, dumping sites, recreational and camping areas, military sites, mines and quarries, petrol stations, and forestry. The hazard of ignition by arson was established by calculating the spatial density of the wildland fires that were caused intentionally. This information was found in the database of wildland fires and was calculated by means of a kernel density operation using a search radius of 5 km.

The hazard of ignition by natural causes was calculated using the probability of a lightning strike, which is a function of the three variables of altitude, slope, and land cover. For each of these variables, three categories were established and calculated based on the proportion of the entire area represented by each and the proportion of lightning strikes within each of these areas. These data were obtained from the database of wildland fires. With this information, the average probability for each possible combination of the values of the three variables was calculated and then weighted according to the proportion of the area covered by each of these combinations. This resulted in the determination of the probability of a lightning strike for each of the possible combinations of the categories of altitude, slope, and land cover.

Proceeding

1. Calculate for each value of each variable area proportion for variable *i* case *j*

$$APij = Aij/Atotal$$

where i = variables: altitude, slope, land cover, j = each of the values the variable may take (ranks of altitude, slope, and types of land cover), x = possible combination of j values for i variables.
2. Area proportion for the combination for each of the combinations of j values of the three variables $APx = Ax / Atotal$.
3. Lightning proportion for variable i case j $LPij = Lij / Ltotal$.
4. Lightning/area proportion for variable i case j $Cij = LPij / APij$.
5. Calculate the average lightning/area proportion for each of the combinations of j values of the three variables. Average of lightning/area proportion for all the possible combinations of j for the i variables $Cx = (Caltitude,j + Cslope,j + Cland\ cover,j) / 3$.
6. $P = Cx \times APx$

The probability of a lightning strike is the average lightning/area proportion (4) multiplied by the area proportion of the specific combination of the values of the variables (2).

The establishment and weighting of the foregoing elements was carried out following an analysis of the causes of wildland fires (i.e. the percentage caused by lightning), using data from the historical database.

The environmental capacity of response summarises the capacity of the natural environment for restoration following a potential wildland fire and takes into account the fragility and potential degradation of that environment. In view of the multiple elements and potential complexity involved in the regeneration of natural vegetation following a fire (such as the intensity and extent of the fire, the plant formations affected, the time of the year, and the meteorological conditions following the fire), this variable needed to be simplified. As a consequence, two indicators of a structural nature were used that considered the potential erosion and the sensitivity of different plant formations to fire and were analysed on the basis of the reproductive strategy and capacity of the plants (Lloret, 2004) (Figure 8).

In common with most mountainous areas in the Mediterranean region, the most significant factor that affects the probability of wildland fires is the intensity of human pressure on the territory. This is greatest in areas that surround centres of population, in the proximity of the busiest roads, and close to particularly hazardous facilities (such as sites of military activity). In addition, an increased fragility of the environment is quite evidently linked to those sectors in which regeneration is more difficult as a consequence of a high occurrence of wildland fires in the area. As a result, the highest values related to the need for forest defence are associated with those regions that have higher levels of urbanisation, and that are located adjacent to areas with recurrent fires.

The presence, and potential hazards, of centres of population determine the need for civil protection. With regard to the types of settlement, WUI situations have received particular attention because these are zones in which wildland fires can readily gain access to and spread through buildings (Pyne *et al.*, 1996). The expansion of the WUI is one of the elements that contributes the most to the increased spatial vulnerability in the Mediterranean area and that currently defines a new and complex scenario in the fighting and prevention of forest fires (Lampin-Maillet *et al.*, 2010a).

As a consequence, a precise delimitation and internal analysis of the WUI was carried out in which the likelihood of damage in relation to the density of buildings and the continuity of vegetation cover was established, both inside the interface and also in the surrounding area (Lampin-Maillet *et al.*, 2010b). The aggregation of vegetation was calculated using the *Fragstats* program (University of Massachusetts,

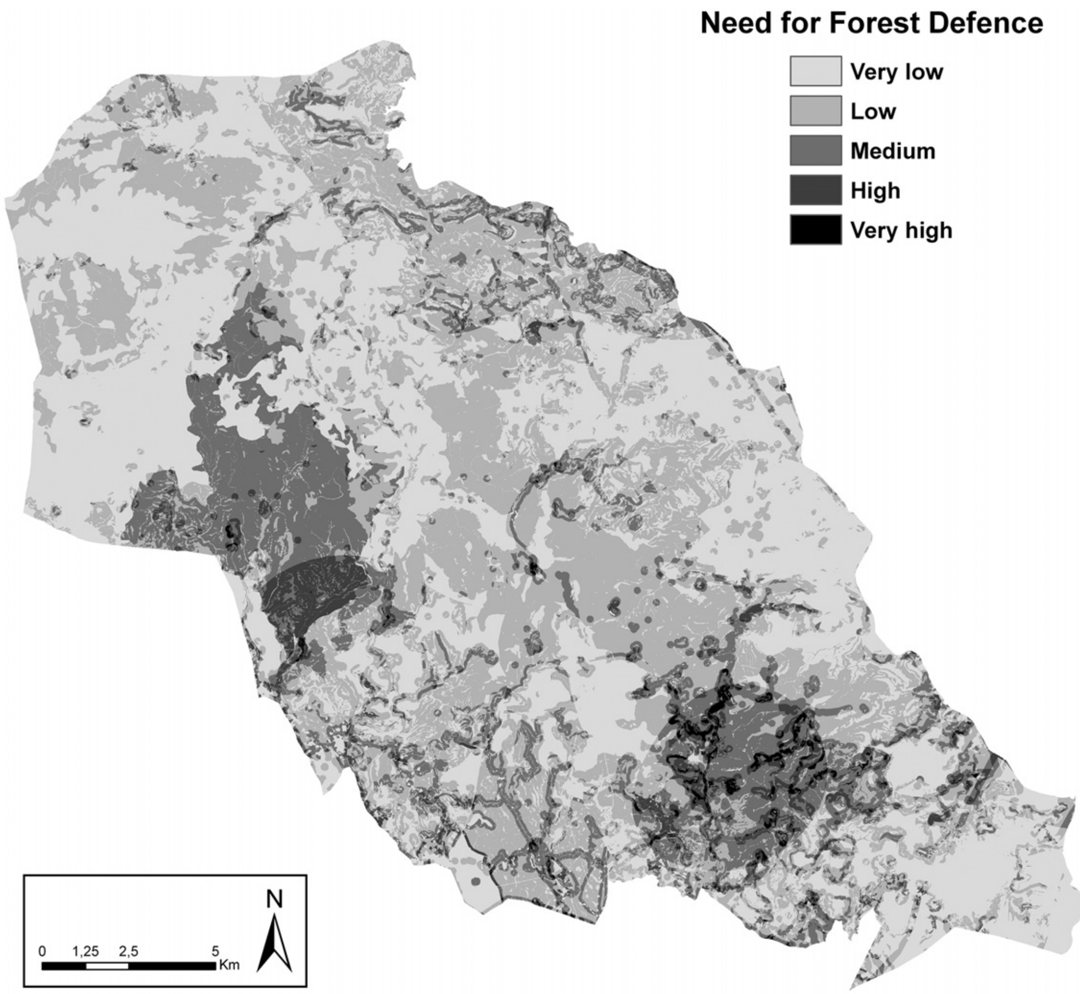

Figure 8 The need for forest defence.

Amhersts, MA, USA) with data derived from satellite images (McGarigal *et al*., 2002). The calculation produced percentage values of aggregation that were classified into three categories (0%, 0–90% > 90%). The density of the buildings was calculated by consideration of a search radius of 200 m and the use of a kernel density. Only data that corresponded to the WUI areas were taken into account. These values were also classified into three categories (0–300 m^2 ha^{-1}, 300–1500 m^2 ha^{-1}, >1500 m^2 ha^{-1}; Galiana-Martin *et al*., 2011) (Figure 9).

The term population dependency expresses the need to assist and protect certain groups in the population in emergencies (e.g. children, the elderly, and the infirm). Population dependency may be defined according to the density and composition of a population by age, as well as the existence of locations with populations that are particularly vulnerable to situations of risk (such as institutions for education, health and assistance) (Figure 10).

Finally, the effects of wildland fires vary in relation to the territorial value of the assets affected. In order to estimate this, a small number of indicators were chosen, each representing one of the various assets considered (such as environmental services and richness of biodiversity). In addition to this thematic criterion, the selection process gave careful consideration to the availability of indicators with a spatial basis that were both socially accepted and institutionalised, such as natural protected areas, the catalogued heritage of cultural interest, and groundwater protection zones. These indicators are conveniently mapped by their respective regulations. The

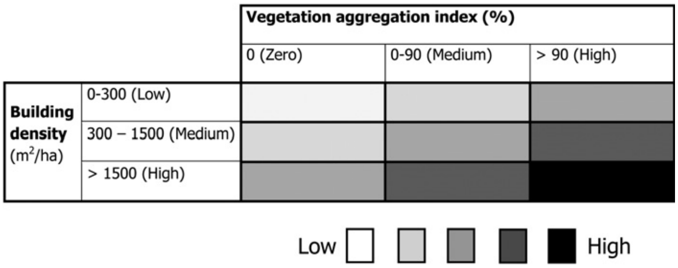

Figure 9 Determination of the internal vulnerability at the wildland–urban interface.

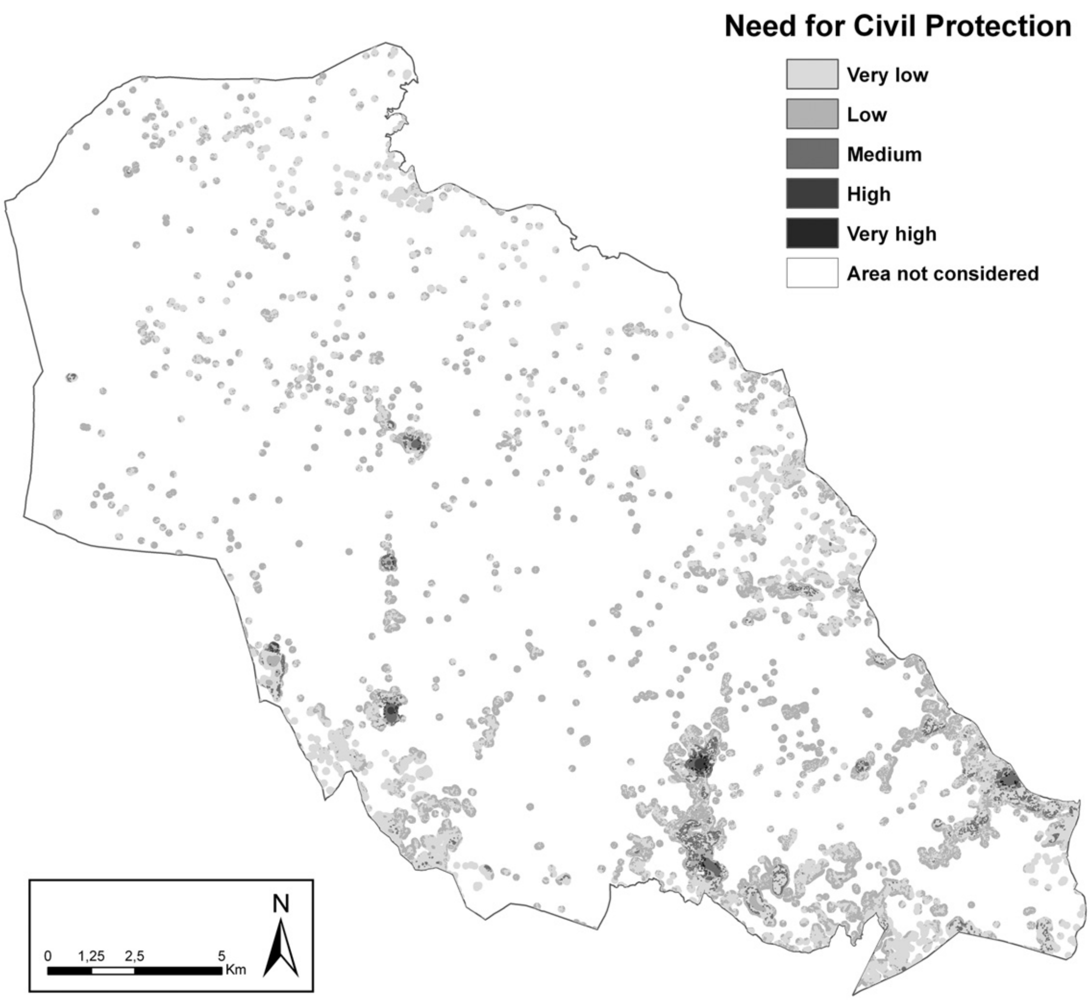

Figure 10 The need for civil protection.

economic valuation was carried out using information about the cover and use of land and established a list of values for each of the defined classes (Figure 11).

The highest territorial values corresponded, firstly, to those territories that called for greater efforts in conservation in accordance with institutional declarations (such as natural protected

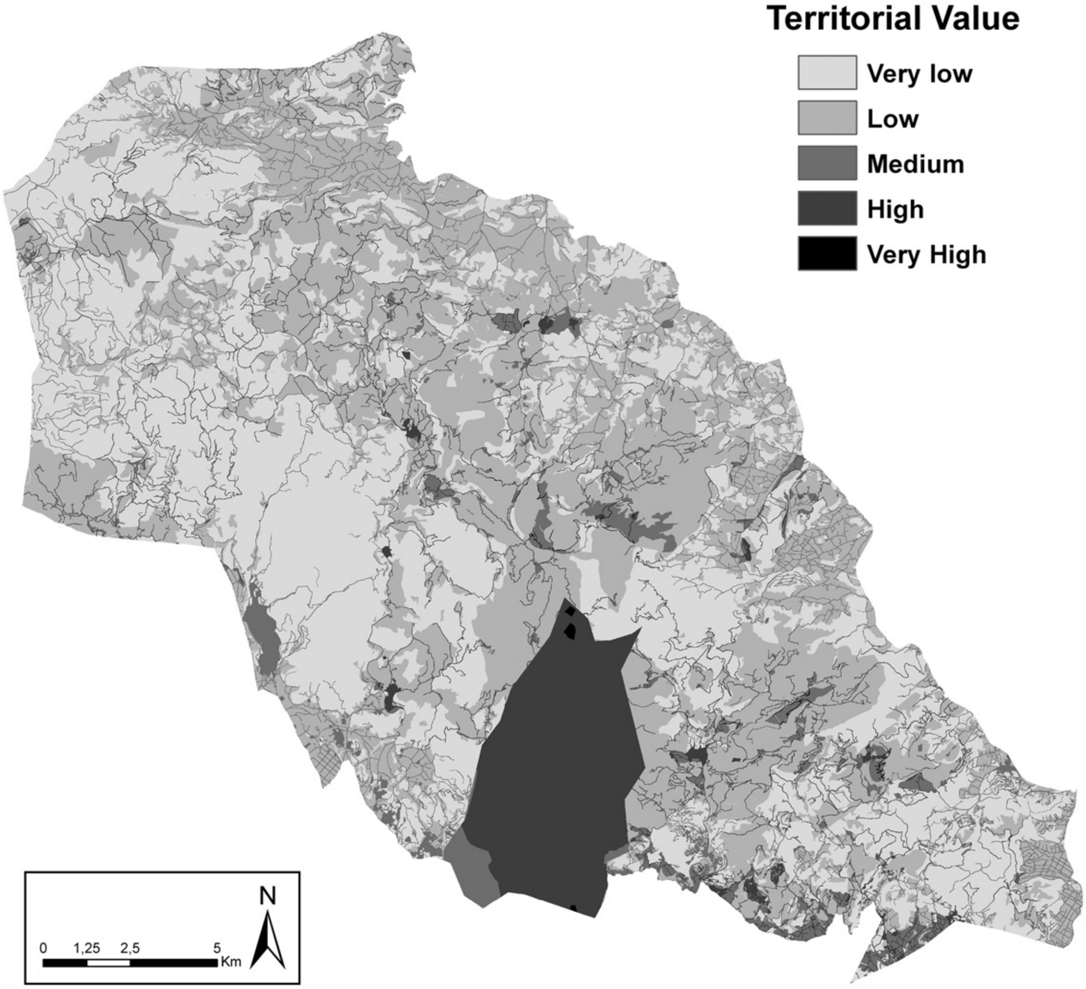

Figure 11 Territorial value.

areas and cultural heritage), which are also zones of great interest because of the environmental services that they provide. Areas with a high density of buildings were also ascribed high territorial values. The most environmentally degraded areas, especially those sectors affected by recurrent fires, had the lowest classification in this category.

Spatial distribution of a synthetic vulnerability index

The components and final index were produced once all the basic variables had been obtained and standardised, according to a direct or inverse relationship with the variable of which they were a component, and aggregated.

The index had a theoretical range from zero (no vulnerability) to 1 (greatest vulnerability). In the Sierra Calderona region, it ranged from 0.06 to 0.73. The lower values were associated with sparsely populated areas, where agriculture was still the main land use and where forest vegetation did not have a high spatial continuity. Where agricultural land had been replaced by forest, the vulnerability was higher, particularly in unmanaged areas. However, the values that corresponded to severe vulnerability (>0.5) were exclusively related to the presence of buildings in forest spaces (WUI), thereby affecting large sectors of the peripheral mountainous areas. Furthermore, these were zones where the pressure for urban development had been accompanied by the abandonment of agricultural practices, resulting in the re-emergence of unmanaged natural vegetation.

Our final result is a map (Figure 12) that shows a general assessment of the spatial vulnerability with regard to wildland fires. Given that risk management entails the individual assessment of the various components, the validity of our map is limited when used for planning related to the management and extinction of forest fires. On the other hand, it is a useful tool for spatial planning. Beyond the informative value of its cartographical output, its main utility lies in its possible use for simulations. The proposed model enables us to perform simulations and to check the effects on the distribution of vulnerability that results from the introduction of new land uses in the territory (such as infrastructure and new building developments), which, in turn, can help to inform decisions that involve the consideration of the spatial component of risk.

Conclusions

The use of the scientific concept of vulnerability within the context of risk geography has proliferated and is now used in a large number of scientific disciplines. This has resulted in the diversification and widening of its meaning. As a consequence, there is no currently accepted definition of this concept within the field of risk assessment.

For similar reasons, it is also not possible to set out any single method of assessing vulnerability. The need to adjust the approach to the different nature of each risk, the specific requirements and

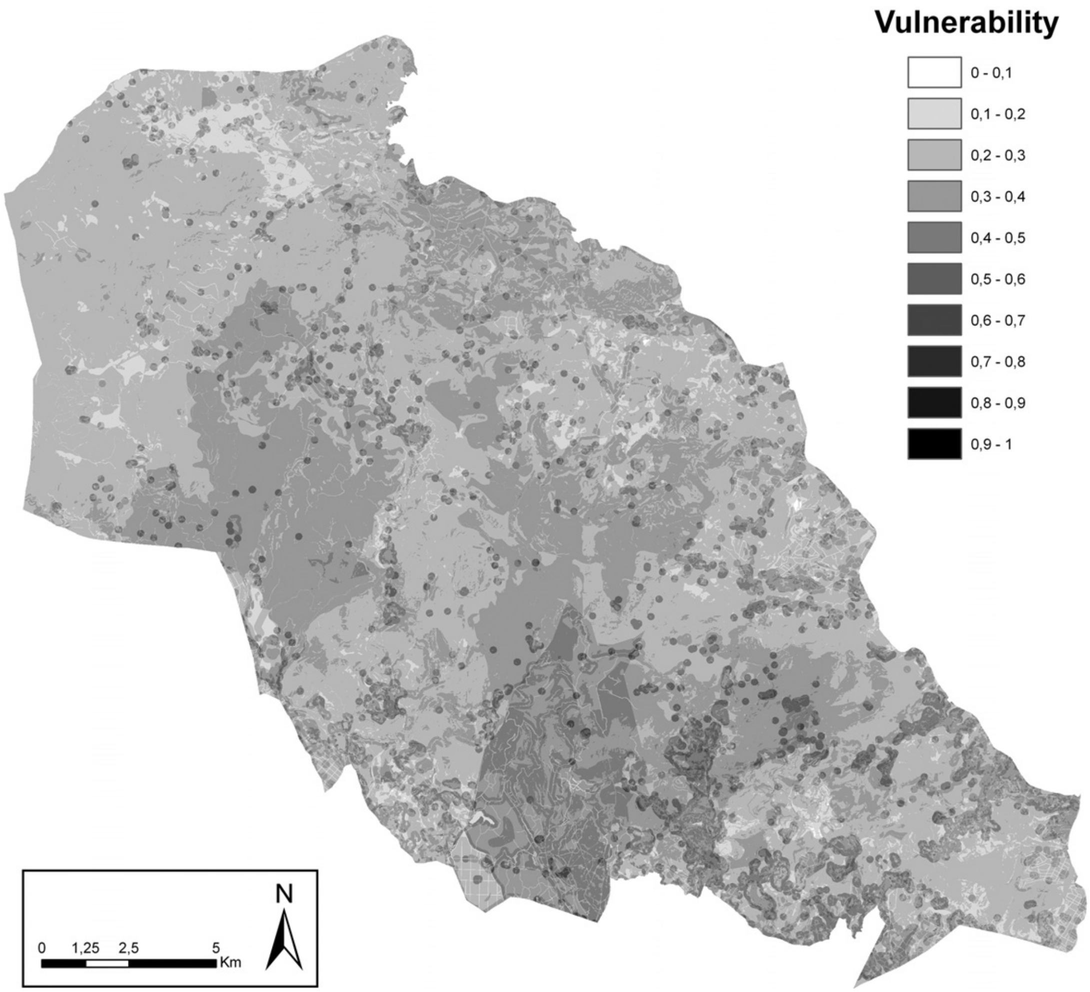

Figure 12 Synthetic index of vulnerability.

objectives of the study, and the necessary unique consideration of each place leads to an individual solution for each case.

Certain tools and instruments are particularly necessary for some of the analysis techniques because of the complexity of the consideration of vulnerability as a spatial characteristic of the socioecological system. In particular, GIS and MCE are useful tools for both quantitative and qualitative analyses that are based on both the thematic organisation and the ranking and weighting of a large volume of information.

The qualitative nature of a significant part of the information and, to a large extent, of the results, is a matter of particular significance. The incorporation of suitably formalised informed judgement is essential for variable weighting, thematic organisation, and ranking. At this point, the introduction, definition, and calculation of intermediate concepts (such as the difficulty of extinction, the need for forest defence, the need for civil protection, and territorial value) are essential for expressing those aspects of vulnerability on which risk management and mitigation must be based. The main innovation of the present research is therefore the introduction, definition, and development of these intermediate concepts.

The assessment method was formulated with a view to the transferability of its approach, structure, and contents to other means of assessing vulnerability and was carried out at an intermediate spatial scale (1/25,000). From this perspective, the proposed methodology meets the requirements of sectoral planning (such as forests, fires, and civil protection) by means of a cartographic output at a scale that adequately represents the various individual components into which vulnerability can be broken down. At the same time, the final synthetic index provides combined information that is of significant relevance to spatial planning and enables, by means of its ability to produce a simulation, an assessment of the future distribution of land uses.

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NOTES

1. Forest fires data base (EGIF) (Dirección General de Medio Natural y Política Forestal del Ministerio de Medio Ambiente y Medio Rural y Marino) (An innovative approach for integrated wildland fire management. Regulating the wildland fire problem by the wise use of fire: solving the fire paradox, 2006–2010).
2. Complete cartographic results can be found in Galiana and Karlsson (2010).

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