A model to evaluate the ecological vulnerability to forest fires in mediterranean ecosystems

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Abstract: Forest fire represents a major agent promoting changes at the landscape level and increasing land degradation risk. The ecological vulnerability to fire can be defined as the susceptibility of the ecosystem to be changed as a consequence of fire. Environmental features, as well as vegetation structure (composition and frequency), are key factors to estimate that vulnerability. The incorporation of GIS and remote sensing opens the possibility of cartographical approaches and temporal analysis, being necessary the development of new methodologies for the evaluation of the vulnerability to fire. This work shows a methodological approach to evaluate the ecological vulnerability to fire in two areas: Valencia (E Spain) and Aragón (inland N Spain), considering the available cartographical information, and being supported by GIS and remote sensing. The analysis of ecological vulnerability has been structured in different stages: at short-term (focussed on soil degradation risk), at medium-term (focussed on changes in plant composition and structure), and coupling the short and medium-term vulnerabilities. The variables to be considered must be obtained and/or expressed in cartographical format. The sensitivity degree for every factor was divided in three categories: high (H), medium (M) and low (L). The factors were integrated applying a matrix method. For the short-term vulnerability, we considered the next environmental factors: rainfall aggressiveness (categories based on maximum rainfall intensity in 24 hours, return period 10 years), slope steepness and a soil erodibility factor (integrating lithological maps with organic matter estimations, the latter based on vegetation maps and remote sensing). We considered that post-fire soil degradation will be modulated by the time of exposure of the soil surface to the environmental factors. According to that, the integration of environmental factors was put together with an estimation of the response capacity of the vegetation. This classification was based in the dominant reproductive strategy (frequency of seeder and resprouter species), water constraints (in relation to the length of the dry period and the slope aspect) and fire frequency (that can influence the soil seed bank and the resprouting capacity).
At medium-term, the ecological vulnerability was determined by the capacity of the community to return after fire to the pre-fire conditions without significant changes in composition and structure (resilience). This capacity was associated with the presence/dominance of species with different reproductive strategies, structure of the community and fire frequency. Environmental data was obtained from climatic maps, records from a network of weather stations and digital elevation model. Fire frequency was obtained from forest services, aerial photography and remote sensing analysis. In order to cartographical classification of vegetation communities, the categories must be based on functional attributes related to response capacity to fire, being the Forest Map of Spain (digital format) the most accurate and applicable source. The first step was gathering vegetation

classes as homogenous as posible according to the main species reflected on the Forest Map of Spain, validated with field work.

Keywords: [Cartographic model, Fire hazard, Mediterranean vegetation, Reproductive strategy**.**]

1. Introduction

The purpose of the FIREMAP Project (http://www.geogra.uah.es/firemap) is to develop a methodology for the cartography and the spatio-temporal analysis of forest fire risks, basing itself on remote sensing and Geographic Information Systems. To obtain this index the occurrence risk and the vulnerability of the affected resources are considered, the latter having up to now been scarcely taken into account in the risk assessment.

In the Project framework, vulnerability is defined as the degree of susceptibility to deterioration faced with the impact of certain actions; or as the inverse of the adsortion capacity of possible alterations without loss of quality (MMA, 2000). The vulnerability will be studied including the damage level (burn severity on different vegetation types) and the value of the resource, from a twofold point of view: socio-economic value (leisure areas, properties, timber productivity) and ecological value (potential erosion, dynamic of vegetation and landscape value).

2. Methodology

According to the FIREMAP Project approach, three components can be considered in ecological vulnerability: erosive activity, dynamic of vegetation and landscape structure. The methodology suggested in this model will especially stress the assessment of damage level on vegetation and in its response capacity in case of fire. This response will be set up for two different time periods: in the short term (less than 1 year) and in the short term (25 years). Thus, the ecological vulnerability analysis has been structured in three stages:

1.- Short term evaluation (less than 1 year) to identify the most erodible areas.
2.- Medium term evaluation (25 years) to identify changes in the vegetation structure and composition due to fire.
3.- Inclusion of both assessments to obtain a synthetic index of the ecological vulnerability associated with fire.

The procedures needed to put the model cartographically into practice will be analyzed in a fourth stage with the purpose of getting an ecological vulnerability map regarding forest fires. The application of the model on regional scales (with the support of remote sensing and Geographic Information Systems) conditions and limits the variables to be integrated. This is the reason why sometimes it will be necessary to resort to making generalizations and simplifications caused by the scale of work.

In a vulnerability evaluation in advance the fire intensity and the subsequent climatology are unlikely to be predicted. In our case, we decide to locate the evaluation in the worst scenario with Mediterranean conditions: summer fire, low humidity of the fuel and climatic conditions similar to those of the summer period historical average. These conditions lead to expect highly intense fires. This theoretical intensity, measured as the energy released by the fire front, will eventually be qualified depending on the fuel load associated with each type of vegetation.

3. Analysis of the ecological vulnerability

3.1. Short term evaluation

For a period of less than a year the ecosystem response capacity in case of fire will be determined by (Figure 1):

1. Physical environment characteristics in terms of erodibility.
2. The affected vegetation characteristics; in this case in terms of response speed in the short term (modified by the possible presence of limiting factors to vegetation regeneration).

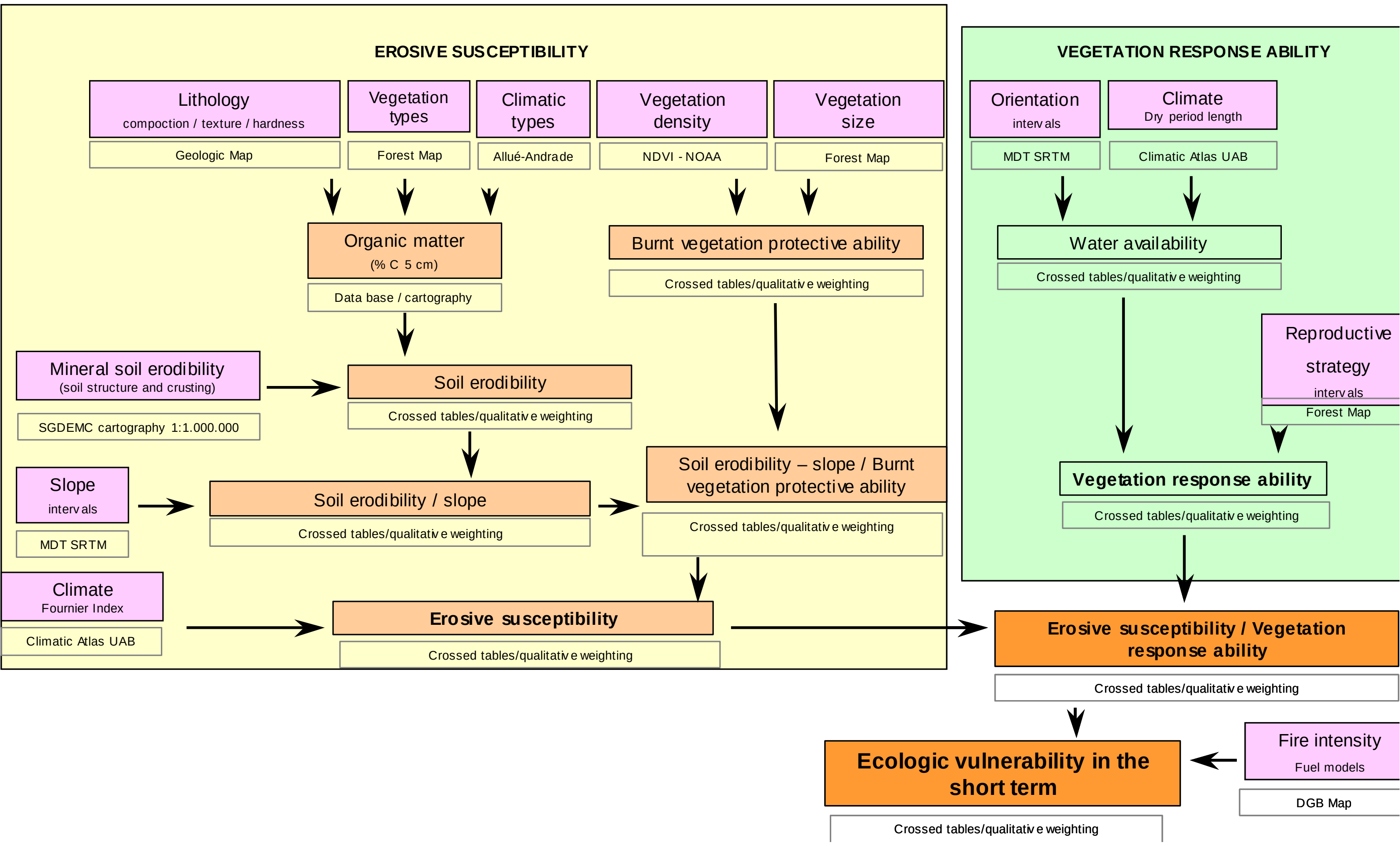

Figure 1. Methodology for the assessment of ecological vulnerability in the short term.

3.1.1. Erodibility

The ecological vulnerability in case of forest fires can be estimated from the erosion risk coming from the loss of vegetation cover. In spite of the numerous modifications and criticism on The Universal Soil Loss Equation structure (USLE), it constitutes a reference to assess the magnitude of soil loss in burnt areas (Giovannini, 1999).

In order to facilitate its applicability and due to the available digital cartographic information limitations, a qualitative approach is carried out in this model assuming the same factors considered by the USLE, (climate, slope, soil erodibility and vegetation) clasiffied in three categories: high, medium and low sensitivity, integrating them by means of reduction matrices. Similar analyses have been carried out in projects with cartographic applications on regional scales, like for example in project CORINE (http://reports.eea.eu.int/COR0-soil/en/soil_erosion.pdf) or in project PESERA, Pan—European Soil Erosion Risk Assessment (http://pesera.jrc.it). In our model the criteria and information sources put into practice in each one of the factors are the following:

Factor lithology/soil: The soil response to erosion is a complex one and it is influenced by numerous factors. Factor K of the USLE model intends to measure the influence of the physical and organic properties when it comes to erodibility considering texture, organic matter content, structure and soil permeability. In our model the analysis of soil erodibility is based on two componentes of the soil surface (we believe that both fire and the later degrading phenomena –rain- have a special influence on the surface): a) organic matter content (O.M.) of the first 5 cm. of mineral soil and b) soil permeability physical characteristics, such as surface structure and soil crusting risk.

a) Organic matter content. For its assessment we have used the profile database obtained during the project “Evaluation of storage and carbon sequestration potential in the soils of the Mediterranean area” (from now on “Carbon Project”). With these profiles’ information and based on a methodology developed within the framework of this project, the O.M. content has been calculated (in % weight/weight) in the first 5 cm. of mineral soil. The methodology developed allows analyzing the O.M. content based on three variables: climate, lithology and vegetation. For its application in the model, the O.M. contents are classified in the categories (>8%, Very high; 8%-4%, High; 4%-2%, Médium; 2%-1%, Low; <1%, Very low).
b) Physical factors. The little cartographic soil information in digital format with regional range limits the possible variables to be considered. The soil cartography available in *Soil Geographical Database of Euro-Mediterranean Countries* will be used to compensate part of these deficiencies. This cartography (scale 1:1.000.000) defines a series of units (*Soil Typological Units).* These units are grouped together in *Soil Mapping Units* considering the functional nature of the pedological systems within the profile. Normally each *SMU* has a surface more extensive than 25 km^2. Each map polygon belongs to a single *SMU*, but each *SMU* can be composed of one *STU* at least. A working group of pedologists (Daroussin & King, 1996) has reached a consensus in defining a set of expert judgments (*pedotranfer rules*) to infer soil qualitative attributes. Thus, from the review of the pedotransfer rules *Top soil structure (STR_TOP)* and *Physi-chemical factor of soil crusting & erodibility (PHYS_CHIM)* have been chosen.

   STR_TOP is divided into 4 categories (Good, Normal, Poor and Humic or peaty topsoil), although in Spain only areas with categories Good and Normal appear.

   PHYS_CHIM is divided into 5 categories (Very favourable, Favourable, Medium, Unfavourable and Very unfavourable), of which 3 (Favourable, Medium and Unfavourable) are present in Spain. Both variables have been integrated to obtain an approach to the soil structural characteristics related to erodibility (Table 1).

Table 1. Integration of organic matter content to structural characteristics to obtain the degree of soil erodibility.

% Organic matter (0-5 cm)	Soil structure		
	Good	**Normal**	**Unfavourable**
Very high	Low	Low	Medium
High	Low	Medium	Medium
Medium	Medium	Medium	Medium
Low	Medium	High	High
Very low	High	High	High

Slope factor: Variable quantified from the Ground Digital Model. Tradicionally in erosion models the slope is associated to a higher speed in the runoff flow and therefore, to a higher erodibility. So, in the erodibility evaluation caused by the slope factor, the model will distinguish among the intervals: <15 %, Low; 15-45 % Medium; >45% High.

Burnt vegetation factor (BV): Although the vegetation protective ability is reduced as a result of fire, the charred remains (lignified structures of bushy or arboreal nature, surface horizons) can limit the flow speed, decrease the precipitation kinetic potential, and in short, to improve the infiltration processes (Pérez-Cabello *et al.,* 2000; Pérez-Cabello *et al.,* 2006). In this sense, if we assume the existence of a positive relationship between the charred remains and the already existing vegetation before the fire, the dense vegetative masses of arboreal nature predictably will be the ones generating a bigger volume of residual biomass and therefore, those which will relate with less post-fire erodible areas.

The hydrological role of vegetation is normally evaluated through indexes setting forth the meaning of this parameter in the whole of the water erosion phenomenon. In this case the burnt vegetation protective ability on the soil has been estimated by means of two biotic parameters: density and structure of the vegetation communities.

For this factor zonification the Spanish National Forest Map has been used, scale 1:200.000 (Ruiz de la Torre,1990), from which the density and structure of the vegetation communities have been obtained. This source offers a wide range of informations related to the vegetation condition, being especially interesting the overloads indicative of the communities' structure and size as well as the evolutionary level. The existing vegetation community types are grouped together in three different classes, assigning them a value based on the soil protection degree. In Table 2 the ensembles' assessment is shown. With regard to density, the cartography is obtained from the evolutionary level of the vegetation communities (Spanish National Forest Map); the weighting of the classes is: evolutionary level < 6, density low; evolutionary level > 6, density High. Table 3 synthesizes the sense of the spatial relations between vegetation size and density.

Table 2. Size assessment based on the forest map information.

Size of the communities (forest map)	Size
Pastures, shrublands and other vegetation communities shorter than 1,5 m.	Low
Scrublands and reafforestations between 1.5 and 3 m.	Medium
Bushy scrublands and natural or artificial arboreal communities taller than 3 m.	High

Table 3. Relation between vegetation size and density.

	Density	
Size	**High**	**Low**
High	High	Medium
Medium	High	Low
Low	Medium	Low

Climate factor: Fournier Index will be used as indicator of the climate erosive ability, which states the quotient between the highest monthly average precipitation and the annual average precipitation. The suggested intervals are: I < 90, low erosive susceptibility; I =90-120, medium erosive susceptibility; I > 120, high erosive susceptibility. For the precipitation values the values available in the Climatic Atlas of the Iberian Peninsula will be considered (http://www.opengis.uab.es/wms/iberia/mms/, except for the situations in which more accurate information is available (e.g. Climatic Atlas of the Valencian Community).

Factors integration

The integration method selected in the model consists of the combination of variables, in groups of two, with qualitative assignments in which a conservative criterion is applied in order to keep the most problematic situations (or combinations) identified (Figure 1). In a first step, slope has been combined with soil erodibility (Table 4) and in a second step erodibility and slope have been combined with burnt vegetation (Table 5).

Table 4. Integration of soil erodibility and slope.

		Slope		
		High	**Medium**	**Low**
Erodibility	**High**	High	High	Medium
	Medium	High	Medium	Medium
	Low	Medium	Medium	Low

Table 5. Integration of soil erodibility, slope and burnt vegetation.

Burnt vegetation	**Erodibility / Slope**		
	High	**Medium**	**Low**
High	Medium	Low	Low
Medium	Medium	Medium	Low
Low	High	Medium	Low

The vulnerability estimated on the basis of soil erodibility, slope and burnt vegetation is integrated in turn with climatic aggressiveness (Table 6). As a result, the erodibility or vulnerability due to physical factors is obtained where, like in the previous case, the most unfavourable situations are overvalued.

Table 6. Integration of soil erodibility, slope, burnt vegetation and climatic aggressiveness.

		Climatic aggressiveness		
		High	**Medium**	**Low**
Vulnerability by soil erodibility, slope and burnt vegetation	**High**	High	High	Medium
	Medium	High	Medium	Medium
	Low	Medium	Medium	Low

3.1.2. Vegetation response ability

The erodibility will be aggravated according to the time during which the soil remains barely vegetated. In the short term after a fire, the factor that will condition stronger or weaker erosion (on an equal basis of climatic and lithological conditions) is determined by the speed in achieving a minimum vegetation cover. This minimum has been estimated in a 30-40%, which is the limit protective role of vegetation against erosion (Thornes, 1995; Elwell & Stocking, 1976; Francis & Thornes, 1990).

On the other hand, to predict the vegetation response ability in case of fire, functional groups that represent life strategies or attributes can be analyzed, like the resprout ability, the seed bank persistency or the growth or dispersal ability (Noble & Slatyer, 1980; Lavorel *et al*. 1997; Lavorel *et al*. 1999; McIntyre *et al*. 1999a, 1999b). In our case, to predict the response ability (that is, the speed in reaching the minimum established of canopy cover fraction) and taking into account the information available, we have considered post-fire reproductive strategy as predictive attribute. We assume that resprouting plants settle more rapidly after a fire than plants with forced germination strategy (Pausas *et al*. 2004; Pausas & Vallejo, 1999) and that the resprouting ability is kept regardless of precipitations. On the contrary, the reappearance of plants with forced germination strategy is highly dependent on the presence of rainfalls during the first autumn and spring after the fire. In spite of the simplification that solely using the life attribute “post-fire reproductive strategy” means, the implementation of this criterion in previous regional analysis has given good results (Alloza, 2003).

Vegetation characteristics.

As it has already been said, the response ability (in terms of speed to cover a minimum of 30-40% of the soil) can be estimated on the basis of the dominant post-fire reproductive strategy, of the fire frequency that has determined the seed bank and of the resprouting ability. Taking into account that the historical fire frequency determines to a great extent the evolution of the vegetation communities affected by a new fire (because of its effects on the seed bank condition and on the resprouting organs of the resprouting plants), the model has been designed in such a way that the “fire frequency” variable can be considered to assess the vegetation response ability in those areas in which digital cartographic information on fires is available for a period of time long enough.

The main vegetation communities have been gather according to the vertical structure (trees/shrubs) and the reproductive strategy. To identify these communities the digital version of the Spanish National Forest Map (Ruiz de la Torre, 1990) has been used. This version has been reclassified focusing on the fields of coverage, overload and main species. For each of the communities identified in the study areas, its vulnerability against fires has been designated, estimating it as the inverse of its response ability in the short term (Table 7).

Table 7. Vegetation vulnerability in the short term according to structure, reproductive strategy in some vegetation types.

Vegetation type	**Communities**	**Vulnerability**
Pastures		Low
Seeder scrubland	*(Ulex_p.)*	Very high
Resprouter scrubland	*Q_coccifera*	Low
Mixed scrubland	*(Ulex_p.+Q_coccifera)*	Medium
Deficient seeder tree covered + Seeder scrubland	*P_nigra+(Ulex_p.)*	Very high
Deficient seeder tree covered + Resprouter scrubland	*P_nigra+(Q_coccifera)*	Medium
Eficient seeder tree covered + Seeder scrubland	*P_halepensis+(Ulex_p.)*	Very high
Eficient seeder tree covered + Resprouter scrubland	*P_halepensis+(Q_coccifera)*	Medium
Resprouter tree covered + Seeder scrubland	*Q_ilex+(Ulex_p.)*	High
Resprouter tree covered + Resprouter scrubland	*Q_ilex+(Q_coccifera)*	Low
Resprouter tree covered + Mixed scrubland	*Q_ilex +(Q_coccifera+Ulex_p.)*	Medium
Mixed tree covered resprouter- deficient seeder + Resprouter scrubland	*Q_ilex+P_nigra+(Q_coccifera)*	Low
Mixed tree covered resprouter- eficient seeder + Seeder scrubland	*Q_ilex+P_halepensis+(Ulex_p.)*	Hight
Mixed tree covered resprouter- eficient seeder + Resprouter scrubland	*Q_ilex+P_halepensis+(Q_coccifera)*	Low

Limitation to post-fire regeneration

The environmental conditions influence both the fire behaviour and the vegetation response (Pausas & Vallejo, 1999). When evaluating vulnerability depending on the type of reproductive strategy (Table 7) we have already considered dependence of the forced germination species on the autumn precipitations. Nevertheless, in the first phases of regeneration the survival and later growth of the seedlings will be conditioned by the precipitations occurring immediately after the fire. However, for evaluation purposes, as the real precipitation that will take place after the fire is unknown, we must resort to water deficit indicators based on historical records. Taking into account the availability of information, the dry period length has been selected (Gaussen Index), qualified by orientation, according to the values of table 8. Table 9 shows vegetation vulnerability qualified according to water limitations

Table 8. Limitation to regeneration due to water availability.

		Dry period length (Months)		
		>= 3	2	<2
Orientation	**South and plains**	High	High	Medium
	Southwest, Southeast	High	Medium	Low
	Northwest, Northeast, North	Medium	Medium	Low

Table 9. Vegetation vulnerability correction in the short term, according to the territory water limitations.

Vegetation vulnerability in the short term	**Water limitations**		
	High	**Medium**	**Low**
Very High	High	High	High
High	High	High	High
Medium	High	Medium	Medium
Low	Medium	Low	Low

3.1.3. Integration

Short term vulnerability will be determined by erodibility (Table 6) and vegetation vulnerability will be corrected by water limitation (Table 9). Qualitatively speaking, both factors can be integrated as shown in table 10.

Table 10. Ecological vulnerability in the short term.

		Vegetation vulnerability correction according to water limitations		
		High	**Medium**	**Low**
Soil erodibility	**High**	High	High	Medium
	Medium	High	Medium	Medium
	Low	Medium	Low	Low

As a standard criterion, for the model implementation the worst posible conditions (summer fires) are presumed. However, in this final phase of the integration, vulnerability in the short term obtained under this assumption can be qualified according to the heat released by the fire front (measured following Byrem's Linear Intensity Equation (1959), by means of the use of fuel models.

In this sense, taking into account that positive relationships between burning intensity and erosive activity magnitude have been identified (Inbar *et al*., 1998; Debano *et al*., 1976; Debano *et al*., 1998; De Luis *et al*., 2003; Hatten, J. *et al*., 2005), an algorithm derived from Byram's Intensity Equation (1959) has been used (Ryan, 1981). And using the flame lengths documented for Rothermel's standard fuel models (1972) (Anderson, 1982; USDA, 2004) as a base, we have given fire intensities to the aforementioned models. The intensity values in this way obtained have been contrasted with the experimental data got for some of these fuel models from experimental fires (Baeza *et al*. 2002) and fire simulations carried out with the FARSITE fire simulator (1994), parameterized for Mediterranean conditions in the GEORANGE project framework (www.georange.org). All this has led to proposing the model ensemble: 1, 8, 9 = low intensity; 2, 5, 6, 7, 10, 11 = medium intensity; 3, 4, 12, 13 = high intensity. Thus, vulnerability in the short term will be qualified depending on the fire intensity predicted for the corresponding fuel model as presented in Table 11.

Table 11. Ecological vulnerability in the short term.

Fire intensity	**Vulnerability in the short term**		
	High	**Medium**	**Low**
High	Very high	High	Medium
Medium	High	Medium	Low
Low	High	Medium	Low

3.2. Medium term evaluation

In the medium term, 25 years after the fire, the affected vegetation community's vulnerability will be determined by the ability to persist with no substantial changes (community structure, specific composition, relative presence of the species). The time period is limited to 25 years so as to avoid the changes caused by the issuing dynamics of vegetation, which are not assessed in the framework of this project. Taking into account the vegetation communities' grouping carried out and the fire historical frequency, ecological vulnerability in the medium term is defined in table 12.

Table 12. Vegetation vulnerability in the medium term, according to structure and reproductive strategy in some vegetation types.

Vegetation type	**Communities**	**Vulnerability**
Pastures		Low
Seeder scrubland	*(Ulex_p.)*	Medium
Resprouter scrubland	*Q_coccifera*	Low
Mixed scrubland	*(Ulex_p.+Q_coccifera)*	Medium
Deficient seeder tree covered + Seeder scrubland	*P_nigra+(Ulex_p.)*	High
Deficient seeder tree covered + Resprouter scrubland	*P_nigra+(Q_coccifera)*	Medium
Eficient seeder tree covered + Seeder scrubland	*P_halepensis+(Ulex_p.)*	Medium
Eficient seeder tree covered + Resprouter scrubland	*P_halepensis+(Q_coccifera)*	Low
Resprouter tree covered + Seeder scrubland	*Q_ilex+(Ulex_p.)*	Low
Resprouter tree covered + Resprouter scrubland	*Q_ilex+(Q_coccifera)*	Low
Resprouter tree covered + Mixed scrubland	*Q_ilex +(Q_coccifera+Ulex_p.)*	Low
Mixed tree covered resprouter- deficient seeder + Resprouter scrubland	*Q_ilex+P_nigra+(Q_coccifera)*	Medium
Mixed tree covered resprouter- eficient seeder + Seeder scrubland	*Q_ilex+P_halepensis+(Ulex_p.)*	Medium
Mixed tree covered resprouter- eficient seeder + Resprouter scrubland	*Q_ilex+P_halepensis+(Q_coccifera)*	Low

3.3. Integration of short and medium term

The short term evaluation will allow obtaining an indicative of the urgency to carry out restoration treatments in fire affected areas. The medium term evaluation will inform us on the risk of degradation/disappearance of the affected communities. The integration of both assessments in an ecological vulnerability synthetic index will indicate the vulnerability of the respective tesserae against fire and therefore the need or convenience of a more or less effective protection (Table 13).

Table 13. Integration in an ecological vulnerability index.

		Ecological vulnerability in the medium term			
		Very high	**High**	**Medium**	**Low**
Ecological vulnerability in the short term	**Very high**	Very high	Very high	High	High
	High	Very high	High	High	Medium
	Medium	High	High	Medium	Medium
	Low	High	Medium	Medium	Low

This integrated analysis gives us information on the resilience of the communities in connection with different fire patterns and, therefore, it will allow to predict in a better way in the short/medium term the landscape structure dynamics with regard to fire and to design better land management policies.

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