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Economic vulnerability of timber resources to forest fires

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The temporal–spatial planning of activities for a territorial fire management program requires knowing the value of forest ecosystems. In this paper we extend to and apply the economic valuation principle to the concept of economic vulnerability and present a methodology for the economic valuation of the forest production ecosystems. The forest vulnerability is analyzed from criteria intrinsically associated to the forest characterization, and to the potential behavior of surface fires. Integrating a mapping process of fire potential and analytical valuation algorithms facilitates the implementation of fire prevention planning. The availability of cartography of economic vulnerability of the forest ecosystems is fundamental for budget optimization, and to help in the decision making process.

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1. Introduction

Socio-economic and demographic changes in Mediterranean countries over the past 25–30 years are inducing an abandonment of the Mediterranean forest causing an accumulation of brush in forest floor (Pérez, 1990; Knapp et el., 2005). Together with significant climatic changes this increase in biomass is leading to more violent forest fires (Pinto, 1993; Piñol et al., 1998). Greater fire intensity and flame length lead to larger socio-economic impacts to the surrounding areas (Regelbrugge and Conard, 1993; Regelbrugge and Smith, 1994; Borchert et al., 2003).

Large forest fires can denude the soil of vegetation cover and cause natural resources degradation (Whelan, 1995; Tuner et al., 1999). The impact of a wildfire occurrence can be in part assessed by the number of trees affected. Following a fire some trees are killed immediately, others are unaffected; some are injured but survive, and there still others that die a short time later. In the short term the direct degradation can be expressed in terms of timber losses, both a reduction in acreage of timber available for harvest, and a decrease in the size available for harvest. Generally, land management plans incorporate tools for maximizing timber benefits and the probability of surviving large fires by using stochastic methods (Armstrong, 2004; Spring and Kennedy, 2005). The main problem faced by managers is depreciation of the timber resource and estimation of tree mortality (McHugh and Kolb, 2003). The rate of deterioration of fire-killed trees depends on a large number of parameters that are not only species-characteristics (e.g., bark thickness, depth of sapwood), but also tree-specific (e.g., diameter at breast height [dbh], age, growth rate). Rate of deterioration is related to fire severity, the season when fire occurred (dormant or growing season) and the time of year the burn took place (Lowell et al., 1992; Menges and Deyrup, 2001).

Many studies address the issue of the probability of forest survivability to fire severity and the natural and from sprouts or adventitious buds regeneration after a fire (Ryan and Reinhardt, 1988; Peterson and Arbaugh, 1989; Weatherspoon and Skinner, 1995; Strasser et al., 1996; Beverly and Martell, 2003; Hély et al., 2003; Rigolot, 2004; Zamora et al., 2010). However, the impact of fire behavior on timber is not included in traditional Spanish valuations (Martínez Ruiz, 2000). Rate of deterioration in fire-killed timber from non-commercial stands (younger stands) would be expected to be greater than that reported in the commercial stands. The difference between commercial and non-commercial timber stands can be explained by the relationship between the rotation length and stand age. Although some approaches have reported greater survivability in stands with an average diameter of 10 cm (Holdsworth and Uhl, 1997) or 18 cm (Pinard and Huffman, 1997), other studies reject the idea that survivability depends only on bole diameter and ascribe the survivability to bark thickness (Vines, 1968, Gignoux et al., 1997; Pausas, 1997; Barberis et al., 2003;

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Keyser et al., 2006), the percent of crown volume scorched (Wyant et al., 1986; Van Mantgem et al., 2003; Fowler and Sieg, 2004; Sieg et al., 2006) or damage to the bole (Van Mantgem and Schwartz, 2004).

An increase in economic losses from wildfires has been corroborated from annual studies completed by environmental agencies (WWF/ADENA 2006). Generally, economic integrated valuations of forest (market and non-markets resources) take place at the local level (Loomis and González-Cabán, 1997, 2008; Pearce, 2001), although one Spanish approach has incorporated most of these resources at a larger scale (MMA, 2007). Recently, Molina (2008) estimated total ecosystem value considering the potential losses caused by wildfires. In general, the potential fire behavior at the regional level is not considered in the comprehensive valuation of ecosystem damages; with the possible exception of the fire risk assessment using remote sensing and geographic information system technologies, FIREMAP project (www.geogra.uah.es/firemap/). One of the most difficult things to do in valuing the economic impact of fire on timber resources is determining the volume or economic value lost. This is due in part because of the large number of variables influencing the rate of timber deterioration. To address this lack of information on timber volume or value lost, the work presented here describes the development of an economic tool to estimate forest fires impacts on timber resources. A new measure for timber vulnerability (potential damage) was developed integrating two elements: timber harvesting (economic value) and fire behavior (potential fire spread). The result of this method is an estimate of the potential net losses from timber production and fire survival probability over different species and stand development stages. This information is also valuable for determining the level of fire protection necessary.

2. Methods and materials

2.1. Study area

Our study area covers the forest in the Córdoba Province, southern Spain (Fig. 1). The local climate is continental Mediterranean, which lends itself to fire ignitions and spread during the summer season where temperatures can be higher than 35 °C. The understory is dominated by shrubs vegetation including *Cistus* spp., *Retama shaerocarpa*, *Quercus coccifera*, *Pistacia lentiscus*, *Pistacia terebinthus*, *Arbutus unedo*, *Olea europaea* var. *sylvestris*, *Teucrium fruticam* and aromatic plants (*Thymus* spp., *Lavandula* spp., *Rosmarinus* spp.). Thorny cushion species such as *Cytisus* spp are located mainly on the highest elevations in the southern part of the study area ("Subbeticas Mountain Range").

More than 80% of the arboreal species stand area is dominated by the very slow growing *Quercus ilex*. This species can be found in association with *Quercus suber* and *Quercus faginea* on shadiest areas. Generally, *Quercus* spp. stands have become low density stands because of human multi-use activities such as livestock and firewood. The remaining areas are mostly conifer forests dominated by *Pinus pinea* and to a lesser degree by the greater timber producing *Pinus pinaster* (more than 40 $m^3 ha^{-1}$ in the best sites) that also command a higher average timber prize (more than 25 € m^{-3}). Non-commercial stands (younger stands) are dominated by *P. pinea* without silvicultural treatments because of budget limitations and the harsh weather conditions (long drought periods). Molina (2008) estimates that average costs associated to afforestation and reforestation activities in these stands, mainly for *P. pinea*, are about 1200 € ha^{-1} and varied based on slope and selected plants. Riparian forests are dominated by fast growth species such as *Populus* spp. and *Eucalyptus* spp. and to a lesser degree by medium growth species like *Fraxinus* spp. Other fast growing species, such as *Pinus canariensis* and *Pinus radiata*, occupy some upper slope areas on public lands of the northern reach of the study area.

2.2. Timber valuation

The methodology for the evaluation of timber products consist of an algorithm integrating the method in the National Fire Management Analysis System (NFMAS[1]) developed by the USDA Forest Service and the method used by the Spanish Forest Service (Martínez Ruiz, 2000). NFMAS is based on the concept of natural restoration while the Spanish system considers artificial restoration based on stand development stage and rotation age of the species.

The damage assessment discriminates by immature (non-commercial harvesting) and mature timber (commercial harvesting) (Fig. 2). Maturity can be determined by species or family; however, to increase model flexibility we use only four groups based on growth rate (fast, medium, slow and very slow). Timber markets are completely dynamic and fluctuating depending on factors such as timber quality, stand health and year of harvesting. Therefore, to reduce complexity we decided to use an average timber price for a healthy stand of average timber quality.

2.2.1. Immature timber valuation

We compute the coefficients of the integration function φ depending on the importance or weight given o the NFMAS based or Spanish Forest Service methodology. The rationale for this is that in the NFMAS system the computations of impacts are based on the stands natural regeneration, while in the Spanish Forest Service system the computations are based on the artificial regeneration of stands. By integrating both approaches we feel we obtain a more accurate representation of the impacts on the ecosystem. Therefore, *a* and *b* are weighted coefficients based on the importance of natural (NFMAS) or artificial restoration (Spanish FS). The coefficient in the numerator takes the value of 1.7 or 2.6 according to protection or recreational function, or timber forests respectively; and the coefficient for the denominator takes the value of 0.85 or 0.25 based on the same reasons.

$$\gamma = \frac{(a^*S^*N)}{(S + b^*N)} \tag{1}$$

where γ is the timber valuation (€/ha), *S* is the valuation according the Spanish system (€/ha), and *N* is the valuation adapted from NFMAS (€/ha). In the Spanish system the value of the immature timber depends on the availability of a volume equal to the one burned. The formula will vary depending on the rate of growth of the species under consideration.

$$S = C_0{}^*t[r^e + i(r^e - 1)] + F^*(r^e - 1) \tag{2}$$

where *S* is the valuation according the Spanish system (€/ha), Co is the reforestation cost per hectare (€/ha), *t* is the percentage of stand burned based on fire behavior, *r* is the compound annual interest rate and depends on species growth rate: fast growth (1.06), medium growth (1.04), slow growth (1.025) and very

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[1] The NFMAS model is no longer used in the evaluation of fire management programs in the US. However, the methodology developed to value timber losses is still valid.

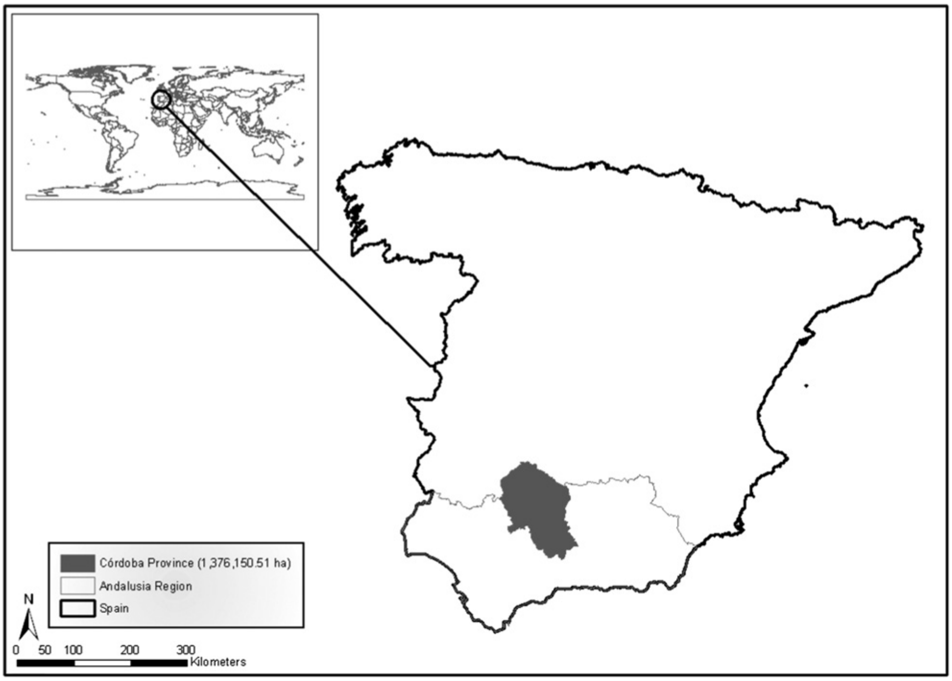

Fig. 1. Study area location.

slow growth (1.015); *i* is the annual silvicultural cost factor[2] and depends on species growth rate: fast growth (1.27), medium growth (1.1) slow growth (1.1) and very slow growth (0.93); *e* is the estimated stand age; and *L* is the average value of treeless area (€/ha).

The NFMAS adapted formula requires knowledge of the intrinsic characteristics of the stand: composition, growing stock, stand age, rotation length and timber prices. Damages are directly related to fire intensity so it is important to know the percentage of stand burned:

$$N = \left[\frac{V^*P^*1.025^y}{1.04^y}\right]^*\left[1-\left(\frac{1.025}{1.04}\right)^e\right]^*[1+M^*c^*t] \qquad (3)$$

where *N* is the valuation according to the NFMAS model (€/ha); *V* is the timber volume (m^3/ha); *P* is the price of the timber (€/m^3); *y* is the time or years remaining in the harvesting rotation; *e* is the estimated stand age when fire occurs; *M* is the tree mortality coefficient depending on fire intensity; *c* is the percentage of immature timber in stand; and st is the percentage of stand affected by fire based on fire behavior. The coefficient 1.025 is the price increase in the harvesting year (2.5% by year) and the value 1.04 is the discount factor (4%).

We estimated the percentage of stand cover by species and timber volume by sampling Spain's National Forestry Inventories. The inventories could be corrected horizontally and quantitatively by Silviculture Treatment Projects and Land Planning Projects depending on the required resolution. The information on the average timber price and rotation age can be obtained from the most recent timber sales, Land Planning projects and the output from the SINAMI project (Rodríguez y Silva and González-Cabán, 2010). The existing relationship between site index and dendrometric parameters is the source for the estimation of stand age.

Finally, a second integration is done based on results from previous work on the valuation of natural ecosystems in Spain according to TRAGSATEC (Castellano, 2003). We incorporate the results from TRAGSATEC using the following equation:

$$L = \frac{1.3^*\alpha^*\varphi}{\alpha+0.65\varphi} \qquad (4)$$

Where *L* is the total loss estimate resulting from the two previous integrations (€/ha), α is the TRAGSATEC natural ecosystems valuation done for the Andalusia government (2003), which provides a mean value by land use category (conifer species are valued at 1650 €/ha, leafy species at 2175 €/ha, mixed stands at 1878 €/ha, or the weighted sum based on the percent cover of each species),

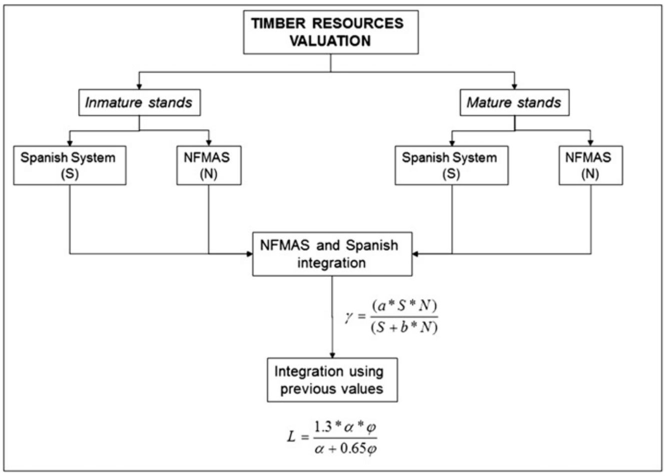

Fig. 2. Methodological scheme for the valuation of timber losses.

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[2] This factor represents the relationship between the annual silvicultural maintenance costs (weeding, pruning, replacement of death plants, etc.) and the initial stand planting costs.

and φ is the resultant value of the integration between the NFMAS and the Spanish methodologies (€/ha).

2.2.2. Mature timber valuation

The mature timber stands are valued by weighting the two proposed methodologies. The integration between the NFMAS and Spanish methodologies is done the same way as for the immature timber. The algorithm variables take one or another value depending on the stand development stage.

The value for the polewood stage (previous to maturity) is given by:

$$S = \frac{C_0}{z} * t\left[r^e + i\left(r^e - 1\right)\right] + \frac{C_0}{z} * 0.5\left[r^e + i\left(r^e - 1\right)\right] \tag{5}$$

The value for the mature timber is given by:

$$S = \left[P * V - P_1 * V_1\right] + P * V\left[\frac{r^{(R-e)} - 1}{i^{(R-e)}}\right] \tag{6}$$

where S is the valuation according the Spanish system (€/ha), Co is the reforestation cost per hectare (€/ha), z is the reduction in reforestation cost due to natural stand regeneration depending on growth rate using values of 6 (fast growth), 10 (medium growth), 20 (slow growth) or 25 (very slow growth), t is the percentage of stand burned based on fire behavior, r is the compound annual interest rate and depends on species growth rate: fast growth (1.06), medium growth (1.04), slow growth (1.025) and very slow growth (1.015); i is the annual silvicultural cost factor that depends on species growth rate: fast growth (1.27), medium growth (1.1) slow growth (1.1) and very slow growth (0.93); e is the estimated stand age; P is the price of cut timber (€/m^3); V is the existing stock volume (m^3/ha); P_1 is the price of salvaged timber (€/m^3); V_1 is the volume of burned timber (m^3/ha); and R is the rotation age.

The NFMAS valuation methodology uses the following equation to estimate mature timber losses:

$$N = V * c * t\left[C * P + (1 - C) * P_1\right] \tag{7}$$

where N is the total value (€/ha); V is the timber volume (m^3/ha); c is the percentage of mature timber in stand; t is the percentage of stand affected by fire based on fire behavior; T is the percent of non-commercial timber; P is the price of cut timber (€/m^3); and P_1 is the price of affected timber (€/m^3).

2.3. Effect on the stand

The economic assessment of fire impacts on market assets requires knowledge of their deterioration rates. The tree mortality coefficient (M) and the percentage of stand burned (t) are computed as a function of fire severity, which is determined by Fire Intensity Level (FIL). Potential fire behavior expressed as spread rate, fire-line intensity, flame length or heat per unit area can be estimated by fire simulators such as FARSITE (Finney, 1998), FlamMap (Finney, 2002), Visual Behave or Visual Cardin (Rodríguez y Silva et al., 2010), or from *in situ* measurements. For this research, we use flame length as a simple parameter for fire severity. A direct relationship between fire severity and flame length increases the flexibility and simplicity of the proposed methodology.

To estimate the rates of depreciation for each stand based on fire behavior we used the following 10 large fires (year of fire in parenthesis) in Andalusia: Huétor (1993), Los Barrios (1997), Estepona (1999), Las Palomas (2001), Ojen (2001), Aznalcollar (2004), El Tranco (2005), Alajar (2006), Obejo (2007) and Cerro Catena (2009). The rate of deterioration in timber resources from fire was shown in percentages. Different sampling plots were established according to forest characteristics and average flame length in each fire event. Species, stand density, stand height, diameter at breast height (dbh) and surface fuel model were identified for each sample unit (15 m square plot). Together with field parameters, existing stock volume and salvaged timber per hectare were calculated using growth models and field information (percentage of timber affected by fire and average tree mortality). In addition, a photographic overview was taken as a visual key for fire officials to recognize the rates of deterioration.

Insects (mainly beetles), stain and decay fungi, and weather all act as deterioration agents to fire-killed timber. A weakened fire surviving tree can be killed by an insect attack. Insect activity usually provides a mechanism for introducing fungi that accelerates sapwood deterioration. Stain has an important economic impact by lowering the value of products graded for appearance. The presence of decay fungi results in a timber volume loss. Both fire-killed and fire-damaged trees must be incorporated in the timber resources vulnerability estimates. In this sense, the tree mortality coefficient (M) includes fire-damaged trees showing the percentage of stand surviving but highly weakened and experiencing post-fire mortality due to for example, beetle activity. An example of this can be found on a study by Steven and Hall (1960) of defoliated conifers attacked by bark beetles after a wildfire.

3. Results

It was necessary to characterize each stand to estimate the economic value of merchantable timber. A stand condition (immature or mature) could be determined from the rate of growth and rotation length, as well as the approximate stand age (Molina et al., 2009; Rodríguez y Silva y González-Cabán, 2010). Once the stand was characterized, a spreadsheet was used to identify the economic vulnerability of each stand. Potential fire behavior on each ecosystem was integrated to the economic valuation by using average rates of deterioration estimated as a function of fire intensity from the Andalusia large fires experience (Table 1).

The tree mortality coefficient (M) or standing timber highly weakened was identified *in-situ* based on three affectation levels (<25% of the stand affected, between 25 and 75% of the stand affected, and more than 75% of the trees affected). The coefficient takes values between 0 (<25% of the stand affected) and 1 (more than 75% of the trees affected) according to post-fire mortality. These values were greater than the reference values in Steven and Hall (1960), and Lowell et al. (1992), because of the greater mortality risk due to extreme climatologic conditions (drought period).

The reduction (depreciation) on price of affected timber is about 30% of the price of cut timber based on timber sales from a study of large fires in Andalusia (Molina, 2008). Other research in Galicia (northern of Spain) showed at 19.78% depreciation on *Pinus* and *Eucalyptus* timber during the period 2005–2006 (Arenas and Izquierdo, 2007). However, this was a period of large timber supply because of 18,900 ha burned, consequently, lowering timber

Table 1
Timber resource deterioration by fire intensity level.

Average flame length (m)	Fire intensity levels (FIL)	Timber resources deterioration (%)	Tree mortality coefficient (x)
< 2	I	8.33 (±6.58)	0
2–3	II	16.65 (±5.89)	0
3–6	III	38.58 (±6.27)	0.5
6–9	IV	57.85 (±13.74)	0.5
9–12	V	82.79 (±1.81)	1
>12	VI	89.41 (±2.82)	1

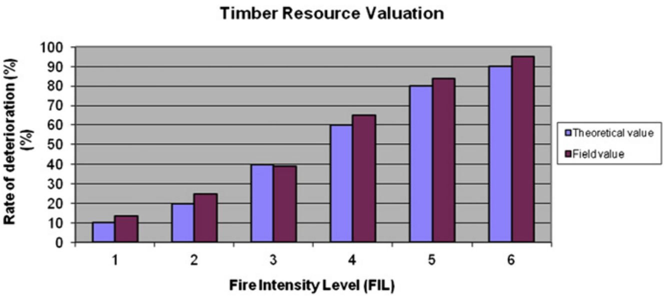

Fig. 3. Timber resource deterioration for the Obejo fire (2007, Córdoba).

prices. We studied Andalusia large fires, from 1993 to 2009, also a large number of species such as *Pinus*, *Quercus*, *Castanea* and *Eucalyptus*.

Analysis of Andalusia's ten large fires provided an average rate of deterioration of 89.41% (±2.82) for timber resources under the highest FIL (Table 1). A theoretical value of 90% for average timber resource deterioration was computed based on field data. Field damages to merchantable timber in areas subject to severe fire spread were similar to the computed 90% theoretical rate of deterioration; therefore, the estimation error was acceptable. On the ground rates of deterioration computed by different FIL for the Obejo fire (2007 Córdoba) were similar to those for thenine reference fires. The estimated acceptable errors by FIL represented no more than 6% of the assigned theoretical value (Fig. 3).

Geographic Information Systems (GIS) was used to estimate vulnerability of timber resources. Firstly, the computerized system allowed us to identify the stand characteristics (species, stand density and existing stock volume) and its spatial distribution, determining the socio-economic valuation of the timber resources for each stand. The availability of the stand location by GIS made it possible to effectively evaluate the fire behavior according to potential occurrence and the spatial characteristics with which they might potentially originate and evolve. Finally, GIS was necessary to establish the relationship between the fire behavior and the economic timber valuation to determine the impacts of forest fires. The integration of the fire behavior and timber valuation, and the automation of calculation and management by means of GIS, constitutes the central axis for this research, based on the fundamental premise of providing a versatile tool for used during operational management by entities and government institutions responsible for forest fire protection. For example, in the study area (Córdoba Province) the stand vulnerability was estimated at 157,420,809 €; with a minimum value of 8.98 € and a maximum value of 1507.88 € per hectare (Fig. 4).

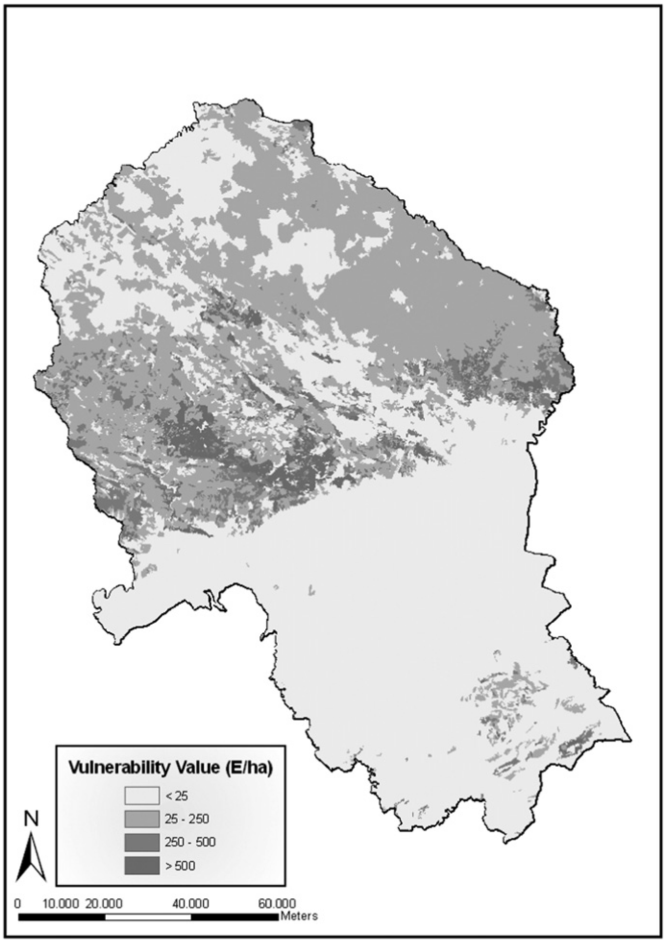

Fig. 4. Timber resources vulnerability for the Córdoba Province.

4. Conclusions

All relevant parameters affecting the survival probability of trees and their rates of deterioration should be considered when assessing fire impacts to market assets. These must include stand characteristics such as the stand age, natural regeneration, existing stock volume and the estimated mortality of the remaining trees after fire, as well as potential fire behavior. On some Mediterranean areas, extreme weather conditions, poor site index and severe fire spread create environmental stresses on the stand slowing the natural dynamics of the ecosystems affected by fire. Thus, the depreciation of the barren soil and reforesting costs must be added to the valuation.

The economic damages assessment must differentiate between mature and immature stands. For mature timber the damage value results from the difference between the value before and after the fire and the actual loss of having to cut the stand before its rotation age, while for the immature stands the criterion used is the availability of a stand equal to the burned one. The integrating algorithm in both the NFMAS and Spanish approaches allows the possibility of a mixed criterion (natural–artificial regeneration) closer to the reality of the restoration projects in Mediterranean conditions.

The relevance of a model for estimating the economic consequences of wildfires is in helping determine fire management and suppression actions to minimize fire impacts. Objective and optimal decision making requires a budget based on spatially objective information. Therefore, Geographic Information Systems are essential for land management and planning activities for fires and prevention in response to disturbances. Recent developments in forest fire protection give us a better understanding of the relationships between investments in these programs and the resultant benefits from said investments. When developing forestry management plans for the Mediterranean region it is imperative to include the probability of fire occurrence as part of any maximization model.

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