The ignition index based on flammability of vegetation improves planning in the wildland-urban interface: A case study in Southern Spain

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Abstract

Forest fires in the wildland urban interface (WUI) are a widespread and growing problem due to changes in land use and climate. The impacts of WUI fire depend on the exposure of homes to dense vegetation (both natural and ornamental), as well as fire intensity, which is determined by meteorological, topographical, and vegetation conditions. In this study, our goal was to identify the ignition index in one risky Mediterranean WUI based on the potential flammability of the main intermix species at the particle level. The flammability of 18 species (natural and ornamental) commonly found in southern Spain was analyzed at the particle level. Flammability experiments ranked the flammability of the different species from moderately flammable to extremely flammable. Flaming duration (a variable related to fire suppression difficulty) and the ignition coefficient of the surrounding vegetation helped to complete the ignition risk for each vegetation aggregation. Thuja orientalis and Ligustrum vulgare showed the greatest individual potential to mitigate fire spread, and are recommended for planting and use as landscaping hedges in the Mediterranean WUI. We concluded that this methodological procedure is a useful tool for prioritization and budget allocation of fire risk reduction treatments. Furthermore, the development of technical guidelines for public urban landscaping as well as landscaping on private residences is required to adequately address and mitigate fire impacts both on homes and the surrounding landscapes.

Keywords: Flammability; ignition fire risk, intermix vegetation, ornamental vegetation, ignition probability

1. Introduction

Wildfires have become a mounting threat to Mediterranean landscapes in southern Spain, and people living in areas affected by wildfires have become increasingly concerned about the risk of wildfire (Andalusia Government, 2013). Changes in socioeconomics, land use, and climate are the major contributing factors in the increase in large wildfires because of their role in promoting large accumulations of available fuel to burn (Kobziar, 2014; Rodríguez y Silva & Molina, 2012). Although recently there has been more money invested in resources and training for fire agencies, the number of small fires has not decreased and the number of large fires has drastically increased in southern Spain due to biomass accumulation (WWF, 2015).

Landscapes are composed of a cluster of interacting land areas (Finney, 2001), including agricultural and forest areas, as well as urban areas. The zone of contact between human infrastructure and wildland vegetation, known as the wildland urban interface (WUI), has increased worldwide over the last few decades and has a direct relationship with the risk of forest fires (Chas-Amil, Touza, & García-Martínez, 2013). Wildfires that impact settlements are becoming increasingly frequent because of the increasing number of houses and infrastructures located within and adjacent to areas prone to wildfires (Marzano, Camia, & Bovio, 2008). Fire can spread easily through the ornamental trees and hedges present in housing developments. Consequently, forest fires have emerged as a civil emergency concern due to the risk to human lives and residential properties in the WUI (Cohen, 2008). However, urban planning rarely takes fire vulnerability into account and housing development in the WUI is frequently unregulated (Madrigal, Ruíz, Planelles, & Hernando, 2013). The identification of high vulnerability fire areas in relation to the complex interaction of meteorological conditions, vegetation, and topography is the key to developing specific preventive measures that improve the legal, preventive, and suppression aspects of wildfire management (Montiel & Herrero, 2010, Madrigal et al., 2013). The responsibility for preventive measures and other fire defense techniques must be shared and coordinated between land managers and homeowners (Butsic, Syphard, Keekey, & Bar-Massada, 2017; Caballero, 2008).

Remote sensing and GIS are fundamental in WUI characterization. There are different methodological approaches in order to assess the hazard and vulnerability of WUI which is based on landscape analysis, on the use of Geographic Information Systems (GIS) techniques and remote sensing (Galiana, Herrero, & Solana, 2011; Mercer & Zipperer, 2012). A new approach has characterized hazardous fuels at the scale of individual structures by integrating aerial photography, airborne laser scanning and cadastral datasets into a hazard assessment framework (Skowronski et al., 2016). WUI characterization should consider vegetation and housing density and the degree of clustering of both components (Price & Bradstock, 2014). Therefore, WUI can be mapped using the WUImap® tool implemented by ArcGIS software (Lampin-Maillet et al., 2010; Madrigal et al., 2013). Other approaches have provided indications of settlement vulnerability based on the relationship between landscape metrics and fire risk using Fragstats software (McGarigal & Marks, 1995; Marzano et al., 2008). Additionally, a risk matrix and a summarize wildfire risk were created based on the population density and burn probability (Haas, Calkin, & Thompson, 2013).

The identification and evaluation of WUI fuels should be basis for improvement of treatment prioritization and budget allocation (Mell, Manzello, Maranghides, Butry, & Rehm, 2010). Flammability characterization is an effort to address these gaps in understanding by providing physical explanations for the relation between species and fire behaviour (White & Zippere, 2010). In this sense, our focus is given to the ignition index (Rodríguez y Silva, González-Cabán, & Molina, 2014) which indicates the capability of accumulated fine fuels to ignite given a heat source, showing the predisposition of fuels to accept heat and start combustion. This index employs an integral approach to modelling vegetation flammability which depends on the probability of ignition (USDA Forest Service, 2004), the ignition coefficient (Rodríguez y Silva et al., 2014), and species flammability. While the probability of ignition and the ignition coefficient can be easily assessed, plant flammability has been widely studied in the laboratory using several methods (Dimitrakopoulos & Papaioannou, 2001; Elvira & Hernando, 1989; Ganteaume, Jappiot, & Lampin, 2012; Hernando, 2009). However, the results obtained by the different vegetation flammability assessment methods depend on the scale considered (Etlinger & Beall, 2004; Ganteaume & Jappiot, 2014). In this sense, the assessment of flammability in the laboratory is limited by the scale of experimentation because plant exposure to heat is frequently not comparable to wildfire conditions (Fernandes & Cruz, 2012). However, field experiments in WUI are often limited by safety constraints and landscape impacts. In spite of these limitations, the classification of fuels surrounding homes is an essential component of fire hazard assessments (Dimitrakopoulos & Papaioannou, 2001; Herrero, Jappiot, Bouillon, & Long-Fournel, 2012; Madrigal et al., 2013; Massada, Stewart, Hammerc, Mockrin, & Radeloff, 2013; White & Zippere, 2010).

The understanding of fire behavior provided by ignition index in and around WUI gives invaluable insights into the factors affecting flammability in different environments. The presence of higher accumulations of vegetation around houses, both natural and ornamental, is one of the main causes of house ignition (Etlinger & Beall 2004). The most efficient way to mitigate the damage to homes caused by fire in WUI areas is to decrease the amount of flammable fuels surrounding the homes (Ager, Vaillant, & Finney, 2010; Calvino-Cancela, ˜ Chas-Amil, García-Martínez, & Touza, 2016). Knowledge of how species differ in their flammability characteristics is needed to develop more efficiency treatments for landscaping homes in the WUI (White & Zippere, 2010). Therefore, less flammable species are recommended as ornamental plants (Ganteaume & Jappiot, 2014; Monroe, Long, & Marynowski, 2003). Vegetation components in the dooryard, such as hedges, ornamental bushes, and trees, affect fire behavior and, as a consequence, fire ignition, propagation, and heat release near the building (Caballero, 2008). WUI homeowners are advised to annually reduce or eliminate highly flammable vegetation and use less flammable species as replacements.

The aim of this study was to identify the ignition index in one risky Mediterranean WUI based on the potential flammability of the main intermix species at the particle level. This index calculates the fuel availability to ignite and propagate through plants as affected by meteorological conditions (ignition probability), the characteristics of fuel model (ignition coefficient) and the species flammability. While the probability of ignition was estimated based on summer conditions in the study area, the ignition coefficient was obtained by field sampling. Flammability identification could become an essential tool for the removal of vegetation and the development of a vegetation maintenance schedule for homeowners to mitigate fire spread and the ecological and socioeconomic impacts of fire.

2. Material and methods

2.1. Study area

The study area is located in Andalusia Region in southern Spain (Fig. 1). A continental Mediterranean climate characterizes the area with daytime summer temperatures above 40 ◦C that are conducive to fire ignition and propagation, and, consequently, a higher risk of fire occurrence. Fire statistics from the Córdoba Province show an average of 13.4 forest fires per year (2001–2012) in the study area, which burn 11.54% of the total burned area in the Province.

The WUI in the study area covers 30,000 ha including three local administrative departments and 39 settlements. Although field studies have shown that the extent of WUI in the study area has remained steady between 1990 and 2014, there are more houses within the same area. In some cases, there are now many houses where before there was only one house. Now, modern houses are built with more fire vulnerable materials than older, traditional buildings. This urban phenomenon has become a real problem for policy makers and decision makers. According to the Andalusia experience, WUI fires have shown that the capacity of road networks collapse during fire events, preventing or severely delaying firefighting equipment access to the area. During a fire, social alarm causes traffic jams because everyone tries to use the existing, narrow escape routes.

Settlements present differences in total area, housing density, and spatial distribution (isolated, dispersed, and compacted distribution). As a consequence, vegetation composition and structure also vary greatly between the settlements. Settlements were classified into 17 typologies (Andalusia Government, 2011; Caballero, Beltrán, & Velasco, 2007) according to the degree of clustering of both vegetation and housing structures (Appendix A in the Supplementary material). Surrounding vegetation (50 m buffer area) is dominated by two evergreens (*Quercus ilex* and *Q. suber*), two conifer species (*Pinus pinaster and Pinus pinea*) and diverse ornamental species, associated with *Arbutus unedo, Ceratonia siliqua, Olea europaea* var. *sylvestris*. The shrub stratum is dominated by *Cistus spp., Retama shaerocarpa, Pistacia lentiscus, Quercus coccifera* and aromatic plants (*Thymus* spp., *Lavandula* spp. and *Rosmarinus* spp.). Among the 62 species identified during samplings, 18 tree and hedge species (>2.5 m) were most representative of the study area based on their spatial frequency and inclusion in the vegetation types associated with all urban typologies (Appendix A in the Supplementary material). Vegetation differences were shown to depend on the urban typology. For example, *Pinus halepensis* was only found as a dominant species in interface models of the agroforestry mosaic. In this sense, this paper has included seven natural species (*Quercus ilex, Quecus suber, Pinus pinea, Pinus pinaster, Arbutus unedo, Ceratonia siliqua, Olea europea var. sylvestris*) and eleven ornamental species (*Eucalyptus camaldulensis Pinus halepensis, Cupressus sempervirens, Cupressus arizonica, Cedrus deodara, Ailanthus altissima, Fraxinus ornus, Ligustrum vulgare, Laurus nobilis, Thuja orientalis and Nerium oleander*).

2.2. Ignition index framework

This paper proposes a methodology based on the ignition risk assessment (Fig. 2). To assess ignition risk, we measured ignition probability, ignition coefficient and flammability, taking advantage of experimental sampling of both natural and ornamental species. The operational process involved in obtaining an ignition valuation model comprises the following stages:

– Evaluation of ignition probability according to fine dead fuel moisture, physiographic characteristics and fuel shading.

Summer meteorological conditions and physiographic parameters of the study area were obtained to calculate the fine dead fuel moisture. Historical weather data was used from a statistical analysis of records for seven weather stations for an 11-year summer period (Appendix A in the Supplementary material). GIS was used to identify fuel model and physiographic parameters (slope and aspect) based on a 10 m2 digital model of the terrain.

– Estimation of ignition coefficient based on field sampling and fuel modelling

Even though different methods of characterization of WUI have been developed based on GIS, the more accurate way to assess risk ignition is through field inventories. Although vegetation sampling in WUI is tedious, its inclusion improves the fit of fire risk indexes due to the presence of intermix vegetation in most of the WUI areas. At the settlement scale, risk should include the presence of fine dead fuel due to its influence on fire spread.

– Identification of flammability based on laboratory experiments and fuel modelling

Flammability depended on the vegetation composition of the WUI areas. Information from satellite imagery and aerial photography was insufficient for the spatial resolution of the study because of the lack of information on intermix vegetation (mixed natural, semi-natural, and ornamental trees and hedges). We developed a GIS database to study the relationship between each vegetation polygon and flammability of the dominant species. Field sampling and more precise spatial information (10 × 10 m) were needed for identification of the ignition index in each WUI.

– Integration ignition risk to manager decisions about fire prevention

2.3. Field sampling

Fuel models proposed by Rodríguez y Silva and Molina (2012) were used in surface fuel characterization. Data were collected regarding both surface and tree variables in order to characterize fuel flammability and fuel load by categories. The inventory included 102 sampling units with circular plots of 1000 m2 for tree inventories and subplots of 1 m2 for surface inventories, following procedures established by Rodríguez y Silva and Molina (2012). The samples were located across the different WUI typologies, and incorporated variables such as stand density, dominant species composition (both natural and ornamental) and surface fuel loads (by categories). Subsequently, 272 visual sampling points were used to extrapolate this field information to the total study area.

Flammability sampling was carried out during the summer when fuel moisture content and fire risk were highest (Ganteaume & Jappiot, 2014; Hernando, 2009), and as a consequence, itis a static index.

The sampling was not conducted on days following rainfall events (Valette, 1990). Selected species were located across six points of adjacent WUIs in order to avoid the effect of site quality and topographical variables (altitude, slope and aspect) on fuel moisture. Fifty samples for two sample-locations with a month interval between two sampling days (July and August) were monitored for each selected species. We collected live leaves from the canopy base height due to its importance in the transition from surface fires to crown fires. Flammability experiments were conducted within 24 h of material collection over three consecutive days in order to prevent changes in moisture content as a result of meteorological changes. To minimize changes in the moisture content of species, laboratory experiments were conducted concurrently with leaf sample collection. Protocols proposed by INRA (Valette, 1990) were used to characterize the flammability of the live fuels; thus, leaves of similar age and size were collected from each species. Dead fuel that were collected in samples was removed from the flammability experiments, despite the large amounts present in samples that included species such as *C. sempervirens* and *P. halepensis*. All samples were labeled and retained in cold storage to minimize changes in original moisture content.

Since live fuel moisture can influence variances in fire behavior (Jolly, 2007), we identified the moisture content at oven-dried basis. Two sampled leaves of each species, location and sampling day (10–20 g) were oven dried for 72 h at 70 ◦C to obtain the moisture of each species in similar meteorological and topographical conditions. There were no significant differences between two sampling days and two sample locations. Therefore, spatio-temporal changes have been not evaluated. Statistical analysis was carried out with 200 samples (50 samples from each location and day) for each species. Analysis of variance (ANOVA) was used to determine if significant differences ($p < 0.05$) existed in live fuel moisture for each selected species. SPSS 10© software was used in all analyses. If significant differences were detected, a Tukey HSD test was performed to determine which specific species was different from another.

2.4. Flammability experiments

We used an epiradiator that develops a power of 500W with a 10 cm diameter radiant disk positioned inside a gas hood to reduce air perturbations. The temperature at steady-state regime was 460 ◦C based on one thermocouple placed in the centre of the radiant disk. Similar to other studies (Elvira & Hernando, 1989; Hernando, 2009;Valette, 1990), fifty samples (1 g of weight) of each species were exposed to the epiradiator. This weight was used for samples to avoid increases in flame length, which would cause differences in flammability (Pellizzaro, Duce, Ventura, & Zara, 2007; Petriccione, Moro, & Rutigliano, 2006). The surface area of the live leaves was maintained in contact with the radiant disk to sustain homogeneous heat transfer. The flame from a bunsen burner (6 cm above the center of the radiant disk) allowed piloted ignition of the gases emitted during combustion of the leaf (Ganteaume et al., 2012; Hernando, 2009).

The ignition frequency was calculated as the percentage of positive ignition tests. Time-to-ignition (TTI) and ability to sustain flame once ignited, or flaming duration (FD), were estimated as the mean value of positive tests. Selected species were classified according to ignition frequency and TTI, ranging from 0 to 5: 0 = slightly flammable, 1 = flammable, 2 = moderately flammable, 3 = flammable, 4 = very flammable, and 5 = extremely flammable (Valette, 1990; Hernando, 2009) (Table 1). Similar to the live fuel moisture, analysis of variance (ANOVA) and Tukey HSD test was performed to determine if significant differences ($p < 0.05$) existed in TTI and FD for each selected species.

2.5. Ignition index

The ignition index describes the probability of vegetation igniting given a heat source based on the ignition probability, ignition coefficient, and flammability coefficient (Eq. (1)).

$$Iig = [\ (Pi * Ci * Fi) * Ai/At] \qquad (1)$$

where “Pi” is the ignition probability depending on the fine dead fuel moisture, ambient temperature and degree of fuel shading (USDA Forest Service, 2004). Ten values in ascending order express every

10% probability. “Ci” is the ignition coefficient for each fuel due to the relation between 1-h dead fuel load and the total fuel load (Rodríguez y Silva et al., 2014). “Ci” value ranged from 0 (lees flammable models) and 0.1 (more flammable models) (Appendix A in the Supplementary material). “Fi” is the flammability coefficient based on the five levels of flammability: 0 = slightly flammable, 1 = flammable, 2 = moderately flammable, 3 = flammable, 4 = very flammable, 5 = extremely flammable (Valette, 1990). “Ai” is the area of each vegetation typology and “At” is the size of each studied WUI.

T-test was used to determinate if significant differences ($p < 0.05$) existed in ignition coefficient and flammability value among WUI models (interface models with dense forest, interface models with shrubland and interface models on agro-forestry mosaic).

Geostatistical techniques can interpolate one (kriging) or more variables (Cokriging) based on random field values and their spatial distribution. Different geostatistical processes were calculated for the set of grid cells that contains data on all of the ignition risk variables. We used 25% of the sample points to test the best ignition index prediction. Statistical analysis allowed us to classify ignition index rating on four categories. We selected natural breaks classification method (Jenks method) in relation to other classification methods such as equal interval, defined interval and geometrical interval. This method is a data clustering method designed to determine the best arrangement of values into different classes. Jenks optimization method seeks to reduce the variance within classes and maximize the variance between ignition classes. Accuracy assessment was validated using a dataset of 374 random control points covering the seventeen WUI typologies. A confusion matrix was obtained to compare the ignition class identified for each control point with the ignition index cartography from the best geostatistical method. In this sense, overall accuracy and the Kappa index were calculated for the geostatistical process.

3. Results

3.1. Flammability experiments

Although spatio-temporal changes have been not evaluated, some species showed significant differences in moisture content (Table 2). A. altissima held the most moisture (297.5%), followed by *N. oleander* (171.19%). In relation to the rest of species, four significant groups were identified according to moisture content: 120%–150% (*C. siliqua, L. vulgare, P. pinaster and P. pinea*), 101%–120% (*A. unedo, C. deodara, F. ornus, L. nobilis, P. halepensis and T. orientalis*), 90%–100% (*C. arizonica and O. europaea* var.*sylvestris*), and < 90% (*C. sempervirens, E. camaldulensis, Q. ilex and Q. suber*). Foliar moisture was less than 90% in natural evergreen species (*Q. ilex and Q. suber*) and two useful ornamental species (*C. sempervirens and E. camaldulensis*). *Q. ilex* showed the least moisture content (72.89%), and as a consequence, was the species most available for fire spread.

Flammability experiments showed differences in both TTI and FD (Table 2). In relation to TTI, *F. ornus* was the most ignitable (6.7 s), closely followed by *Q. suber* (7.48 s). TTI was shorter for *P. halepensis, E. camaldulensis, Q. ilex and A. altissima*, while *P. pinaster and T. orientalis* required the longest ignition time. TTI was significantly increased in *C. arizonica, L. vulgare* and *N.oleander* (15 s) compared with the other species. Although there were no significant differences in TTI between some species (e.g. TTI for *E. camaldulensis, L. nobilis, and P. halepensis* was similar), the FD of L. nobilis was significantly lower than that of *E. camaldulensis and P. halepensis*. FD was significantly increased in *P. halepensis, P. pinea and Q. suber* when compared with other ornamental species, such as *A. altissima, L. nobilis, L. vulgare, and T. orientalis*.

According to ignition frequency and ignition time (Valette, 1990), while *C. siliqua, E. camaldulensis, F. ornus, L. nobilis, P. halepensis, Q. ilex and Q. suber* were included in the most flammable category, *A. altissima* was in the least flammable category (Table 2).

3.2. Ignition index

It was necessary to compute three variables identified in methodology section: the ignition probability, the ignition coefficient and the flammability coefficient (Eq. (1)). According to summer meteorological conditions in the study area (daytime summer temperatures above 30 ◦C), the differences in the index resulted more from the ignition coefficient and flammability than from ignition probability. There was no significant difference in ignition probability due to the lack of variability in relative humidity and temperature in the study area (30,000 ha). Therefore, the analysis of ignition probability showed a high value (> 80%) for almost 80% of the study area. Fuel shading resulted in an increase of fine dead fuel, 5% of the total area. In contrast, the ignition coefficient ranged from 0.1 to 0.026 based on the type of material and fuel size (Appendix A in the Supplementary material). The ignition coefficient reached values of about 0.1 for grasslands and litter under broadleaf stands, but showed lower values in shrublands and understory fuel models. Although the ignition coefficient was significantly increased in interface models on agro-forestry mosaic when compared with interface models with shrubland ($t = 1.165$, $p < 0.05$), it was similar in interface models with dense forest in comparison to interface models with shrublands ($t = -0.685$, $p > 0.05$).

A greater spatial resolution was used for WUI areas based on the field inventories and flammability experiments. The new flammability values were estimated as the sum of the representativeness of each species inside the buffer area (%) and its flammability value (1–5). For example, fifty flammability values were identified in relation to nine previous values from five settlements (Fig. 3). The improvement of spatial resolution showed significant differences among WUI models: interface models with dense forest and interface models with shrubland ($t = 1.442$, $p < 0.05$) and interface models with shrubland and interface models on agro-forestry mosaic ($t = -1.393$, $p < 0.05$). There were no significant differences between interface models with dense forest and interface models on agro-forestry mosaic ($t = -0.805$, $p > 0.05$).

For risk visualization, the criterion to convert the quantitative scale of the ignition index to four risk categories was based on the premise of simplicity required by the support tools used in routine decision-making. According to final values, we identified four categories of ignition risk using Jenks optimization method: Low (4.2) (Fig. 4). The Cokrigring method with three datasets (altitude, slope and aspect) had the best results for the mean absolute error (MAE). The MAE of the ignition risk predicted by Cokriging method was 6.41% (±4.99), which was substantially lower than Kriging (9.94%). Classification accuracy was 93.58% based on overall agreements (Table 3). The lowest value of user accuracy was obtained for “High category” (82.95%). “Very High category” was more frequently miss-reported as “High category” due to their similar natural species compositions.

4. Discussion

Live fuel moisture is an important component of fire behavior models (Jolly, 2007), and is crucial for identifying the relationship between live fuel moisture and fire occurrence (number of fires and burned area) in the Mediterranean area (Chuvieco, González, Verdú, Aguado, & Yebra, 2009). Changes in live fuel moisture content are related to physiological activity of the vegetation, and this activity is greatly influenced by the season of the year (Hernando, 2009). Field studies and flammability experiments were carried out during the hottest part of season with higher fire risk. Species selected for flammability experiments were located in nearby locations in the same sampled WUI in order to avoid the effect of site quality and topographical variables (altitude, slope and aspect) on fuel moisture (USDA Forest Service, 2004). In spite of this sampling procedure, the moisture content of different species varied from 72.89% (*Q. ilex*) to 297.5% (*A. altissima*).

Flammability results should be included in ignition assessment to improve the behaviour of the fire risk indexes (White & Zippere, 2010). In this sense, our ignition risk included the flammability results of selected species. A. altissima was the most difficult to ignite and had the lowest FD once ignited. Despite the fire mitigation properties (mainly in settlements in agroforestry mosaic), this species has also been reported to lead to biodiversity loss due to its allelopathic effects (Gomez-Aparicio & Canham, 2008a, 2008b). For this reason, it must not be used as an ornamental plant (although it may be useful in fuelbreaks). Six ornamental species (*C. deodara, C. arizonica, C. sempervirens, L. nobilis, L. vulgare and T. orientalis*), which are usually planted in hedges in southern Spain, were sampled in the flammability experiments. According to Valetteıs´ classification (1990), which considers ignition frequency and TTI, these species were ranked from flammable (*C. deodara and T. orientalis*) to very flammable (*C. arizonica, C. sempervirens and L. vulgare*) and extremely flammable (*L. nobilis*). The species with the largest broadleaves such as *L. nobilis* had the lowest values for TTI and for FD, similar to other studies (Dimitrakopoulos & Papaioannou, 2001; Ganteaume et al., 2012). Larger leaves created an open fuelbed structure that burned more rapidly because of stronger air flow (Scarff &Westoby, 2006). Leaf size was shown to be the most important characteristic influencing the sustainability of fires, more than chemical factors (Parker & LeVan, 1989). L. nobilis showed this outcome due to its low level of estimated Volatile Organic Compound (VOC) emissions (Nowak, Crane, Stevens, & Ibarra, 2002).

Although *T. orientalis, C. arizonica and L. vulgare* were the most difficult to ignite, *L. nobilis, L. vulgare and T. orientalis* had the lowest FD. The lower flammability of the Ligustrum genus was previously reported by Batista and Biondi (2009). Even though *C. sempervirens* showed a higher TTI than *P. halepensis* and other forest species, similar to other studies (Della Rocca et al., 2015), it was not one of the less flammable species according to its TTI and FD. This flammability result was similar to that observed in an experiment by Liodakis, Bakirtzis, and Lois (2002), but it was in contrast to other studies (Ganteaume & Jappiot, 2014). These differences could be explained as a result of the flammability measurement method, foliar moisture content, and/or the different plant heights from which material was collected. In conclusion, *T. orientalis and L. vulgare* are the most recommended species for use in WUI hedges based on the their higher TTI and lower FD and, as a consequence, their potential to reduce fire behavior and facilitate suppression.

Differences between needle species and broadleaf species must also be taken into account in relation to leaf size and air flow (Parker & LeVan, 1989). *N. oleander* was characterized as very flammable, opposite to the results of two studies by Etlinger and Beall (2004) and Ganteaume and Jappiot(2014). This result could be explained by the direct relationship between foliar moisture content and TTI (Dimitrakopoulos & Papaioannou, 2001). *P. halepensis* is used as an ornamental species in the study area due to its fast growth and resistance to urban stress. It was also faster to ignite than other *Pinus* species (*P. pinaster and P. pinea*). According to Valetteıs´ classification (1990), *P. halapensis* was classified as extremely flammable, *P. pinea* was very flammable, and P. pinaster was flammable. Although the limonene has been identified as a product which potentially accelerates combustion in *P. halepensis* (Courty et al., 2012), differences between *P. halepensis* and the other two *Pinus* species could be related to its lower moisture content. Our *P. pinaster* flammability classification contrasts with that obtained in studies by Hernando (2009) and Xanthopoulos, Calfapietra, and Fernandes (2012). The lower flammability of *P. pinaster* could be related to stand density, needle age, and the maturity of selected trees. Future studies should test this flammability level with samples from other WUI settlements. *P. pinaster* had both the highest TTI and the highest FD. As a result, it could be recommended for use in mixed stands between different species of Pinus genus.

The rest of the species were classified from very flammable (*O. europaea* var. *sylvestris*) to extremely flammable (*A. unedo, E. camaldulensis, F. ornus, Q. ilex and Q. suber*), according to Valetteıs´ classification (1990). The flammability results for *O. europaea* var. *sylvestris* were similar to several other studies (Elvira & Hernando, 1989; Dimitrakopoulos & Papaioannou, 2001). In our study, *Q. suber and A. unedo* were classified as extremely flammable, but were classified as very flammable in a study by Elvira and Hernando (1989). *O. europaea* var. *sylvestris* and *A. unedo* were the most difficult to ignite and to sustain flames. The rapid TTI of *Q. suber* could be related to the decayed condition of this species in the selected WUI (based on visual inspection of the trees). Oil, lignin content, and VOCs play a role in ignition and FD of species (Behm, Duryea, Long, & Zipperer, 2004), showing differences based on water availability (Filella, Penuelas, & Seco, 2009). *Eucalyptus* and the *Quercus* genus have been identified as emitting high amounts of isoprenes and monoterpenes (Nowak et al., 2002), but they are not stored in the leaves.

The flammability of landscaping vegetation in housing settlements is higher than portrayed in previous risk maps. The ignition index here provided precisely that kind of information by identifying sectors in the WUI with the highest degree of fire risk. In this sense, the ignition index improves planning and optimization of fuel management treatments in the WUI. This information could help fire managers and houseowners to strategically place existing budget to increase their fire protection effectiveness and minimize the consequences of the fire. The ignition index could be an important management tool when the prevention actions cannot be implemented because of economic and/or time constraints.

Spatial explicit predictions of fuel conditions are crucial for quantifying fire danger indexes and as inputs to fire behavior models. The ignition index (Rodríguez y Silva et al., 2014) is calculated as an function of the ignition probability, ignition coefficient, and flammability. This integral information provides an interesting risk framework for assessing the fire vulnerability of WUI at a scale that meets fire manager needs. However, changes in annual precipitation, air temperature and relative humidity are directly related to ignition probability (USDA Forest Service, 2004) and flammability (Hernando, 2009). Future studies should include temporal evolution of the ignition probability and flammability in order to improve WUI vulnerability assessments. The availability of data in remotely sensed time series could present an advantage to this approach improving the ignition index towards a dynamic ignition index (Nolan et al., 2016; Resco et al., 2015). Subsequently, these changes are more complicated because they not only affect moisture content, but also affect the live and dead fuel loadings (Ganteaume et al., 2012) and, as a consequence, the ignition coefficient. Therefore, in a dynamic ignition index the ignition coefficient should vary indirectly as a function of meteorological conditions. Among the diverse elements that shape fire behavior, such as meteorological factors (temperature, relative humidity, and wind) and topographic conditions (slope and aspect), fine dead fuels (< 0.6 mm) greatly influence fire spread (Andrews, 1986). Higher values of the ignition index occurred with higher levels of fine dead fuels, mainly in grass-shrub and flammable understory fuel models (Rodríguez y Silva & Molina, 2012). Similar to other approaches, increases in fuel bulk density frequently resulted in a lower ignition condition (Glitzenstein, Streng, Achtmeier, Naeher, & Wade, 2006; Plucinski & Anderson, 2008).

5. Conclusions

Forest fires in the WUI of southern Europe are a growing problem with social and economic impacts. The best method of mitigating the likelihood of homes being damaged by fire is to decrease the flammability of the surrounding areas. *T. orientalis and L. vulgare* should be considered fire-wise species for landscaping use in the WUI. Regarding live leaf flammability at the particle level, meteorological conditions (ignition probability) and fine dead fuels (ignition coefficient) of each must be considered in any ignition assessment. Due to the limitations of heat transfer processes in laboratory experiments, future field studies should conduct controlled burns of ornamental vegetation to test our flammability results. Urban planning rarely takes into account fire risk at any scale: landscape, settlement, or house. However, WUI homeowners are annually advised to reduce the highly flammable vegetation because forest agencies are not responsible fuels in home ignition zones. There are different points of view regarding responsibility for maintaining less flammable areas because of annual budgetary needs. Given this reality, improving the quality of ignition measurements and cartography is a high priority for efficient allocation of limited economic resources. Future studies could improve ignition index cartography towards a dynamic index.

Acknowledgements

The authors of this work express special gratitude to the INFOCOPAS (RTA2009-00153-C03-03) and GEPRIF (RTA2014- 00011-C06-03) projects of the Ministry of Science and Innovation. We also thank three anonymous reviewers for their help in improving presentation of the material.

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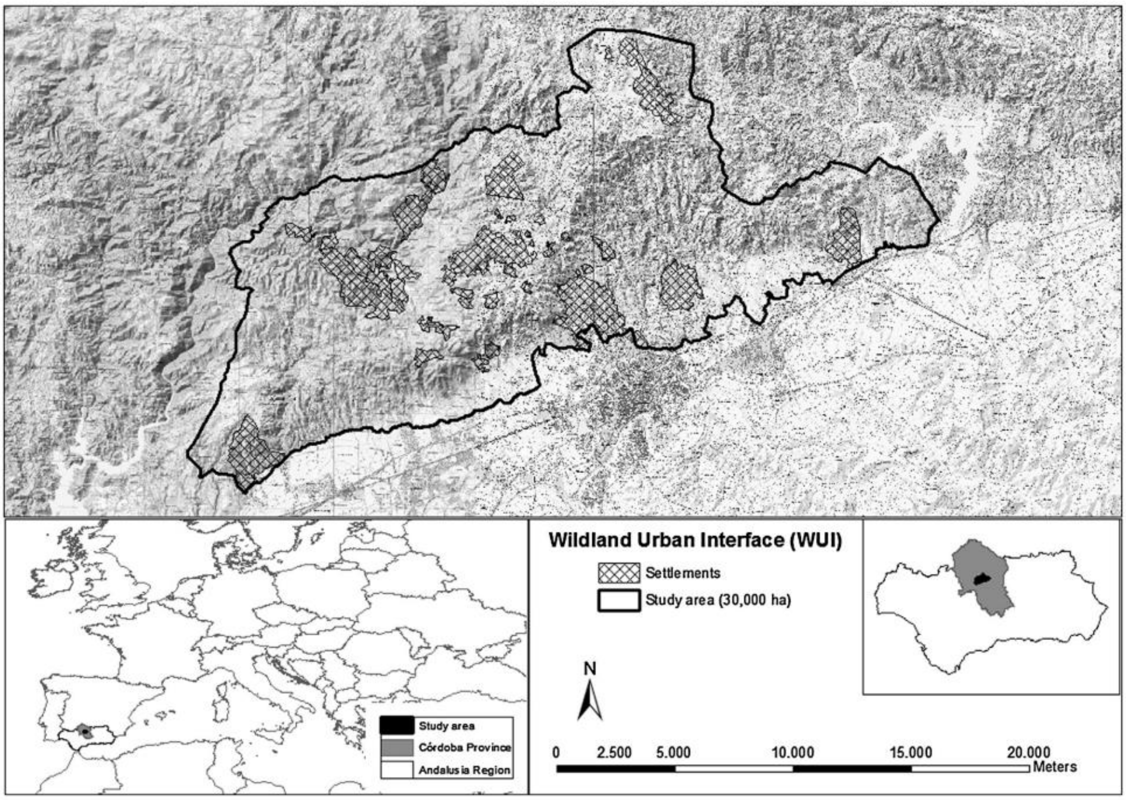
Figure captions

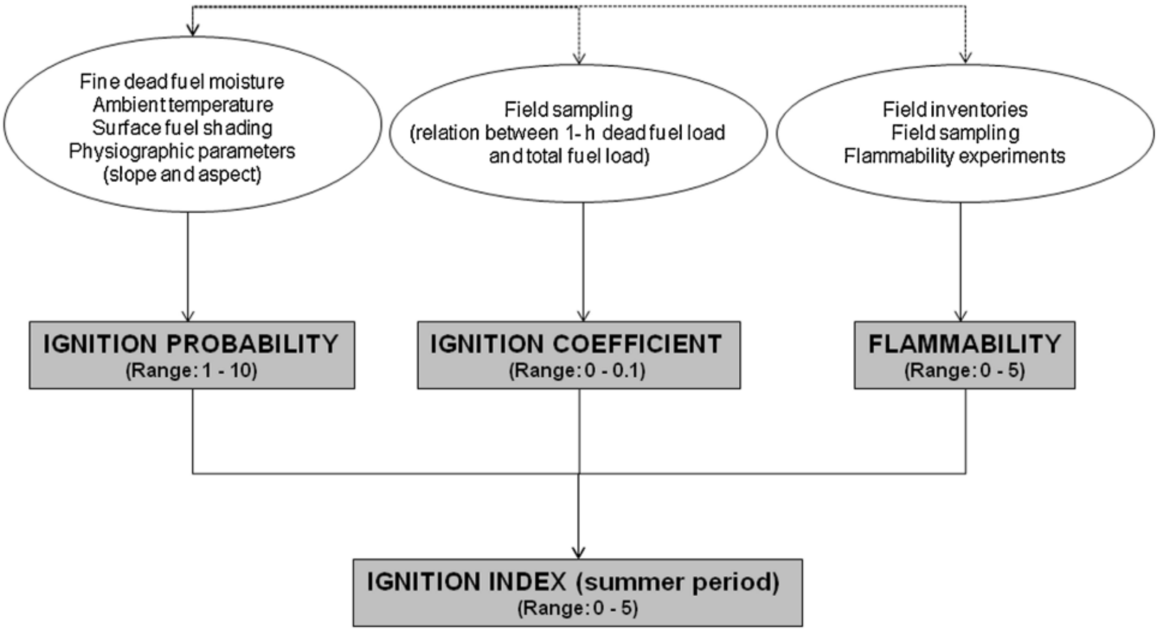
Figure 1. Study area location.

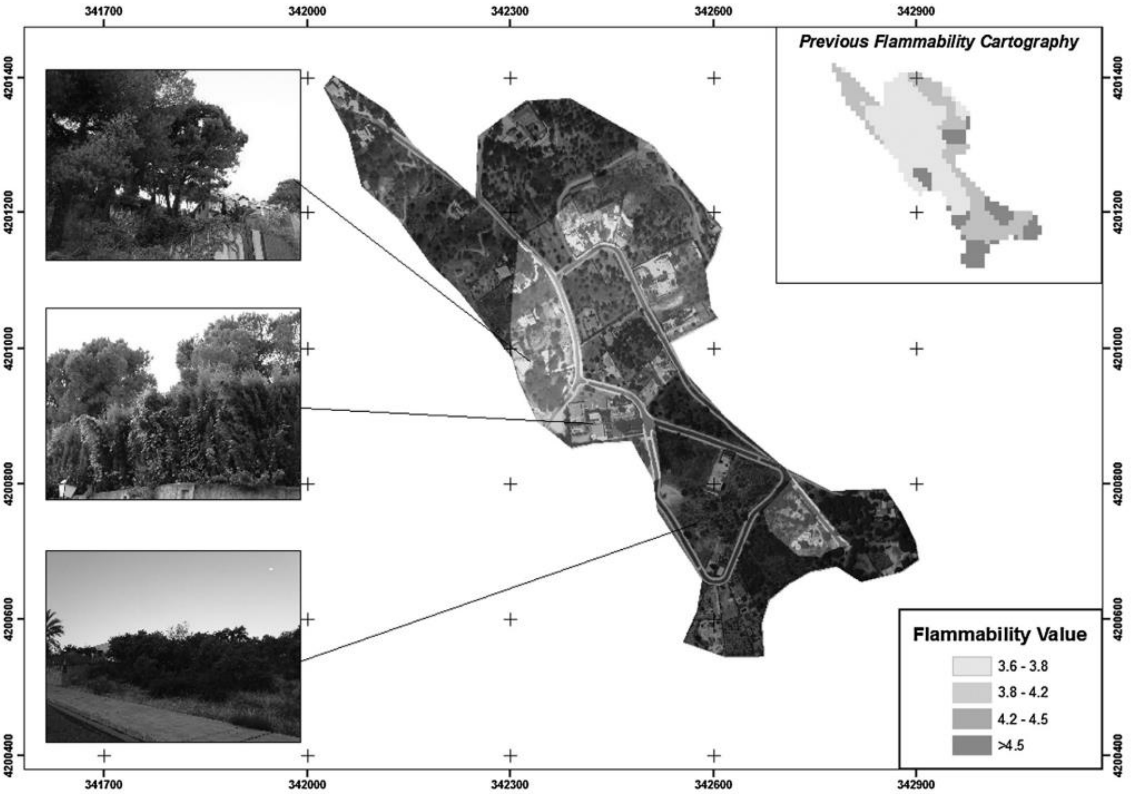
Figure 2. Framework for ignition risk calculation.

Figure 3. Flammability valuation for one WUI example based on the representativeness of each natural and ornamental species.

Figure 4. . Ignition index in the study area according to ignition risk categories.


Wildland Urban Interface (WUI)
Settlements
Study area (30,000 ha)
N
0
2.500
5.000
10.000
15.000
20.000
Meters
Study area
Córdoba Province
Andalusia Region


Fine dead fuel moisture
Ambient temperature
Surface fuel shading
Physiographic parameters
(slope and aspect)
Field sampling
(relation between 1-h dead fuel load and total fuel load)
Field inventories
Field sampling
Flammability experiments
IGNITION PROBABILITY
(Range: 1 - 10)
IGNITION COEFFICIENT
(Range: 0 - 0.1)
FLAMMABILITY
(Range: 0 - 5)
IGNITION INDEX (summer period)
(Range: 0 - 5)


341700
342000
342300
342600
342900
4201400
4201200
4201000
4200800
4200600
4200400
Previous Flammability Cartography
Flammability Value
3.6 - 3.8
3.8 - 4.2
4.2 - 4.5
>4.5

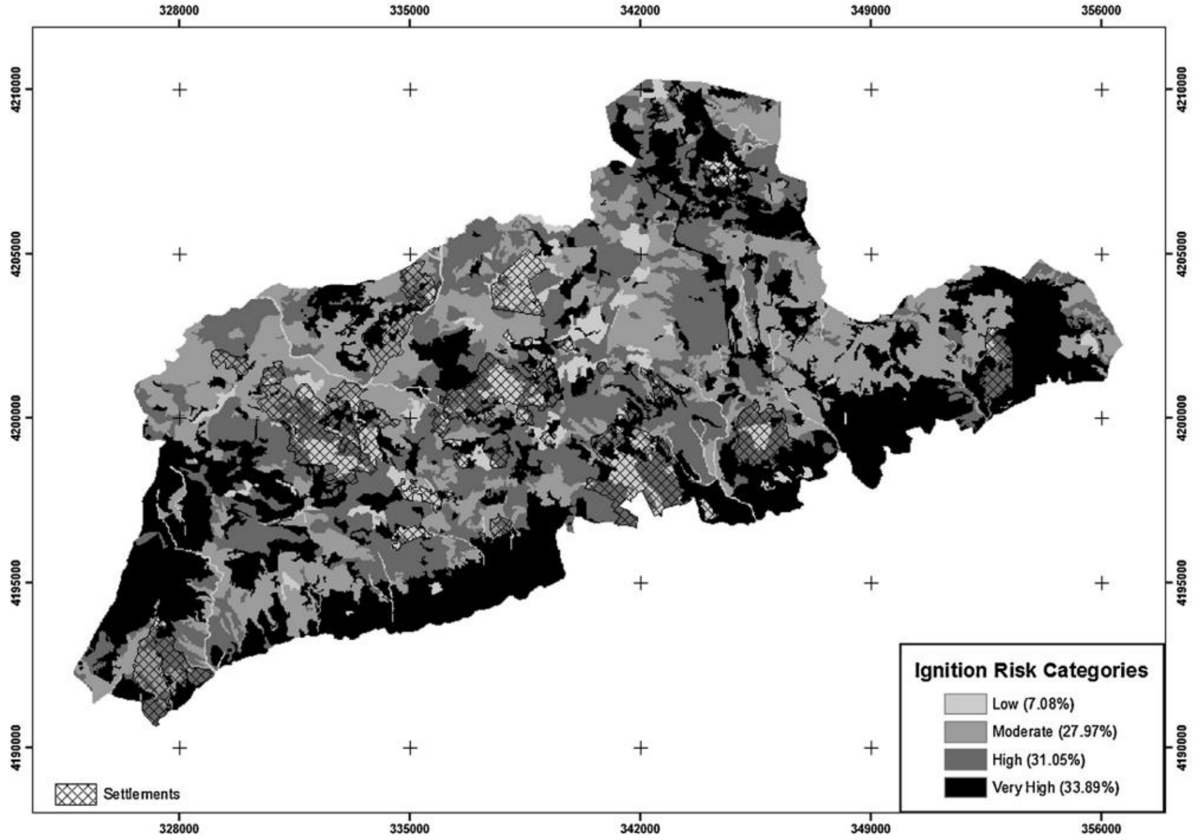
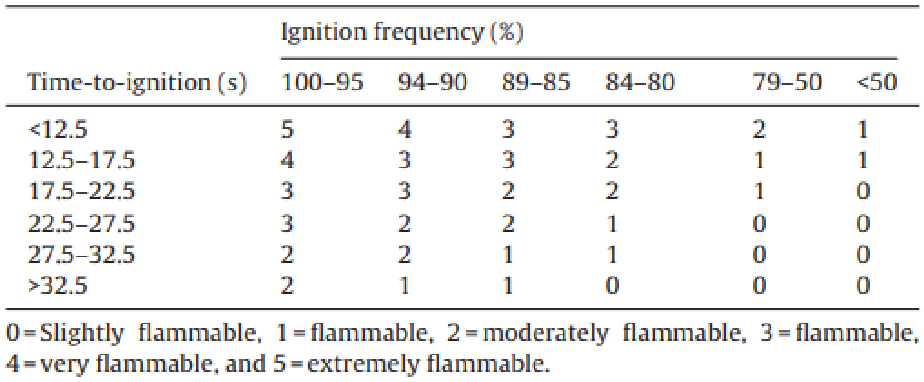

328000
335000
342000
349000
356000
4210000
4205000
4200000
4195000
4190000
Ignition Risk Categories
Low (7.08%)
Moderate (27.97%)
High (31.05%)
Very High (33.89%)
Settlements

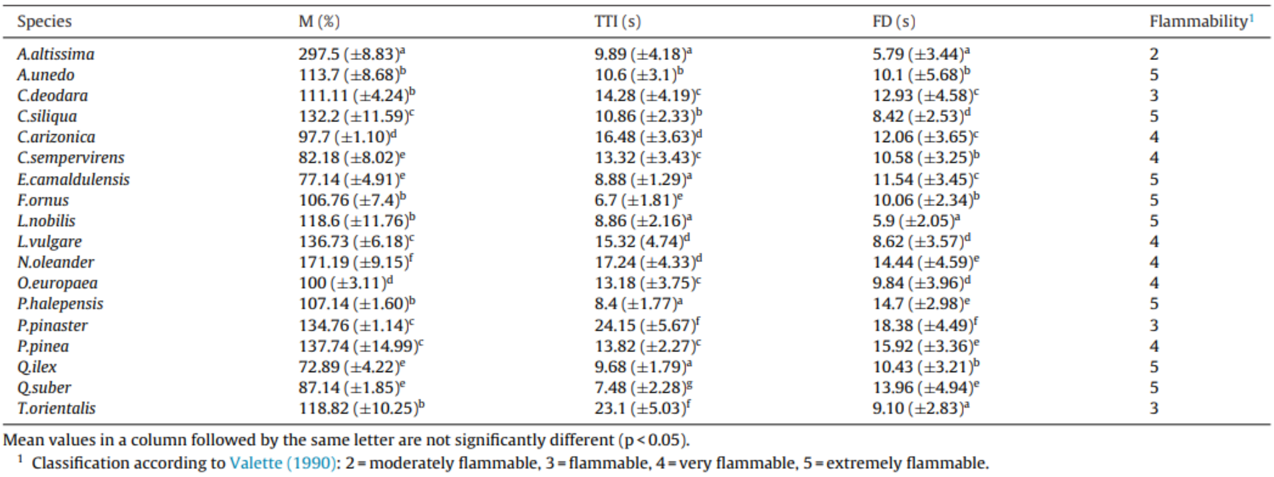
Table 1. Flammability classification according to ignition frequency (%) and time-to-ignition (TTI) (Valette, 1990).



	Ignition frequency (%)					
Time-to-ignition (s)	100–95	94–90	89–85	84–80	79–50	<50
<12.5	5	4	3	3	2	1
12.5–17.5	4	3	3	2	1	1
17.5–22.5	3	3	2	2	1	0
22.5–27.5	3	2	2	1	0	0
27.5–32.5	2	2	1	1	0	0
>32.5	2	1	1	0	0	0

0 = Slightly flammable, 1 = flammable, 2 = moderately flammable, 3 = flammable, 4 = very flammable, and 5 = extremely flammable.

Table 2. Species differences in foliar moisture content (M), time-to-ignition (TTI), flame duration (FD) and flammability category.

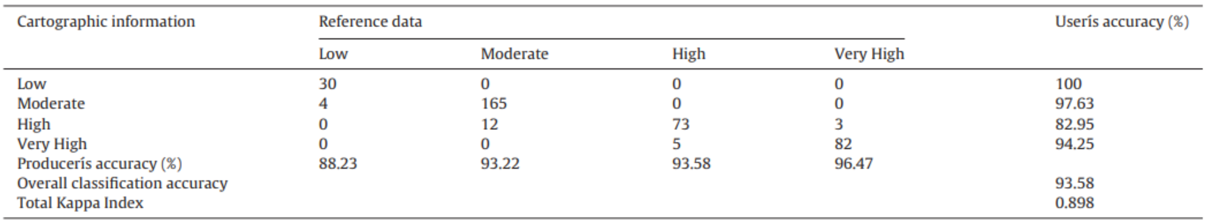


Species	M (%)	TTI (s)	FD (s)	Flammability[1]
A.altissima	297.5 (±8.83)^{a}	9.89 (±4.18)^{a}	5.79 (±3.44)^{a}	2
A.unedo	113.7 (±8.68)^{b}	10.6 (±3.1)^{b}	10.1 (±5.68)^{b}	5
C.deodara	111.11 (±4.24)^{b}	14.28 (±4.19)^{c}	12.93 (±4.58)^{c}	3
C.siliqua	132.2 (±11.59)^{c}	10.86 (±2.33)^{b}	8.42 (±2.53)^{d}	5
C.arizonica	97.7 (±1.10)^{d}	16.48 (±3.63)^{d}	12.06 (±3.65)^{c}	4
C.sempervirens	82.18 (±8.02)^{e}	13.32 (±3.43)^{c}	10.58 (±3.25)^{b}	4
E.camaldulensis	77.14 (±4.91)^{e}	8.88 (±1.29)^{a}	11.54 (±3.45)^{c}	5
F.ornus	106.76 (±7.4)^{b}	6.7 (±1.81)^{e}	10.06 (±2.34)^{b}	5
L.nobilis	118.6 (±11.76)^{b}	8.86 (±2.16)^{a}	5.9 (±2.05)^{a}	5
L.vulgare	136.73 (±6.18)^{c}	15.32 (4.74)^{d}	8.62 (±3.57)^{d}	4
N.oleander	171.19 (±9.15)^{f}	17.24 (±4.33)^{d}	14.44 (±4.59)^{e}	4
O.europaea	100 (±3.11)^{d}	13.18 (±3.75)^{c}	9.84 (±3.96)^{d}	4
P.halepensis	107.14 (±1.60)^{b}	8.4 (±1.77)^{a}	14.7 (±2.98)^{e}	5
P.pinaster	134.76 (±1.14)^{c}	24.15 (±5.67)^{f}	18.38 (±4.49)^{f}	3
P.pinea	137.74 (±14.99)^{c}	13.82 (±2.27)^{c}	15.92 (±3.36)^{e}	4
Q.ilex	72.89 (±4.22)^{e}	9.68 (±1.79)^{a}	10.43 (±3.21)^{b}	5
Q.suber	87.14 (±1.85)^{e}	7.48 (±2.28)^{g}	13.96 (±4.94)^{e}	5
T.orientalis	118.82 (±10.25)^{b}	23.1 (±5.03)^{f}	9.10 (±2.83)^{a}	3

Mean values in a column followed by the same letter are not significantly different ($p < 0.05$).

[1] Classification according to Valette (1990): 2 = moderately flammable, 3 = flammable, 4 = very flammable, 5 = extremely flammable.

Table 3. Confusion matrix based on cartographic information generated from Cokriging with three datasets (altitude, slope and aspect).



Cartographic information	Reference data				Userís accuracy (%)
	Low	Moderate	High	Very High	
Low	30	0	0	0	100
Moderate	4	165	0	0	97.63
High	0	12	73	3	82.95
Very High	0	0	5	82	94.25
Producerís accuracy (%)	88.23	93.22	93.58	96.47	
Overall classification accuracy					93.58
Total Kappa Index					0.898