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## Forest fire risk maps: a GIS open source application – a case study in Norwest of Portugal

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Forest fires are widely recognized as one of the most critical events in global change. Successful fire management depends on effective fire prevention, detection, and pre-suppression, having an adequate fire suppression capability, and consideration of fire ecology relationships. Geographical information systems (GIS) provide tools to create, transform, and combine georeferenced variables. In Portugal, as in many other countries, it is mandatory that all the municipalities produce forest fire risk maps on an annual basis, following the rules of the Portuguese Forest Authority, a governmental association. This article presents the results of a research project aimed at producing forest fire risk maps in a GIS open source environment in Portugal. The requirements of an open source application are better quality, higher reliability, more flexibility, lower cost, and an end to predatory vendor lock-in. Three different open source desktop GIS software projects were evaluated: Quantum GIS (QGIS), generalitat valenciana, Sistema d'Informacio Geografica, and Kosmo. Taking into account the skills and experience of the authors, the main advantage of QGIS relies on the easiness and quickness in developing new plug-ins, using Python language. Therefore, this project was developed in QGIS platform and the interface was created in Python. This application incorporates seven procedures under a single toolbar. The production of the forest fire risk map comprises several steps and the production of several maps: probability, susceptibility, hazard, vulnerability, economic value, potential loss, and finally the forest fire risk map. The forest fire risk map comprises five classes: very low risk (dark green), low risk (green), medium risk (yellow), high risk (orange), and very high risk (red). This application was tested in three different municipal governments of the Norwest zone of Portugal. This application has the advantages of grouping in a unique toolbar all the procedures needed to produce forest fire risk maps and is free for the institution/user. Beyond being an open source application, this application may be faster and easier when compared with the GIS proprietary solutions that usually comprise several steps and the use of different software extensions. This work presents several contributions for the area of the GIS open source applications to forest fire risk management.

**Keywords:** forest fire; risk map; open source software; desktop GIS; QGIS

### 1. Introduction

A forest fire is defined as any wildfire or prescribed fire that is burning in forested areas, grass, or alpine/tundra vegetation (Merrill and Alexander 1987). Forest fires are widely

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recognized as one of the most critical events in global change, particularly for their effects in land-cover alterations and atmospheric chemistry. Fire and climate/weather are intimately linked (Johnson 1992, Swetnam 1993), which means that the fire regime will respond rapidly to changes in climate. The season of the year at which fire occurs is one of the determinants of the successional trajectories on which ecosystems embark after fire. Furthermore, it may affect fire intensity through differences in surface and crown fuel moisture contents. Fire type refers to crown, surface, and ground fires, which are largely controlled by fire intensity and fuel characteristics (structure, load, and moisture). Fire severity is a description of the depth of burn into the surface soil organic layers and therefore another important controlling factor of post-fire ecosystem structure and function through direct impacts on underground plant root and reproductive tissues, soil seed bank, and forest floor microbial populations (Flannigan *et al.* 2003). There are numerous other factors such as ignition agents, topography, vegetation, landscape fragmentation, and fire management activities that could influence the fire activity in a region. The agent of ignition can be lightning or ignition can be caused by a wide variety of human activities. Topography, slope, and orientation can significantly influence fire behavior (Van Wagner 1977). Vegetation can also play an important role as aspects of fuel amount, continuity, moisture, arrangement, and structure are key determinants in fire occurrence and spread.

Portugal, like many other countries, suffers from forest fires. The high frequency at which forest fires occur in recent years reinforces the need for a better understanding of forest fire risks, given the importance of sustaining forest resources. The management of these disasters is of importance to both government authorities and the public. The fire management activity involves the strategic integration of several factors such as knowledge of fire regimes; probable fire effects; value-at-risk; level of forest protection required; cost of fire-related activities and prescribed fire technology into multiple-use planning; decision-making; and day-to-day activities to accomplish stated resource management objectives. Successful fire management depends on effective fire prevention, detection, and presuppression, having an adequate fire suppression capability, and consideration of fire ecology relationships (Merrill and Alexander 1987). Geographical information systems (GIS) provide tools to create, transform, and combine georeferenced variables. Every analysis of geographical data with GIS preserves the spatial dimension of variables being processed, because all transformations are performed cartographically. Therefore, GIS oriented toward fire risk mapping may portray the geographical location of those areas where risk factors are most severe. Fire protection programs may then be spatially and temporally oriented to the areas labeled as having high risk (Deng *et al.* 2007). Since fire risk is a spatial and temporal process, it should be addressed both spatially and temporally. Several GIS applications have been developed in the last decade to improve management of fire risk (Chuvieco *et al.* 2010). A GIS can spatially integrate several hazard variables, such as vegetation, topography, climatology, and fire history, which can cover the whole study area. The use of GIS is quite obvious in this regard, since these tools are ideal to manage spatial information, providing adequate spatial processing and visualization of results. For this reason, several previous studies on fire risk estimation have been based on GIS (Yool *et al.* 1985, Chuvieco and Congalton 1989, Chou 1992, Abhineet *et al.* 1996, Chuvieco and Salas 1996, Castro and Chuvieco 1998, Vasconcelos *et al.* 2001, Nourbakhsh *et al.* 2006). Most of these models are locally oriented and cover areas at different resolutions. The grid size is typically less than 100 m. However, 1 km and 10 km grids were also employed (Chuvieco *et al.* 2010, Bisquert *et al.* 2011). Most of these models were developed in a proprietary

GIS software. Within this environmental context, the interest of having better tools for fire prevention and assessment should be emphasized. A GIS application based on open source software may be faster and easier than GIS proprietary solutions, as will be described in this article.

The development of free and open source software has experienced a boost over the past few years. In the GIS domain, the widespread use of free and open source software (FOSS) is apparent as well. This rise in popularity of free GIS tools can be measured using four indicators: the large number of projects started in the last years; the increasing financial support by governmental organizations for the foundation of FOSS GIS projects; the high download rates of free desktop GIS software; and finally, the increasing number of use cases of open source GIS software for the geospatial database PostGIS (Steiniger and Bocher 2009).

A couple of terms, such as 'proprietary,' 'free,' and 'general public license (GPL),' are often used with respect to open source software. In 2007 Stallman notes: 'When we call software "free," we mean that it respects the users' essential freedoms: the freedom to run it, to study and change it, and to redistribute copies with or without changes. This is a matter of freedom, not price, so think of "free speech," not of "free beer" ' (Stallman 2007). For this reason, the opposite domain to 'free software' is not 'commercial software,' where 'commercial' indicates that the software is sold or used to make a living or benefit. The opposite of 'free software' is 'proprietary software,' where 'proprietary' indicates ownership (Steiniger and Bocher 2009).

Often the terms 'open source' and 'free' software are used synonymously. However, the term 'open source' describes that on the one hand source code is accessible, and on the other hand the source code can be studied. Even so, it does not encompass the freedom of modification and redistribution; therefore, the term 'free' is more appropriate to describe software that fulfills the above-mentioned four conditions (Steiniger and Bocher 2009). Software can be certified by the Open Source Initiative (OSI) as being 'open source' (OSI 2011).

The open source GIS community has also been represented since 2006 by the Open Source Geospatial Foundation (OSGeo). Driven by the need for a public point of contact within and from outside the FOS GIS community, this organization was founded out of several FOS GIS user communities and projects in Chicago (USA) in February 2006. More information on free and open source GIS software projects may be found in Steiniger and Bocher (2009).

In Portugal, as in many other countries, it is mandatory that all the municipalities produce forest fire risk maps on an annual basis following the rules of the Portuguese Forest Authority (AFN – *Autoridade Florestal Nacional*), a governmental association. These rules are published in technical guide for forest fires management for municipalities (DFCI 2008). The forest fire risk assessment model that is proposed in this article is based on the rules published in this technical guide (DFCI 2008) published for the Portuguese Forest Authority (Figure 1). Other features were created, such as triangulated irregular network (TIN) and aspect analysis, not specified in the technical guide, but that could be an asset to future applications of this tool.

The main objective of this work was creating an open source GIS application to produce forest fire risk maps for Portuguese municipalities. The risk factors and the criteria to integrate risk factors were already fixed in the technical guide published for the Portuguese Forest Authority (DFCI 2008).

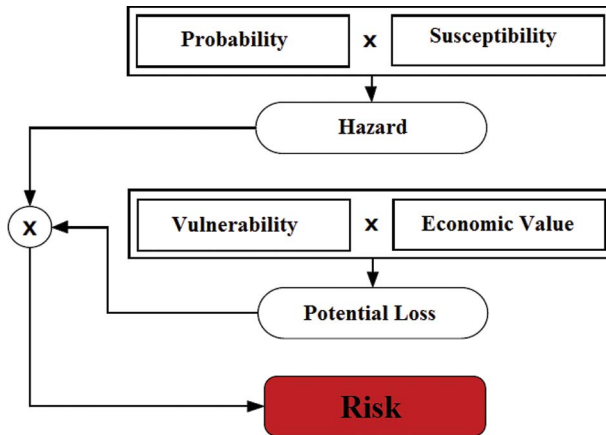


Figure 1. Forest fire risk model components (adapted from DFCI (2008)).

## 2. Methodology

### 2.1. Open source desktop GIS software selection

A desktop GIS is a mapping software that is installed on and runs on a personal computer and allows users to display, query, update, and analyze data about geographic locations and the information linked to those locations (ESRI 2008). Steiniger and Bocher (2009) provide an overview of major free desktop GIS projects and several possible evaluation criteria. The evaluation criteria include application focus; user level; supported operating systems; development platform; and software license. Several desktop GIS projects were analyzed and compared, such as GRASS, Quantum GIS (QGIS), UDig, gvSIG, Kosmo, and JUMP/OpenJUMP, among others. Based on the characteristics of the analyzed software projects and taking into account the objectives of the project to be carried out, three different open source desktop GIS software projects were evaluated under the scope of this study: QGIS (QGIS 2011), generalitat valenciana, Sistema d'Informacio Geografica (gvSIG) (gvSIG 2011), and Kosmo (Kosmo 2011).

- QGIS. The QGIS project started in 2002 with Gary Sherman, and it is an official project of OSGeo. The original aim was to provide an easy to use and fast geographic data viewer for Linux-based systems (Hugentobler 2008). The QGIS project evolved the idea emerged to use QGIS as a simple graphical user interface (GUI) for GRASS itself (Steiniger and Bocher 2009). QGIS is licensed under the GNU GPL and it runs on Linux, Unix, Mac OSX, and Windows. The QGIS is developed in C++ programming language and is complemented with extensions – plug-ins (in Python). These plug-ins represent advantages regarding speed and effectiveness on developing new features. In the QGIS version 1.6 ‘Copiápo,’ the symbology has some improvements relating to the old versions, such as better support for creating and selecting gradients and the new graduated classification, which consists in grouping classes of a specific attribute using a single symbol, where the classification is defined by the color intensity.
- gvSIG. The gvSIG software was started in 2004 and it was developed by the Conselleria d'Infraestructures I Transports of Valencia Community to replace software of similar functionality as ESRI's (Redlands, California) ArcView in

municipal authorities, since the regional government aims to switch all systems to a Linux-based computer infrastructure (gvSIG 2011). As QGIS, gvSIG is licensed under the GNU GPL and it is a project of Open Geospatial Consortium (OGC). The programming language for the development of gvSIG is JAVA. gvSIG also has extensions, such as Sextante (GRASS), which are also developed in JAVA. The gvSIG is integrated with a geographic database PostGresSQL/PostGIS, MySQL, and Oracle Spatial, and it is divided into three platforms: Desktop, Portable, and Mobile. This software supports OGC standards such as WMS, WCS, WFS, and KML.

- Kosmo. The last evaluated software was Kosmo. The software project was started in 2005 by the Spanish company SAIG and focuses on Spanish users that need functionality similar to that provided by ESRI's ArcView (3.x). The original JUMP software has undergone a partial redesign to form what is now called Kosmo. Kosmo provides additional functionality that incorporates raster analysis functions and geo-processing tools. Kosmo was the first free GIS cooperative platform, and it is also distributed under the GNU GPL. This software presents four versions: Kosmo Server (vectorial and raster cartography server), Kosmo Desktop (GIS software with associated geographic analysis tools), Kosmo Web Client (cartographic browser that connects with services based on OGC standards), and Kosmo Mobile (a GIS software for mobile devices). Kosmo is interfaced with a geographic database, for instance, PostGresSQL/PostGIS; MySQL; and server software, such as GeoServer and Deegree, to publish data from any major spatial data source (such as PostGIS and MySQL) using open standards. In terms of publishing on the Internet, Kosmo is probably the better option. The programming language for the development of Kosmo is JAVA.

Table 1 presents the main characteristics of the three selected open source desktop GIS projects with respect to desktop GIS functionality. In terms of requirements/needs, the three compared software projects have the required functionalities. Despite several advantages and weaknesses not mentioned, QGIS presents several strengths:

- Allows overlapping vector and raster data in different formats and projections without the need to convert to an internal format.
- Allows for creating, editing, and exporting spatial data.
- Has a friendly interface.
- Performs spatial analysis using the fTools plug-in for shapefiles or the GRASS plug-ins for other formats and allows for publishing maps on the Internet.

For this specific application and taking into account the skills and experience of the authors, the main advantage of QGIS relies on the easiness and quickness in developing new plug-ins, using Python language (Python 2011). Additionally, QGIS has its own application programming interface (API) (QGIS API) with functionalities and programs to develop new features, and a new developer can easily find tutorials and online official documentation to develop new plug-ins in QGIS.

For these reasons, the software chosen to develop this application was QGIS.

Table 1. Characterization of the three selected open source desktop GIS projects with respect to desktop GIS functionality (adapted from Steiniger and Bocher (2009)).

Data type	Functionality	File type	QGIS (v. 1.6)	gvSIG (v. 1.10)	Kosmo (v. 2.0)	
Vector	Read	SHP	Y	Y	Y	
		GML	Y	Y	Y	
	Write	DXF	Y <sub>GRASS</sub>	Y	Y	Y
		SHP	Y	Y	Y	Y
		GML	Y <sub>GRASS</sub>	Y	Y	Y
		DXF	N	Y	Y	Y
	Read	JPEG	Y	Y	Y	Y
		GeoTiff	Y	Y	Y	Y
		GRID	N	N	N	N
		JPEG	Y	Y	Y	Y
Database Links	Read	GeoTiff	Y	Y	Y	
		GRID	N	N	N	
	Write	PostGIS/PostgreSQL	Y	Y	Y	Y
		MySQL	N	Y	Y	Y
		Oracle Spatial	N	Y	Y	Y
		Spatial Lite	Y	N	N	N
		ArcSDE	N	Y	Y	Y
		PostGIS/PostgreSQL	Y	Y	Y	Y
		MySQL	N	Y	Y	Y
		Oracle Spatial	N	Y	Y	Y
SpatialLite	Y	N	N	N		
ArcSDE	N	Y	Y	Y		
OGC Compliance (supported standards)			WMS, WMS-C, WFS, WFS-T, GML	WMS, WCS de MapServer, WFS, KML	WMS, WFS	
Thematical Mapping (symbolology)		Y (bar, line chart, graduated symbol, individual value, label, ranges)	Y (bar, line chart, graduated symbol, individual value, pie chart, label, ranges, dot density)	Y (bar, line chart, graduated symbol, individual value, pie chart, label, ranges, dot density)	Y (graduated symbol, individual value, label)	
Scripting Functionality		Python (plug-ins)	Jython	Jython	JavaScript	
Data creation and editing (points, lines, area)		Y	Y	Y	Y	
Topology creation		Y <sub>GRASS</sub>	Y (RED Network Analysis)	Y	Y	

## 2.2. Programming language

Python is a powerful high-level programming language. It is also an interpreted language, since it uses an interpreter to read and interpret directly the source code. Python is object oriented, easy to use and understand, quick, and efficient in several applications. This programming language is, frequently, compared with other languages such as Tcl, Perl, Ruby, Scheme, or JAVA. Python can be integrated with objects COM, .NET, and CORBA. One of its advantages relies on the development of extensions and modules in C++ or C language which, afterward, can be integrated in Python. Python is cross-platform and it can be used in systems such as Windows, Linux/Unix, OS/2, and Mac, among others. It is a friendly and easy language to learn due to the documentation and tutorials provided by the online community (Python 2011). The Python implementation is under an open source license administrated by the Python Software Foundation (Python 2011). Python language combines a clear and concise syntax with resources of standard libraries and modules or frameworks already developed. One of the main objectives of Python was to increase the user productivity. With this language it is not necessary predeclaring the variables, since the block control is made by indentation and offers high-level types such as strings, lists, and tuples, among others. The possibility of developing extensions or plug-ins with this language was crucial in this project.

### 2.2.1. Plug-in development

Based on the architectural structure to develop plug-ins in QGIS (QGIS 2011), the files and structure were organized, as shown in Table 2.

The developed plug-ins comprise 19 classes: one class for the general toolbar where all the buttons are named; nine classes (Ui\_name.py) that are integrated with Gui module; and other group of nine classes (Name.py) that are integrated with Core module. The Toolbar class allows for creating the application buttons through the Core module classes and GUI module classes. These classes allow building the feature graphic interfaces. The code development contains all the scripts, commands, and connections that the plug-ins needed. The described classes and components connections are shown in Figures 2 and 3. Afterward, all the plug-ins were tested in order to verify if they work correctly. These tests can be performed during the plug-in development. Finally, the plug-ins can be published in QGIS repository.

### 2.2.2. Application programming interface (API)

An API is a set of routines and standards that can be used and reused in several projects. It is a set of functions that allows for building applications. In general, an API is an interface

Table 2. Structure of the QGIS plug-ins.

File	Description
init__.py	Contains general information, version, name, description, author, and main code
Plugin.py	Contains the main code and all the actions related to it
Resources.qrc	.xml document compiled by editor that contains icons information
Recources.py	.xml document compilation
Form.ui	Files created by the editor related to the application graphic interface. These files can be manually created or created by Qt Designer
Form.py	Editors' interpretation of the previous file



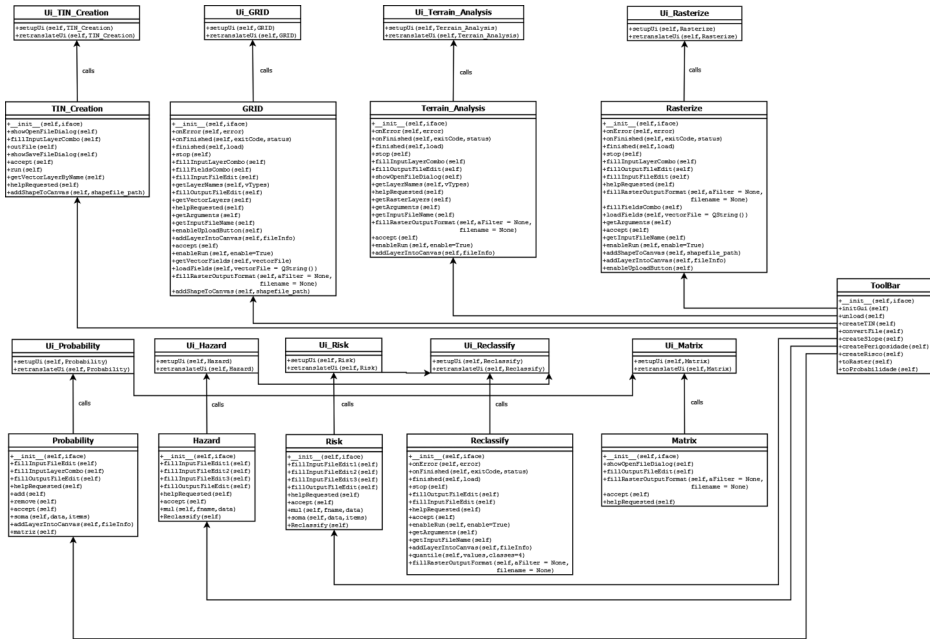


Figure 2. Plug-in class diagram.

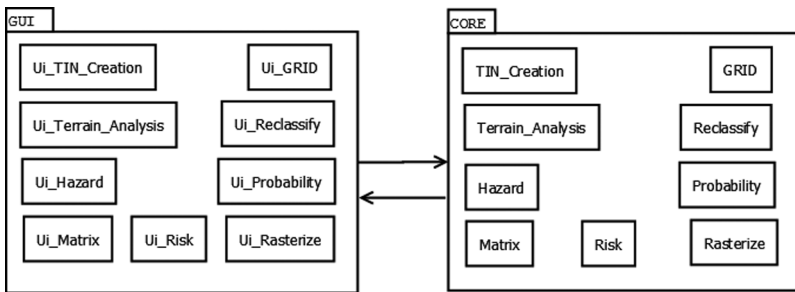


Figure 3. Tool components.

that is behind everything. A human that uses an application does not notice the presence of an API. An API defines the most adequate way to use the services of a certain program. There are several APIs for Windows systems, file systems, database systems, and networking systems.

Trolltech's Qt (<http://doc.qt.nokia.com/>) represents a standard framework used for high-performance applications. This framework contains an API, which is used for application development due to its complex graphic structure (GUI), and it is absolutely object oriented. Qt API was started in 1996 and, since then, it is used in several applications such as Google Earth, Adobe Photoshop Elements, and Skype. It is supported by several platforms, Microsoft Windows, Unix/X11, Mac OS X, and Linux, and it is distributed in two editions, namely Qt Commercial Editions used by proprietary software and Qt Open Source Edition used under the license GNU GPL for free software. For plug-ins creation, this library presents two APIs: a high-level API for extensions to Qt itself and a low-level

API for extensions of Qt applications. Qt API has some modules such as QtCore, QtGui, QtNetwork, QtOpenGL, and QtMultimedia, among others. In this project QtCore and QtGui were used. QAction, QDialog, QFileInfo, QFile, and QProcess are some examples of API classes used in this project.

The QGIS API is composed of four modules: QGIS core library, QGIS GUI library, QGIS analysis library, and Map Composer. In this project, classes of the two first modules were used. The first one is constituted by all GIS basic features. Some examples are QgsCoordinateTransform, QgsMapLayer, QgsVector, and QgsRasterLayer. The second module links the first module with the graphical interface and then links the result with the desktop.

PyQt4 (<http://www.riverbankcomputing.co.uk/software/pyqt/download>) is a library or a set of tools that allows the development of GUI and Core applications. With these applications, the user can interact with digital devices through graphic elements such as icons and menus. This interaction can be done using a mouse or a keyboard to allow the manipulation of the symbols, also called widgets. These tools are available in libraries. QtGui module, one of the modules of PyQt4, was used in this project and has the necessary graphic components and their classes that include buttons, windows, state bars, toolbars, and colors, among others. PyQt4 contains, besides QtGui, other modules composed of classes written in Python, such as QtCore, QtNetwork, QtXml, QtSvg, QtOpengl, and QtSql and represents a fusion between Python programming language and Qt Library. PyQt4 runs in Windows, UNIX, and Mac. This package has two licenses according to the user option, GNU GPL, and commercial license. Besides QtGui, this project also used QtCore, which allows the user to manipulate time, files, and directory variables. This module controls the action simulations of the application. The other modules are described here: QtNetwork contains classes used in network programming; QtXml contains classes that manipulate XML files; QtSvg provides classes with the SVG files; QtOpengl is used for graphical interpretation in two and three dimensions using the OpenGL and QtSql, which provides classes that connect to databases. The first API described, Qt API and PyQt4 API are independent of the GIS chosen tools, QGIS, whereas the QGIS API is part of the QGIS software. Other libraries were used, such as Geospatial Data Abstraction Library (GDAL) which contains a GDAL/OpenGIS Simple Features Reference Implementation (OGR) API: the GdalTools is a set of programs that allows for manipulating raster formats. In this application, two commands of the GdalTools were used: GRID feature and Rasterize feature development. The OGR Simple Feature Library was used to manipulate vector files. The numpy library was used to perform mathematical operations with raster files; the *sys* module provides a number of functions and variables that were used to manipulate different parts of the Python runtime environment; the *os* module provides a unified interface to a number of operating functions; the *re* module provides a set of regular expressions and facilities; and the scipy library was also used in the mathematical operations. The scipy is integrated with numpy to improve the manipulation of mathematical operations. Some APIs, as QGIS API, do not have the functions and commands needed for this specific application. Therefore, the integration of different APIs allows to improve the application performance and the results. Figure 4 shows the application architecture and the relationship between the classes and modules.

### 3. Results

#### 3.1. Toolbar

The toolbar developed for this application was implemented using the plug-in 'Toolbar.py.' This plug-in contains the code for the events related to the toolbar managed. The toolbar

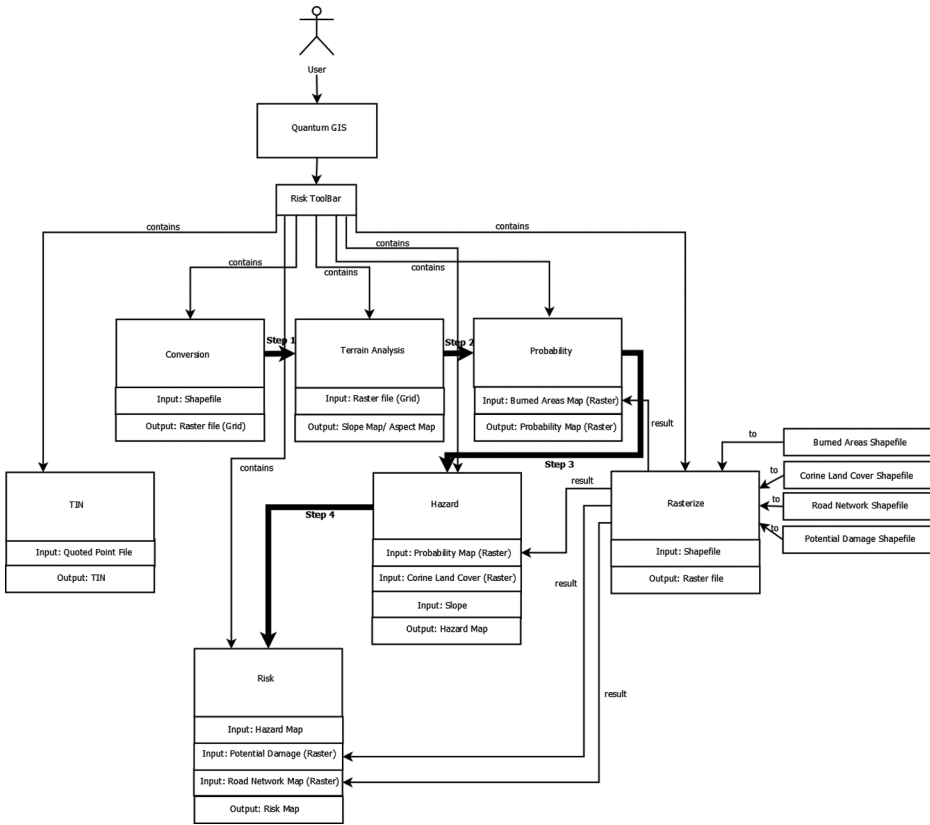


Figure 4. Application architecture.

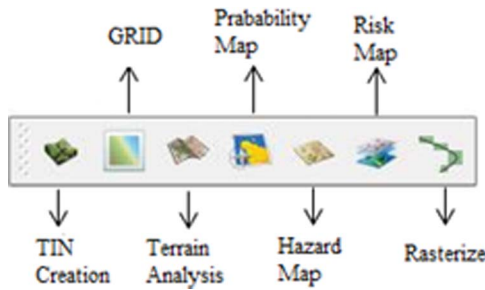


Figure 5. Application toolbar (adapted from Teodoro and Duarte (2011)).

icons are also in this file and are compiled in the resources file. This application, developed through QGIS plug-ins, incorporates seven procedures under a single toolbar: TIN Creation, GRID, Terrain Analysis, Probability Map, Hazard Map, Risk Map, and Rasterize (Figure 5). Each button was developed based on other commands or plug-ins. Each one has a window with several options, such as menus, labels, edition windows, combo boxes, and simple buttons, such as Ok, Close, and Help, among others, that help the user to access input and output directories. Figure 6 – left presents the graphical interface of Risk Map feature.

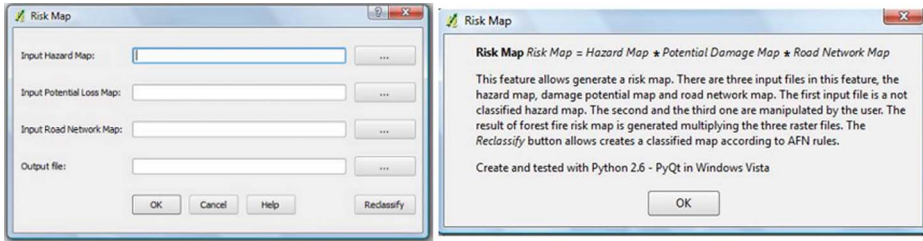


Figure 6. Graphical interface of Risk Map feature (left) and Risk Map help button (right).

The Help button opens a window where the users get information on the features of the program, and their input, output, fields, and functions. This button should be used when the user wants more information on any feature. Figure 6 – right presents the Risk Map Help button.

All the input and output files were referred in each feature description. A workflow is shown in Figure 7. According to the feature type, the input or output information is saved in a vector file (shapefile format) or in a raster file (tif format). Figure 7 presents a workflow of the sequential steps showing how the user interacts with the tool, with the input and output

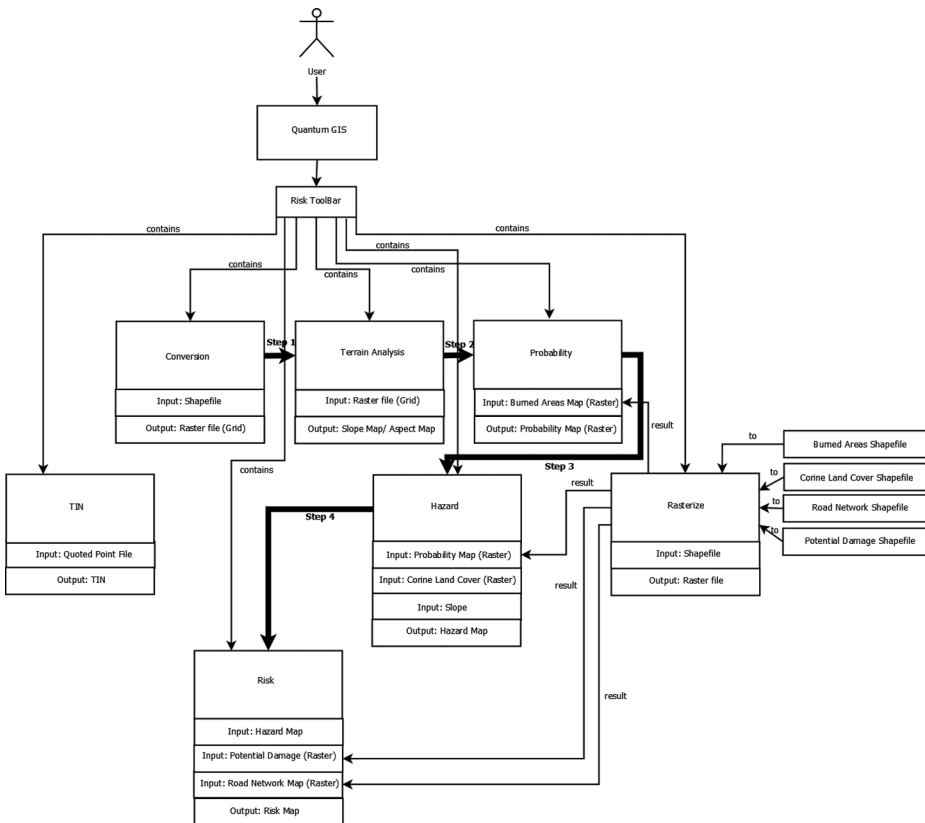


Figure 7. Inputs and outputs of the tool.

files, and the relationship between the procedures developed, according to the technical guide for forest fires management for municipalities (DFCI 2008). The hazard variables required in this application are Digital Elevation Model (DEM) slope map, aspect map, burned areas map, CORINE Land Cover (CLC), and road network map. There are other variables that can be incorporated into Risk Map creation in the future.

### 3.1.1. TIN Creation

The first feature, TIN Creation, allows for a TIN generation based on Delaunay triangulation (Barber *et al.* 1996). This instruction allows for generating a TIN from a set of irregularly distributed points (shapefile). This feature is composed of two fields (Figure 8 – left). The term ‘fields’ refers to the place, in a GUI, where data can be entered. The first field is the input directory. The user can access the input file from two different ways: from a directory defined by the user or by selecting the existing layer in the desktop. It is mandatory that the files are in vector format. The second field is defined by the output directory. The result is another vector file.

The TIN feature described is not used in this application (DFCI 2008). However, it was already developed and incorporated in this application and can be used in the future by other users/institutions or in a next version of the technical guide for forest fires management for the Portuguese municipalities.

### 3.1.2. GRID

The GRID feature allows for a grid generation considering as input a vector file and it is composed of five fields. In this case, the input file is the elevation information (vector file) and defines the first field. This conversion involves the pixel size definition in the second and third fields. The pixel size must be the same in all raster files in this project. This is an important issue because it will be necessary to perform several mathematical operations between raster files. In this work the pixel size defined was 25 m, according to the Portuguese Forestry Authority rules. The next field is defined by the elevation attribute of the vector file and is automatically filled when the first field is defined. The last field is the output file (raster file). In the code developed for this feature (GRID.py), the extent of input field, *x* minimum, *x* maximum, *y* minimum, and *y* maximum were necessary to define the cell size. These values can be acquired with a GDAL/OGR library command (<http://www.gdal.org/ogr/>). OGR is used for vector files and GDAL for raster files. The input file is a vector, so it was used as the command for OGR library. Besides this option,

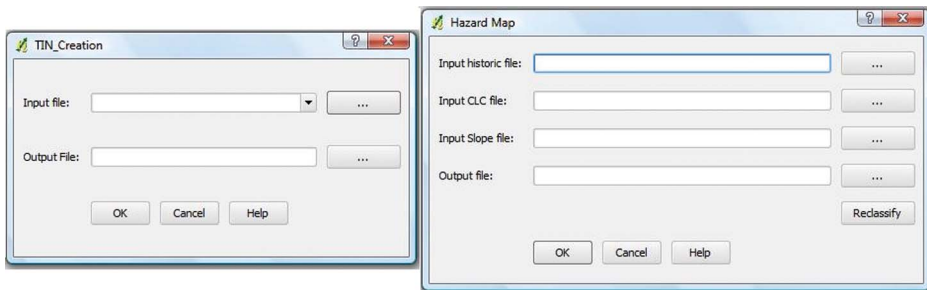


Figure 8. TIN (left) and Hazard Map (right) interfaces developed.

there is an OGR API that allows the manipulation of the vector files also with the GetExtent command. In this case, the result is a tuple and it was used in the resolution calculation of input file,  $\Delta X$  and  $\Delta Y$ . Pixel size (m) was related to the file extent in number of rows and number of columns as follows:

$$\text{Rows} = \Delta Y/25; \quad \text{Columns} = \Delta X/25 \quad (1)$$

### 3.1.3. Terrain Analysis

Terrain information is necessary to create Hazard and Risk Maps. The Terrain Analysis icon allows for generating the Slope and Aspect Maps. Slope is the rate of maximum change in  $z$ -value from each cell. The use of a  $z$ -factor is essential for correct slope calculations when the surface  $z$  units are expressed in units different from the ground ( $x, y$ ) units. For percentage rise, the range is from 0 to near infinity. A flat surface is 0%, a 45° surface is 100%, and as the surface becomes more vertical, the percentage rise becomes considerably larger. Aspect is the direction of the maximum rate of change in the  $z$ -value from each cell in a raster surface. Aspect is expressed in positive degrees from 0° to 360°, measured clockwise from north. Cells in the input raster of zero slope – for example, flat – are assigned an aspect of  $-1$ . This feature is composed of three fields. The input file, defined in first field, is the raster file generated by the GRID icon. In the second field, there is a combo box that allows the user to choose between Slope or Aspect Map. Lastly, the third field (output file), is also a raster file. There is also a check box that allows generating a classified slope or aspect map with five classes according to the Portuguese Forest Authority rules (DFCI 2008), where each one has an associated color. These colors are in a gradient palette, typically used for Slope and Aspect Maps, which is an option for the user. If the user wants to choose the number of classes, it has to be done manually. But, in this case, the map is represented in grey scale in the desktop due to the limitations of QGIS in terms of visualization. The classification into five classes (color and intervals) is based on the rules published in the technical guide for the Portuguese Forest Authority (DFCI 2008), which describes the forest fire risk cartography methodology. The Slope Map and Aspect Map classes are presented in Figure 9. The Aspect feature is not used in this application, but the classes are defined in the technical guide (DFCI 2008). Nevertheless, such as the TIN feature, it was already incorporated into this application and can be later used.

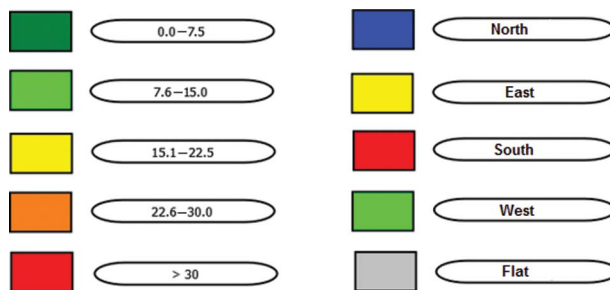


Figure 9. Slope Map (left) and Aspect Map classes (right).

### 3.1.4. Probability Map

The Probability Map feature gives the Probability Map that will be used in Hazard Map generation. This command was built to make an addition between several raster files. This procedure used a shapefile with burnt areas data. This file can be obtained in AFN official web page (<http://www.afn.min-agricultura.pt/>). The Probability Map creation is separated into a manual component and a computational component, the last one being the Probability Map feature help. The manual component lies in separating all the years into different shapefiles and adding a column with the value 1 to each attribute table. Therefore, the burnt areas are classified with value 1. Then, the user needs to convert all the shapefiles into raster files with the Rasterize feature. After that, the set of shapefiles is added to the Probability Map feature as a list through Add button. The button Empty Raster allows the creation of a raster file with a matrix filled with 0s. This matrix is used when there are no fire occurrences in a year, and so it can be added to the list. The button Remove allows the removal of any file from the list. The input and output fields are identical to the other features.

### 3.1.5. Hazard Map

According to Merrill and Alexander (1987), the fire hazard describes the potential fire behavior without regard to the state of weather-influenced fuel moisture content, and/or resistance to fireguard construction for a given fuel type. This may be expressed in either the absolute or comparative sense. Such an assessment is based on physical fuel characteristics (e.g., fuel arrangement, fuel load, condition of herbaceous vegetation, and the presence of ladder fuels). The Hazard Map represents the probability of occurrence of several destructive phenomena in a certain time period. The forecast of forest fire risks can be achieved with the use of maps that allow preventing the cause. Hazard Maps are a tool to evaluate this phenomenon. According to the following equation, Hazard Maps are a result of the mathematical product of Probability and Susceptibility Maps.

$$\text{Hazard Map} = \text{Probability Map} \times \text{Susceptibility Map} \quad (2)$$

The Susceptibility Map contains the Slope Map and the land-cover information – CLC. The nomenclature of the Susceptibility Map is indicated in the following equation, which consists of the mathematical product of a numerical slope and a numeric (weight factor) land-cover value (see Table 4):

$$\text{Susceptibility Map} = \text{Slope Map} \times \text{CLC} \quad (3)$$

The Slope Map can be generated by Terrain Analysis feature and the CLC is available online for Portugal. However, the CLC can be in vector or raster format. If it is in vector format, the user has to convert to raster through the Rasterize feature. In this procedure, the initial extent values must be inserted, the correct attribute and the values must be verified, to ensure they are integers. Otherwise, a column must be created with the integer values. So, the three input files of Hazard Map feature are the Probability Map, the Slope Map, and CLC Map. This feature comprises four fields, where the last one defined the output directory, as shown in Figure 8 – right. The Reclassify button allows creating a classified map according to AFN rules. This command comprises two fields, namely the input file (Hazard

Map) and the output file (new classified map). The method used in the classification was the quantiles method. The color gradient is present in Figure 9.

In the code developed for this feature (Hazard.py), the `mquantiles` function of `scipy` (scientific tools for Python) was used. The `scipy` library together with the `numpy` library, which deals with arrays, allows for the manipulation of numbers and operations in a quick and easy way.

### 3.1.6. Risk Map

The risk should be understood as the sum (or integral) of probabilities of events times their corresponding costs. In order to complement the Hazard Map information on fires phenomenon, a forest fire risk map was also created. A Risk Map allows the evaluation of the potential loss in a certain hazard zone. According to AFN rules, the forest fire risk map is created multiplying the Hazard Map by the Potential Loss Map. The last one is created through the mathematical product of Vulnerability Map and the Economic Value Map.

The Vulnerability Map contains the values which represent the damage level of an element at risk and varies between 0 and 1. These values need to be added by the user to a shapefile that contains the land use.

The Economic Value Map contains the price, in euros, of the land for each pixel. This economic value allows for evaluating the money needed to recover the lost elements. These economic values and the vulnerability values are given by the local authorities and are public, such as CAOF (commission for monitoring of forest operations) tables, Gabinete de Planeamento e Política Agro-Alimentar (GPPAA) (accounts of the culture of vegetables) tables, government procurement, and decree-laws.

As shown in Figure 6 – left, there are three input files in this feature: the Hazard Map created in Hazard feature, the Potential Loss Map, and the Road Network Map (a shapefile with road information, which can be obtained from local authorities). The first input file was the unclassified Hazard Map already created in last feature. The second one, Potential Loss Map, was manipulated by the user. First, to calculate the vulnerability values, the CLC shapefile converted to a raster file was used with the potential damage as an attribute field and it was inserted in the second input field. Forest fire risk zoning requires integration of natural (topography) and anthropogenic factors, such as roads and settlements. So, the third input file is a Road Network Map which is manipulated like the CLC file. The result of forest fire risk map is generated by multiplying the three raster files described. The Reclassify button is identical to Hazard Map button and the color gradient used in the Risk Map is the same used for the Hazard Map and is presented in Figure 10. The result is a raster file.

### 3.1.7. Rasterize feature

This feature was created to convert vector files into raster files. This procedure is necessary in several operations. The Rasterize feature is composed of eight fields and considers as input a vector file which can be accessed through a directory or selected in a combo box. The second field allows to define the pixel size, which is 25 m according to AFN rules, but can be changed by the user. The next field selects the attribute to generate the raster vector. If the values in that attribute column are defined as a string, the user has to change them to integer values. The next four fields define the file extent ( $x$  minimum,  $x$  maximum,  $y$  minimum, and  $y$  maximum), which, in the project, must be the quoted point file extent. The last field is the output field (raster file).



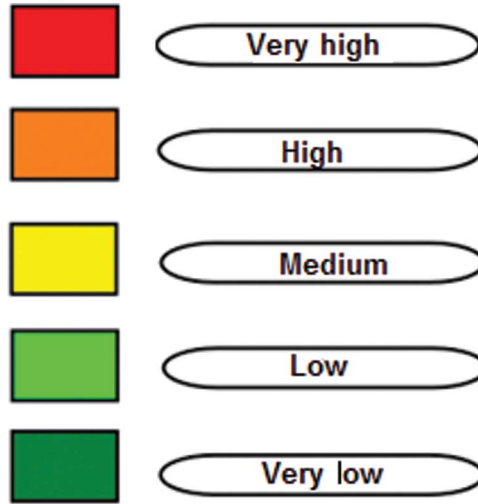


Figure 10. Hazard Map and Forest Fire Risk Map classes.

### 3.2. Forest fire risk model: Portuguese case

The methodology described in the previous sections was applied to three municipalities of the Norwest of Portugal – Santa Maria da Feira, Trofa, and Oliveira de Azeméis. In these municipalities, as in all the Portuguese municipalities, the forest fire risk maps were produced according to the Portuguese Forestry Authority rules and mainly developed in GIS proprietary solutions. The application developed in this work allowed to create, through a unique toolbar and using open source software, several thematic maps (Probability, Susceptibility, Hazard, Vulnerability) that can be used to produce the forest fire risk map. In this article, the results obtained for the Santa Maria da Feira municipality will be presented.

#### 3.2.1. Portuguese Forestry Authority

The Portuguese Forestry Authority objective is the forest and associated areas protection and preservation, encouraging the Portuguese forest resources development. The main targets of the Portuguese Forestry Authority are the protection against forest fires, the forest policy, and the forest management and protection. All the procedures described in this article are based on Portuguese Forestry Authority technical and methodological guides.

The evaluation of the forest fire risk cartography reinforces the need to clarify the concepts that determine the risk model adopted by Portuguese Forestry Authority, intending to establish a common basis for working production of these maps, and presents some benchmarks and common sources of information, which could achieve greater uniformity of results (not despite the natural and expected scale effects). This cartography is created in a municipality base, not allowing inter-municipality comparisons or generalizations for regional units. Finally, it is also important to alert to the differences between the Hazard Map (usually and incorrectly called Risk Map) and the Risk Map. Figure 1 presents the risk model adopted by the Portuguese Forestry Authority with the several steps. This model is used for all the Portuguese municipalities independently.

### 3.2.2. Hazard Map

As already stated in Section 3.1.5, hazard evaluation comprises probability and susceptibility. It is evaluated in time and space, through fire occurrence historic data, and through natural conditions in a certain zone, respectively.

The Probability Map incorporates the information on the number of fires that occurred in the last 15 years for each pixel. After, an annual average is calculated, in percentage, for each pixel. The probability is expressed as an annual average percentage, which means 'in this pixel, there will be a probability average annual of  $x\%$  that a fire occurs.' The following equation was used to calculate this annual probability for each pixel:

$$\frac{(f \times 100)}{\Omega} \quad (4)$$

where  $f$  represents the number of fire occurrences for each pixel, which is calculated as a sum of the fires considered in the time series and  $\Omega$  represents the number of years of the time series. The number of fire occurrences for each pixel ( $f$ ) is multiplied by 100 and the decimal part is ignored (in order to use integer values in the GIS analysis). Afterward, the raster is reclassified in order to give the same value (to 0) to the pixels that never burned or just burned once. This operation allows for eliminating fortuitous cases.

The susceptibility values allow to evaluate if each pixel is more or less propitious to fire occurrence. These values make possible the evaluation of hazard in space, according to the factors and circumstances in a certain area. As already referred in Section 3.1.5, the information needed to calculate these values is the Slope Map and CLC. The Slope Map classes, which are in accordance with the Portuguese Forestry Authority rules (DFCI 2008), are presented in Table 3.

Fuel type is important for characterization of fire behavior, fuel loading, and emission efficiency. Fuel type data can be generated from land-cover/land-use type. In this work, the land-cover/land-use information was obtained from the CLC. The CLC nomenclature is organized by classes, with weights that define the ease of soil burning. The CLC nomenclature is a document and can be obtained with a CLC file. According to CLC nomenclature, levels 2 and 3 are agricultural areas and forest and semi-natural areas, respectively. Levels 1, 4, and 5 are artificial surfaces, wetlands, and waterbodies, respectively. These areas are not propitious to fire occurrence. The CLC can be used when there is not any more detailed information. The CLC code values, levels 2 and 3, are used to classify the fire occurrence susceptibility. Table 4 presents the CLC classes and the correspondent weight factors and susceptibility indices.

### 3.2.3. Risk Map

The Risk Map comprises five classes, according to Portuguese Forestry Authority rules (DFCI 2008). The method used was the quantiles method (Wilcox 1997).

Table 3. Slope classes.

Slope (%)	Weight factor	Slope index
0–5	2	Very low
5–10	3	Low
15–20	4	Medium
15–20	5	High
>20	6	Very high

Table 4. CLC classes.

CLC classes	Weight factor	Susceptibility index
212, 213, 221, 222, 241, 331	2	Low susceptibility
211, 223, 231, 242, 244	3	Medium susceptibility
243, 311, 312, 313, 321, 322, 323, 324, 332, 333, 334	4	High susceptibility

The potential loss allows determining which elements must be protected, according to vulnerability and economic value of each element.

The vulnerability scale comprises five classes, ranging between 0 and 1. The elements with value 1 suffer total loss and the elements with value 0 do not suffer any damage (Table 5).

The economic value is the price, in euros, and can be achieved in public tables. After loss or destruction of an element, these values allowed for quantifying the investment needed to recover the element. Table 6 presents the vulnerability value and the economic value for some elements. Figure 11 presents the maps produced through the GIS open source application developed.

#### 4. Discussion and conclusions

The Hazard Map, that combines the probability and the susceptibility, represents the potential of a land for the fire occurrence. This map is particularly indicated for prevention actions. The Risk Map combines the hazard component with the potential loss component (vulnerability and economic value) in order to quantify the degree of loss after a fire event.

Table 5. Vulnerability weights.

Vulnerability weights	Description
0	The element is not affected
0.25	The element is slightly affected but does not need repairs
0.50	The element is affected and needs a slight repair
0.75	The element is severely affected and needs deep repair
1	The loss is total, the element is irreversibly affected requiring rebuild or replacement

Table 6. Vulnerability and economic values for some elements considered.

Element	Vulnerability weights	Economic value <sup>a</sup>
Resinous trees	1.00	€84/ha
Built for commerce, industry, and services	0.75	Not indicated
Built for houses (zones I, II, and III)	0.75	€741/ha, €648/ha, €587/ha
Eucalyptus	0.75	€136/ha
Holm oak	0.50	€112/ha
Cork	0.50	€618/ha
Roads	0.25	Not indicated

<sup>a</sup>Reference values are given in DFCI (2008).

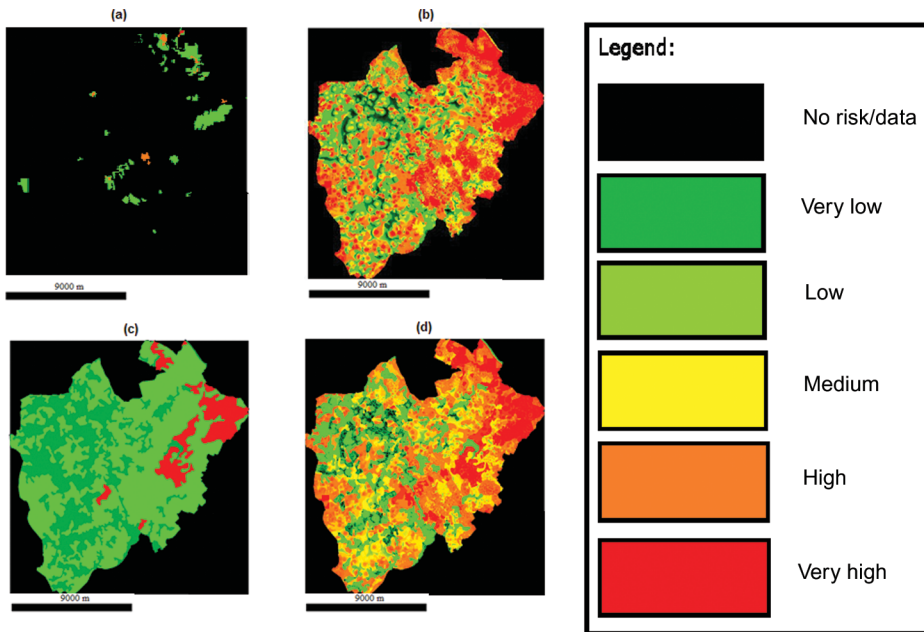


Figure 11. Maps produced for the Santa Maria da Feira municipality: (a) Probability Map, (b) Hazard Map, (c) Potential Loss, and (d) Forest Fire Risk Map.

The forest fire risk model presented in this article provides not only the Risk Map, but also the Hazard Map. These two maps can be used together in order to better understand and prevent the fires occurrence. However, this model does not provide the capacity of modeling future conditions or incorporate different variables. Even so, as an open source application, it can be modified by any user that wants to adapt this application to another case study and incorporate other variables or different weights. Beyond being an open source application, this application may be faster and easier when compared with the GIS proprietary solutions that usually comprise several steps and the use of different software extensions.

In order to compare the performance of the application developed, the forest fire risk map procedures described in this article were carried out in two different software projects: in a GIS proprietary software and through the open source tools developed within this application in QGIS. These procedures were performed in the same environment: same computer, same CPU (Intel® Core™ 2 Duo CPU T8300 @ 2.40 GHz (2 CPUs) ~2.4 GHz), same memory (3262 MB RAM), and same operating system (Windows Vista™ Home Premium 6.0). In both cases, a Hazard Map and a Risk Map were created following the AFN rules (DFCI 2008) and clocked all the procedures (Table 7). Several conclusions can be drawn by analyzing the results presented in Table 7. The total time recorded does not include the conversion of the burnt areas to raster. The total value obtained with the proprietary software was 11' 3.82", better than 23' 12.80" obtained with this open source tool. This difference is explained due to the GRID feature developed which takes a long time to process (around 19 min). This feature was developed based on GdalTools, a set of programs used in GIS plug-ins. QGIS has a plug-in named Raster that provides these buttons. GRID is one of them and was used in the application. Without the GRID feature, the total processing time recorded was 10' 4.21" in the proprietary solution and 4' 9.74" with this application. The main cause of this time reduction is due to the processing time taken in

Table 7. Hazard Map and a Risk Map time requirements.

Procedure	Processing time	Time (s)	
		ArcGIS	QGIS
GRID	TIN	24.09	1143.06
	GRID.ESRI grid	25.80	
	GRID.tif	9.72	
	Total (GRID)	59.61	1143.06
Slope Map	Slope Map	22.96	6.49
	Reclassified Slope Map + Gradient palette	78.87	12.07
	Total (Slope Map)	101.83	18.56
Probability Map	Raster file creation filled with 0s <sup>a</sup>	$32.86 \times 3 = 98.58$	$23.18 \times 3 = 69.54$
	Reclassified burnt areas	257.14	72.19
	Probability calculation <sup>b</sup>	62.44	
	Total (Probability Map)	418.16	141.73
Hazard Map	Hazard Map	22.13	48.08
	Reclassified Hazard Map + Gradient palette	22.56	12.67
	Total (Hazard Map)	44.69	60.75
Risk Map	Risk Map	21.94	15.70
	Reclassified Risk Map + Gradient palette	17.59	13.00
	Total (Risk Map)	39.53	28.7
Rasterize <sup>c</sup>	Convert to Raster (Rasterize)	30.56	46.55
Total <sup>d</sup>	Total (with GRID creation)	663.82	1392.80
	Total (without GRID creation)	604.21	249.74

<sup>a</sup>Empty Raster (QGIS).

<sup>b</sup>Fórmula – Raster Calculator (ArcGIS).

<sup>c</sup>Tested on one file.

<sup>d</sup>Without conversion of burnt areas to raster file.

Probability Map creation. According to Table 7, an expert operator creates a Probability Map in 6' 58.16" in the GIS proprietary solutions. Using this open source application, the time spent was reduced to 2' 21.73". The main cause for this time reduction is related to the raster reclassification. In the proprietary GIS software, the raster reclassification procedure is done manually file by file, and in this open source solution this procedure is automated.

The performance of this open source solution was also evaluated in the GRID creation, when the number of quoted points was reduced to 50% of total points (Table 8). The results presented in Table 8 are very interesting and allow us to conclude that the number of quoted points used in the GRID creation did not interfere with the time procedure in the GIS proprietary solutions. Instead, in the open source solution, the time procedure was reduced to 50% when the number of quoted points used was also reduced to 50%. The GRID

Table 8. GRID processing time.

Procedure	Processing time	Time (s)	
		ArcGIS	QGIS
GRID ( $\approx$ 50% of quoted points)	TIN	24.09	1143.06
	GRID.ESRI grid	25.80	
	GRID.tif	9.72	
	Total (GRID)	59.61	1143.06
GRID (100% of quoted points)	TIN	20.53	2102.60
	GRID.ESRI grid	26.41	
	GRID.tif	9.73	
	Total (GRID)	56.67	2102.60
	File size	ESRI GRID/TIF 2.34 MB/2.62 MB	TIF 4.57 MB

creation was incorporated into this application, but it is not a prerequisite of the Risk Map model because most of the municipalities have this information (GRID file) *a priori*. This button was performed to complement/improve this application and for the uncommon case where the GRID is not already available.

This work aims to develop an open source application to create forest risk maps required for all the Portuguese municipalities. It was not, nor could it be our intention, to validate or check the accuracy of the generated maps. This procedure should be performed by the competent authorities (Portuguese Forest Authority).

In future versions of this application, we intend to produce the forest risk maps according to INSPIRE data specifications (<http://inspire.jrc.ec.europa.eu/>). The INSPIRE directive aims to create a European Union spatial data infrastructure. The INSPIRE directive came into force on May 2007 and will be implemented in various stages, with full implementation only required by 2019.

This application has a great potential of application for other places. It can be directly used in Portugal and could be easily adapted to the rules of other countries. The code is open and can be modified according to the user requirements. Other advantage in publishing the plug-ins and the application code is the possibility of other users to improve this application (available at ([http://www.fc.up.pt/pessoas/amteodor/QGIS/Forest\\_Fire\\_Risk.rar](http://www.fc.up.pt/pessoas/amteodor/QGIS/Forest_Fire_Risk.rar))). This is the basic idea of the open source.

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### References

- Abhineet, J., *et al.*, 1996. Forest fire risk modelling using remote sensing and geographic information system. *Current Science*, 70, 928–933.
- Barber, C.B., Dobkin, D.P., and Huhdanpaa, H.T., 1996. The Quickhull algorithm for convex hulls. *ACM Transactions on Mathematical Software*, 22, 469–483.
- Bisquert, M.M., Sánchez, J.M., and Caselles, V., 2011. Fire danger estimation from MODIS enhanced vegetation index data: application to Galicia region (north-west Spain). *International Journal of Wildland Fire*, 20, 465–473.

- Castro, R. and Chuvieco, E., 1998. Modeling forest fire danger from geographic information systems. *Geocarto International*, 13, 15–23.
- Chou, Y.H., 1992. Management of wildfires with a geographical information system. *International Journal of Geographical Information Science*, 6, 123–140.
- Chuvieco, E. and Congalton, R.G., 1989. Application of remote sensing and geographic information systems to forest fire hazard mapping. *Remote Sensing of Environment*, 29, 147–159.
- Chuvieco, E. and Salas, F.J., 1996. Mapping the spatial distribution of forest fire danger using GIS. *International Journal of Geographical Information Science*, 10, 333–345.
- Chuvieco, E., *et al.*, 2010. Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, 221, 46–58.
- Deng, Y., *et al.*, 2007. Multi-scale linkages between topographic attributes and vegetation indices in a mountainous landscape. *Remote Sensing of Environment*, 11, 122–134.
- DFCI, 2008. *Plano Municipal da Defesa da Floresta Contra Incêndios* [online]. Technical Report. Available from: <http://www.afn.min-agricultura.pt/portal/dudf/gtfs/planeamento-dfci-municipal/guia-metodologico-para-a-elaboracao-do-pmdfci> [Accessed 22 February 2011].
- ESRI, 2008. *GIS dictionary* [online]. Available from: <http://support.esri.com/index> [Accessed 11 October 2011].
- Flannigan, M., Stocks, B., and Weber, M., 2003. Fire regimes and climatic change in Canadian forests. In: T.T. Veblen, W.L. Baker, G. Montenegro, and T.W. Swetnam, eds. *Fire and climatic change in temperate ecosystems of the Western Americas*. *Ecological Studies*, vol. 160, New York, NY: Springer, 97–119.
- gvSIG, 2011. *gvSIG asociación* [online]. Available from: <http://www.gvsig.org/web/> [Accessed 11 February 2011].
- Hugentobler, M., 2008. Quantum GIS. In: S. Shekhar and H. Xiong, eds. *Encyclopedia of GIS*. New York: Springer, 171–188.
- Johnson, E.A., 1992. *Fire and vegetation dynamics: studies from the North American boreal forest*. Cambridge: Cambridge University Press.
- Kosmo, 2011. *Kosmo, La Plataforma SIG – Libre Corporativa* [online]. Available from: <http://www.opengis.es/> [Accessed 12 February 2011].
- Merrill, D.F. and Alexander, M.E., 1987. *Glossary of forest fire management terms*. Ottawa, ON: National Research Council of Canada, Committee for Forest Fire Management.
- Nourbakhsh, I., *et al.*, 2006. Mapping disaster zones. *Nature*, 439, 787–788.
- OSI, 2011. *Open Source Initiative* [online]. Available from: <http://www.opensource.org/> [Accessed 16 February 2011].
- Python, 2011. *Python Programming Language* [online]. Available from: <http://python.org/> [Accessed 21 February 2011].
- QGIS, 2011. *Quantum GIS Project* [online]. Available from: <http://www.qgis.org/> [Accessed 11 February 2011].
- Stallman, P., 2007. *Why ‘Open Source’ misses the point of free software* [online]. GNU Operating System. Available from: <http://www.gnu.org/philosophy/open-sourcemisses-the-point.html> [Accessed 02 February 2011].
- Steiniger, S. and Bocher, E., 2009. An overview on current free and open source desktop GIS developments. *International Journal of Geographical Information Science*, 23, 1345–1370.
- Swetnam, T.W., 1993. Fire history and climate change in giant sequoia groves. *Science*, 262, 885–889.
- Teodoro, A.C. and Duarte, L., 2011. Forest fire risk maps in a GIS open source environment for Norwest of Portugal. Advances in remote sensing and GIS applications in forest fire management. From local to global assessments. In: J.S.-M. Ayanz, I. Gitas, A. Camia, and S. Oliveira, eds. *Proceedings of the 8th international EARSeL FF-SIG workshop, Stresa (Italy)*, Ispra, VA: European Commission, Joint Research Centre, Institute for Environment and Sustainability, 65–69.
- Van Wagner, C.E., 1977. Effect of slope on fire spread. *Canadian Forest Services, Bi-Monthly Research Notes*, 33, 7–8.
- Vasconcelos, M.J.P., *et al.*, 2001. Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. *Photogrammetric Engineering & Remote Sensing*, 67, 73–83.
- Wilcox, R.R., 1997. *Introduction to robust estimation and hypothesis testing*. Waltham, MA: Academic Press. ISBN: 978-0127515458
- Yool, S.R., *et al.*, 1985. Describing the brushfire hazard in southern California. *Annals of the Association of American Geographers*, 75, 417–430.