Journal of Environmental Management 173 (2016) 65–71

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Applying GIS to develop a model for forest fire risk: A case study in Espírito Santo, Brazil

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ARTICLE INFO

Article history:
Received 26 November 2014
Received in revised form
11 February 2016
Accepted 13 February 2016
Available online 11 March 2016

Keywords:
Risk map
Environmental preservation
Geotechnology

ABSTRACT

A forest fire risk map is a basic element for planning and protecting forested areas. The main goal of this study was to develop a statistical model for preparing a forest fire risk map using GIS. Such model is based on assigning weights to nine variables divided into two classes: physical factors of the site (terrain slope, land-use/occupation, proximity to roads, terrain orientation, and altitude) and climatic factors (precipitation, temperature, water deficit, and evapotranspiration). In regions where the climate is different from the conditions of this study, the model will require an adjustment of the variables weights according to the local climate. The study area, Espírito Santo State, exhibited approximately 3.81% low risk, 21.18% moderate risk, 30.10% high risk, 41.50% very high risk, and 3.40% extreme risk of forest fire. The areas classified as high risk, very high and extreme, contemplated a total of 78.92% of heat spots.

1. Introduction

Forest fires are a recurring problem in forests worldwide, and information on the spatial distribution of fires is necessary to improve fire prevention strategies and tactics (Tian et al., 2013). The spatial scale of analysis for fire occurrence may provide new information to guide planning efforts and reduce the risk of fire (Yang et al., 2007).

Controlled burning is typically adopted by rural landowners in developing countries to clean sites for pasture renewal. However, the incorrect planning and execution of controlled burns can result in a loss of control within the burned region, thus resulting in forest fire (FAO, 2006).

Several measures for preventing and combating fires have been adopted to minimise the negative effects of fire. According to Oliveira (2002), fire risk zoning is a basic element required in planning for the protection of forested areas.

According to Ferraz and Vettorazzi (1998), several measures that utilise information obtained from risk maps may help reduce fire occurrence, including higher surveillance in the at-risk areas, restricted access to these sites, construction of firebreaks, reorganisation of management practices, and aid in firefighting, which includes the construction of roads for faster access to at-risk sites and resource allocation for firefighting at strategic points.

A fire risk zone is defined based on the cause of ignitions and pattern of their occurrence, and it is identified by common environmental characteristics that translate into the same risk potential. The final stage of zoning is the overlaying of several maps that define the areas according to the level of risk as a function of the weighted sum of the partial risks of each previously analysed variable (Batista, 2000). Site planning tools are created and used as "automators" for preparing zoning maps through remote sensing combined with a geographic information system (GIS) (Encinas, 2000).

Researchers have used diverse methods to develop forest fire risk zoning maps that link a region's environmental factors with the potential for forest fires, thus enabling risk potential mapping

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http://dx.doi.org/10.1016/j.jenvman.2016.02.021
0301-4797/

according to the sensitivity of the analysed factors related to fire. Liu et al. (2012) modelled fire occurrence in boreal forests in Northeastern China from 1965 to 2009, Renard et al. (2012) worked with hierarchical levels to evaluate fire susceptibility for the Western Ghats of India, Yang et al. (2007) analysed the effects of land cover, topography, roads, etc. on fire occurrence in the Missouri Ozark Highland, Díaz-Delgado et al. (2004) analysed the spatial patterns of fire occurrence in Catalonia (NE Spain) from 1975 to 1998, and Chou et al. (1993) constructed a model to determine the probability of forest fire occurrence in the San Jacinto Mountains, California, USA. Oliveira (2002) suggests that the best weighting model is defined according to the conditions of local fire occurrence and considers the importance of each variable according to the study area.

The main goal of this study was to develop a statistical model for preparing a forest fire risk map using GIS. This model assigns weights to nine variables, chosen by the practicality of its application and direct relation to the occurrence of forest fires, divided into two classes: physical factors of the site (terrain slope, land-use/occupation, proximity to roads, terrain orientation, and altitude) and climatic factors (precipitation, temperature, water deficit, and evapotranspiration).

2. Materials and methods

2.1. Physical aspects of the study area

The study area is Espírito Santo State, Southeastern Brazil, with a land area[1] of 46,052.64 km^2, which is located between 17°53′29″ and 21°18′03″ S latitude and 39°41′18″ and 41°52′45″ W longitude, and it borders the Atlantic Ocean to the east, Bahia State to the north, Minas Gerais State to the west, and Rio de Janeiro State to the south. The state has four climate types according to the Köppen classification: Cwb, a subtropical highland climate with dry winters and mild summers that is found in the state's mountainous region; Cwa, a subtropical climate with dry winters and hot summers that is found in the state's southwestern region; Am, a humid or subhumid tropical climate that is found in the state's northeastern region; and Aw, a tropical climate with dry winters that is found in the state's western region.

2.2. Development of methods for mapping fire risk

The following methodological steps were necessary for mapping forest fire risk in Espírito Santo (FFR-ES).

2.2.1. Digital elevation model

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM) was used to map the terrain; according to Ferrari (2012), this model better represents the altitudes of the relief, reveals a higher correlation with the altitudes measured in the field, and has a lower mean square error.

The ASTER DEM is composed of a grid of cells with spatial resolution of 30 m based on the Global Elevation Digital Model (GEDM) of ASTER, which has been provided by the File Transfer Protocol (FTP) server of the United States Geological Survey (USGS). This model is available in GeoTiff format, and it can be directly used in modelling terrain that is georeferenced to Datum WGS 84 in decimal geographic coordinates and referenced to the Earth Gravitational Model 1996 (EGM96) geoid undulation.

2.2.2. Preparation of the meteorological data

The consistency of the meteorological data was verified based on a 34-year historical series (1977–2011) from 110 stations within Espírito Santo State and its surroundings (Fig. 1). Small errors in the monthly or annual precipitation series were found for certain stations, and they were corrected by applying the regional weighting method.

The data obtained from the 110 stations were used to calculate the climatological water balance using the method by Thornthwaite and Mather (1955) via the “BHnorm” program, which was prepared in a Microsoft Excel® spreadsheet by Rolim et al. (1998). A 100-mm value was used for the available water capacity (AWC), and the potential evapotranspiration (PET) was estimated using the method by Thornthwaite (1948). The water balance provides estimates for the real evapotranspiration (RET), water deficit (DEF), water surplus (SUR), and water storage in the soil (STO).

After calculating the water balance, data from the stations were integrated into a point shapefile. Each point was spatialised according to their geographical coordinates onto a universal transverse mercator (UTM) projection in the SIRGAS 2000 ellipsoid zone 24 K.

2.2.3. Generation of base maps

In this step, base maps were prepared and integrated into the statistical model for forest fire risk. The maps were independent from the model because each variable affect the occurrence of forest fires in a particular way. The classes and the weights were distributed in consonance with amounts already described in the literature. For variables not found in the literature, the weights were determined in discussions with researchers. The nine variables that were studied and spatialized in matrix format are as follows:

a) Precipitation: The annual means were interpolated for the study area using the exponential kriging method, which produced a satisfactory correlation between the real and estimated values and the lowest mean square error compared with the other interpolation methods that are commonly used.

A reclassification was performed based on the matrix image in reference to the study area's mean annual precipitation to obtain a new matrix file containing five classes (Table 1) that correspond to the following risk levels: low, moderate, high, very high, and extreme. A weight that indicated the level of risk was assigned to each class.

b) PET: The annual means were extracted from the water balance and interpolated for the study area using the spherical kriging method, which produced a satisfactory correlation between the real and estimated values and exhibited the lowest mean square error compared with the other interpolation methods commonly used.

A reclassification was performed based on the matrix image in reference to the mean annual PET for the study area to obtain a new matrix file containing five classes (Table 2). A weight indicating the level of risk was assigned to each class.

c) Water deficit: The annual means were extracted from the water balance and interpolated for the study area using the spherical kriging method, which produced a satisfactory correlation between the real and estimated values and the lowest mean

[1] This state's land area was slightly modified from what was initially presented in this study because of the "sawteeth" that were formed by the matrix image used for calculating fire risk.