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Geographical information system-based forest fire risk assessment integrating national forest inventory data and analysis of its spatiotemporal variability

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ABSTRACT

Improvements in forest fire risk estimation and mapping fire risk zones are vital to reduce the negative impacts of fire and to facilitate planning for the protection of forested areas. This is especially important for places with little previous data on fire history. This paper presents an improved conceptual scheme for the assessment and mapping of fire risk using a Forest Resource Inventory Database, based on four aspects of topographical, human activity, climate, and forest characteristics factors. We selected 12 variables based on our defined conceptual scheme to generate a synthetic forest fire risk index (FRI) to quantify potential forest fire risk and map risk zones in the Wuyishan Scenery District (WSD), a world heritage site that located in the northwest of Fujian province, People's Republic of China. Spatial statistics were used to examine the spatio-temporal variation of FRI. The results showed the main fire risk zones in the WSD were in the low or moderate categories (accounting for 76.7% of the total area of the WSD in 1997 and 79.2% in 2009). The spatial heterogeneity of FRI showed anisotropic variability characteristics which changed over time. From 1997 to 2009, there was an increasing influence from both autocorrelation factors and random factors. Moreover, these factors played almost equally important roles in forest fire processes in the WSD. The fire risk map was applied to assess the vulnerability of cultural heritage resources in the WSD. Most were located in low- or moderate-risk areas, and therefore would be at low risk from potential fire damage.

1. Introduction

Forest fires play a critical role in landscape transformation, vegetation succession, soil degradation, and air quality. Spatial estimation of forest fire risks has become increasingly significant for the protection of forest resources and fire management at different spatial and temporal scales (Wu et al., 2015). Fire risk zoning is a basic element required in planning for the protection of forested areas. Currently, building probabilistic models of fire occurrence and usage of fire behavior modeling tools are two main ways to map risk zones of a forest fire and simulate its evolution in a certain area (Finney, 2004, 2005; Chuvieco et al., 2014). The former is easily restricted to historical numbers or probabilities of discovered ignitions in the targeted study area. The widespread use of the latter case is often limited in regions or countries where basic scientific research in forestry are underdeveloped due to strict requirements for model parameters, even if this approach integrated by fire behavior modeling tools has been well used in North America regions where researches on forest fires or wildfire have been well developed.

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). Information on the spatial distribution of fires is necessary to improve fire prevention strategies and tactics (Tian et al., 2013). As a result, for sites where both methods mentioned above cannot be applied, geographical information system-based (GIS-based) forest fire risk assessment could be an alternative way. And this method have been used to develop forest fire risk zoning

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maps that link region's environmental factors with the potential for forest fires, thus enabling the mapping of risk potential in different types of ecosystem (Shinneman et al., 2012; Helfenstein and Kienast, 2014; Hernandez-Leal et al., 2006; Lira et al., 2012). However, for previous studies of GIS-based forest fires, little attention has been done to integrate natural forest features as an indicator to assess forest fire risk and map risk zones. Moreover, we still need more evidence to facilitate a better understanding of the spatial and temporal varation in the risk of forest fires.

The main goal of this study was to develop an improved conceptual scheme for fire risk mapping and further explore the spatio-temporal variability for forest fire risk with landscape change, using the Wuyishan Scenery District (WSD), a world heritage site, as a case study. Specific objectives were to: (1) establish a conceptual frame for fire risk mapping, integrating the Forest Resource Inventory Database (FRID) in sites where there is a shortage of fire-related research data; (2) quantify the potential forest fire risk and map risk zones; and (3) examine the spatio-temporal variation of forest fire risk.

2. Materials and methods

2.1. Study area

Located in the northwestern part of Fujian Province, Mount Wuyi is the most outstanding area for biodiversity conservation in Southeast China and provides a refuge for a large number of ancient relictual species, many of them endemic to China. In December 1999, Mount Wuyi was included on the World Natural and Cultural Heritage List by the 23rd Session of the World Heritage Committee of UNESCO. The WSD covers an area of approximately 70 km^2 (117°35′–118°01′E, 27°35′–27°43′N), and forms the core tourist region of Mount Wuyi, as it has a wealth of natural and cultural heritage resources (see Fig. 1a). The WSD is a hilly area with an altitude ranging from 100 to 800 m. The climate is a typical, subtropical humid monsoon system. The annual average temperature is 17.9 °C and average annual precipitation is >2000 mm. There are many cultural heritage resources, such as the Edo Neo-Confucianism culture, religious culture, tea culture, cliff inscriptions, ancient buildings, and ruins, in the WSD.

The forest ecosystem forms an important landscape element in the WSD and accounts for nearly 62% of the total area. *Pinus massoniana* is a dominant tree species, covering more than half of the WSD, and plays an important role in maintaining the health of forest ecosystems in the WSD (You et al., 2011). As an evergreen, *P. massoniana* also forms a flammable forest community (Chen et al., 1995). Since 1999, few forest fires have occurred because management plans were implemented to conserve this world heritage site. Only one recent fire event has happened in the WSD with a minor burned area of 300 m^2 in 2003 due to lightning strikes. This has resulted in a lack of basic data for forest fires. However, between 1985 and 2009, climate data in the WSD showed a rise in the annual average temperature, an increase in the frequency of droughts, and a reduction in the annual average precipitation level (see Fig. 2a–c). The probability of higher temperatures, more droughts, and a drier climate increases the potential risk of forest fires (Amraoui et al., 2015; Sun et al., 2014). Furthermore, more activity from local residents and visitors in the WSD creates frequent human disturbance (Fig. 2d), which is more likely to lead to a fire-prone forest ecosystem in the region (Wu et al., 2014). These factors make it necessary to undertake research into forest fire risk in this susceptible and important world heritage site.

2.2. Data selection

According to the availability of data and actual situation of WSD, we selected both 1997 and 2009 to do this study based on these following reasons: (1) the year of 1997 was a crucial year during the stage of development of WSD. In 1997, the local government and stakeholders started to apply for the qualification of being including on World Heritage List (Mount Wuyi inscribed on World Heritage List in 1999). Then, a series of improved planning and new policies were implemented to facilitate the process of application for a heritage site. WSD experienced the fastest development of local economy and tourism in the next decade after 1997 so that land cover and landscape structure in WSD were altered and transformed obviously. (2) A time span is too short to

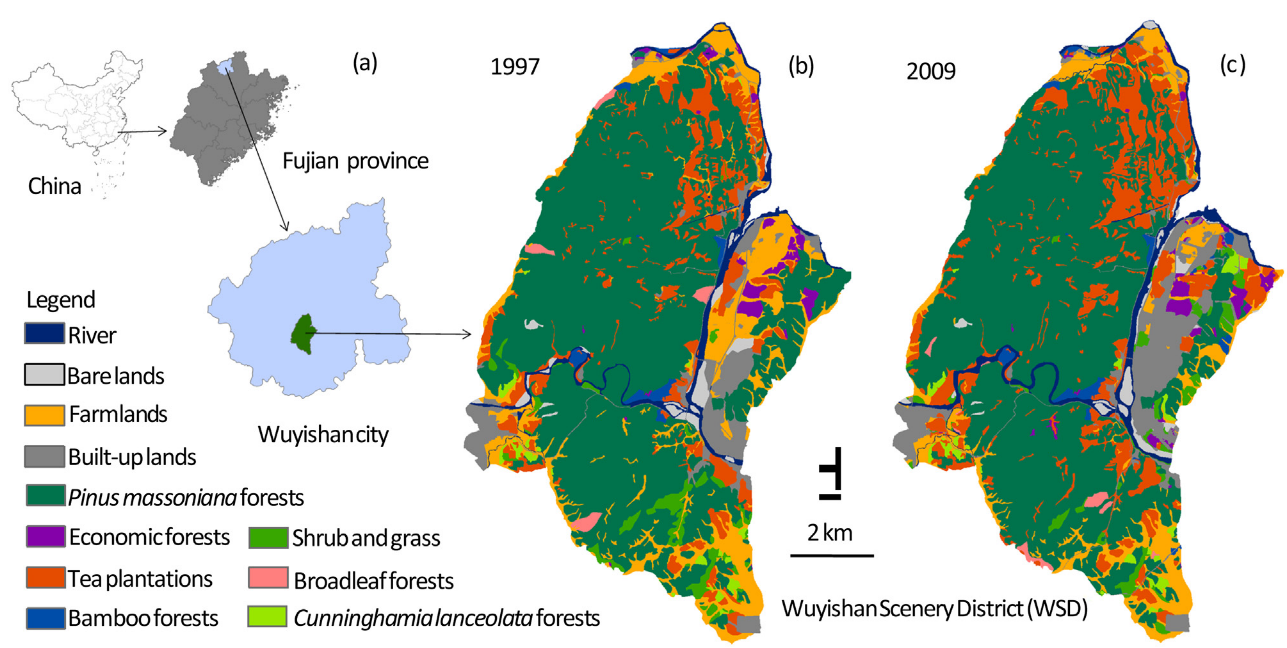

Fig. 1. Location of study area (a), its classification map in 1997 (b) and in 2009 (c).
Source: Authors' elaboration according to previous research mapping (You et al., 2011).