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Understanding fire patterns and fire drivers for setting a sustainable management policy of the New-Caledonian biodiversity hotspot

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ABSTRACT

New Caledonia (NC) is a biodiversity hotspot sheltering terrestrial ecosystems of high ecological and conservation value including tropical dry forests, rainforests, and maquis. However, uncontrolled bushfires threaten this exceptional biodiversity. A science-based fire management policy could reduce the impact of unwanted fires and help facing climate change. However, to date, data on the location, extent, causal factors and spatial patterns of fires had not been collected. We compiled a 13-year-long (1999–2011) spatially-explicit fire database for NC using MODIS and Landsat data. Using boosted regression trees we disentangled the role of anthropogenic factors, physiography, weather and vegetation on fire activity. We also characterized the location of fires and the vegetation composition at the fire edges, in order to determine which ecosystems were especially vulnerable. Fire size distribution was typically asymmetric with many small fires (<10 ha) and very few large fires (>500 ha). Ignitions were preferentially located close to villages, cities or roads, at low elevation and linked to high values of fire weather index. Fires were larger at the end of the dry season and during El Niño events. Most fires were bushfires burning in savannas, thickets and maquis, while rainforests were rather 'avoided' by fire. However, bushfires generally propagated towards forests of high-conservation value, thus increasing the potential for forest edge erosion. As savanna-forest and maquis-forest mosaics are dominant in the landscape, we discuss the extent to which NC could become a 'fire trap' where fire cannot be easily extirpated. Based on our spatially-explicit information on fire activity, we make recommendations for a sustainable forest and fire management policy which would balance the traditional use of fire and the conservation of the most valuable ecosystems. In particular, it may help by reducing the damages of large and destructive bushfires ignited during drought peaks.

1. Introduction

New Caledonia (NC, southwest Pacific, −21°S, 165°E) has long been recognized as a remarkable biodiversity hotspot (Myers, 1988; Myers et al., 2000; Mittermeier et al., 2004) harboring terrestrial ecosystems of high ecological and conservation value (Jaffré et al., 1998), encompassing tropical dry forests, rainforests, and maquis (shrublands). About 75% of the 3371 plant species of NC are endemic (Morat et al., 2012). However, fires and other disturbances have destroyed more than 50% of the original vegetation existing before the Melanesian settlement (ca. 3000 BP). Original rainforest, dry forest and maquis have been partly converted into secondary vegetation, mainly savannas, secondary thickets and maquis (Jaffré et al., 1998). Nowadays, a major concern is to what extent the present fire regime may threaten this exceptional flora (Jaffré et al., 1998; Pascal et al., 2008). It is acknowledged worldwide that science-based fire management policies can reduce the impact of unwanted fires and help facing climate change and uncertainties (e.g. FAO, 2007; van Wilgen et al., 2014). However, to date, no georeferenced database exists in NC and fire distribution, drivers and impacts on ecosystems are poorly known.

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Fire has driven vegetation dynamics for millennia in NC as in many tropical countries (Cochrane, 2003; Bond, 2005) because it is both a natural disturbance and a management tool. Palaeoecological records suggest that fires occurred long before the human settlement of NC (ca. 3000 BP, Hope and Paske, 1998; Stevenson, 2004), with alternating periods of drought with more frequent fires promoting the expansion of shrubland (so-called maquis) on ultramafic rocks, and wetter periods with few fires characterized by rainforest expansion and the establishment of secondary forest (McCoy et al., 1999). The increase of fires since settlement of humans had major implications for the landscape of NC. First, it coincided with the sudden expansion of savannas (McCoy et al., 1999; Stevenson, 2004). Savannas, probably maintained by fire and grazing, currently cover 30% of NC and have replaced large areas of dry forest and rainforest (Gillespie and Jaffre, 2003; Ibanez et al., 2013). Second, on the ultramafic substratum, wildfires combined with forest explotation and mining has led to the replacement of most original forests by secondary forests (Jaffre et al., 2010) and shrubby vegetation in recent decades. Presently, fires threaten some endemic conifer species (Perry and Enright, 2002; Jaffre et al., 2010) but also species typical of the dry forest (Bocquet et al., 2007). In this context, bushfires (i.e. fires originating in grasses, maquis, thickets or secondary forests) constitute one of the main threats to NC biodiversity in the future (Jaffré et al., 1998; Pascal et al., 2008). Indeed, large and uncontrolled bushfires such at the *Montagne des Sources* (December, 2005) can burn thousands of hectares of maquis and forests. This has dramatically increased the concerns of decision-makers about biodiversity conservation, as the ongoing climate change could also increase fire activity (Leblon, 2005).

In this context, it was increasingly urgent to collect accurate and extensive data on recent fires in NC to focus fire management efforts on the most valuable ecosystems that are at risk. Until now, the exact boundaries of most fires were unknown and limited information about fires has come from time-consuming studies of fire scars on trees (e.g. McCoy et al., 1999) and contemporary newspaper reports (e.g. Chevalier, 1996). Burned areas and fire hotspot datasets now available from satellite observations (such as MODIS; Roy et al., 2008) and Landsat provide information at short time intervals and offer data to characterize fire patterns. Characterizing the major causes and locations of fire ignitions, as well as the extent, pattern and location of burned areas are key issues for the long-term management and conservation of many types of ecosystems throughout the world (e.g. Bergeron et al., 2002; Keeley, 2002; Andersen et al., 2005; Bond, 2005). Actually, the spatial pattern of fires in the landscape results from interactions between several top-down and bottom-up factors which drive fire ignition and fire spread (Falk et al., 2007). They include anthropogenic drivers (ignitions, fire prevention and fire suppression) and biophysical factors such as fire weather, vegetation, and topography (e.g. Rothermel, 1983; Badia-Perpinya and Pallares-Barbera, 2006; Moreira et al., 2011). In NC fire ignition is predominant due to human activity (Perry and Enright, 2002), and lightning fires are rare as in many tropical areas (Stott, 2000; Cochrane, 2003). Anthropogenic fires are started for a variety of reasons including range management, land clearance for cultivation, hunting and combating wild pigs, controlling weeds, limiting the populations of the invasive little fire ant *Wasmannia auropunctata*, and as a result of social conflicts (Udo, 2011; Dumas et al., 2013). It is likely that large fires may result from ignitions by livestock breeders in grasslands to eliminate invading shrubs and trees, while most small fires in mountainous areas may be lit for cultivation purpose. Some fires may get out of control and become very large particularly when lit during prolonged or intense dry spells, on steep slopes, in areas difficult to access, or when firefighting resources are overwhelmed. Many studies worldwide have shown the ‘preference’ or the ‘avoidance’ of fires for certain types of vegetation or certain topographic features (Viedma et al., 2009; synthesis *In* Moreira et al., 2011). This selectivity results from the non-random location of anthropogenic ignitions and from the local variations of physiography, fire weather, and vegetation’s composition and moisture content (Leblon, 2005). Assessing the drivers of and the spatial pattern of ignitions is crucial for fire prevention and pre-positioning of firefighters, while assessing the drivers of burned areas has implications for fire suppression and adapting land management practices.

In this study we constructed the first georeferenced fire database for NC (1999–2011) using several remote sensing sources (MODIS, Landsat). We also collected georeferenced information on anthropogenic and environmental drivers, and on fire weather. Using these databases, we characterized the spatial and seasonal pattern of fires and we identified which factors explained the ignitions versus the extent of burned areas. We finally sought to determine the extent to which NC forests of high ecological and conservation value were affected by bushfires ignited in flammable secondary vegetation (savannas, maquis and thickets) by analyzing the contacts between those vegetation types along the fire edges. Our final goal is to help improve the present fire management policy for biodiversity conservation.

2. Materials and methods

2.1. Study area

New Caledonia is an archipelago of ca 18,500 km^2 located in the southwest Pacific (21°30 S, 165°30 E); it has a subtropical oceanic climate with a mean air temperature of 23 °C (Caudmont and Maitrepierre, 2006). Mean annual rainfall ranges from 850 to 4500 mm, with considerable spatial variation: the windward east coast is much wetter than the leeward west coast. Temperatures and rainfall also vary seasonally, with a dry season from May to November, which corresponds roughly to the main period (i.e. August to December) of bushfires (Barbero et al., 2011), and a cool season from June to September. NC is under the influence of the El Niño Southern Oscillation (ENSO) phenomenon (Ropelewski and Halpert, 1987; Nicet and Delcroix, 2000), which has a strong impact on spatial and interannual climate variability: rainfall decreases to less than 50% of its usual value during El Niño episodes, especially “Central Pacific” events, when anomalous positive sea surface temperature anomalies (SSTA) peak around the dateline, while humid La Niña episodes reduce fire occurrence (Barbero et al., 2011). Trade winds from south-east are predominant, and strong winds (>8 $m\ s^{-1}$) occur frequently and favor the spread of fire (Caudmont and Maitrepierre, 2006).

The main island of New Caledonia (The *Grande Terre*) has an elongated central mountain range with peaks at 700–1100 m a.s.l. (Fig. 1) including two peaks higher than 1600 m, located close to the windward eastern coast. A major contrast exists with respect to the soils, which are ultramafic or volcano-sedimentary. Ultramafic soils are nutrient-poor and contain nickel at toxic concentration, with local iron crusts (McCoy et al., 1999) and they are covered by the rainforest and the ultramafic maquis. Volcano-sedimentary soils are generally richer in nutrients and more suitable for plant growth; they are covered with thickets, savannas and rainforests (Fig. 1).

Savannas, ultramafic maquis and secondary thickets represent the predominant vegetation types, covering ca. 67% of the main NC island (source: Land Cover map of New Caledonia, DTSI 2008; Table 1). The NC dry forests ecoregion contains only 240 small forest fragments with 337 native plant species and it covers less than 10,000 ha in 2010 (ca. 1% of the original forest area ; Jaffre et al., 1998; Gillespie and Jaffre, 2003). This dramatic contraction has