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Effect of landscape fires on the demography of the endangered New Caledonian conifer *Callitris sulcata*

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ABSTRACT

New Caledonia is a global biodiversity hotspot and an epicentre for Gondwanan conifers, many of which are threatened by mining and by altered fire regimes. We studied the distribution, abundance and demography of the endangered *Callitris sulcata*. The largest populations are restricted to one river system in the south-east of the island, with satellite populations in adjoining rivers. The local distribution is controlled by the fire protection afforded by terrain features such as scree slopes, creeklines and small cliffs. Adult trees, which have comparatively thick bark, are able to tolerate and recover from infrequent surface fires, but severe fires kill trees and the seeds they store, a pattern similar to that in many Australian *Callitris* species. Radiocarbon dating revealed the species is slower growing than Australian *Callitris* species, possibly due to the extreme infertility of the ultramafic soils. The species is of high cultural value to the indigenous population who also prizes the durable and aromatic timber, and harvests have been traditionally regulated. Illegal cutting of trees has become a problem, but uncontrolled fires, which have caused substantial population declines, dwarf this threat. Given these threats, conservation of the species hinges on ensuring some populations remain remote and rarely visited by humans.

1. Introduction

New Caledonia, an archipelago located 1300 km east of Australia, is a biodiversity hotspot (Myers et al., 2000; Mittermeier et al., 2004). It contains 3371 indigenous vascular species, of which 74.7% are endemic, one of the highest endemism rates in the world (Morat et al., 2012). New Caledonia is renowned for its rich endemic conifer flora, with 45 species in the families Taxaceae, Podocarpaceae, Araucariaceae and Cupressaceae (Morat et al., 2012). The New Caledonian Cupressaceae include two species of *Callitris* (*Callitris sulcata* & *Callitris neocaledonica*) and the closely allied *Neocallitropsis pancheri*, the only extra-Australian members of the otherwise endemic Australian clade. The genus includes some remarkably drought resilient trees (Jaffré, 1995; Piggin and Bruhl, 2010; Brodribb et al., 2014). The New Caledonian *Callitris* species are of special importance to understanding the radiation of Gondwanan conifers in general and the *Callitris* clade in particular, as well as the evolution of drought tolerance.

The origin of the New Caledonian flora is hotly debated. The diversity of the current fauna and flora has been attributed to adaptive radiation following long distance dispersal and vicariant speciation by species originating from Australia, Melanesia and New Zealand (Murienne et al., 2005; Smith et al., 2007; Pascal et al., 2008; Grandcolas et al., 2008; Morat et al., 2012). This widely accepted view is based on the assumption that all terrestrial life on New Caledonia was eliminated between submersion of the landmass in the Paleocene (66–56 Ma ago), and re-emergence during the Oligocene, 35–40 Ma ago (Grandcolas et al., 2008; Richer de Forges and Pascal, 2008). However, some researchers posit that the species assemblage is truly relictual, evolving from meta-populations on transient islands that persisted during the tectonic upheavals of this micro-continental fragment of Gondwana (Ladiges and Cantrill, 2007; Heads, 2010). Humans colonised New Caledonia 3350 years ago, causing the loss of more than half its natural vegetation, and extinction of many vertebrates due to overhunting, landscape burning and shifting agriculture (Jaffré et al., 1998; Sand et al., 2005; White et al., 2010). Anthropogenic impacts intensified following European colonisation in the 19th century, resulting in land clearance for agriculture and mining. New Caledonia is currently one of the biggest nickel producers in the world, and this economic development has been accompanied by further habitat loss and fragmentation (Kettle et al., 2007; Pascal et al., 2008; Jaffré et al., 2010), wildfire

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(McCoy et al, 1999; Ibanez et al,., 2013a), urbanization and human population growth, and the introduction of invasive species (Gargominy et al., 1996; Meyer et al., 2006; Pascal et al., 2006), which all act synergistically to threaten the endemic flora and fauna.

C. sulcata is an exemplar of the issues that surround the conservation of the New Caledonia endemic flora. This species is restricted to about 226 km^2 of the South Province of New Caledonia. Its distribution is centred on the Mt Humboldt massif, between 15 and 300 m above sea level (Laubenfels, 1972; Jaffré, 1995) and has been estimated to cover a total area of 20 km^2 (IUCN Red List, Thomas, 2010). Like most New Caledonian conifers, *C. sulcata* grows on soils derived from ultramafic rock, which are characterised by deficiencies in nitrogen, phosphorus, potassium and calcium, and can have excessive amounts of magnesium, nickel and manganese (Jaffré, 1995). Growth rates and recruitment are thought to be very slow, although there are no data on the demography of *C. sulcata*, and little is known of its ecology, distribution and response to fire. It is threatened by mining activity, increasingly frequent wildfires and timber harvesting (Cabalion et al., 2003; Jaffré et al., 2010; Haverkamp, 2012). *C. sulcata* is currently listed by the IUCN as endangered (Thomas, 2010), but it has been suggested that its status should be upgraded to critically endangered (Cabalion et al., 2003; Haverkamp et al., 2013). Although *C. sulcata* is a protected species, and hence it is now illegal to collect any part of the plant according to the South Province environmental code, it is not currently represented in New Caledonia's network of protected areas (Jaffré et al., 2010).

Known as Comboui Fir-tree or “Nié” in Xârâguré (Borendi district vernacular language), *C. sulcata* is esteemed by the local population as much for its totemic value as its exceptional qualities in traditional and ceremonial building (Haverkamp et al., 2013). Indeed, *C. sulcata* is exceptionally durable (Compton, 1922) and because of the essential oils it contains (Hnawia et al., 2008) it is resistant to decay, termites and fungal attack (Cabalion et al., 2003). Traditionally, the Borendi district tribes closely regulated the harvest of *C. sulcata* trees, but illegal harvesting has recently occurred (Haverkamp et al., 2013). A tripartite partnership was established between the local Thio Council, Noé Conservation and the New Caledonian Agronomic Institute (IAC) to undertake an action plan to improve the management and conservation of *C. sulcata* by increasing knowledge about the ecology and biology of the species, as well as a socio-anthropologic study. Here, we present the results of a study originating from the action plan, which focused on the distribution and demography of *C. sulcata*, and aimed to quantify the threats to its populations. Specifically, we aimed to determine the current distribution of the species, analyse stand structures and relate these to past logging and fire activity, and investigate the reproductive biology of the species to understand the capacity of the species to recover from fire disturbance. We contextualised the biology and ecology of *C. sulcata* by comparing it with some of the better-studied Australian *Callitris* species, some of which are threatened by changed fire regimes. Finally, we discuss the findings of our study in relation to the conservation and management of this endangered conifer.

2. Material and methods

2.1. Distribution

C. sulcata is known to occur along the Comboui, Dumbéa and Tontouta Rivers and their tributaries, so detailed mapping of *C. sulcata* populations was undertaken along these rivers, and along the nearby Ngoi and Néfacia Rivers, where indigenous testimony had indicated that some individuals were present. Our mapping combined field checking with binoculars from a helicopter in river valleys surrounding the known distribution, and a foot traverse of the lower 6 km of the Comboui River (Fig. 1; Appendix Aa and b). We used a polygon drawn in a GIS to estimate stand area. All *C. sulcata* populations were mapped (1:50 000) according to three density classes: *high density*, where *C. sulcata* dominated forest stands; *medium density* for mixed stands of *C. sulcata* and other species; and *low density* for stands with scattered *C. sulcata* trees. Corresponding densities of trees with diameter at breast height (DBH) ≥5 cm were: > 300, 150 to 300 and <150 trees ha^{-1} respectively for high, medium and low densities respectively.

2.2. Stand structure

The region where *C. sulcata* occurs is remote, rugged and largely inaccessible, so we restricted demographic analyses to the lower Comboui River. Because wildfire is known to be a threat to *C. sulcata* populations, we selected stands with three fire histories: (i) Unburnt — no evidence of fire, i.e., no visible fire scars to the lower trunk; (ii) Old burnt — evidence of fire scars on weathered wood, with no visible new fire scars on trunk; (iii) Recently burnt by a wildfire (in 2011). We recorded in 2012 stand structure data from 20 m × 20 m, plots. The plots were representative of the target population and centred on a large tree so as to capture as many seedlings and juveniles as possible. Five plots were established in unburnt stands, and four plots each in old burnt and recently burnt stands (a total of 13 plots). Aspect, elevation, slope, presence of boulders and stand density were recorded for each plot (Appendix B).

All *C. sulcata* individuals, including dead trees and cut stumps, which persist for many years given the durable timber, were identified in each plot. Height was measured for all plants, and DBH for those >1.5 m tall, which were considered ‘trees’. ‘Seedlings’ had germinated in the current year and could be distinguished by the presence of cotyledons and a pale green main stem (Appendix Ac). ‘Juveniles’ were defined as plants that germinated before the current year but with only juvenile foliage, and ‘saplings’ were plants < 1.5 m tall but with some adult foliage (Appendix Ad). ‘Small mature trees’ were >1.5 m tall and with a DBH < 5 cm. ‘Medium mature trees’ were classed as those between 5 and 20 cm DBH, and ‘large mature trees’ were those ≥20 cm DBH (Appendix Ae). Presence of male or female cones, fire scars, and % of crown burnt were also recorded.

2.3. Bark thickness

Because bark thickness is a key determinant of a tree's resistance to surface fires (Lawes et al., 2011), it was measured with a bark thickness gauge at three points in each of 31 *C. sulcata* trees growing at one site along the Dumbéa River (Fig. 1). The measured trees ranged from 2–51 cm diameter at 10–30 cm height for saplings and 1.3 m (breast height) for trees.

2.4. Tree ages and growth rates

Stem sections were collected from seven stumps that were illegally felled in 2011, for growth ring analysis and accelerator mass spectrometry (AMS) ^{14}C dating. Sections were sanded with sandpaper, and then sections were scanned and growth rings counted and measured using WinDendro (Regent Instruments Inc., Quebec City, Canada). Because sections are not perfectly circular, rings were counted and measured along 3–7 radii, according to size (Appendix C), and the maximum number of rings was recorded (Waring and O'Hara, 2006). The *C. sulcata* growth rings were exceptionally narrow. A sample of wood from the pith of Tree 46 and five samples of wood from along a growth radius of Tree 66 were used for radiocarbon analysis (Appendix C). It is important to note that these wood samples were small (<3 mm width) but unavoidably included several growth rings. The wood samples were pre-treated to extract alpha-cellulose using the method described in Hua et al. (2004). Alpha-cellulose was then combusted to CO_2 and reduced to graphite (Hua et al., 2001) for ^{14}C analyses using the STAR accelerator mass spectrometry (AMS) facility at the Australian Nuclear Science and Technology Organisation (ANSTO; Fink et al., 2004).

Age calibration was performed using OxCal 4.2 (Bronk Ramsey, 2009) with bomb radiocarbon data for the Southern Hemisphere Zone