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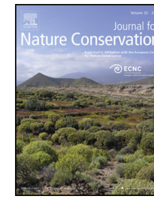

Edaphic niches of metallophytes from southeastern Democratic Republic of Congo: Implications for post-mining restoration

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ABSTRACT

In southeastern D. R. Congo, about 550 metallophytes grow on soils with high copper and cobalt concentrations, 57 of which are endemics to these metalliferous environments. About 70% of those endemics are considered threatened by destruction of habitats through mining activities. To provide guidelines for future restoration programs, the edaphic ecological niches of eight endemic metallophytes (i.e. copper endemics) were studied using a pragmatic sampling method adapted for urgent conservation needs. Niches were modelled using violin plot along Cu, Co and C:N gradients representing the two main independent edaphic gradients among nine edaphic variables (C, N, C:N, K, P, pH, Co, Cu, and Mn). Copper endemics presented distinct edaphic niches along the copper and cobalt gradients, but differentiation was lower along the C:N gradient. In addition, edaphic elements presented covariations among them and metalliferous soils had higher nutrient and element content compared to the non-metalliferous soils of the region dominated by the *Miombo* woodland. The complexity of the soil composition and the edaphic niches of copper endemics revealed an important challenge in the implementation of the species conservation and the habitat restoration strategies of post-mining sites.

1. Introduction

Metal-rich outcrops in many parts of the world are recognised as major foci of biodiversity (Whiting et al., 2004). These ecosystems host highly distinctive plant communities due to their ecological isolation and strong environmental selective pressures (Baker, Ernst, Van der Ent, Malaisse, & Ginocchio, 2010; Bizoux, Brevers, Meerts, Graitson, & Mahy, 2004). These plants occurring on heavy metal-enriched soils are called metallophyte and present various physiological mechanisms to tolerate the excess of metal in soils (Hall, 2002; Shaw, 1990). Such plants communities often include rare and endemic taxa (Whiting et al., 2004) and are of high conservation value.

Southeastern Democratic Republic of Congo hosts one of the most important metalliferous areas in the world. The *Katangan Copperbelt* includes some 160 outcrops (i.e., copper hills) scattered over more than 300 km (W-E) in a *Miombo* woodland matrix (Brooks and Malaisse, 1985; Duvigneaud & Denaeyer-De Smet, 1963). Mineralization of the parent rocks promoted a copper and cobalt enrichment of the soils along the slope of hills with concentrations of copper from 20 to 10,000 mg kg^{-1} and cobalt from 2 to 1000 mg kg^{-1} toward the top of the copper hills (Séleck, Bizoux et al., 2013; Séleck, Lebrun et al., 2013). The *Katangan Copperbelt* is recognised as a hotspot for metallophytes diversity (Brooks & Malaisse, 1985). Two main vegetation types are found on the copper hills: a steppic savanna on the lowest and intermediate metal concentrations; and, a steppe on the highest metal concentrations (Saad et al., 2012; Séleck, Bizoux et al., 2013; Séleck, Lebrun et al., 2013). These plant communities host more than 550 species tolerant to high cobalt and copper concentrations (Chipeng et al., 2010; Faucon, Shutcha, & Meerts, 2007; Lange et al., 2014; Leteinturier, 2002). Among those tolerant species, 57 have been identified as endemic from the Katangan copper hills (i.e., copper endemics). Two levels of endemism have been described: the broad copper endemics having more than 75% of population occurrence on copper hills in Katanga; and, the strict endemics occurring solely on the copper hills (Champluvier, 2011; Faucon et al., 2010).

Due to a recent revival of mining activities, most copper hills in Katanga have now been allotted to mining companies and will be exploited in the coming years and decades. Mining activities have already totally or partially destroyed several sites (Faucon et al., 2010). Although some copper metallophytes may actually benefit

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from secondary habitats created by the mineral industry (Faucon et al., 2011), there is no doubt that the copper endemics could be considered highly threatened. A recent assessment of their conservational status suggested that according to IUCN criteria, about 80% of copper endemics would be considered threatened (i.e., critically endangered, endangered, vulnerable) (Faucon et al., 2010).

The best strategy from a biodiversity conservation point of view includes preservation of a proportion of copper endemic populations in protected areas (International Council on Mining and Minerals, ICMM, 2006). However, this may turn out to be a limited and economically unrealistic option considering the increasing demand for copper and cobalt in the world and the high contribution of the copper-cobalt market to the economy of D. R. Congo. In mining sites, the most realistic way to ensure the preservation of threatened metallophytes may be to promote their *ex situ* conservation during mining activity associated with their use in ecological restoration at mine closure (Faucon et al., 2011; Saad et al., 2012; Whiting et al., 2004). However, designing *ex situ* conservation programs and restoring ecosystems that can support viable populations of copper endemics require sufficient knowledge about the ecology of those species (Whiting et al., 2004).

The characterisation of the edaphic niche of metallophytes is particularly critical (Ellstrand & Elam, 1993; Whiting et al., 2004). Metallophytes present a broad variation of tolerance to heavy metals resulting in specific distribution in relationship to soil properties. Absolute metallophytes are restricted to metalliferous soils, whereas facultative metallophytes show various proportions of metallicolous and non-metallicolous populations (Baker et al., 2010). Even among absolute metallophytes, tolerance to heavy metals may vary. Recent studies point out that other edaphic factors may also be important to explaining the distribution of plant species on copper hills (Faucon et al., 2012; Saad et al., 2012; Séleck, Bizoux et al., 2013; Séleck, Lebrun et al., 2013). In contrast to most metalliferous soils worldwide, metalliferous soils from the *Katangan Copperbelt* present high concentrations of nutrients such as P, Ca and Saad et al. (2012) suggested that nutrient status may also be of prime importance in explaining plant community variability.

The complexity of plant-soil relationships in the copper hills requires the development of quantitative approaches to characterise the ecological niches of copper endemics. For a long time, botanists have relied on the seminal work of Duvigneaud for taxonomy, ecology and distribution of Katangan metallophytes (Duvigneaud & Denaeyer-De Smet, 1963; Duvigneaud & Timperman, 1959). Those studies suggest that copper endemics may present different niche optimum and width in relationship to copper and cobalt. However, these studies were based on qualitative approaches and did not provide an understanding of the fine scale variation of edaphic niches (Leteinturier & Malaisse, 1999; Saad et al., 2012).

The classical methods of ecological niche modelling along edaphic or climatic factors implies the collection of large amount of species' presence (or abundance) and absence data (Heikkinen and Mäkipää, 2010; Vetaas, 2002; Wiser, Peet, & White, 1998; Yee and Mitchell, 1991). Presence-only data can be used at large scale provided pseudo-absence data are generated (Guisan, Edwards, & Hastie, 2002; Zaniewski, Lehmann, & Overton, 2002). However, in critical situations like the Katangan Copperbelt, where the exponential development of mining activities may rapidly overcome conservation efforts, it is crucial to develop pragmatic, conservation-oriented methods to survey the endemic taxa and to characterise their relationship with edaphic factors.

In this study, a conservation-oriented method using transects was selected to survey eight endemic metallophytes of the Katangan Copperbelt and to characterise their edaphic niches on copper hills in order to understand their relationship with determinant soil factors and to derive implications for conservation at species scale including these taxa in future habitat restoration strategies.

2. Methods

2.1. Study site and plant materials

This study was performed in the south-eastern Democratic Republic of Congo between Tenke (10.61°S; 26.12°E) and Fungurume (10.62°S; 26.32°E). This region has a humid subtropical climate (Köppen-Geiger: CWa) tempered by the relatively high elevation (c. 1300 m a.s.l.). Rainy season extends from November to the end of March, and dry season is from May to September.

Eight copper endemics with putative threatened IUCN status *sensu* Faucon 2010 (Table 1) were considered in the present study: *Barleria lobelioides* Champl. (Acanthaceae), *Basananthe kisimbae* Malaisse & Bamps (Passifloraceae)—endangered; *Commelina zigzag* P. A. Duvign. & Dewit (Commelinaceae)—critically endangered; *Euphorbia cupricola* (Malaisse & Lecron) Bruyns (Euphorbiaceae)—critically endangered; *Lopholaena deltombei* P. A. Duvign. (Asteraceae)—critically endangered; *Sopubia neptunii* P. A. Duvign. & Van Bockstal (Orobanchaceae)—vulnerable; *Tinnea coerulea* var. *obovata* (Robyns & Lebrun) Vollesen (Lamiaceae)—vulnerable; and *Triumfetta likasiensis* De Wild (Malvaceae)—vulnerable.

Identifications of taxa were based on (Bamps (1973–1993), Board of Trustees Kew Royal Botanic Gardens (1960–2010)) and Flora of Tropical East Africa (Kew Royal Botanic Gardens, 1952–2008) completed with more recently published taxonomic literature for particular genera and species (Leteinturier, 2002; Séleck, Lebrun et al., 2013).

2.2. Field data collection

To assess the edaphic niches of each studied species, a sampling method requiring the collection of substantially less data than the classical presence-(pseudo–)absence samplings was used. This approach is applied in botany and plant ecology, and, is based on the characterisation of population density and soil parameters at key positions along transect performed on the heavy metal gradients found on the copper hills. The survey was performed during the growing season 2012 (Table 1).

The first step consisted of characterising the distribution of the population along the environmental gradients (Fig. 1). For each species, three copper hills where the species occurred were sampled for a total of 10 copper hills. Topography is a good proxy of the copper-cobalt gradient on copper hills (Séleck, Bizoux et al., 2013). On each hill, a two-meter wide transect was materialised from the bottom to the top of the hill. All individuals of the studied metallophytes were numbered based on their position in the transect. In a second step, the rank distribution of individuals was used to select five key positions: the two individuals at the extremities of the population; the individual with median rank; one individual at the 1st quartile rank; and, one individual at the 3rd quartile rank. In the third step, a one-square-meter plot was centered on each key position. In the plot, the species density was recorded, and four 10 cm-deep soil samples were randomly collected and pooled. A total of 15 plots was sampled per species (3 hills*5 key positions).

To compare the nutrient and metal concentration of the copper hills with the non-metalliferous soils of the region, soil samples were taken in the non-perturbed areas of the plain of Lubumbashi located in the *Miombo* woodland. For this sampling, 145 (for the analysis of C, N, K, pH and Mn) and 53 plots (for the analysis of Cu) were performed (Hick, unpublished).