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INVASION NOTE

The tree fern *Dicksonia antarctica* invades two habitats of European conservation priority in São Miguel Island, Azores

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Abstract Sixty fern species are considered problematic worldwide because of their invasiveness, but only two of them are tree ferns. This paper reports the invasion by the Australian tree fern *Dicksonia antarctica* to the eastern part of São Miguel Island (Azores archipelago—Portugal). It probably escaped from cultivation in the nineteenth century and has spread to an area of over 48 km^2, mainly at high altitude (>500 m a.s.l.). The invaded area is characterized by high precipitation (mean = 2,857 mm/year), high relative humidity (mean = 96.4%), and mild temperatures (mean = 12.1°C). The species has invaded forest plantations, exotic forests and two habitats of European conservation priority: native laurel forests and blanket bogs. *Dicksonia antarctica* plantlets (individuals with no trunk) were predominant in exotic forests, *D. antarctica* shrubs (trunk height < 1 m) were most frequent in blanket bogs and forest plantations whereas trees (trunk height > 1 m) in gardens. Blanket bogs had the maximum percentage (90%) of fertile individuals (i.e. with sporangia). The large size and poor access of invaded area makes full eradication from the island impossible. We recommend complete elimination in blanket bogs and to take control measures in native laurel forests as these are priority conservation habitats.

Keywords Blanket bog · Invasive · Laurel forest · Macaronesia · Pteridophyta · Soft tree fern

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Introduction

Several fern species, both aquatic and terrestrial, can be invasive and hence have a negative impact upon the communities they invade, affecting resource use or even human health (reviewed by Robinson et al. 2010). Of over 12,000 described fern species, about

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60 are problematic due to their invasive nature, affecting resource use, human health and plant communities (Robinson et al. 2010). Of these 60 species, only two are tree ferns, *Dicksonia squarrosa* and *Sphaeropteris cooperi*. This note reports the invasion by *Dicksonia antarctica* Labill. (Soft Tree Fern; Dicksoniaceae) in São Miguel Island (Azores archipelago—Portugal). This species is native to south-eastern Australia and Tasmania, where it inhabits high rainfall forests from sea level to 1,000 m a.s.l. (Jones 1998). Individuals can reach up to 5–6 m, with an apical rosette of leaves 2–6 m in diameter, and may live for 500–1,000 years (Unwin and Hunt 1996). It has been widely cultivated in European gardens, being mentioned in Flora Europaea (Tutin et al. 1993) as cultivated for ornament in south-western England and south-western Ireland without being naturalized. Although *D. antarctica* is referred to as a potential ecological concern (Robinson 2009) it was rarely reported as an escaped ornamental, with records in Ireland and Madeira Island in Portugal (Reynolds 2002; Vieira 2002). In the Azores this species is only known on São Miguel (Borges et al. 2010).

This work details the distribution, and also the density and size class structure, of this invasive fern in native and exotic habitats on São Miguel. Macroclimatic and topographic variations have long been considered to be the fundamental factors controlling plant species distribution at global and regional scales (e.g. Körner 2007). This is also valid for invasive species (Christenhusz and Toivonen 2008). We focused on the main physical habitat variables affecting invasion that determine plant potential distribution, however positive (mutualistic) and negative (competition-predation) interactions between exotic species and the species of the recipient communities are of great importance (Traveset and Richardson 2006; Padrón et al. 2009). The first objective of this note was to describe the area of occupancy of *D. antarctica* on São Miguel, by assessing its distribution range in relation to altitude, temperature, precipitation and relative humidity. This can be the first step for a future study of the long-term trend of this species. The second objective was to assess its density and size class structure (using size class as a proxy for age), which can be important to evaluate the impacts of the species in the different habitats where it occurs.

Materials and methods

Study area

São Miguel is the largest island of the Azores, an archipelago of volcanic origin located in the North Atlantic Ocean, about 1,500 km from mainland Europe (Fig. 1a). The climate is temperate oceanic with mean annual temperature of 17°C at sea level. Relative humidity is high and annual rainfall ranges from 1,000 mm in the coast to well above 3,000 mm in the highest altitudes of the volcanic buildings (Hortal et al. 2010). Human settlement in the Azores began in the fifteenth century. Thereafter, several activities have altered native plant communities, in particular the replacement of the original vegetation cover by cereal crops, pasture and forestry and the introduction of numerous crop, fodder, forest, ornamental and hedgerow plant species (Silva and Smith 2004). Remaining native laurel forest in São Miguel is composed of evergreen trees (e.g. *Erica azorica*, *Ilex perado* subsp. *azorica, Juniperus brevifolia, Laurus azorica, Vaccinium cylindraceum*) and an understory dominated by evergreen ferns (e.g. *Culcita macrocarpa*, *Dryopteris affinis*, *Pteris incompleta*, *Woodwardia radicans*) and winter deciduous ferns (e.g. *Blechnum spicant*, *Osmunda regalis*, *Pteridium aquilinum*).

Fieldwork was completed from March to July 2008 in the eastern part of São Miguel (37°47′N, 25°13′W) corresponding to the areas where *D. antarctica* was detected (Fig. 1b). The study area covered 282 km^2, ranging from sea level to 1,105 m (Pico da Vara, highest point of the island). Study sites consisted of natural habitats, mostly in mountainous areas with steep ground, densely vegetated with native and exotic flora (native laurel forests at various stages of invasion by *Clethra arborea* and *Hedychium gardneranum*, forest plantations of *Cryptomeria japonica*, exotic forests of *Pittosporum undulatum* and blanket bogs of *Sphagnum* spp. and *Polytrichum* spp. with a few vascular plants like *Juncus effusus*, *E. azorica*, *J. brevifolia* and *V. cylindraceum*) and also some highly disturbed habitats (pastures, agricultural fields, gardens and urban areas). Native laurel forests and blanket bogs are considered habitats of conservation priority by the European Union Habitats Directive (codes 7130 and 9360, respectively, in the Council Directive 92/43/EEC).

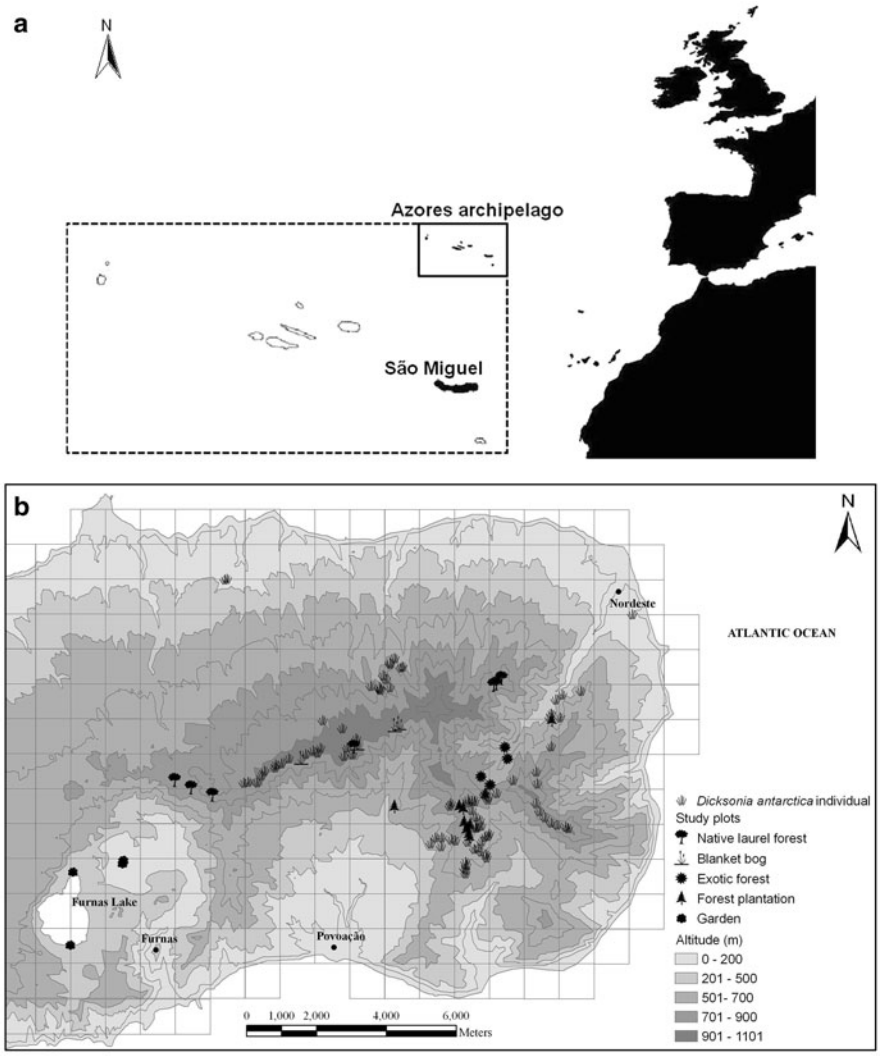

Fig. 1 Location of study area in the eastern part of São Miguel Island (Azores archipelago—Portugal). The map shows all individuals of *Dicksonia antarctica* found and the 40 × 5 m plots used to evaluate size class structure. Grid corresponds to 1 × 1 km UTM

Distribution

The study area was divided in 282 units, 1 × 1 km UTM, in order to map the distribution of *D. antarctica.* Some units were not visited because they were very steep; the accessible ones were walked using paths and roads. All detected individuals of *D. antarctica* were georeferenced with a handheld GPS (Garmin 60CSx) and presence/absence data for each 1 × 1 km UTM study unit were considered as representative of the distribution of this species. We used four explanatory variables: altitude, annual precipitation, mean annual relative humidity and mean annual temperature to characterize the environmental factors affecting each *D. antarctica* record. To characterize the climate at each individual record we extracted values from CIELO, a spatial prediction model of climatic variables for the Azores Islands, (http://www.climaat.angra.uac.pt/; Azevedo 2005) using a Geographic Information System, ArcGIS 9.3 (ESRI, Redlands, CA, USA). These individual values were compared with the island values of precipitation, humidity and temperature by means of Chi-square test.

Size class structure

To evaluate the population structure of *D. antarctica* we marked 32 plots (40 × 5 m), within the areas where the species was present, in five habitats: native laurel forest (7 plots; Fig. 1b), blanket bog (4 plots), exotic forest (4 plots), forest plantation (11 plots) and garden (6 plots). The garden habitat included three private gardens located in the village of Furnas and close to Furnas Lake, in the south-eastern part of São Miguel. Except for this habitat, where all the *D. antarctica* individuals found were included in the plots, the number of plots in each habitat was proportional to their area within the study area. On March 2008, all the individual sporophytes within each plot were recorded and observations were noted in three different size classes: (1) plantlet (i.e. young sporophytes), corresponding to individuals without trunk; (2) shrub, with a trunk less than 1 m tall; and (3) tree, with a trunk higher than 1 m. Fertility was also recorded for shrubs and trees in the plots, distinguishing between fertile and sterile individuals according to the presence or absence of leaves with sori (i.e., clusters of sporangia either containing spores or not), correspondingly. The frequencies of the three size classes were compared among habitats by means of Chi-square test. The differences in the frequencies of fertile and sterile individuals (plantlets, not included) among habitats were also evaluated with a Chi-square test. Significant departures from expected frequencies were tested by analyzing the standardized residuals, as proposed by Haberman (1973).

Results

Distribution

A total of 440 *D. antarctica* individuals were detected in 48 out of the 282 sampled 1 × 1 km UTM in the eastern part of São Miguel (Fig. 1b). Most of the individuals (80%) were found above 500 m, although *D. antarctica* occurred between 122 and 1,101 meters a.s.l. (Table 1). Annual values of precipitation and mean relative humidity in the points where *D. antarctica* was detected were significantly higher than for the whole island (precipitation: 2,857 and 2,332 mm, $\chi^2_1 = 163.236$, $P < 0.001$; humidity: 96.4 and 89.6%, $\chi^2_1 = 416.327$, $P < 0.001$). Mean annual temperature in the *D. antarctica* range was significantly lower than the average for São Miguel (12.1 and 14.1°C, $\chi^2_1 = 317.900$, $P < 0.001$) (Table 1).

Table 1 Environmental variables used to characterize *Dicksonia antarctica* distribution in São Miguel Island

Variable	Range	Mean ± SD
Altitude (m)	122–1,101	669 ± 192
Annual precipitation (mm)	997–3,600	2,857 ± 502
Mean annual relative humidity (%)	79.7–100.0	96.4
Mean annual temperature (°C)	9.5–18.3	12.1 ± 1.4

Values at each *D. antarctica* record ($N = 440$ individuals) were obtained from the CIELO model (http://www.climaat.angra.uac.pt/). *SD* standard deviation

Size class structure

Mean *D. antarctica* density (individuals/plot) did not differ considerably between the five habitats considered: native laurel forest, 34.4; blanket bog, 30.3; exotic forest, 27.3; forest plantation, 26.3; garden, 21.2. However, the frequencies of the three size classes differed significantly among habitats ($\chi^2_8 = 358.594$, $P < 0.001$). Shrubs were most abundant in blanket bogs and forest plantations whereas plantlets were predominant in exotic forests and trees in gardens (Fig. 2a). Although, the tallest individuals, with trunks up to 4 m tall and diameter at breast height = 0.4 m, were found in exotic forests. The abundance of fertile and sterile individuals also varied significantly among habitats ($\chi^2_4 = 110.327$, $P < 0.001$). The percentage of fertile individuals was highest in blanket bogs (90%; Fig. 2b) and lowest in exotic forests (13%).

Discussion

We found the Australian tree fern *D. antarctica* in 48 study units (1 × 1 km UTM) in several habitats of São Miguel Island (Azores, Portugal). This is the first documented occurrence of *D. antarctica* as a naturalized species in Europe and the first invasion described for this fern species. We hypothesize that it escaped from cultivation during the so-called European fern craze of the mid-nineteenth century (Nelson 1992). This is in agreement with the age estimated for the largest and probably oldest naturalized individuals found in exotic forest. Given that *D. antarctica*, growing under forest canopy, needs more than 100 years from the time of germination to develop a

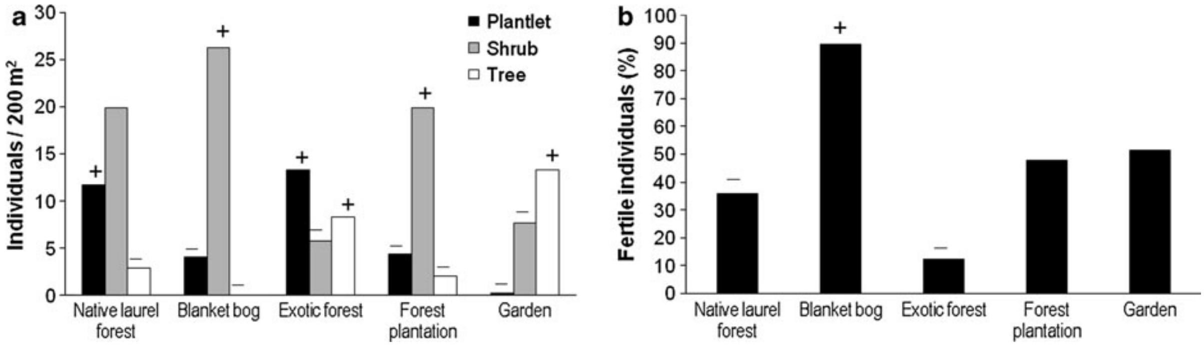

Fig. 2 **a** Mean density of plantlets (individual with no trunk), shrubs (trunk height < 1 m) and trees (trunk height > 1 m) in each habitat type, and **b** percentage of fertile individuals (plantlets not included) recorded on 32 plots (40 × 5 m) chosen within the five habitats where *Dicksonia antarctica* was present in São Miguel Island. The symbols + and − above the *bars* indicate significant excess or deficit, respectively, relative to expected frequency

2 m trunk (Forest Practices Authority 2009), those 4 m individuals are well over a century old. Accordingly, the biggest collection and most of the older individuals are located in Terra Nostra Garden (Furnas, south-eastern São Miguel), suggesting that the invasion started from this garden. This is the most important historic garden in the whole Azores archipelago, founded in 1780, although most plants of Australian origin were imported in the mid-nineteenth century.

Many invasive fern species share two characteristics which contribute to their invasiveness (Robinson 2009). First, they can spread rapidly by means of spore dispersal, rhizome growth, fragmentation or a combination of these mechanisms. Second, they tend to occupy sun-exposed sites during their sporophyte stage. *Dicksonia antarctica* meets the first characteristic since it prefers shady environments beneath a forest canopy (Jones 1998). However, ecophysiological studies showed that *D. antarctica* can tolerate high light conditions and water deficit (Hunt et al. 2002; Volkova et al. 2009, 2010). In São Miguel, *D. antarctica* occupies shady understory of three forest habitats, where canopy cover is above 63% (Arosa et al. 2009), but also open areas of blanket bogs. In these areas, located on top of hills above 900 m a.s.l. where strong winds can limit growth by causing water stress (Hunt et al. 2002), individuals showed reduced growth and none reached the tree size (defined as trunk height > 1 m, Fig. 2a). Although, the highest percentage of fertile individuals was found in this habitat (Fig. 2b), suggesting that the species can thrive in sun-exposed areas when there are no dampness restrictions.

A single fertile leaf has been estimated to produce as many as 750 million viable airborne spores (Page 1979). Sporophytes lack asexual reproduction and thus are strictly dependent on spore dispersal and gametophyte fertilization for population establishment and maintenance (Unwin and Hunt 1997). In ferns, moisture availability may be critical to establishment of the gametophyte and to the fertilization of the female gametangia by motile sperms (e.g. Watkins et al. 2007). However, *D. antarctica* lives chiefly at high altitude in São Miguel (mainly above 500 m), where the relative humidity is highest (annual mean 96%, Table 1) and annual precipitation (2,857 mm) triples that in its native range (Neyland 1986). These environmental data indicate that gametophyte development and sporophyte formation are not limited by water availability. In agreement, we found abundant plantlets throughout the study area, especially in exotic forest and native laurel forest (Fig. 2a) where shady areas under canopy can promote establishment and growth of *D. antarctica* sporophytes.

Our study shows an old and extensive invasion of São Miguel Island by *D. antarctica*. Given the large area invaded, complete eradication is not feasible. Management strategies are constrained by two additional facts. First, many individuals grow in rough terrain or inaccessible areas. Second, high proportions of individuals are fertile and produce large amounts of spores which may be ubiquitous in soil spore banks (Dyer and Lindsay 1992). These soil spore banks can act as a reservoir for re-invasion of cleared areas. Where eradication is not appropriate, the next-best alternatives are limiting the spread (containment) of invasive species and reducing the population abundance (control) in order to keep damage at an acceptable level (Genovesi 2007). Management strategies must be focused on the natural habitat types of European conservation priority: blanket bogs and native laurel forests. Although there is a high number of fertile shrubs in blanket bog, complete elimination of *D. antarctica* seems possible in this case, as this habitat occupies an easily accessible, discrete area. Nevertheless, further investigation should be carried in order to weight the cost of controlling the species against its impacts in the habitat. On the other hand, native laurel forest is highly fragmented and many habitat patches have poor access and therefore the goal of management should be to reduce the abundance and spread of the fern. As far as we know our study is the first to report invasive *D. antarctica* and therefore control methods have not been tested. Next step could be to test on this species the physical and chemical methods successfully used for *S. cooperi* (Motooka et al. 2003), another Australian tree fern. *Sphaeropteris cooperi* is one of the most troublesome invasive alien ferns in the Azores archipelago, where it occurs in eight of the nine islands (Borges et al. 2010). In São Miguel it invades the same forest habitats as *D. antarctica*: native laurel forest, exotic forest and forest plantation. As part of a long-term conservation project, the most aggressive invasive plant species (mainly *C. arborea* and *H. gardneranum*) have been eliminated from the largest and best preserved patches of native laurel forest (Ceia et al. 2011). The control of *D. antarctica* and *S. cooperi* can be easily integrated in these conservation actions. Parallel monitoring of the success in controlling both species could give useful guidelines for the management of invasive tree ferns in other parts of the world.

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