Acta Botanica Brasilica, 2022, 36: e2022abb0048
doi: 10.1590/0102-33062022abb0048

Short communication

New records of *Plantago trinitatis*: spontaneous regeneration of a species considered extinct or sampling gaps on Trindade Island?

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Received: February 24, 2022
Accepted: July 18, 2022

ABSTRACT

Trindade Island has lost much of its original vegetation cover as a result of approximately three centuries of human occupation and intense herbivory caused by invasive mammals. Since the eradication of some of these herbivores, the recovery of some plant species has started. *Plantago trinitatis* is an endemic herb from Trindade Island, which was considered extinct until 1998, when it was rediscovered in the higher areas of the island. The regeneration of the species was attributed to the soil seed bank. This communication reports new records of *P. trinitatis* close to sea level on Trindade Island, at lower altitude than previously documented. The new records suggest that *P. trinitatis* is recolonizing the island, but leaves doubts whether sampling gaps in the past have led to the non-detection of the plant in its vegetative form in these locations, emphasizing that other species considered extinct may share this issue. Regardless of recolonization or sampling gaps, the eradication of invasive herbivores is necessary as a strategy to protect local flora and native vegetation. Understanding the population status can help in making decisions about the need of environmental management and species population recovery.

Keywords: invasive mammals, oceanic island, Plantaginaceae, *Plantago trinitatis*, plant recolonization

Invasive species are potentially from any taxonomic group and may affect wildlife and native vegetation, causing expressive environmental changes (Maron & Crone 2006; Jeschke *et al.* 2014; Russell *et al*. 2017) and influencing global biodiversity (Clavero & Garciaberthou 2005; Blackburn *et al*. 2019). Among several ecological impacts caused by invasive species are changes in trophic (Wilmers *et al*. 2003; Sax & Gaines 2008; McNatty *et al.* 2009) and competitive relationships (Brown *et al*. 2002; Damas-Moreira *et al*. 2020), which can suppress native species and culminate on their local extinction (Clavero & Garciaberthou 2005; Sax & Gaines 2008; Russell *et al*. 2017). The natural environment can also be modified, for example by the loss of soil by erosion and by the change in the availability of water and nutrients, among other factors (Maron & Crone 2006; Russell *et al*. 2017), and these modifications may occur when vegetation is suppressed (Russell *et al*. 2017). Particularly on islands, where most species are endemic (Berglund *et al.* 2009; Kier *et al*. 2009), these effects may be higher because the space is more limited and native species are particularly vulnerable to ecological and environmental changes (Berglund *et al*. 2009; Russell *et al*. 2017).

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For these reasons, the control and eradication of invasive species represent an important strategy for the conservation of native species, in continental and in island environments (Vander Zanden *et al.* 2010; Jones *et al.* 2016; Courchamp *et al.* 2017; Tilman *et al.* 2017), and when effective, some natural populations can recover (Alves *et al.* 2011; Silva & Alves 2011).

Trindade Island is located about 1,200 km from Vitória, in the state of Espírito Santo (ES), in southeastern Brazil, which is the closest continental area (Fig. 1). This oceanic island, together with the Martin Vaz islands, represents the eastern end and the emerging part of the Vitória-Trindade chain, which is composed by a range of extinct volcanoes (Alves 1998). Trindade Island has an area of approximately 10 km^2 and 620 m of altitude (Alves 1998). Once the constructive volcanism was stopped, the intense erosion of original topography created an extremely rugged relief. Currently, the island has narrow and deep valleys interspersed with cliffs and steep escarpments, as well as other topographic elements (*e.g.* alluvial plateaus and canyons), all of them distributed at different altitudes (Alves 1998). The regional climate is tropical oceanic with an average annual rainfall of 923 mm (Machado *et al.* 2017). Trindade Island is the only Brazilian oceanic island to have perennial streams, presenting 33 watersheds distributed among the categories of pattern *i* (extensive drainage areas, water springs and streams with significant water flow), pattern *ii* (smaller in area, but also with water springs and streams) or pattern *iii* (with no water springs, drained only by rainfall events; for more details, see Marques *et al.* 2019; Fig. 1). Before human occupation, in 1700, the vegetation of Trindade Island was mostly represented by a forest dominated by *Colubrina glandulosa* subsp. *reitzii* (M. C. Johnst.), a tree species that covered about 85 % of the island (Alves 1998). In addition to *C. glandulosa* forest, a forest dominated by the tree fern *Cyathea delgadii* Sternb. occupied much of the southwest side, while grassland occupied the lowlands of the island (for more details, see Alves 1998). Little is known about the species associated with the aforementioned vegetation, mainly about the herbaceous species, of which no traces that assist in the reconstitution of their spatial distribution. This lack of information is due to the fact that the first consistent biological studies only started when the "Museu Nacional do Rio de Janeiro" was founded (second half of the 18th century), nearly two centuries after human occupation, when possibly several species had already been lost (according to Alves 1998).

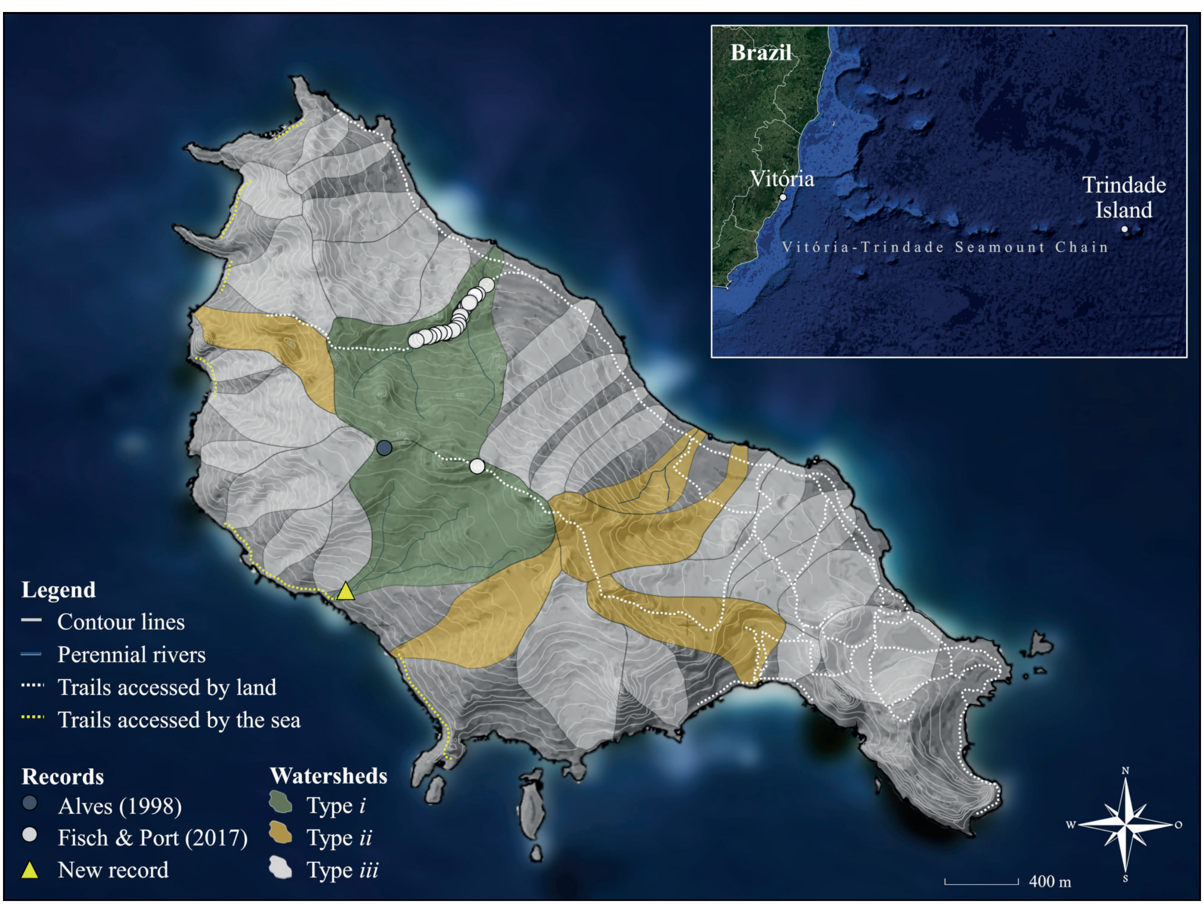

Figure 1. Location of Trindade Island in relation to Vitória (Espírito Santo), in southeastern Brazil, being located in the extreme east of the Vitória-Trindade Seamount Chain (top left corner). Location of historical and new records of *Plantago trinitatis* on Trindade Island with watersheds areas and types (based on Marques *et al.* 2019). The blue and white dots also represent current records.

Associated with the human occupation, large herbivorous mammals were introduced and some of them settled at Trindade Island (Alves *et al*. 2011). Among the large species, goats (*Capra hircus* Linnaeus, 1758) and pigs (*Sus scrofa* Linnaeus, 1758), both introduced in 1700, and sheep (*Ovis aries* Linnaeus, 1758), introduced in 1781, showed greatest population growth, reaching about 800, 200 and 300 individuals, respectively (Alves *et al*. 2011). It is important to note that the goat population doubled after the 1950s, reaching the population of 800 individuals in the 1960s. Pigs and sheep were eradicated in 1965 and goats in 2005 (Alves *et al*. 2011). Currently, the mouse *Mus musculus* Linnaeus, 1758 is the only mammal (and invasive) that remains on the island (Silva & Alves 2011), with records of the species until at least June 2015 (Rosa *et al*. 2020). In addition to the cited species, donkey (*Equus asinus* Linnaeus, 1758; introduced in 1916 and eradicated in 1965), cattle (*Bos taurus* Linnaeus, 1758; two individuals introduced in 1916, but they did not survive) and the guinea fowl (*Numida meleagris* Linnaeus, 1758; introduced several times between 1700 and 1980) are examples of species introduced at Trindade Island over time (Alves *et al*. 2011).

As a result of approximately three centuries of impact caused by introduced species (*e.g.* herbivory and trampling), the populations of many native plants have suffered extreme reduction and some of them, including endemic species, become extinct (Alves 1998; Alves *et al*. 2011). The removal of original vegetation resulted in total exposure of the soil in some locations, also contributing to reduction of water availability and acceleration of the erosion process and, finally, in almost total loss of the island's organic soil (Alves 1998). After the eradication of the goats, the natural regeneration of vegetation showed advances (Silva & Alves 2011; Fisch & Port 2017). However, the current vegetation differs from the original, being mainly composed of grasses (Alves 1998; Faria *et al*. 2012) and a small nebular forest that persisted and thrives on higher areas (≥ 400 m), where a large part of the remaining vascular plant species is located. The native species *Myrsine guianensis* (Aubl.) Kuntze and the tree fern *C. delgadii* dominate the nebular forest (Alves 1998; Faria *et al*. 2012), where there are also individuals from other tree species. Among the species considered spontaneous and that occur in the current vegetation, 12 (21.8 %) are considered endemic (based on data available in Alves 1998). The island's original vascular flora was possibly richer and with a higher rate of endemism than that found today (Alves 1998). Notably, most of the island's fertile soil is currently associated with the cloud forest (Clemente *et al*. 2009) and, with the exposure of the matrix rock in most of the island, plant recolonization is difficult (Alves 1998).

Plantago trinitatis Rahn, an endemic plant on Trindade Island, is one of the plant species affected by introduced herbivores (Alves 1998). This herbaceous species was first collected by Johann Becker in 1965, who reported having found "a dozen specimens" in a place known at that time as "Fazenda", of which the exact location is not known (Alves 1998). In 1974, based on this sample, the species was described by Knud Rahn (Rahn 1974). After that, the plant was considered extinct because of the intensive pressure exerted by the goats, which intensified after the 1960s (Alves 1998). In 1998, with the reduction of the goat population (about 20 individuals), a relictual population of the plant was rediscovered in the "Pico Trindade", at 590 m of altitude, where the regeneration of the species was attributed to the soil seed bank (Alves 1998; Fig. 1). With the complete eradication of the goats, the plant species showed rapid recovery in the highest parts of the island (about 800 specimens, Alves *et al*. 2011). In 2013, the species was registered for the first time at lower altitudes, with specimens distributed between 80 and 240 m of altitude, in a valley in the northeastern portion of the island (Fisch & Port 2017; Fig. 1). Aiming to add information about the distribution of *P. trinitatis* on Trindade Island, here we report the occurrence of the species in a new area located at lower altitude than previously documented after the rediscovery of this plant.

The new records were obtained between April and June 2015. During this period, different points of the island were visited, on all regions and altitudes, and covering the three categories of hydrographic basins described for Trindade Island (Fig. 1). Sampling was performed along trails (linear transects), and the transects located on the most remote beaches, on the west and southwest portions of the island, were accessed by the sea using a boat (Fig. 1). The locations where the plant was recorded were georeferenced and the altitude was defined. In addition, each location was characterized according to general aspects of the environment, considering the relief (*e.g.* ridge or valley), type of substrate (presence of rocks and/or unconsolidated sediment), presence of watercourses and vegetation structure.

Individuals of *P. trinitatis* were recorded along the trail that crosses "Fazendinha" (a place located at about 540 m of altitude), under shrub and arboreal vegetation, occupying the understory, in organic and humid soil in the ridge regions of the island. Individuals were also recorded on the access trail to "Pico do Noroeste", in a valley on the northeast portion of the island located along a stream, being associated with fluvial deposits of wet unconsolidated substrate between blocks of rock, and the local vegetation is poorly structured and represented mainly by grasses. The locations of these records are the same previously documented locations (Alves 1998; Fisch & Port 2017; the blue and white dots in the Fig. 1 also represent current records). In addition to these records, individuals of *P. trinitatis* were recorded at a new point, located in a valley in "Enseada da Cachoeira" (20°30'54,4"S; 29°20'09,2"; in the southwestern part of the island), at 33 m of altitude (Fig. 1).

Close to that point, also in the valley channel, a water film was running over the gravitational deposit of blocks and boulders, and this being the main drainage channel of the sampled hydrographic basin. Both in the valley of the northeastern portion of the island and in "Enseada da Cachoeira", the vegetation is composed only of small herbaceous species (mainly spaced grasses), forming environments with little plant cover. Thus, regardless of the vegetation structure and proximity to watercourses, the specimens occur on unconsolidated and humid substrate, and in rock cracks to a lesser extent (Fig. 2A-C).

Plantago species present ombro-hydrochory (Gutterman 1990) or hydrochory (Wolters *et al.* 2004; Chan *et al.* 2011; Liu *et al.* 2014) as dispersion mechanisms. During this process, the seeds are transported by rain (runoff) and can reach greater distances when they reach water courses. Due to this characteristic, the dispersion of seeds is favored in depressions and cracks in soil, where the establishment of its populations can occur more easily (Gutterman 1990). The valleys where the historical and current records were made are in the two largest watersheds (pattern *i*) on Trindade Island. The watersheds occupy 15 % of the island's terrestrial

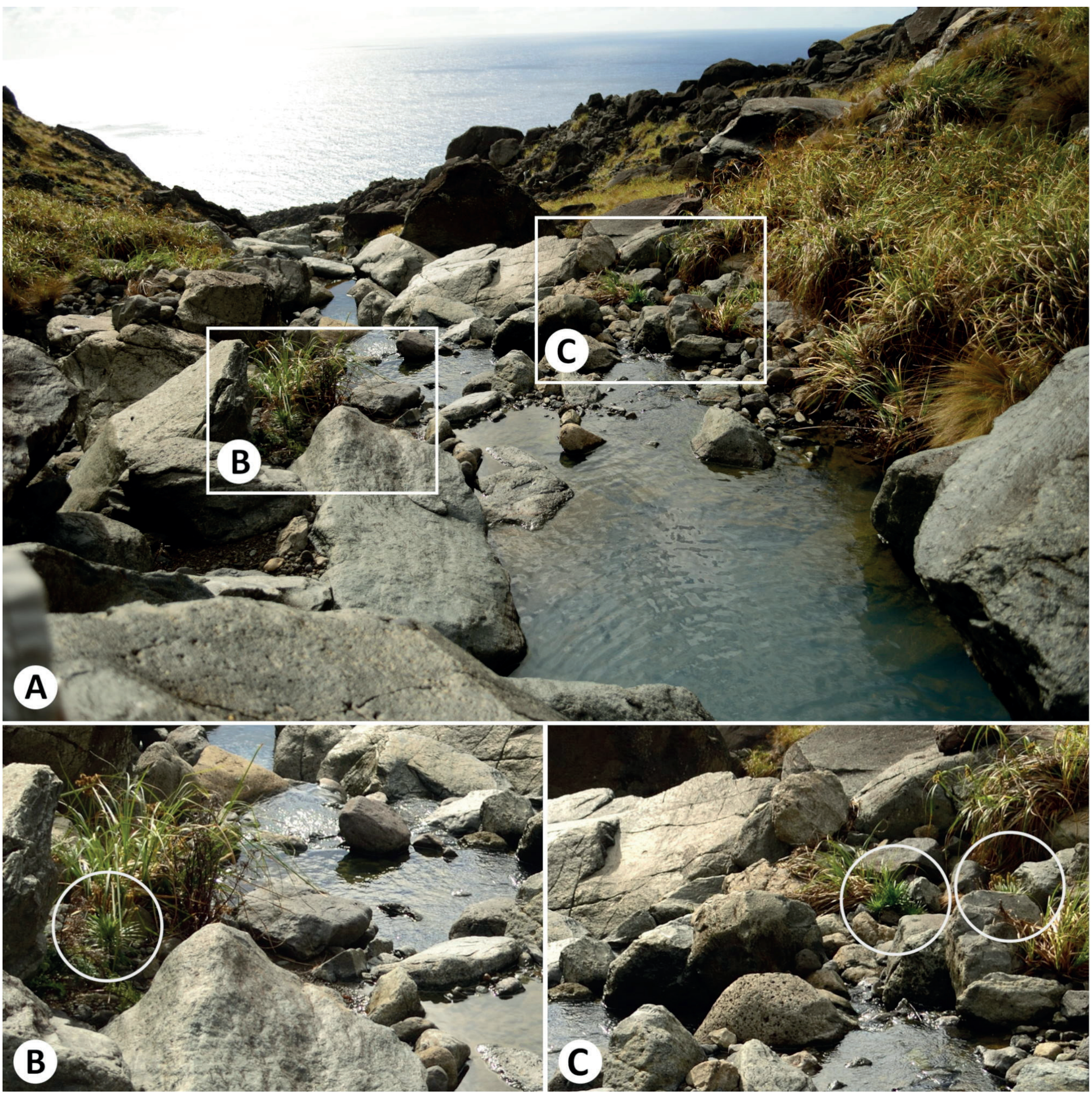

Figure 2. Representation of the environment where new groupings of *Plantago trinitatis* were recorded on Trindade Island (**A**), with details of some individuals in an unconsolidated and humid substrate associated with a watercourse (general panorama in the upper image and details of the highlighted points in **B** and **C**).

environment, have water springs and their river channels show significant water flows, covering two of the three most flowing water courses on the island (Marques *et al*. 2019). As a result, the record locations are wetter than the other sampled points. Additionally, these watersheds originate in higher areas (Marques *et al*. 2019), where the rediscovery of the species was done in 1998 (Pico Trindade). Considering that the species occurred only in the highest areas in the period of its rediscovery, it can be suggested that the recolonization has started from the highest points, with the seeds being carried out and deposited in the valleys, in places with lower altitudes, where the propagules can establish new groupings. Interestingly, until now, *P. trinitatis* seems to be associated only with watersheds classified as pattern *i* because those of pattern *ii* and *iii*, many of which also connected to the highest points on the island and here sampled, had no records of the species (Fig. 1).

Even today, erosion (also in the river channels) and sediment transport are intensified resulting in low fluvial deposition (Marques *et al*. 2019), which can also harm the deposition of organic material and seeds delaying plant colonization. However, small deposits of unconsolidated sediment are observed distributed along river channels (Marques *et al*. 2019, personal observation). This can favor the establishment of the seeds, since the presence of specimens seems to be associated, in most part, with the presence of this type of sediment, as observed in the places of our records (ridges and valleys). Humid locations can also favor the maintenance of *P*. *trinitatis*, since in dry conditions the species of these genus become less tolerant to additional stresses and are more susceptible to herbivory and pathogens (Orians *et al*. 2019). Considering these facts, the locations where our records were done may have favored the presence of the species because they are more humid than other terrestrial environments on the island. We emphasized that the highest areas are influenced by clouds (Alves 1998), while the valleys receive water by runoff and water springs (Marques *et al*. 2019), and the shading of the rugged relief keeps the humidity for more time (Alves 1998). Most of the island's river channels have similar characteristics and are connected to the higher areas (Marques *et al*. 2019), and probably the species has already been established in other points than those presented here.

Although human actions have caused the effective extinction of different species around the world (Ceballos *et al*. 2010; Humphreys *et al*. 2019; Le Roux *et al*. 2019), we should also point out that several species considered extinct in the past, mainly due to the absence of records at long time intervals, were rediscovered (Alves 1998; Brandão *et al*. 2008; Camargo & Álvarez-Castañeda 2019; Humphreys *et al*. 2019). Only for plants, 1,234 species have already been considered extinct at any moment, according to the compilation of published data carried out by Humphreys *et al*. (2019). However, 571 (46 %) of them were confirmed to be currently extinct, while 431 (35 %) of them were rediscovered and 232 (19 %) were synonymized (Humphreys *et al*. 2019). In this sense, some species currently classified as extinct may, in fact, not have been detected, for example, due to low natural population density or due to anthropic interference, associated with sampling gaps. This raises doubts if *P. trinitatis* was extinct in the vegetative form before regenerating through the seed bank, as pointed by Alves (1998), or if the plant persisted in other parts of Trindade Island, as the areas of lower elevation, and was not previously detected due to the sample gaps.

Anyway, historical data demonstrate the highly destructive effect of invasive species on the vegetation of Trindade Island; and the locations of new occurrences pointed out by Alves (1998) and Fisch & Port (2017) correspond to trails widely used by researchers. These facts suggest that *P. trinitatis* was not actually present at these points when it was declared extinct. This corroborates the hypothesis that *P. trinitatis* may be expanding its occupation to the higher and lower altitude areas of the island from the seed bank. With that, we suggest conducting actions aimed at the continuous combat of introduced species so that the population of *P. trinitatis* can remain in recovery. The introduced species in this case include mice, since they are efficient predators of seeds and seedlings on the island (Alves 1998). It is also noteworthy the existence of new threats, such as those caused by invasive plants, which already affect the local vegetation (Carvalho-Silva *et al*. 2013), emphasizing that a large part of the plant species registered on the island over time is invasive or cultivated (see Alves 1998). Climate change may also represent another important threat since it can promote changes in temperature and precipitation, reducing distribution and contributing to extinction of plants in island environments (Ferreira *et al*. 2019).

The records presented here expand the known distribution of *P. trinitatis* in terms of area and altitudinal range, both considering historical records and records associated with its rediscovery in 1998. We suggest that this species may be recovering at Trindade Island, providing one more example that species can recover when the threats that led to the decline of populations (effects of invasive species, for example) are controlled in time. In this way, we recommend conducting new sampling to detect other locations with occurrence of *P. trinitatis*, not only in the hydrographic basins adjacent to those where the occurrence of the species was already confirmed. New studies may also help to clarify how close the species was to being extinct or whether sampling gaps were responsible for the consideration that the species was extinct in the past. This can help to review conclusions that may have resulted from possible sample gaps. This may also reinforce the importance of searching for individuals of species considered extinct at a given moment (*e.g. Asplenium beckeri*, *Elaphoglossum beckeri* and *Peperomia beckeri*; Alves *et al*. 2011; Silva *et al*. 2013) and also of species difficult to study due to the reduced populations. Increasing efforts aimed at detecting these plants, determining their population status, and verifying their permanence over time may contribute to decision making about the need for actions to recover these populations.

Acknowledgments

We thank the Projeto TAMAR and the Programa de Pesquisas Científicas na Ilha da Trindade (PRO-TRINDADE) for the logistical support and accommodation on Trindade Island.

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