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SHORT NOTE

A recolonization record of the invasive *Poa annua* in Paradise Bay, Antarctic Peninsula: modeling of the potential spreading risk

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Abstract Antarctica is one of the most extreme environments for vascular plants occurrence worldwide, and only two native vascular plants have colonized this continent: *Deschampsia antarctica* and *Colobanthus quitensis*. Nevertheless, in recent years, several alien plant species has been found in Antarctica with negative effects on the native flora. In this study, we show a recolonization record of the most widespread plant invader in Antarctica (*Poa annua*) and the risk of a potential spreading in a highly visited site on the Antarctic Peninsula. Overall, two new *P. annua* individuals were recorded, where four specimens were previously reported and removed in 2010, suggesting that either a propagule load is continuous, or that a seed bank prevailed in the site. On the other hand, the spreading modeling suggests that the probability to colonize and spreading of *P. annua* increases notoriously with the possibility of dispersion of propagules, with consequent risk of displacement for the native flora. Biological invasions are a major threat to the integrity of native biodiversity in all biomes, and they have the potential to change irreversibly Antarctica's fragile ecosystems.

Keywords Antarctica · Biodiversity · Invasions · *Poa annua*

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Introduction

The Antarctic continent is one of the most extreme environments for flowering plants occurrence worldwide. This environment is characterized by low temperatures, high irradiance and low availability of water and nutrients (Robinson et al. 2003; Wasley et al. 2006). Most of the Antarctic continent surface is covered by permanent ice and snow, and only 0.34 % of it is available for colonization by plants, with most of the ice and snow-free lands are found along the Antarctic Peninsula (Convey et al. 2009). The Antarctic vegetation is mostly composed by cryptogams (mosses, liverworts and lichens) and only two native flowering plants: *Colobanthus quitensis* and *Deschampsia antarctica* (Smith 2003; Molina-Montenegro et al. 2013). Nevertheless, in recent years, several alien plant species has been found inhabiting in the South Shetland Islands as well as in the Antarctic Peninsula (Smith 1996; Olech and Chwedorzewska 2011; Molina-Montenegro et al. 2012; Pertierra et al. 2013; Molina-Montenegro et al. 2014).

Biological invasions are a major threat to the integrity of native biodiversity in all biomes, and they have the potential

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to change irreversibly Antarctica's fragile ecosystems (Frenot et al. 2005; Hughes et al. 2010). An important number of plants has already invaded Antarctica (Chwedorzewska 2008, 2009) and sub-Antarctic islands (Frenot et al. 2005), but scarce studies have evaluated the potential ecological effects of alien plants on the native Antarctic flora (but see Molina-Montenegro et al. 2012). Introduction routes of alien organisms are largely associated with movement of people and cargo from scientific programmes and, to a lesser extent, tourist operations (Frenot et al. 2005; Hughes et al. 2010; Chwedorzewska et al. 2011; Chown et al. 2012; Molina-Montenegro et al. 2012). All cargo, personal luggage, clothes and equipment of people visiting Antarctic stations can be potentially contaminated by alien propagules (see Chown et al. 2012). In fact, in a recent study, Huiskes et al. (2014) have provided further evidence that tourism and scientific activities have a high potential of plant propagules transferring into Antarctic ecosystems with unsuspected impact on native flora. On the other hand, once alien species are occurring in a site, different human activities (walking and use of heavy vehicles, in a very limited area) can help to spread the propagules, and therefore enhance the possibility of colonization and invasion locally and promote regional colonization.

Different methods have been developed to explore the invasion processes in order to predict the spread and potential effects of alien species on native communities (e.g., Heger and Trepl 2003). Ecological modeling has proved to be an appropriate tool to simulate the outcome of plant–plant interactions, particularly when dynamic models consider temporally explicit environments (Argent 2004). One of the most realistic methods is the "individual-based model (IBM)", accounting for the interactions between native and alien organisms in the complex contextually of real conditions (De Angelis and Mooij 2005). In fact, the IBM has been widely used with different kinds of species and ecosystems to predict the spread and effect of exotic species interacting with native ones (Higgins et al. 1996, 2000). Thus, IBM is an appropriate tool to assess and predict the potential spread of exotic plants that have arrived in recent years, and thus, estimate the possibility that they will really invade the Antarctic.

Poa annua is the most conspicuous invasive plant species in the Antarctic continent. This species is commonly associated with anthropogenic habitats, but can also be found in natural habitats in the Antarctic and sub-Antarctic islands (Frenot et al. 2005; Chwedorzewska 2009) and in some places of the Antarctic Peninsula (Molina-Montenegro et al. 2012, 2014). For instance, at Henryk Arctowski Station, a large population of *P. annua* has grown, set seed and spread without any attempts to control it (Wódkiewicz et al. 2014). It has also been recorded and collected around of some building of Antarctic bases on Paradise Bay (Molina-Montenegro et al. 2012). The sustained increase in tourism and scientific activities appears to promote the successful establishment of this alien plant in natural habitats with potential negative effects for the native flora (Huiskes et al. 2014; Molina-Montenegro et al. 2014).

Here, we report a new record of the invasive *P. annua* growing again around of Gabriel González Videla station in Paradise Bay (64°S). In addition, we developed a spatially explicit computational simulation in which we evaluated the consequence of different dispersal scenarios facilitated by human activities to assess how *P. annua* would spread across this site.

Methodology

During the Chilean Scientific Expedition no. 50 (Austral summer 2013/2014), we visited different sites along Paradise Bay searching for *Colobanthus quitensis* and *Deschampsia antarctica*, both native components of the Antarctic flowering flora. Close to the main building of Gabriel González Videla station (64°49′S; 62°51′W), we found two individuals of *Poa annua* species (Fig. 1). Both individuals were collected from the field and dried for its taxonomic identification. A voucher (Chile, Región de Magallanes y Antártica Chilena, Base Gabriel González Videla, 64°49′S, 62°51′W, January 28, 2014, Molina-Montenegro & Torres-Díaz s.n.) was deposited at the herbarium of the Faculty of Agronomy, University of Concepción (CONC-CH), Chillán, Chile (36°35′S, 72°05′W). The botanical identification was made using taxonomical bibliography (Tzvelev 1983; Giussani et al. 2012). Photographs were made with a stereophotomicroscope Zeiss Stemi 2000C using the software ZEN 2011.

Computational simulations

We built individual-based model (IBM) on the base of: (1) a previous study which showed that, under laboratory conditions, *P. annua* can outcompete the two native vascular plants from Antarctica (Molina-Montenegro et al. 2012) and (2) the results from a recent study and datasets that suggest that spread of *P. annua* is largely facilitated by human activities (Molina-Montenegro et al. 2014) where it seeds can be dispersed at different distances as seen by the seed banks (Molina-Montenegro, unpublished data).

The individual-based model was implemented by simulations in two kinds of space conceived as "limited" (plane) and "toroidal", each consisted of a 250 × 250 pixel square. In the limited space setting, every new plant that goes out of the simulation borders is discarded, while in the toroidal space, every new plant going a given

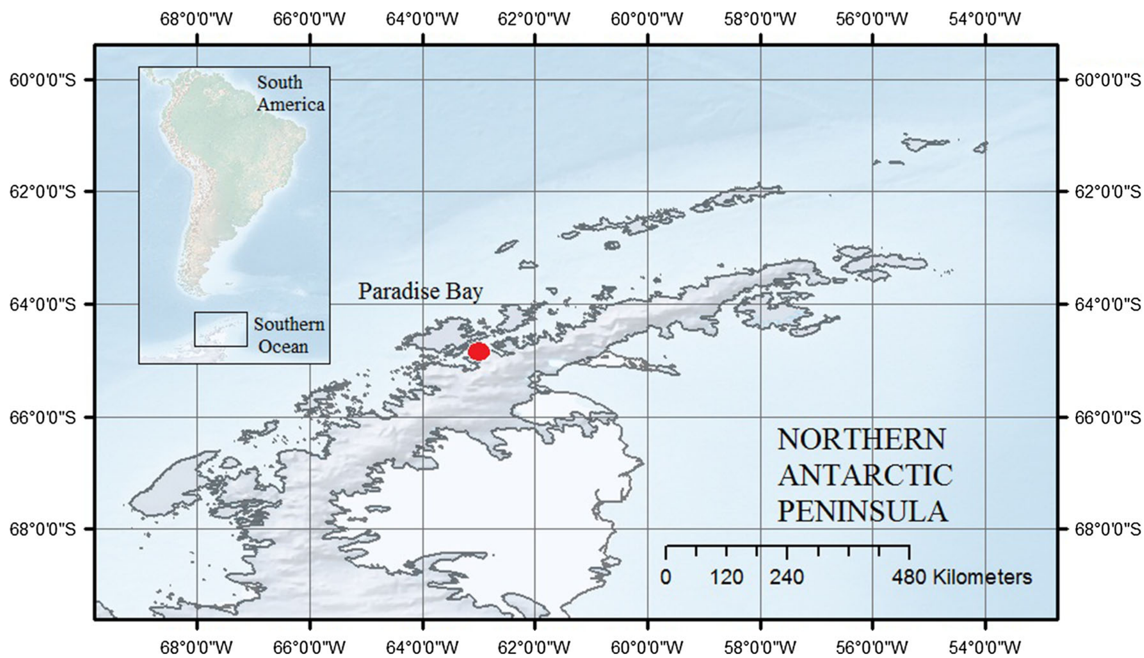

Fig. 1 Site where individuals of *Poa annua* were recorded (*red circle*) growing close to the Chilean Antarctic base "Gabriel González Videla" on the Paradise Bay, Antarctic Peninsula. (Color figure online)

distance out of the simulation borders re-appears at the same distance from the opposite border. Each plant has spatial properties (size, location and dispersion range), reproduction rate and survival probability (which is a function of local densities of *P. annua* recorded in situ). The identity of the plant (native or invader) determines different initial numbers of individuals (N_n for native and N_i for invader plants) and the linear relationship between survival probability P_s and local relative density of local competitors f ($P_s = -\beta \times f + \alpha$), where f is the relative abundance of plants of the same identity and the number of competitors within a circular neighborhood of eight pixels in diameter, and β and α are the slope and intercept of empirical regressions, respectively. Simulations started with a fixed number of native plants $N_n = 500$ and the invasive plants $N_i = 1$, based in the relative abundance of *P. annua* measured by ten 2 × 2 m quadrants in the study site on February 2011 (2 ind./km^2). These abundances correspond to 0.5 % with respect to the abundance of the native plants. In each simulation cycle, ($n = 100$) each plant had the opportunity to produce an offspring per growing season both for native as well as for invader species. Plant size was represented as a square of four pixels diameter, thus the neighborhood of competition is four times the plant surface area. Plant superposition in space was not allowed, and location coordinates were represented as floating-point numbers, avoiding a simple grid spatial topology. Plant locations are randomly assigned by a uniform probability distribution.

Taking into account field data of plant dispersal—estimated by seed bank samples obtained in the study site for *P. annua*—we explored three dispersal distance ranges. The minimal rate of decrease value of 1.5 used for simulations was considered equivalent to the average of the exponential distribution fitted to data, i.e., 132 cm of dispersion from any target plant, while higher rate of decrease (3.0 and 6.0) would represent the increased dispersion caused by human activities or other factors equivalent to 264 and 528 cm, respectively.

Results

After the taxonomic analysis, studied specimens were identified as *Poa annua* L. (Poaceace). The specimens showed the following features: plants 4–6 cm high; leaf blades 4–6 cm long × 1–1.8 mm wide, flat, glabrous; ligule 2.5 mm long; panicle 2 cm long, 0.6–1.2 mm wide; spikelets 2–3-flowered, 4 mm long; first glume 1.2 × 0.4 mm, 1-nerved, glabrous; second glume 2.2 × 0.5 mm, 1–3-nerved, glabrous; lemma 2.5–2.6 mm, glabrous, not webbed at the base, nerves glabrous; palea 2-nerved, the nerves smooth, 2 mm long; and anthers 3, 0.6–0.8 mm long (Fig. 2). Plant collected showed mature floral development with seeds produced at its removal stage.

Regarding the computational simulation, the predicted effect for the spread of *P. annua* was different considering the different distances of propagules dispersion (Fig. 3).

Fig. 2 Reproductive and vegetative morphology of *Poa annua* growing close to the Chilean Antarctic base "Gabriel González Videla", Paradise Bay, Antarctic Peninsula. **a** Inflorescence. **b** Spikelets. **c** Leaf blades and ligule (li). All from Molina-Montenegro and Torres-Díaz (CONC-CH). *Scale bar* 1 mm

When considering the shorter distance of dispersion (132 cm), *P. annua* reached ca. 2 % of presence in the site compared with the natives *D. antarctica* and/or *C. quitensis*, but when longer distances of dispersion are considered (264 and 528 cm), *P. annua* reached ca. 12 and 40 %, respectively (Fig. 3). The pattern found suggests that the probability to colonize and spreading of *P. annua* increases notoriously with the possibility of dispersion of propagules of this invader species, with consequent risk of displacement for the native flora (Fig. 3).

Discussion

A recolonization of *Poa annua* in Paradise Bay, where four specimens were previously reported and removed in 2010 (see Molina-Montenegro et al. 2012), suggests that either a propagule load is continuously reaching the site or that a seed bank prevailed in the site after its previous removal. Identification of the origins of such recolonization may not be a trivial task. As the plant collected produced seeds by the time of the removal, new germinations could be expected in the area. Thus, an exhaustive monitoring is recommended on the following years to prevent further seed productions from any new sprouts tentatively emerging, as part of a contingency plan. However, due to the heavy visitation of the Paradise Bay, this alone may not prevent entirely new occurrences in this zone. In the Antarctic region, introduction routes are tightly associated with movement of people and cargo in association with national scientific programs and tourist operations (Chwedorzewska et al. 2011; Chown et al. 2012). Tourist and research vessels also undertake activities on sub-Antarctic islands and then visit a range of Antarctic locations. Without strict controls, such operations may transport large quantities of non-native and potentially invasive species propagules, including those from the southern tip of South America, where they may already be preadapted to harsh environmental conditions (Frenot et al. 2005; Convey et al. 2008). In recent decades, the atmospheric and oceanic barriers to dispersal around Antarctica (Barnes et al. 2006) have been increasingly circumvented by the rapid increase in human activities. For example, tourist numbers visiting the continent annually have increased nearly fivefold in the last two decades (Lynch et al. 2010). In a recent study, Huiskes et al. (2014) provided overwhelming evidence showing both tourists and scientists are important vectors for seeds transportation of non-native species into Antarctica. Moreover, it is widely assumed that soil disturbance enhances resource availability (*e.g.*, Davis et al. 2000), and some have shown positive effects of soil disturbances on the establishment of *P. annua* in Antarctica (Molina-Montenegro et al. 2014). Therefore, the arrival and subsequent establishment of alien plants into Antarctica is being largely facilitated by human activities (tourisms and scientific research) through seed transport, soil disturbance and propagules movements around research stations. In fact, further propagules movements would enhance the invasion success and its negative impacts, as shown in this study.

With rapid climate change occurring in some parts of Antarctica, in particular, the Antarctic Peninsula (Convey et al. 2009), an increasing number of successful dispersal and establishment events are likely (Frenot et al. 2005). In this sense, here we demonstrated by computational modeling that with only a pair of individuals, *P. annua* could spread in the locality where it is present currently. Scientific expeditions remain in one place much longer than tourists, also bringing large quantities of supplies and equipment, which may be contaminated with propagules, as well as contributing to the dispersion of such propagules present in the seed bank around of bases. It is widely

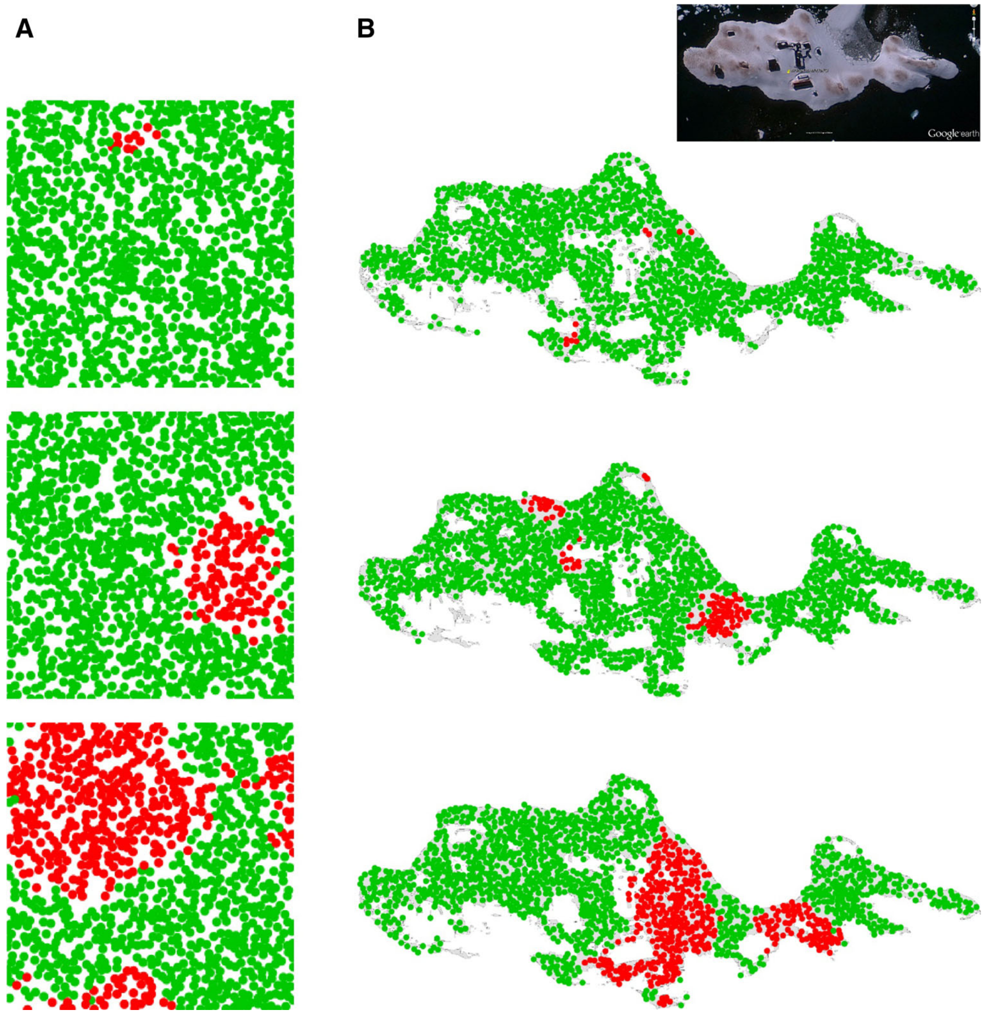

Fig. 3 Simulation trials performed in a toroidal space (**a**), and a geographically realistic space (**b**) based on the Chilean Antarctic base "Gabriel Gonzalez Videla" (see *upper right satellite image*). *Green circles* represent native plants (*Deschampsia antarctica* and/or *Colobanthus quitensis*) and *red circles* exotic plants (*Poa annua*). From *top* to *bottom*, different degrees of *P. annua* spread are shown considering 132, 264 and 528 cm of dispersion from any target plants. (Color figure online)

recognized that Antarctic station operations cause local soil disturbance in due to the construction of buildings (e.g., physical and chemical disturbances). Thus, the areas surrounding each station could be subjected to higher human impact than other regions of Antarctica (Chwedorzewska and Korczak 2010). Most of stations are built in ice-free areas, providing the most favorable microclimate in Antarctic. Delivering supplies to stations and the upkeep of their infrastructure requires the use of heavy vehicles. These operations are typically concentrated in very limited area and also have the potential to damage the soil structure. Thus, human activities (tourism and scientific) affecting the physicochemical soil conditions and propagules movements could have direct effect on establishment and spread of invader plants, being this process faster when dispersal of propagules is higher.

In this study, we show the risk of a potential spreading of *P. annua* in a highly visited site, as Paradise Bay on the Antarctic Peninsula. The outstanding ecophysiological performance, germination and survival capacity, and competitive effects of *P. annua* on native plants (Molina-Montenegro et al. 2012, 2014), suggest a future spread of this invasive species across Antarctic habitats as well as a potential local displacement of the native vascular flora unless dedicated biosecurity actions are effectively implemented. The effects of biological invasions in the Antarctica are difficult to predict and to manage, but a strict protocol of safety or eradication plan should be implemented in order to avoid the introduction of non-native organisms to Antarctica. Finally, we propose that non-native species introduction should be classified as an "environmental emergency" in Antarctica in order to maintain the biodiversity in one of the most pristine places worldwide (see Hughes and Convey 2014).

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