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Citizen engagement in the management of non-native invasive pines: Does it make a difference?

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Abstract Civil society can play a relevant role in supporting local environmental management, as volunteer efforts can be carried out at low cost and therefore be sustained over time. We present in this paper the assessment of the effectiveness of a volunteer program for the control of invasive pines in a protected area (PA) in a coastal zone of southern Brazil. Volunteer work has been ongoing for 8 years and the current state of invasion was compared with three simulation scenarios of species distribution that considered suitable habitats for pine invasion. Our results suggest that management actions have been effective. In the absence of any control efforts, pine trees would cover a high percentage of suitable habitats within the PA. Eliminating adult pine trees that function as seed sources and not allowing the next generation to reach maturity has been an efficient control strategy that has led to changes in the population structure of pines in the PA. Reaching neighboring private property owners is key for the future effective control of pines in the area, as all sources of pine seeds need to be eliminated. The approach used in our study may be applied to broader spatial scales to provide a baseline for management efforts needed to effectively control non-native invasive species.

Keywords Coastal scrub · Control program · Habitat suitability models · Invasive pines · Simulations · Volunteering

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Introduction

Citizen engagement in biological invasion projects has greatly expanded the amount of data available on the occurrence of non-native species, often filling gaps in the spatial distribution of invasive species (Brandon et al. 2003; Delaney et al. 2008; Crall et al. 2010; Bois et al. 2011; Gallo and Waitt 2011; Crall et al. 2015). Data gathering by citizens can be a low-cost method

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for the early detection of new invasion *foci* (Pocock et al. 2016), increasing the feasibility of eradication of incipient populations. However, citizen participation in invasive species issues can be extended beyond surveillance and early detection. The involvement of citizens as volunteers can increase the success of invasive species management programs and reduce the amount of financial resources spent on control programs (Simberloff 2003; Bryce et al. 2011; Ingwell and Preissler 2011; Ford-Thompson et al. 2012; Miralles et al. 2016; Ricciardi et al. 2017). Besides, engaging volunteers in the management of invasive species helps raise awareness and build public support for confronting the challenge posed by invasive species (Simberloff 2003), as well as provide additional assistance for actual work.

The movement of plant species around the globe by human action has significantly increased throughout the history of mankind (Bossdorf et al. 2005). *Pinus*, *Eucalyptus* and *Acacia* are among the most important genera in forestry plantations globally (Richardson 1998). Many species in these genera have been introduced to a range of new habitats, creating ample opportunities for invasion. Species in the genus *Pinus* have been introduced to nearly all countries in the southern hemisphere, outside their native ranges (Richardson et al. 1994; Simberloff et al. 2010; Nuñez et al. 2017). They have adapted, reproduced and spread from plantations to invade adjacent vegetation (Richardson and Higgins 1998). Pines often occupy marginal habitats, degraded areas or disturbed sites such as roadsides. As the seedlings are light-demanding, they invade open ecosystems such as grasslands, savannas, wetlands, and coastal scrub (Richardson et al. 1994).

Pines are a new life form in treeless habitats, therefore directly affecting ecosystem properties and the native biota. Registered impacts include changes in soil properties (Simberloff et al. 2010; Rundel et al. 2014; Valduga et al. 2016), high water consumption (Le Maitre et al. 2000), increase in fire risk because of low decomposition rates of pine needles (Ziller and Galvão 2000), exclusion of shade-intolerant indigenous species, simplification and homogenization of habitat structure leading to local extirpation (Simberloff et al. 2010; Valduga et al. 2016) and, therefore, a reduction of species richness and native plant cover (Franzese et al. 2017). Fire can further damage vegetation that lacks fire adaptations (Simberloff et al. 2010), such as the Atlantic Forest and associated ecosystems in Brazil (coastal scrub, wetlands) as well as deforested and degraded areas within this biome.

This paper addresses biological invasions by *Pinus elliottii* Engelm which lead to significant landscape changes in coastal scrub and sand dunes in southern Brazil. We assessed the outcomes of a volunteering program that began in 2010 to restore areas invaded by pines in a protected area (PA). Volunteers have been removing invasive pines by pulling seedlings and cutting young trees with hand saws. A prioritization scheme was developed based on the population structure of pines and pine size/age to maximize control success. Because every biological invasion is different due to varying environmental conditions, propagule pressure and habitat suitability, creating uncertainty in predicting management results, adaptive management strategies were used in the program (Zalba and Ziller 2007; Foxcroft and McGeoch 2011).

The main aims of this study were (1) to document the results and costs of the volunteering program in controlling pine invasions in a PA, (2) to map the potential distribution of invasive pines based on habitat suitability models to prioritize management and monitoring efforts, and (3) to simulate the potential distribution of pines in the absence of management and under distinct control efforts in order to compare these results with the success of the volunteering program. The simulations were conducted for a time interval of 18 years (2010–2028), since the beginning of the control program (2010).

Materials and methods

Study system

The Dunas da Lagoa da Conceição Municipal Park (27°36′24″–27°38′39″S and 48°26′49″–48°28′05″W) is a protected area (PA) located on the Island of Santa Catarina, Florianopolis, in southern Brazil. It protects an area of coastal scrub on sand dunes, part of the extensive Atlantic Forest domains in the subtropical region of Brazil. The regional climate is Cfa type—humid subtropical climate according to the Köppen-Geiger classification. The mean temperature ranges from 26 °C in summer to 16 °C in winter, with an annual mean of 20 °C (INMET 2017). Rainfall is well distributed throughout the year, but higher in the summer months, with an annual average of 1500 mm (INMET 2017). The PA covers approximately 500 hectares of sand dunes, coastal scrub and wetlands which provide habitat for 326 plant species (Guimarães 2006). Microhabitats in the PA include beaches, frontal dunes, interior mobile, semi-fixed and fixed dunes, and low areas which can be dry, damp or periodically flooded, forming temporary and permanent pools (Guimarães 2006). This variety of microhabitats is occupied by a high diversity of shrubs, grasses and herbs, with some aquatic species thriving in the wet season. Some endemic and regionally endangered species such as the herb *Petunia integrifolia* (Hook.) Schinz and Thell. (Solanaceae), the shrub *Campomanesia littoralis* (Myrtaceae) and endemic species such as *Solanum pelagicum* (Solanaceae) and *Aechmea comata* (Bromeliaceae) occur in the area (Klein 1990, 1997; Guimarães 2006). The first records of the birds *Anas flavirostris*, *A. versicolor* (Anatidae), *Tachybaptus dominicus* (Podicipedidae) and *Gallinula melanops* (Rallidae) in Florianopolis were obtained in permanent waterholes in the PA (Ghizoni et al. 2013).

The first pine and eucalyptus plantations on the Island of Santa Catarina were established in 1963, when a governmental forestry trial station was installed in an area of nearly 500 hectares along the northeastern coast. Several smaller plantations were then established all over the island until 1973, creating sources of pine seed dispersal intensified by strong ocean winds. By 1974, 133,075 pine and eucalyptus trees had been planted on the island, most of which were *P. elliottii* (Caruso 1990). Other seed sources lie along PA borders in private properties where pines were planted decades ago to stabilize the movement of sand.

Pinus elliottii and *P. taeda* are fast growing conifers from southeastern United States (USDA Plants Database 2017). Adult trees grow to 12 or 15 m in height and start producing cones at 5 years of age in southern Brazil (Bechara et al. 2013; Tomazello Filho et al. 2016). *Pinus taeda* seeds take 3 years to mature, with 70% viability, while *P. elliottii* seeds are formed in 2 years (Jankovski 1985). An average 4.1% of seeds still retain 50% viability 1 year after the cones open (Jankovski 1985). Seed production by *Pinus taeda* is estimated at 526–690 seeds/m^2 (Jankovski 1985), while *P. elliottii* maintains a continuous seed rain along the year, dispersing approximately 204 viable seeds/m^2 per year (Bechara et al. 2013).

Pinus elliottii and *P. taeda* have invaded the PA, forming small populations of multiple ages or isolated trees. Although no systematic study was conducted, we observed that most of the pine trees present in the PA belong to *P. elliottii* (personal observation). The PA is susceptible to pine invasions because the native vegetation is formed by small, scattered patches of dense cover by shrubs and occasional small trees (Guimarães 2006). Most of the native species, as in other open or treeless ecosystems, are light dependent and cannot develop in the shade of pines.

Control activities and collection of field data

A volunteering program created by the Horus Institute for Environmental Conservation and Development, a non-profit organization in Florianopolis, Santa Catarina, has been in operation in the PA since 2010. This program aims to restore invaded areas and conserve native species by controlling pines in the PA and its surroundings. A sequence of priority target areas for pine control was defined based on surveys of pine populations in the entire PA. The surveys focused on the most suitable habitats for the establishment of pine trees, represented by areas covered in herbaceous vegetation close to temporary and permanent pools as well as by areas surrounding adult trees and/or planted trees in adjacent private properties. The PA was subdivided in three large areas in which two work fronts have been controlling pines (Fig. 1). One front consisted of two chainsaw operators hired to cut down large pine trees; the other front was formed by volunteers whose work is to pull out seedlings (height < 50 cm) and cut down juveniles (height > 50 cm and < 300 cm) with hand saws. Chainsaws owned by a few volunteers are also used to cut down adult trees up to medium size (height: 3–5 m). Professional chainsaw operators contributed to the volunteer program by charging reduced wages that basically cover operational costs. Areas A (45 ha) and C (26 ha) on the map were composed of a mosaic of shrubs and herbaceous vegetation, whereas area B (140 ha) was characterized by herbaceous vegetation with sparse shrubs, permanent water bodies and temporary pools (Fig. 1).

Pine populations were surveyed annually to provide priority-setting data for the following year. A

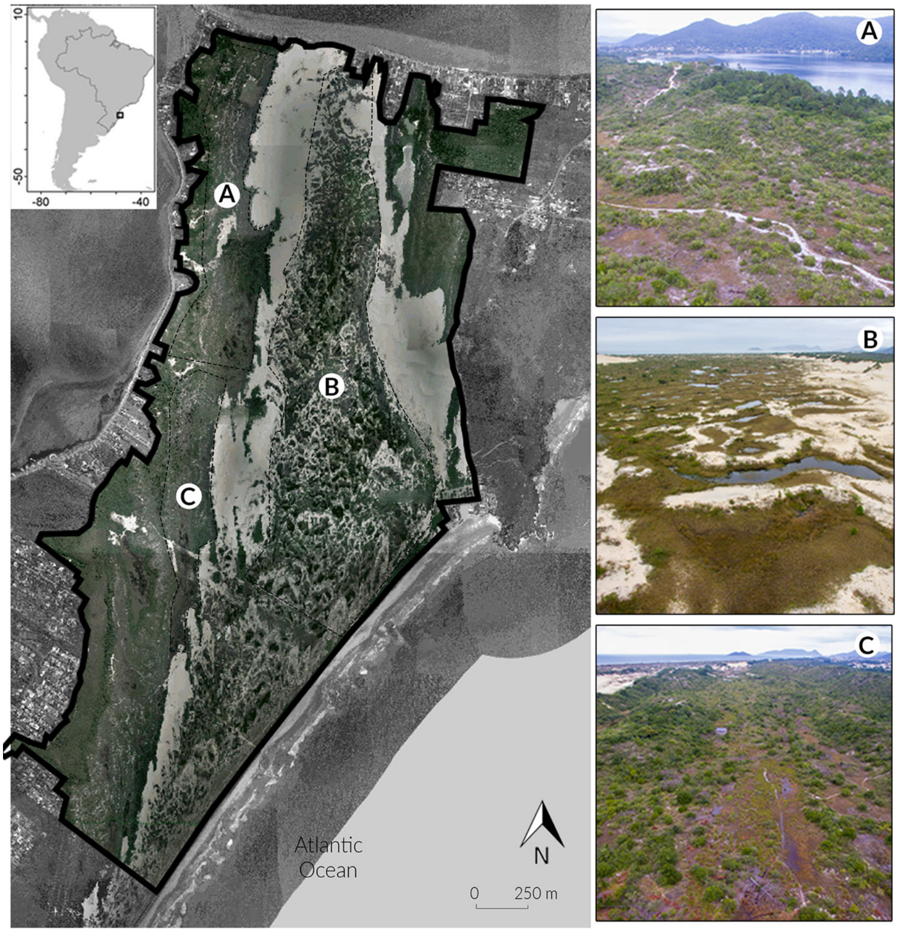

Fig. 1 Location of the Dunas da Lagoa da Conceição Municipal Park (Florianopolis, southern Brazil), and the three focal areas for control of invasive pines (A, B, C)

sequence of priority areas and/or populations was defined for each work front based on the size of patches/populations and on the size of adult and juvenile plants. The highest priority for professional chainsaw operators were isolated trees and small populations of adult trees, followed by larger populations of large adult trees. On the other hand, the highest priority for volunteers were populations with large juvenile trees (that have just begun to produce cones, bear developing cones or are about to release seeds), followed by dense populations of juvenile plants. The aim of this management strategy was to eliminate potential sources of propagules and juvenile pines before they reproduced and renewed the seed bank.

Although management priorities were set to eliminate adults and juveniles, seedlings were also pulled out by volunteers, regardless of size. The number of pine plants eliminated was counted by each person by size class: seedlings-plants that are pulled out, height varying from 5 to 50 to 100 cm; juveniles-plants cut down with hand saws, height between 100 and 300 cm; and adults: plants higher than 300 cm which could only be eliminated with the use of chainsaws. Some of the volunteers used chainsaws to cut down large juvenile and small adult trees. The numbers of trees eliminated were registered by each volunteer along the process, then summarized in the middle (during a break) and at the end of the activity by the program coordinator.

The number of hours of all activities (volunteers and chainsaw operators) have been registered since the beginning of the program in 2010. The average wage of a field employee with 6–8 years of experience in 2018 (https://www.sine.com.br/media-salarial-para-auxiliar-de-servicos-gerais) was used to estimate the financial resources saved since 2010. The average wage in 2017 was divided in 40 h (standard number of working hours per week in Brazil) in order to have an average cost equivalent to 1 h of labor for volunteers and chainsaw operators (R$ 41.50 which corresponds to US$ 10.70-dollar value in July 2018). The final costs were calculated for volunteers and chainsaw operators, considering the number of hours of each activity multiplied by the number of volunteers/chainsaw operators multiplied by the number of activities in all years. The reduced wages paid to chainsaw operators to cover operational costs (e.g. gasoline and oil to the chainsaw, tool maintenance) was subtracted from the final cost.

Habitat suitability model

High-resolution geographic data was obtained from orthophotographs (year 2010) provided by the Santa Catarina State Secretary for Sustainable Economic Development (SIGSC 2017). Orthophotographs with a resolution of 0.39 m were classified based on five main land cover categories: bare sand (no vegetation), herbaceous vegetation, forest patches, permanent water bodies and temporary pools. These categories were selected based on field observations of the habitat types more prone to pine establishment. According to our observations, forest patches, dunes and water bodies are unsuitable for the establishment of pine trees, while temporary pools and herbaceous vegetation are suitable. The classification of images was performed with the software Multispec v.3.4 (Biehl and Landgrebe 2002) for land cover predictors (forest patches, herbaceous vegetation, sand dunes, water bodies and temporary pools).

To identify pine trees in the PA, freely available high-resolution orthorectified satellite images from 2012 were obtained and analyzed using Google Earth (resolution of 0.5 m). All geographic coordinates of the pine trees identified were recorded. Most of the 810 pines identified were adult trees large enough to be seen on the images. Younger pines tended to be overlooked because they could not be seen on the images. Complementary field verifications were carried out to ensure correct identification and collect geographic coordinates of adult and juvenile pines. Once a pine population was identified, the coordinates were verified in a more recent image. When the population was no longer present, it meant that those pines had been eliminated by the control program (Online resource—Fig. S1).

Once the location of pine trees was recorded, a displacement error was introduced. In order to minimize the bias caused by the displacement error, which could generate wrong values for land cover categories, a grid (5 m resolution in each grid cell) covering the whole PA was created to sample the values from land cover category maps. The proportion of land cover categories ($\sim$ 164 grid cells of 0.39×0.39 m) in each cell of the grid was then obtained. The proportion of each land cover category obtained from each cell of the grid was used to run habitat suitability models. An absence background was generated by random sampling of 806 grid cells without pines. Absence sampling was performed only within the geographical limits of invasion inside the PA.

To improve habitat suitability predictions, a suitability map using an ensemble modeling approach was produced (Araújo and New 2007). The presence/absence of pines represented the response variable, while the coverage values of the categories in each grid were used as predictors [bare sand (no vegetation), herbaceous vegetation, forest patches, permanent water bodies and temporary pools]. Three models were then fitted: a generalized linear model (GLM), boosted regression trees (BRT) and random forests (RF). To evaluate model performances, the data set was divided into 80% for training and 20% for testing, and the area under the curve (AUC) was analyzed. A consensus map using the predictions produced by each model was created to produce a habitat suitability map. Model predictions were weighted by the correspondent AUC values (Online resource—Fig. S2). Data was prepared using the *sdm* package to run the habitat suitability models in the R software (R Core Team 2016; Naimi and Araújo 2016). In addition, to explore the direction and intensity in which the predictors affect habitat suitability, Spearman correlation tests were performed between predictors (sand dunes, temporary pools, herbaceous vegetation, forest, permanent water bodies) and habitat suitability values from the final prediction map.

Simulations

The seed shadow of *P. elliottii* was initially estimated using secondary data of seedling establishment from Bechara et al. (2013) because we could not find data of direct seed dispersal to different distances for this species. These authors found a steep decrease in seedlings per m^2 with increasing distance from *P. elliottii* plantations, with very few seeds reaching and establishing 50 m away from plantations. This information agrees with previous data indicating that most of the wind-dispersed seeds of *P. elliottii* spread to short distances (Queensland Government 2011), with more than 90% of seeds falling within 45 m of the source tree (Cooper 1957). The number of seedlings found at different distances and seed production (2500 seeds per year by a single adult tree; all data from Bechara et al. 2013) were then modeled using a generalized linear model with binomial distribution and logit link. The resulting predicted probabilities for increasing distances were used as a dispersal kernel for *P. elliottii* seeds (Online resource—Fig. S3).

Afterwards, the growth of pine populations across the study area was modeled using the "MigClim" (Engler et al. 2012) package in the R software (R Core Team 2016). MigClim implements a cellular automaton-based simulation and explicitly incorporates specific information about both dispersal ability and environmental associations. First, we parameterized the simulations with the known location of 810 adult trees of *Pinus* spp. identified on orthorectified satellite images from 2010. Second, the risk of invasion resulting from suitable habitat distribution was represented in the suitability map from the "*Habitat suitability model*" section. Habitat suitability was used as a continuous numerical surface. A 15% threshold of habitat suitability was also added, a value under which habitat suitability was converted to zero because local observations suggest that there is almost no chance of establishment by pines in such habitats. Third, the probability of establishment was defined depending on the dispersal kernel described in the beginning of this section, with dispersal probability decreasing with distance. Distance-decay dispersal was allowed up to 50 m from adult trees, while invasion occasionally occurred at greater distances due to long distance dispersal (LDD) events. It was assumed that LDD events had 10% frequency from 50 up to 4000 m and decreased to zero beyond 4000 m from parent plants. Fourth, propagule production was parameterized to start in the fifth year after a grid cell was colonized, starting with 1% seed production in the first year and increasing each year, as follows: 1, 5, 10, 25, 50, 90, and 100%. Seed production was simulated as an annual event. Each simulation spanned 23 years with the first 5 years used only to generate a structured population as found in the field in 2010, while the following years were subjected to varying management as described below. Simulations were run with rasters with a resolution of 5.06 × 5.06 m.

To assess the effectiveness of management actions to control invasive pines in the PA, three different scenarios were simulated. Simulations aimed to allow for comparisons either between the current state of invasion (2018) and predicted future states of invasion under different management intensities up to 2028. The first scenario (scenario 1) simulated the absence of any management to project the current state of invasion if no control action had ever been implemented.

The second scenario (scenario 2) simulated current management until the end of 2017. In this scenario, three focal areas (A, B and C—Fig. 1) were visited from 2010 to 2017 with differing efforts between the years, the removal of all adult pines was reached in 2018 in the entire PA, and a future management scheme was simulated for 2019 to 2028. In the first period (2010–2017), portions of area A were managed in all these years, portions of area B were managed from 2015 to 2017, and portions of area C from 2014 to 2017 (Online resource—Table S1). To simulate these changing efforts, we split the three focal areas by the number of activities undertaken each year. We then selected the coordinates of all adult trees in each split and constructed a buffer with a 50 m radius around each of them (Online resource—Fig. S4). All pines falling within a buffer in any simulation step were excluded. This design is very similar to past control activities through our management program in which adult pine trees were normally located first, nearby areas inspected for juveniles and seedlings followed by removal of all pines found. Because the spatial location of past activities was not recorded, we randomized ten times the spatial order of past control activities during simulations. We also generated 50 m buffers around all remaining adult pine trees identified in the PA for 2018, excluding those in the three focal areas and in an area under dispute described below. For future control activities (2019–2028), we generated a spatial prioritization scheme according to the number of pines identified in past control activities in each area (Online resource—Fig. S5). Specifically, area A was split in three portions, and areas B, C and the remaining extent of the PA in two portions each, totaling nine portions. Three portions were simulated to have all pines removed every year with returns to each portion every 3 years to check for reinvasion.

The third scenario (scenario 3) was similar to the second one in the first stage (2010–2017). After that, control activities included private properties and areas under dispute along the PA boundary, where the elimination of pine trees is to be undertaken by the owners. This area contains adult pine trees and functions as source of propagules for the PA. For 2018, a 50 m buffer was established around remaining adult pines in both the area under dispute and in the remaining extent of the PA outside focal areas. Future management (2019–2028) was slightly modified from the second scenario. Management in areas A, B, and C was kept the same, but the remaining extent of the PA was managed without subdivisions and the area under dispute was added as the last portion, therefore again totaling nine portions (Online resource—Fig. S5).

Finally, to compare the effectiveness of managed and unmanaged scenarios, total filling of suitable habitat over time was calculated and the areas more likely to be invaded in the end of the simulations were mapped. These results were based on 100 replicates of each simulated scenario.

Results

Control activities

From 2010 to 2017, 308,014 pines were eliminated in the PA. Around 60% (182,247) of these plants were eliminated in area C, 35% in area A (109,745) and 5% (16,022) in area B. Around 55% of all plants (169,161) were seedlings, 38% (118,050) juveniles and 7% (20,803) adults. The total number of control interventions conducted by chainsaw operators was 46, with an average of 452 adult trees eliminated in each activity; 82 control events with volunteers resulted in an average of 2063 seedlings and 406.6 juveniles eliminated per event. A total of 768 volunteers participated in the activities since the beginning of the program. The number of volunteers has been increasing over the years (26 in 2010, 116 in 2014, 164 in 2016 and 175 in 2017). The total amount of financial resources which were saved due to the work of volunteers and chainsaw operators is R$ 136,596.00 (US$ 35,209); R$ 12,748.00 (US$ 3286) refers to the work by volunteers and R$ 9108.00 (US$ 2347) to chainsaw operators [difference between R$ 13,800.00 (US$ 3557) (paid reduced wages) and R$ 22,908.00 (US$ 5905) (normal wages)].

The highest pine density was registered in area C (0.7 pines/m^2) followed by area A (0.24 pines/m^2) and area B (0.01 pines/m^2). Control actions focused almost exclusively in A from 2010 to 2013, in C in 2014 and in B in 2015 (Fig. 2). The three areas are currently being monitored and managed simultaneously, but all adult trees have already been eliminated in A (2011–2012) and B (2015) (Fig. 2).

Differences in the structure of pine populations are evident when comparing areas that underwent control interventions for different periods of time. In 2011, most of the plants were seedlings due to large numbers of seeds stored in serotinous cones that have matured over successive seasons and been retained on adult trees; in 2017, most of the plants eliminated were juveniles. This shows that seedlings have barely established in the last 3 years due to the exhaustion of the seed bank and the absence of adult trees (Fig. 2). Conversely, because of the ongoing control of adult trees in area C, which started in 2015, approximately the same number of seedlings and juveniles (~ 35,000 of each class) was eliminated in 2017 (Fig. 2).

Habitat suitability model

The three models run (GLM, BRT, and RF) generated AUC values 0.77, 0.78 and 0.71, respectively. The mean contribution of predictors in the model was 0.64 for sand dunes, followed by temporary pools (0.27), herbaceous vegetation (0.25), forest (0.24) and permanent water bodies (0.15) (Online resource—Table S2). Bare sand ($r = -0.156$), water bodies ($r = -0.150$) and forest ($r = -0.277$) had a negative correlation with habitat suitability for pines, whereas herbaceous vegetation ($r = 0.278$) and temporary pools ($r = 0.152$) had a positive correlation with habitat suitability for pine establishment.

When considering the three managed areas in the PA, about 81% (21 ha) of area C, 57% (80 ha) of B and 87% (39 ha) of A were considered susceptible to pine establishment and invasion (Fig. 3). A was mainly covered by land cover categories classified as suitable to establishment (temporary pools and herbaceous vegetation). The percentage of suitable area was

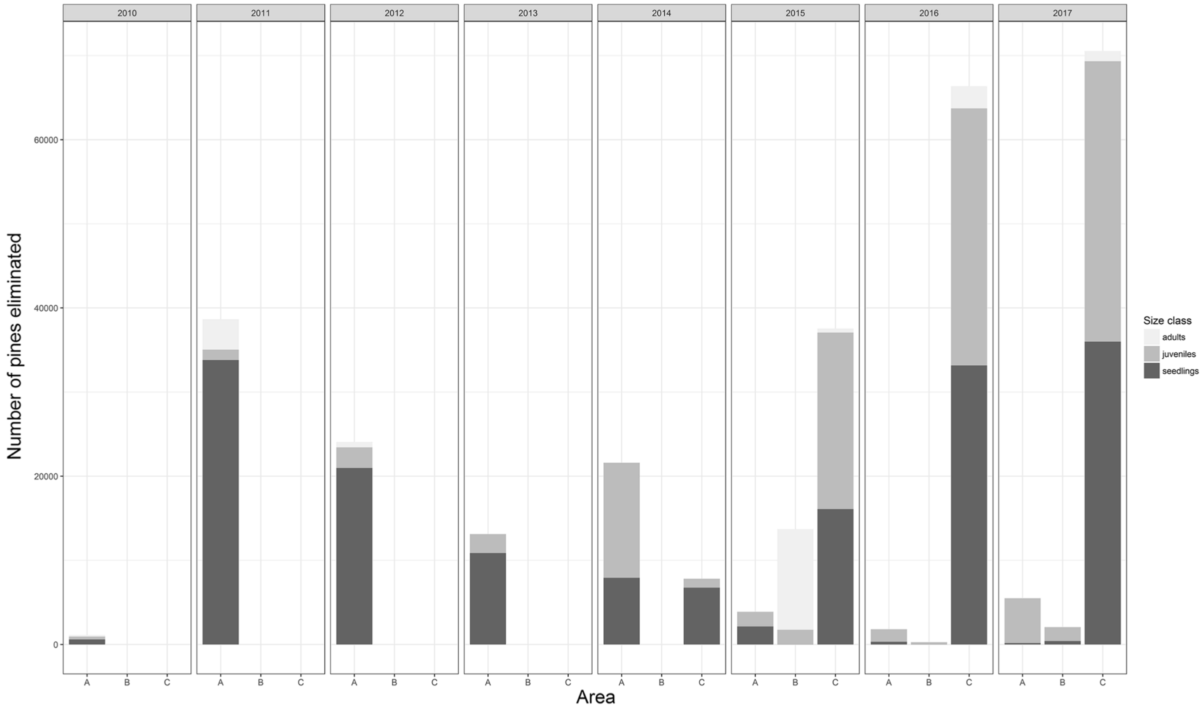

Fig. 2 Results of the control program showing the total number of eliminated pines divided in size classes in each focal area (A, B and C), from 2010 to 2017 in the Dunas da Lagoa da Conceição Municipal Park (Florianopolis, southern Brazil). Adults: large adult trees cut by professional chainsaw operators; juveniles: height > 50 cm and < 300 cm cut with hand saws by volunteers; seedlings: height < 50 cm pulled out by volunteers

obtained using a threshold of 15% of habitat suitability (see section below).

Simulations

The results of the simulations suggested distinct outcomes depending on pine control efforts (Table 1; Figs. 4, 5). In the absence of any management actions (scenario 1), an area of 150.4 out of 305.1 ha suitable for colonization by *P. elliottii* would be at high risk of invasion – defined as average invasion probability > 50% across replicates in the end of the simulations, totaling a filling of nearly half of the suitable area (Table 1; Figs. 4a, 5). Simulation of past management actions reduced the high risk of invasion to approximately 49 ha for both the second and the third scenarios in 2018, indicating a reduction by 2.3 times when compared to the same period in the scenario without management (Table 1; Fig. 5). Simulation of future management (2019–2028) led to different results when all three scenarios were compared (Figs. 4, 5). Control efforts in the PA only (scenario 2) resulted in a reduction by 4.1 times of the extent of invasion when compared to the first scenario in 2028 (Table 1; Figs. 4a, b, 5). When comparing scenarios 1 and 3 (management in both the PA and in the area under dispute), the reduction in the extent of invasion was 150 times (Table 1; Figs. 4a, c, 5), and 37 times between scenarios 2 and 3 (Table 1; Figs. 4b, c, 5). The latter differences are likely due to the suppression of an important source of propagules only in the third scenario (Figs. 4b, c, 5).

Discussion

This study shows that a control program for invasive pines involving citizen engagement can be effective and result in the reduction of the abundance and distribution of pine trees in PAs. Overall, our results indicate that past management actions were effective, with decreasing risk of invasion and filling of suitable habitats by pines in the PA. Although only 12% of suitable habitats would be occupied by pine

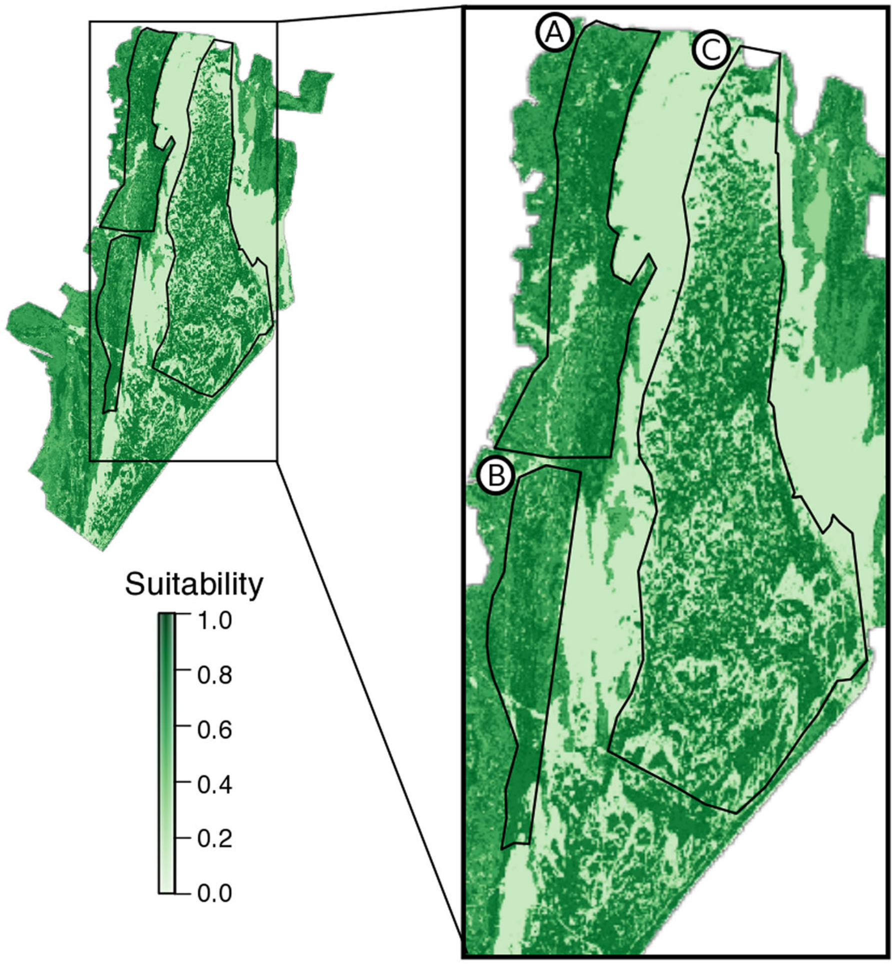

Fig. 3 Habitat suitability map for the non-native invasive species *P. elliotti* and *P. taeda* in the Dunas da Lagoa da Conceição Municipal Park (Florianopolis, southern Brazil). The darker the color the greater the suitability for pine tree establishment. The three focal areas for control of invasive pines are limited and identified with different letters (A, B, C)

Table 1 Filling of suitable habitats and confidence interval (%) and approximate extent of invasion (ha) for the overall protected area (Dunas da Lagoa da Conceição Municipal Park, Florianopolis, southern Brazil) in 2010, 2018 and 2028, considering three different management scenarios—no management (scenario 1), management in the PA (scenario 2) and management in the PA and in the area under dispute (scenario 3)

Year	No management	Management in the PA	Management in the PA + area under dispute
Filling of suitable habitats and confidence interval (%)			
2010	18.6 (18.5–18.8)	18.1 (18–18.2)	18.1 (18–18.3)
2018	36.4 (36.3–36.6)	16.1 (13.6–17.8)	16.1 (14.2–19.6)
2028	49.3 (48.4–50.5)	12.1 (11.7–12.9)	0.3 (0–0.9)
Approximate extent of invasion (ha)			
2010	56.9	55.3	55.4
2018	111.1	49	49.1
2028	150.4	36.9	1

trees if the past control effort is continued over the next 10 years (2019–2028), new cycles of reinvasion might be expected if the management is restricted to the PA (scenario 2). A key contribution is the management of seed source populations along the border and beyond PA limits from 2019 to 2028,

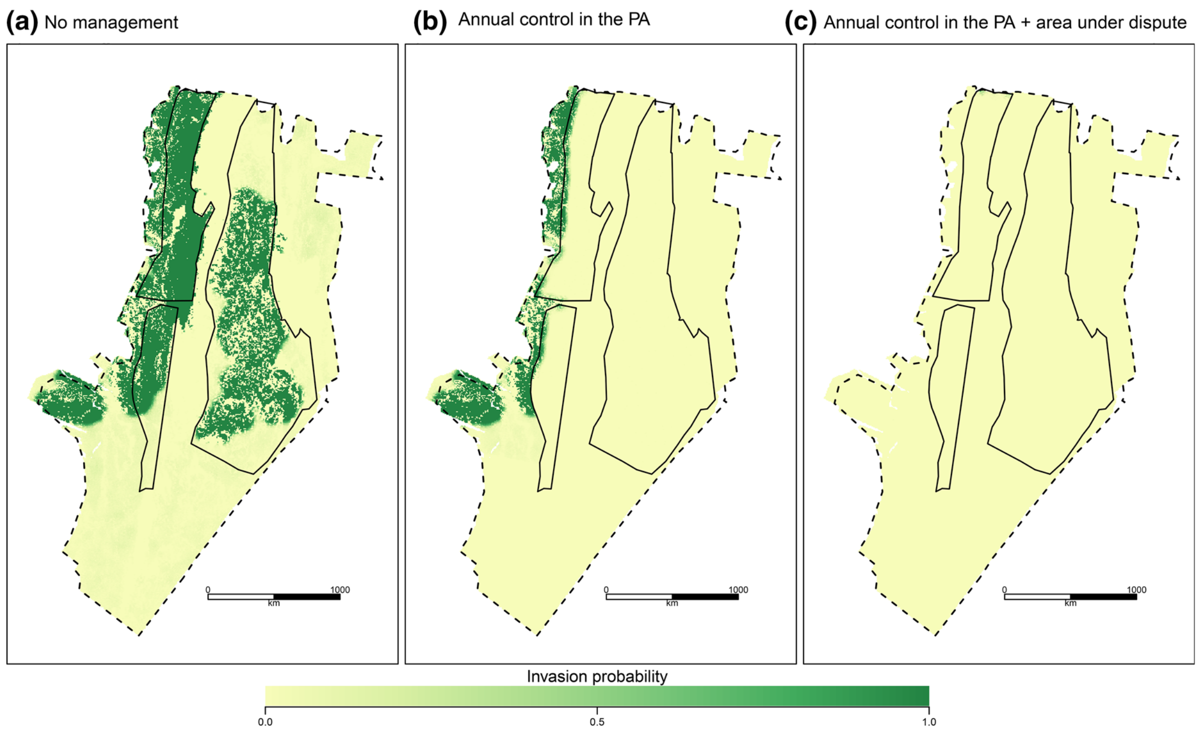

Fig. 4 Results of simulations showing the potential distribution of pine invasions under three distinct scenarios in the Dunas da Lagoa da Conceição Municipal Park (PA) (Florianopolis, southern Brazil). **a** no management (scenario 1); **b** annual control in the PA (scenario 2); and **c** annual control in the PA and surroundings (area under dispute and private land; scenario 3)

which would most likely result in the eradication of pine trees from the PA (scenario 3). In the absence of any control efforts (scenario 1), pine trees would have reached a large amount of suitable habitats in the PA, degrading almost half of the PA in two decades.

The approach used in our study may be applied to broader spatial scales to provide a baseline for management efforts needed to effectively control non-native invasive species. The engagement of volunteers reduces costs and increases public awareness on biological invasions (Simberloff 2003; Kueffer et al. 2013; Baret et al. 2013). However, there are some conditions for a management program involving volunteer work to be successful. Protected areas are recommended to be the focus of volunteer programs due to their social and environmental relevance, and also because they are at a lower risk of future conversion to other land use than areas that are not formally protected (van Wilgen et al. 2016). Our approach could be applied especially to small protected areas with easy access and for species that do not require chemical control, which would increase the environmental risk of control activities and require training of the volunteers. Volunteers can be helpful even in larger protected areas (e.g. thousands of hectares) but their effort must be part of a concerted effort between volunteers and professionals to ensure long-term success (Baret et al. 2013). Such joint management programs could include the work of volunteers in lightly invaded areas and/or in monitoring and follow-up activities combined with management activities conducted by professionals focused on highly-invaded areas and/or on species that require chemical control. In all cases, it should be supervised by a technical coordinator capable of planning control activities based on the prioritization of species and areas and to apply effective techniques for the control of target non-native invasive species. Nevertheless, management strategies to deal with plant invasions in PAs are context-dependent, varying with different levels of protection (e.g. managed resource PAs to strict nature reserve PAs) as well as with socio-political contexts (Foxcroft et al. 2017).

The main aims of our volunteer program are the restoration of ecosystem structure and functioning, the conservation of biodiversity and of the local

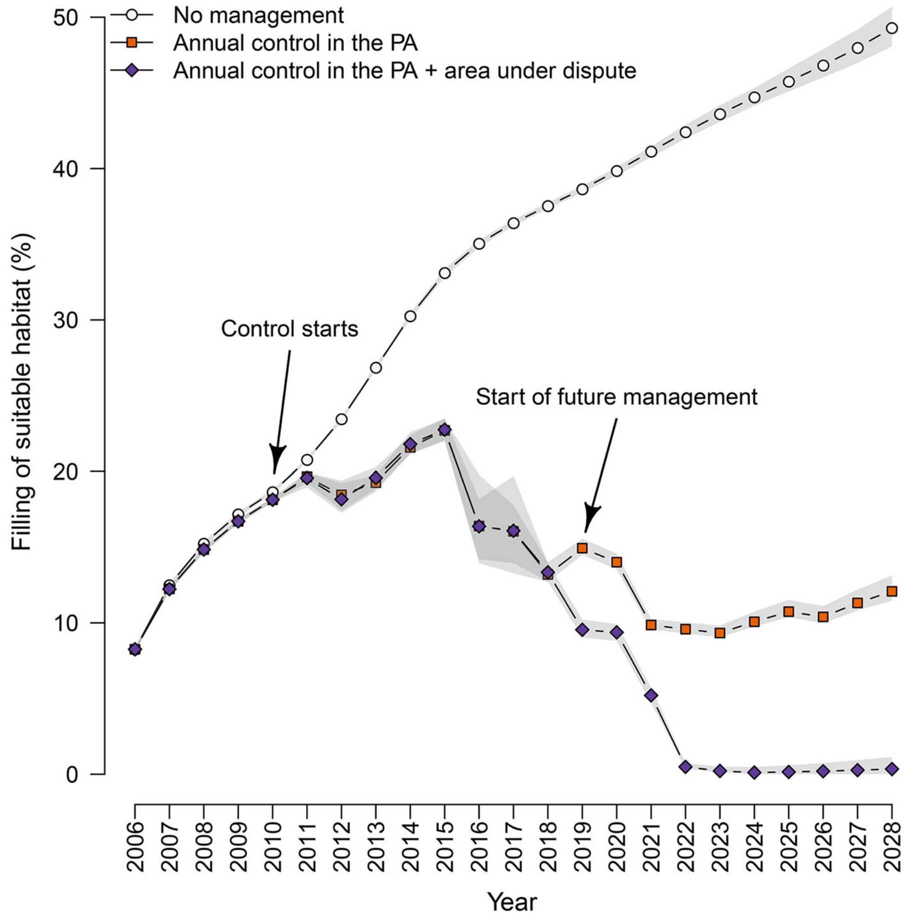

Fig. 5 Results of simulations showing potential filling of suitable habitat by invasive pines under three distinct scenarios: no management (scenario 1); annual control in the Dunas da Lagoa da Conceição Municipal Park (PA; scenario 2); and annual control in the PA and surroundings (area under dispute and private land; scenario 3). The starting point of comparison between the simulations was 2010 (highlighted as "control starts"), and 2019 for future management (highlighted as"start of future management")

landscape, which are more inspirational than simply focusing on the elimination of invasive pines. A permanent program of committed volunteers was formed along the years, one of the main challenges in citizen participation in the early detection, surveillance and management of invading populations (Miralles et al. 2016; Ricciardi et al. 2017). The prominent change in the landscape and the visual recovery of native vegetation are encouraging and might be interpreted as reasons for the long-term commitment of volunteers (Pagès et al. 2017), especially of those who participate regularly. Small groups of trained and more experienced volunteers can potentially be engaged in more challenging activities such as control and follow-up actions in areas of difficult access (e.g. rugged terrain) or chemical control.

Pines have been widely disseminated for economic interest in forestry, but also widely promoted as fast-growing species (Franzese et al. 2017). This has led to the inappropriate use of pines for shade, live fencing, esthetic purposes, sand fixation, or simply because seedlings were commonly distributed free of charge in Florianopolis (Caruso 1990). Pine trees in neighboring properties to the PA are currently the main seed sources to the park and, as mentioned before, were planted decades ago to hold back or stabilize sand dunes, having no economic or ornamental value in the present. The management of these adult trees (scenario 3) would result in only one percent of suitable habitats being occupied by invasive pines inside the PA when compared with the scenarios in which these adult trees are not eliminated (Fig. 5). Citizen participation can draw the attention of neighboring property owners to environmental issues related to their backyards. In addition, the Florianopolis municipal legislation (Municipal Law 9097/2012 and *Decreto Municipal* 17938/2017) establishes that all pine trees must be eliminated from private properties by December 2019. If the legislation is enforced, the removal of these main seed sources will greatly reduce propagule arrival and population increase in the PA and in other areas on the island. The main limitation to management in these areas is the lack of action by the municipal environmental agency in giving notice about the municipal law that requires pines to be eliminated. The lack of action by this stakeholder in communicating with private property owners hinders management actions, as their authorization is needed and the cost of management in these areas should be covered by each owner. For these reasons, no management has been pursued in private areas so far.

Despite the generalization that there is no chance of eradication when alien non-native species become established and widespread (van Wilgen et al. 2016), eradication could be a feasible goal of the volunteer program if some factors were to considered. As there are no pine plantations in the vicinity of the PA, which would represent a ready and continuous source of seeds from which cleared areas could be re-invaded (McConnachie et al. 2016), if local stakeholders effectively enforce the Municipal Law in due time there will not be any seed sources within the PA and in the neighboring private properties in about 10 years. The high density of pine seedlings in the PA is possibly explained by a continuous seed rain, high germination rate and a dense, permanent seedling bank (Bechara et al. 2013). On the other hand, the short longevity of pine seeds in the soil (Bechara et al. 2013), the absence of adult pine trees in the PA and in the neighboring private properties, and the small size of invaded areas within the PA (Pitcairn and Rejmánek 2002) make eradication a realistic goal for our management program.

Uncertainty should not be used as an excuse to postpone management actions. If diagnostics are treated as hypotheses and management actions tested as solutions, there is always room for improvement from local experimentation and much information can be gained from records of population structure over time, in turn used to improve management (Zalba and Ziller 2007). For instance, rings on stumps of young trees have been counted during control efforts, showing that pines mature at age 4–5 in the region, as observed by Bechara et al. (2013) for *P. elliottii*, and by Tomazello-Filho et al. (2016) for *P. taeda* in Parana state, southern Brazil (25°59′48,47″S, 51°40′2″W; 826 m.a.s.l.). This information was used to establish the maximum interval for monitoring and control actions in each area subject to management. In addition, although seed germination and seedling density were higher in the first year, the seedling mortality rate increases along the first 3 years after adult trees are felled, as described by Bechara et al. (2013). As a consequence, the first control action of seedlings and juveniles by volunteers must preferably occur 2–3 years after the felling of adult pine trees.

One of the main goals of the program is to eliminate all pines before they reach maturity, avoiding the establishment of new seed sources and a new seedling bank. Our ongoing work has shown that control aimed at eliminating adult trees that have reached maturity to suppress seed production leads to changes in population structure over time and may be the most effective way of reducing the rate of population growth and dispersal, which agrees with Pichancourt et al. (2012). Therefore, registering changes in the population structure of species in control programs is an important part of adaptive management and of measuring control effectiveness for continuous improvement and increasing efficiency. Reaching neighboring private property owners with support from the municipal administration is key for the future eradication of pines in the area, as adult pines outside PA limits are currently the main seed sources to the park. In addition, modeling species distribution and simulation frameworks are alternative sources of information to guide control actions and to assess the benefits of volunteering in management programs where no control sites are available.

Biological invasions are a relatively recent environmental issue in Brazil (Zenni et al. 2017). Although some management action has been taking place in a few state and federal protected areas, there is not a concerted management effort to control existing invasions. A more integrative approach to deal with biological invasions must include science, management, governance and funding, as well as citizen engagement to support long-term control work. In this sense, pine species could be used as a model group not just for learning about plant invasions (Richardson 2006), but also for cross-regional learning in the management of invasive plants at broader geographical scales (Nuñez et al. 2017). The engagement of volunteers must be included in regional and national strategies for the management of invasive plants in PAs. Civil society can play a relevant role in supporting local management, as volunteer efforts can be carried out at low cost and, therefore, be sustained over time. Volunteer programs also contribute to increase public awareness of environmental issues as well as to empower people to take local action.

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