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ORIGINAL PAPER

Invasive plants in Brazil: climate change effects and detection of suitable areas within conservation units

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Abstract Invasive exotic plants may compromise the survival, growth, and reproduction of native species and are among the leading causes of worldwide biodiversity losses. Climate changes—which will affect species distribution—may even amplify the problems caused by invasive species. Here, we used ecological niche models to evaluate the current and future distribution of 108 invasive plants in the entire Brazilian territory and the country's conservation unit facilities (CUFs). Overall, our results did not indicate a significant change in the potential distribution of invasive plants between the current and future climate scenarios, although we expect that 67.5% of the species will decrease its range in Brazil in the future. The proportion of the plants' invasive range inside conservation units varied from 1 to 12%, and results suggest that this would not increase or decrease in the future. Taken together, our results do not indicate that climate change will amplify the effects of existing invasive plants—although it may facilitate the

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invasion of other species. Both current and future scenarios suggest high suitability for invasive plants in the southern, southern, southeastern, and eastern coast of Brazil, comprising the Caatinga, Cerrado, and Mata Atlântica Brazilian biomes, the most populated areas of the country. We advise that conservation unit managers and authorities within these regions should continuously monitor such invasive plants to take early responses to avoid their establishment.

Keywords Invasive species · Bioinvasions · Invasive plants · Ecological niche models

Introduction

The invasion by exotic species constitutes one of the main risks to biodiversity, along with land-use changes, habitat loss, fragmentation, global climate change, among other anthropic processes that have been increasing exponentially and defying the conservation of natural resources (Tylianakis et al. 2008; Laurance et al. 2014). Exotic species are introduced to new locations either voluntarily or involuntarily and may cause severe environmental and economic problems (Richardson et al. 2000; Pimentel et al. 2005; Tylianakis et al. 2008; Pejchar and Mooney 2009). These species tend to be excellent competitors and may rapidly become dominant, altering the dynamics of biological interactions while monopolizing resource use before they are available to other species (Didham et al. 2005). Once invasive species establish in a new location, the difficulty in eradicating them is notorious, and there is no consensus on which actions, whether they are proactive or reactive, would be the best ones to avoid the establishment of new populations in the new invaded range (Simberloff and Stiling 1996; Mack et al. 2000; Pimentel et al. 2001; Shah and Shaanker 2014).

Global climate change caused by greenhouse gas emissions may amplify the establishment and the pervasive effects of invasive species (Theoharides and Dukes 2007). One of the reasons this may happen is that species are expected to change their geographic distribution to track their ecological niches, increasing the current range occupied by invasive species (Hijmans and Graham 2006; Parmesan 2006; Pauchard et al. 2016). So, measuring the effects of climate change on the potential distribution ranges of invasive species could provide regulatory agencies and decision-makers with useful information regarding areas that may become suitable for future invasions (Guisan et al. 2013).

In Brazil, conservation unit facilities (CUFs) were designed to protect the country's biodiversity against invasive species, although they do not always fulfill this aim (Dudley and Stolton 2008; Brasil 2011). Brazilian CUFs are bounded to the National Conservation Units System (*Sistema Nacional de Unidade de Conservação*—SNUC in Portuguese) and are organized in different governmental authority levels (i.e., federal, state, and municipal). The Brazilian CUFs are classified according to their use limitation into (1) strict use CUFs (StUCUFs hereon), and (2) sustainable use CUFs (SUsCUFs hereon). While the exploration and use of resources are more restricted in StUCUFs areas—to protect nature and guarantee the indirect use of resources—, SUsCUFs areas aim to conciliate nature protection with the sustainable use of natural resources by local communities (Brasil 2011).

A better understanding of the invasion process by exotic invasive species is precluded by the lack of knowledge on their geographic distribution ranges—the so-called Wallacean deficit (Whittaker et al. 2005)—, and by the lack of knowledge on their tolerance to abiotic conditions—the Hutchinsonian deficit (Cardoso et al. 2011; Hortal et al. 2015). To circumvent such a problem, ecological niche models (ENMs hereon) have been intensively used to predict invasive exotic species' potential spatial distribution (Václavík and Meentemeyer 2009; Newbold 2010). The ENMs correlate species' occurrence data and climatic variables to estimate the species' multivariate climatic niche space, which can then be projected onto the geographic space to indicate suitable areas for the species' occurrence (Guisan and Zimmermann 2000; Elith and Leathwick 2009). Such predictions may help stakeholders direct management actions, optimizing their financial resources' execution (Jiménez-Valverde et al. 2011; Araújo and Peterson 2012).

Although ENMs constitute commonly used tools for different conservation purposes (Elith and Leathwick 2009), researchers and stakeholders must be aware that these methods are no silver bullets and, in general, do not consider population-level processes, such as species interactions (Anderson 2017). Despite such limitations, in Brazil's political and economic scenario of budget cuts to environmental conservation (Escobar 2015, 2018, 2019), such methods can optimize the use of available resources. These tools may also help stakeholders implement pro-active management plans for CUFs, focusing on impeding the establishment of (new) populations of invasive species within these areas, rather than reactive management plans, which usually occur when the invasive species populations are already established. For instance, previous works already attempted to evaluate whether future climate changes could increase the invasion rate in CUFs (Bellard et al. 2013; Kariyawasam et al. 2020). Moreover, ENMs could be used on a system of early detection and rapid response within the CUFs and their surroundings (Simpson et al. 2009; Martinez et al. 2020; Marshall Meyers et al. 2020; Reaser et al. 2020).

Here, we evaluated the current and future vulnerability of the Brazilian CUFs to 108 invasive exotic plant species—recently identified by Zenni and Ziller (2011). Specifically, we modeled the ecological niche of these invasive species and mapped their current and future suitable areas in Brazil to understand: (1) whether climate change will affect the potential spatial distribution of the invasive exotic species in Brazil; and (2) how much of the geographic distribution range of invasive plants could potentially fall inside the limits of each of Brazilian's conservation unities under the current and future environmental conditions.

Methods

Species occurrences dataset

We built an occurrences dataset for the exotic plant species ranked by Zenni and Ziller (2011) as invasive in Brazil using the following online databases: Global Biological Information Facility—GBIF (http://www.gbif.org); Species Link (http://www.splink.cria.org.br); Global Invasive Species Information Network—GISIN (http://www.gisin.org). We complemented the occurrences dataset with occurrences from the National Survey of Non-Native Invasive Species, from the Instituto Hórus de Desenvolvimento e Conservação Ambiental (http://bd.institutohorus.org.br/). Once several species have different varieties and subspecies, in our study, we considered them under a unique taxonomic name, considering the species list developed by Zenni and Ziller (2011) and Ziller et al. (2018). We checked the invasive status for all the modeled species in the *Flora do Brasil* dataset (http://floradobrasil.jbrj.gov.br). After assessing the species in this dataset, we observed that some were classified as native into some Brazilian regions/biomes after Zenni and Ziller's (2011) published their list of invasive species, the base for our analyses.

Nonetheless, these same species invade other Brazilian regions/biomes from where they are not considered native. For instance, some of these species are native to some Brazilian biomes but are invasive to others and may affect the dispersal of native species from that region and even affect succession when they invade areas at the beginning of the regeneration process. Therefore, we considered the species *Christella dentata, Clitoria fairchildiana, Cortaderia selloana, Hippobroma longiflora*, *Hura crepitans*, *Nephrolepis cordifolia*, *Scleria mitis*, *Urena lobata*, and *Vachellia farnesiana* as invasive in our study, even though they are native to some of the Brazilian regions/biomes.

To reduce errors in our species occurrences dataset, we removed occurrences from the same species with repeated coordinates, occurrences representing the centroid of countries, states, or municipalities, and those occurrences found beyond the study's extent (South America). We used a grid over South America with a cell size of $\sim$ 4 km (0.041° or 2.5 arc-min) at the equator. Although such an extent may be criticized, we prioritized using such grid cell size to retain the most exotic invasive species in our modeling procedures, especially those with few available occurrences in all of those online datasets. The occurrence dataset is available for anyone interested upon authors request.

Environmental variables

We defined our extent area as the region comprising the South American continent. We used a spatial resolution of grid cells with 4 km (2.5 arc-min or 0.041° at the equator). To model the distribution of our plant species, we combined the 19 variables available from WorldClim (http://www.worldclim.org) and 65 variables related to physical–chemical soil features obtained from SoilGrids (http://www.isric.org/data/soilgrids), totaling 84 primary variables (See Table S1). We standardized all variables, so their averages are equal to zero, and their variance is equal to |1|, impeding all variables to influence the models unequally. Later, we conducted a principal component analysis (PCA) to reduce the number of original environmental variables to a smaller set of orthogonal/independent principal components (PCs). This method also decreases the environmental variables' collinearity and model overprediction (Jiménez-Valverde et al. 2011). We selected the first 11 PCs—that captured 95% of the original environmental variation—as the new predictor variables to model the invasive plants' ecological niche.

We used the 19 bioclimatic variables available for 17 Atmosphere–Ocean Global Circulation Models (AOGCMs) from WorldClim to model the species in the future scenarios of climate change: ACCESS1-0, BCC-CSM1-1, CCSM4, CNRMCM5, GFDL-CM3, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRICGCM3, and NorESM1-M. In all scenarios, we used the more severe/pessimist carbon dioxide emission perspective (Representative Carbon Pathway—RCP 8.5) defined by the most recent IPCC report on world climate (IPCC 2013). In this emission scenario, it is expected that mean global temperatures will rise 3.7 °C (varying from 2.6 to 4.8 °C) in 2080–2100 (Taylor et al. 2012; IPCC 2017), with a constant emission of carbon dioxide and frequent land-use changes. A significant increase in the human population is also expected, resulting in increases in fossil fuel consumption and the lack of effective worldwide climate policies to mitigate carbon dioxide emissions (Riahi et al. 2011).

To the 19 bioclimatic variables in all scenarios (both current and future ones), we added 65 edaphic soil variables from SoilGrids (http://soilgrids.org), totaling 84 environmental variables in each future scenario. We also standardized the environmental variables from each scenario to have an average of zero and the standard deviation of |1|. Considering the linear coefficients we obtained for the current scenario, we projected them onto the 17 future AOGCMs we used to predict the plant species distribution range in South America. In each scenario from the original 84 PCs we had, we also utilized the first 11 ones as predictor variables of the plant species.

Ecological niche modeling procedures and model evaluation

We geographically partitioned the species records into two subsets of approximately 50% of the data in each. This procedure promotes the geographic partition of the species data into different cells, resembling a checkerboard table. It has been recognized as one of the best procedures to fit and evaluate species distribution models (Bahn and McGill 2013; Muscarella et al. 2014; Roberts et al. 2017). Each subset is used to fit the model and serves as an evaluation subset for the models fitted onto the other subset. We used all occurrence records for both current and future scenarios to produce the final species distribution ranges.

We used the R environment version 3.4.0 to generate our distribution models and used the ENMTML package (Andrade et al. 2020). We considered five different modeling methods in our modeling study: Gaussian process—GAU (Vanhatalo et al. 2012); Maximum Entropy—MaxEnt (Phillips et al. 2006; Peterson et al. 2011); Maximum Likelihood—MLK (Royle et al. 2012); Support Vector Machines—SVM (Tax and Duin 2004; Peterson et al. 2011); Random Forest—RDF (Breiman 2001).

We used a threshold that maximizes the sum of sensitivity and specificity, better quantifying both omission and commission errors to determine the species' potential distribution (Allouche et al. 2006). To measure our modeling methods' predictive ability, we used true skill statistics (TSS), a threshold-dependent metric that varies from − 1 to + 1 (Allouche et al. 2006). Models reaching values near + 1 indicate distribution ranges very similar to known occurrences of the modeled species, while values around zero or negative indicate potential distributions no better than a random distribution (Allouche et al. 2006). Values equal to or higher than 0.5 are usually considered acceptable, and values above 0.7 indicate a modeling method's good predictive ability under this evaluation metric.

After producing the distribution models for our target invasive plant species in Brazil in all climatic scenarios, we used a consensus method to concatenate the models produced with different techniques in each scenario. Therefore, we used a PCA of those predictions that reached TSS values above the average, which allows us to preserve all the original prediction variability for each species (Araújo and New 2007).

Invasive exotic plants threat evaluation in Brazil and its CUFs

We then quantified the potential number of invasive exotic plants that could occur in each of the Brazilian CUFs, using their modeled potential distribution. Moreover, we used a procedure adapted from Rodrigues et al. (2004), where, for each species, we calculated the amount of its distribution range that overlaps with the CUFs' original area.

We tested two scenarios, according to the IUCN's category of the Brazilian CUFs. In the first scenario, we only considered the strict use CUFs (IUCN's categories I to IV) the PI scenario hereon, while in the second scenario, the CUFs with IUCN's categories V and VI were also considered along with those from categories I to IV, the PI + US scenario hereon (Brasil 2011). Considering our interest scenarios, we also assessed the CUFs' risk of invasion by invasive exotic plants, comparing the proportion of each of these species' distribution range overlaps with CUFs both in the PI and PI + US in both current and future climatic scenarios. For that, we used two dependent t-tests comparing PI vs. PI + US scenarios in both current and future scenarios. We also used Pearson's pair-wise correlations to compare the modeled species distribution range sizes, considering the sizes of Brazilian CUFs in PI and PI + US scenarios in both current and future climatic scenarios.

Results

We sampled a total of 46,883 occurrence records for all 108 species we analyzed here, with a raw amount of occurrences varying from 27 to 2,041. After data cleaning and filtering, the number of spatially unique records of these species went from two to 640. From the original 108 species, we modeled 108 species that had at least ten spatially unique records. The species removed from the analysis were: *Acacia holosericea*, *Albizia falcata*, *Bambusa textilis*, *Curculigo capitulata*, *Musa rosacea*, *Ophiopogon japonicus*, *Pteris vittata*, and *Urochloa stolonifera*.

The average TSS of our models were excellent (0.95 ± 0.06; average ± standard deviation; Table 1). In the present scenario, the potential distribution of invasive exotic species varied from narrow (*e.g. Musa ornata* = 518.660 Km^2; *Senecio madagascariensis* = 544.120 Km^2; *Archontophoenix cunninghamiana* = 665.750 Km^2) to wide-range species (*e.g. Urena lobata* = 7,124,650 Km^2; *Andropogon gayanus* = 7,131,040 Km^2; *Urochloa mutica* = 7,321,330 Km^2; *Megathyrsus maximus* = 7,513,010 Km^2). The average distribution range of the species was 3,241,145 ± 2,014,755 Km2 (Table 1).

Our results indicate that in the future scenario, 35 species could increase their ranges in Brazilian territory [*e.g. Agave sisalana* (∼ + 101%), *Eucalyptus robusta* (∼ + 70%), *Dracaena fragrans* (∼ + 55%)], but we expect a decrease for 73 species [*e.g. Pinus oocarpa* (∼ − 84%), *Pinus caribaea* (∼ − 55%), *Ligustrum vulgare* (∼ − 43%)]. In the future scenario, the estimated average size of the invasive plant species' distributions was 3,186,926 ± 2,190,473 Km^2 (Table 1). We found that for 19 species, future climate may increase their suitable areas within StUCU areas, while that for 17 species, climate change may cause range reductions (Table 1). When we included the sustainable use areas with the strict use ones (StUCUFs + SUsCUFs scenario), the number of species showed an increment in the suitability within CUFs, increased to 23, while 19 may decrease suitability within CUFs in the future (Table 1). Nonetheless, t-tests indicate no substantial differences between present and future climate in both scenarios: StUCUFs ($t = -1.26$; d.f. = 107; $p = 0.21$) and StUCUFs + SUsCUFs ($t = -1.47$; d.f. = 107; $p = 0.14$).

We observed that the highest potential species richness of invasive exotic plants, in both climatic scenarios, occurred mainly all over the southern and southeastern Brazilian regions and in the country's Atlantic coast, along with the Mata Atlântica biome (∼ 90 species). On the other hand, species richness was intermediary (30 to 50 species) in areas covering the southern Pampa biome and also in the central-western and northeastern regions of Brazil, in the Cerrado and Caatinga biomes. Nonetheless, for the whole northern and the central-western region, which covers the Amazonia, Pantanal, and portions of the Cerrado biomes, the invasive species richness was the lowest, reaching less than 40 species (Fig. 1).

Brazilian CUFs environmental suitability to the occurrence of invasive species varied geographically in both current and future scenarios. The StUCUFs seem to be less adequate in the future to invasive species in the northern region of the country, in the Amazonia biome—where most StUCUFs are concentrated (Figs. 2 and 3, inset 2). For the other country's regions and biomes, we observed an increase in the

Table 1 Exotic invasive plant species in Brazil that we modeled in our study and organized by botanical family, amount of occurrence records (total and filtered), models evaluation metric values (TSS), predicted range size in each climatic scenario, and the proportion of the range of the species within Brazilian conservation unities facilities of strict use (PI) and strict + sustainable use (PI + US), sin Km^2

Botanical family/ species	Records			Current			Future			Difference proportion (Fut/Cur) (%)
	Total	Unique	TSS	Km^2	PI (%)	PI + US (%)	Km^2	PI (%)	PI + US (%)	
Acanthaceae										
Thunbergia alata	755	276	0.96	3734.28	2	4	4769.79	4	8	+ 28.00
Thunbergia grandiflora	123	66	0.92	2595.30	2	4	2493.71	1	3	− 4.00
Anacardiaceae										
Mangifera indica	870	353	0.94	6321.70	3	7	5596.46	3	5	− 11.00
Apiaceae										
Ammi majus	44	33	0.94	1032.37	2	4	776.54	2	4	25.00
Centella asiatica	433	165	0.99	2294.23	1	3	2357.36	1	3	+ 3.00
Apocynaceae										
Calotropis gigantea	46	25	0.92	1146.75	1	2	1040.92	1	2	− 9.00
Calotropis procera	755	256	0.96	3068.65	2	3	2759.20	2	4	− 10.00
Cryptostegia grandiflora	168	74	0.95	1920.43	2	4	2866.15	2	4	+ 49.00
Arecaceae										
Archontophoenix cunninghamiana	58	12	0.92	665.75	1	2	450.64	1	2	− 32.00
Elaeis guineensis	177	92	0.96	827.95	1	2	825.05	2	3	+ 0.00
Livistona chinensis	39	19	1.00	1336.40	1	3	1657.26	1	3	+ 24.00
Asparagaceae										
Agave sisalana	44	19	0.95	1702.93	1	3	3421.59	2	3	+ 101.00
Asparagus setaceus	84	36	0.97	1368.85	1	3	1023.25	2	4	− 25.00
Dracaena fragrans	44	30	0.97	1286.17	2	3	1998.58	3	9	+ 55.00
Sansevieria trifasciata	104	52	0.92	3255.05	1	3	2923.22	1	3	− 10.00
Asteraceae										
Cirsium vulgare	299	162	0.96	726.02	2	4	621.09	1	4	− 14.00
Coleostephus myconis	50	17	0.94	757.38	1	2	730.58	1	2	− 4.00
Senecio madagascariensis	179	67	1.00	544.12	1	2	532.74	1	2	− 2.00
Athyriaceae										
Deparia petersenii	455	153	0.99	1485.57	1	3	2295.45	6	12	+ 55.00
Balsaminaceae										
Impatiens walleriana	400	174	0.96	3983.67	2	4	4372.47	3	7	+ 10.00
Bignoniaceae										
Spathodea campanulata	283	118	0.96	2708.64	1	3	2832.58	1	3	+ 5.00
Tecoma stans	1630	640	0.95	4292.98	2	4	3458.23	2	3	− 19.00
Cactaceae										
Opuntia ficus-indica	204	98	0.98	2366.14	2	5	1978.06	1	5	− 16.00
Campanulaceae										
Hippobroma longiflora	379	162	0.99	4210.02	3	7	3233.66	3	6	− 23.00

Table 1 continued

Botanical family/ species	Records			Current			Future			Difference proportion (Fut/Cur) (%)
	Total	Unique	TSS	Km^2	PI (%)	PI + US (%)	Km^2	PI (%)	PI + US (%)	
Caprifoliaceae										
Lonicera japonica	493	111	0.97	1310.46	1	3	955.54	1	3	− 27.00
Casuarinaceae										
Gymnostoma sumatranum	284	77	0.95	2734.14	1	3	2613.64	1	3	− 4.00
Combretaceae										
Terminalia catappa	407	149	0.95	5505.06	2	5	5223.86	2	5	− 5.00
Commelinaceae										
Tradescantia zebrina	309	111	0.97	3017.96	2	4	2366.31	1	4	− 22.00
Cucurbitaceae										
Sicyos edulis	250	120	0.96	2027.91	1	3	1710.20	1	3	− 16.00
Cupressaceae										
Cupressus lusitanica	285	108	0.96	1814.54	1	3	1666.02	1	3	− 8.00
Cyperaceae										
Cyperus rotundus	776	283	0.97	6961.66	3	6	8380.43	4	9	+ 20.00
Scleria mitis	382	165	0.96	6756.76	4	7	7242.14	3	7	+ 7.00
Euphorbiaceae										
Aleurites moluccanus	68	33	0.97	2297.47	1	3	2993.55	2	3	+ 30.00
Euphorbia tirucalli	155	73	0.97	4061.97	2	4	3920.88	1	4	− 3.00
Hura crepitans	585	213	0.96	4358.42	6	12	3411.78	5	12	− 22.00
Ricinus communis	1721	566	0.94	6245.41	2	5	7899.47	4	8	+ 26.00
Fabaceae										
Acacia auriculiformis	40	24	1.00	4544.73	5	10	5224.68	4	10	+ 15.00
Acacia longifolia	173	57	0.96	1952.01	1	3	1947.20	1	3	+ 0.00
Acacia mangium	221	101	0.98	5701.87	4	9	5240.90	4	9	− 8.00
Acacia mearnsii	246	92	0.95	1438.98	1	3	1298.80	1	2	− 10.00
Acacia podalyriifolia	193	51	0.98	1699.46	1	3	2000.85	1	3	+ 18.00
Clitoria fairchildiana	435	133	0.94	4524.52	2	4	4833.49	2	4	+ 7.00
Crotalaria juncea	207	74	0.97	4870.40	2	4	3553.51	1	3	− 27.00
Crotalaria spectabilis	185	81	0.96	3431.72	1	4	2735.92	1	3	− 20.00
Leucaena leucocephala	1225	423	0.95	6211.92	2	5	8506.85	4	9	+ 37.00
Parkinsonia aculeata	1060	368	0.97	2465.42	1	4	2225.12	1	4	− 10.00
Prosopis juliflora	776	307	0.97	2005.28	2	4	2244.47	2	4	+ 12.00
Pueraria phaseoloides	291	123	0.95	6057.52	5	11	6621.03	5	10	+ 9.00
Ulex europaeus	315	90	0.99	1105.62	2	4	1087.76	1	4	− 2.00
Vachellia farnesiana	474	189	0.96	3321.93	2	4	2387.46	1	3	− 28.00
Iridaceae										
Crocosmia crocosmiiflora	326	156	0.97	1246.36	2	3	1198.78	2	4	− 4.00
Lauraceae										
Persea americana	984	399	0.96	5563.08	3	6	4825.93	2	6	− 13.00
Malvaceae										

Table 1 continued

Botanical family/ species	Records			Current			Future			Difference proportion (Fut/Cur) (%)
	Total	Unique	TSS	Km^2	PI (%)	PI + US (%)	Km^2	PI (%)	PI + US (%)	
Sterculia foetida	40	11	0.45	815.32	2	6	926.34	2	6	+ 14.00
Thespesia populnea	95	34	0.91	922.77	1	3	896.43	1	2	− 3.00
Urena lobata	1360	472	0.97	7124.65	4	9	7216.96	4	9	+ 1.00
Meliaceae										
Azadirachta indica	506	277	0.99	5045.74	3	5	5798.25	3	7	+ 15.00
Melia azedarach	825	307	0.95	5282.05	2	4	5673.01	2	5	+ 7.00
Moraceae										
Artocarpus heterophyllus	129	71	0.97	5051.73	2	5	6078.38	3	7	+ 20.00
Morus nigra	339	137	0.96	3296.16	1	2	2837.16	1	3	− 14.00
Musaceae										
Musa ornata	34	19	0.79	518.66	1	4	501.60	2	4	− 3.00
Myrtaceae										
Eucalyptus robusta	150	43	0.93	1758.49	1	3	2993.87	3	7	+ 70.00
Psidium guajava	964	426	0.96	6510.77	3	6	6983.17	3	7	+ 7.00
Syzygium cumini	708	233	0.97	6275.15	3	7	6338.45	3	7	+ 1.00
Syzygium malaccensis	28	13	1.00	2207.22	3	6	2857.51	3	6	+ 29.00
Nephrolepidaceae										
Nephrolepis cordifolia	615	212	0.98	3108.59	2	4	3955.78	2	5	+ 27.00
Oleaceae										
Ligustrum japonicum	113	41	1.00	1418.54	1	3	1191.56	1	3	− 16.00
Ligustrum lucidum	208	74	0.95	1762.57	1	3	1749.02	1	3	− 1.00
Ligustrum vulgare	27	15	0.93	846.01	1	3	483.64	1	3	− 43.00
Pinaceae										
Pinus caribaea	84	44	0.91	2130.88	2	5	967.87	2	4	− 55.00
Pinus elliottii	324	154	0.97	1080.64	1	3	845.70	1	3	− 22.00
Pinus oocarpa	35	14	1.00	1377.05	1	3	215.85	1	3	− 84.00
Pinus patula	71	35	1.00	1411.69	1	3	1234.79	1	3	− 13.00
Pinus taeda	197	115	0.99	1219.03	1	3	1015.56	1	3	− 17.00
Pittosporaceae										
Pittosporum undulatum	317	59	0.95	1057.11	1	3	695.43	2	4	− 34.00
Poaceae										
Andropogon gayanus	208	90	0.93	7131.04	4	9	7412.41	4	9	+ 4.00
Arundo donax	122	68	0.96	2520.67	1	4	1621.78	1	3	− 36.00
Bambusa vulgaris	146	56	0.93	4369.47	2	3	4563.65	2	3	+ 4.00
Cenchrus ciliaris	714	295	0.98	2892.38	2	4	2457.31	1	3	− 15.00
Cenchrus clandestinus	136	72	0.94	1140.34	2	4	856.60	2	4	− 25.00
Cenchrus purpureus	700	330	0.94	3811.16	2	4	2900.53	1	4	− 24.00
Cortaderia selloana	258	120	0.98	1758.26	1	4	1458.58	2	4	− 17.00
Cynodon dactylon	1522	518	0.94	4317.91	2	4	3483.71	1	4	− 19.00
Digitaria eriantha	51	27	1.00	1934.38	1	3	1787.42	1	3	− 8.00

Table 1 continued

Botanical family/species	Records			Current			Future			Difference proportion (Fut/Cur) (%)
	Total	Unique	TSS	Km^2	PI (%)	PI + US (%)	Km^2	PI (%)	PI + US (%)	
Echinochloa crus-galli	987	249	0.96	5159.85	2	4	4752.42	2	5	− 8.00
Eragrostis plana	164	82	1.00	1645.83	1	3	1642.76	1	3	+ 0.00
Hyparrhenia rufa	1076	400	0.96	5681.79	2	5	5559.19	2	5	− 2.00
Megathyrsus maximus	139	69	0.96	7513.01	4	9	8136.37	5	9	+ 8.00
Melinis minutiflora	1992	412	0.96	5607.53	2	5	7744.15	4	8	+ 38.00
Melinis repens	1668	554	0.93	4463.87	2	4	4019.95	2	4	− 10.00
Urochloa brizantha	572	209	0.98	6360.38	3	7	6220.53	3	7	− 2.00
Urochloa decumbens	627	324	0.95	5276.55	2	6	3900.82	2	5	− 26.00
Urochloa humidicola	355	195	0.98	6094.58	4	9	5062.88	4	8	− 17.00
Urochloa mutica	285	137	0.95	7327.33	4	9	6096.05	4	8	− 17.00
Urochloa plantaginea	424	183	0.96	4749.42	2	6	4138.91	2	5	− 13.00
Urochloa ruziziensis	54	19	0.84	870.19	1	2	720.08	1	2	− 17.00
Urochloa subquadripara	60	40	0.95	3301.75	1	2	3222.44	1	2	− 2.00
Proteaceae										
Grevillea banksii	136	54	0.96	2145.48	1	3	1909.15	1	3	− 11.00
Grevillea robusta	180	65	0.89	2594.84	1	3	2340.32	1	3	− 10.00
Rhamnaceae										
Hovenia dulcis	646	232	0.98	1170.40	1	3	879.60	1	2	− 25.00
Rosaceae										
Eriobotrya japonica	381	171	0.98	2606.10	1	3	2749.20	2	6	+ 5.00
Rubiaceae										
Coffea arabica	2041	372	0.95	6534.53	4	8	5714.77	3	7	− 13.00
Rutaceae										
Citrus limon	442	183	0.99	6672.48	3	6	7253.76	3	7	+ 9.00
Citrus sinensis	352	170	0.98	5342.30	2	5	5296.06	2	5	− 1.00
Thelypteridaceae										
Christella dentata	1447	506	0.96	3205.64	1	3	2570.77	1	3	− 20.00
Macrothelypteris torresiana	748	358	0.97	3230.13	1	3	2695.70	1	3	− 17.00
Zingiberaceae										
Hedychium coccineum	38	23	1.00	914.45	1	3	657.33	1	3	− 28.00
Hedychium coronarium	515	256	0.98	3906.68	2	3	3094.70	1	3	− 21.00
Hedychium gardnerianum	39	19	1.00	708.25	1	3	480.70	1	3	− 32.00

Difference (Fut/Cur) regards the percentage change in the species range from one scenario to the other

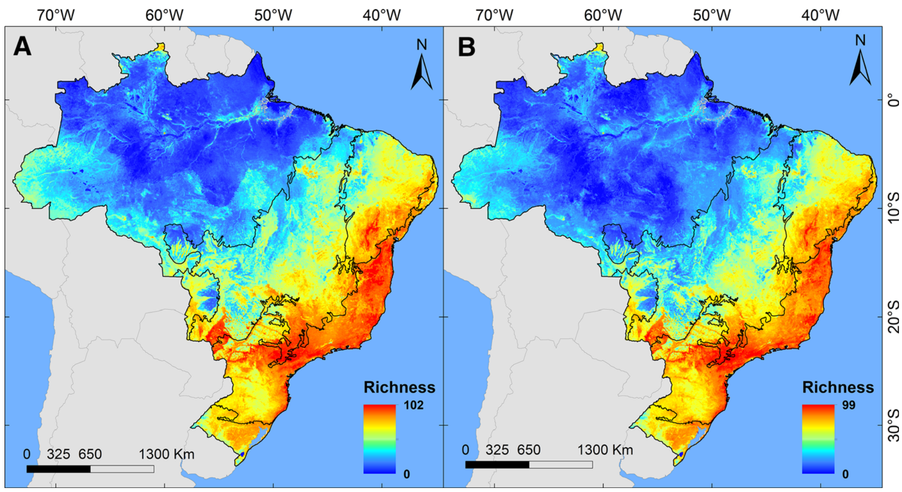

Fig. 1 Modeled species richness of invasive exotic plants in Brazil, considering all Brazilian biomes in both current (**A**) and future (**B**) climatic scenarios

potential occurrence of invasive exotic plant species in the future, mainly at the southern, southeastern, and Atlantic coast regions, covering the Caatinga, Cerrado, and Mata Atlântica biomes (Figs. 2 and 3, insets 3, 6 and 4).

In the scenario StUCUFs + SUsCUFs, the northern region covering the Amazonia biome again showed the lowest richness of modeled species richness of invasive exotic plants, although most CUFs in Brazil (Figs. 4 and 5, inset 2). In this scenario, CUFs in the northeastern and Atlantic coast regions of the country, comprising both Mata Atlântica and Caatinga biomes, are the most affected by the modeled invasive exotic plants (Figs. 4 and 5, insets 3 and 4). The environmental suitability of the CUFs located in both southeastern and southern regions, which comprise Mata Atlântica and Pampa biomes, also increased (Figs. 4 and 5, insets 4 and 5).

Still, when weconsider both current and future scenarios, the total distribution sizes of the species did not change significantly (t = 0.82; d.f. = 107; $p = 0.41$). We observed a positive correlation between the distribution ranges of the invasive exotic species in both current and future climatic scenarios (r = 0.95; $p < 0.05$) (Fig. 6A), and also considering their range within strict use (r = 0,88; $p < 0{,}05$; StUCUFs in Fig. 6B) and strict use plus sustainable use (r = 0,88; $p < 0{,}05$; StUCUFs + SUsCUFs in Fig. 6C) scenarios. In summary, when considering both of these scenarios, the invasive plants' distribution range patterns were similar.

Discussion

Overall, our results did not indicate a significant change in the potential distribution of invasive plants between the current and future climate scenarios, although—considering only abiotic factors—we expect that 67.5% of the species' future ranges will decrease in Brazil. We also found that the southern, southeastern, and Atlantic coast Brazilian regions, covering both Pampa and Mata Atlântica biomes, had the highest potential species richness of invasive exotic plants, in both current and future scenarios. The central and northeastern Brazilian regions, comprising both Cerrado and Caatinga showed intermediate values of invasive species' potential richness, while the northern and central-western Brazilian regions, including the Amazonia and Pantanal biomes, showed the lowest values in both current and future scenarios.

Exotic invasive species have been invading CUFs worldwide and affecting their effectiveness to conserve biodiversity (Allen et al. 2009; Spear et al. 2013). Still, information on the distribution of invasive exotic plants within CUFs is scant (Petenon and Pivello 2008), consequently making comprehensive management and control actions against them too ineffective. Despite this, the recurrent use of ENMs as

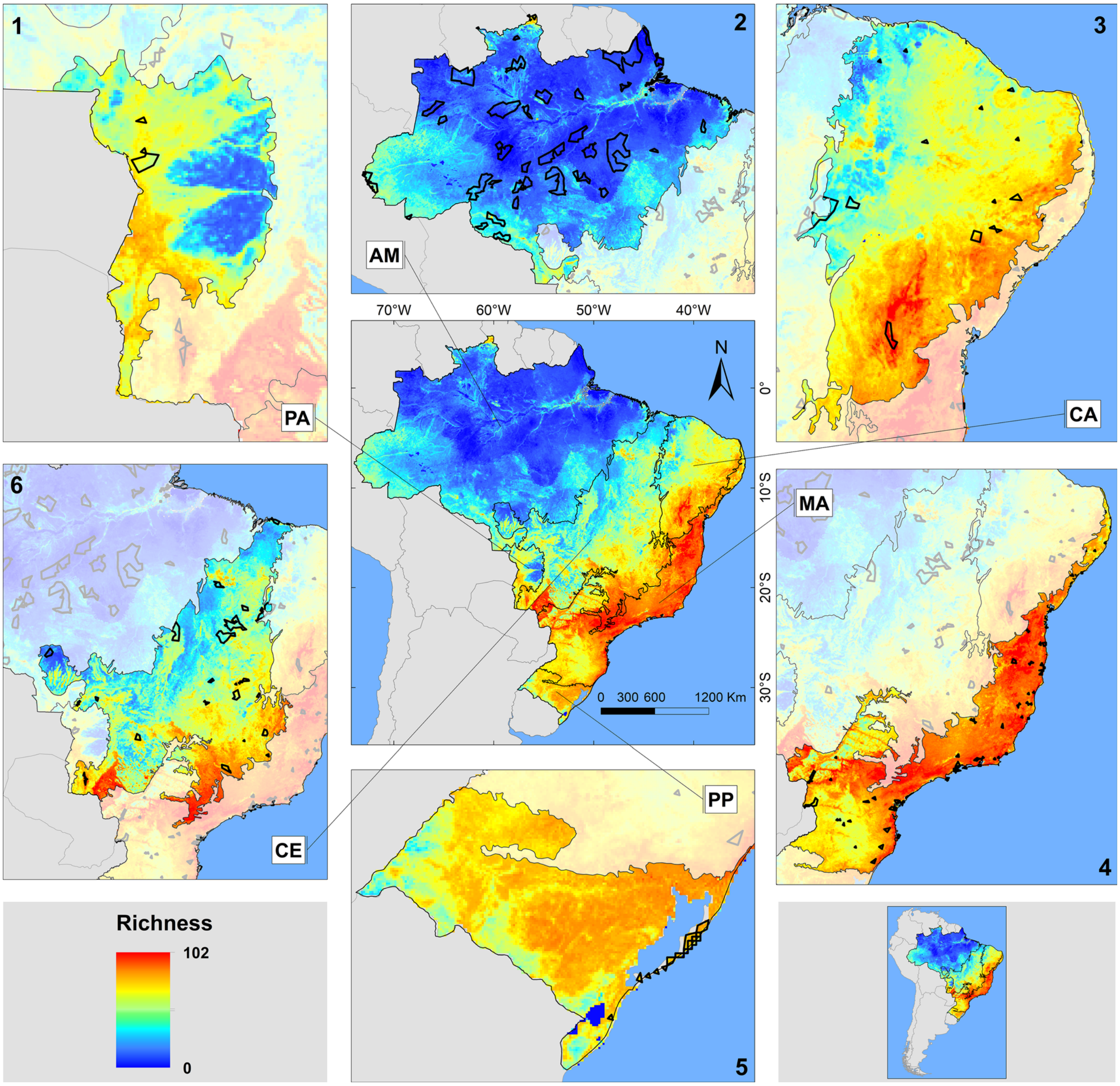

Fig. 2 Modeled species richness of invasive exotic plants within Brazilian conservation unit facilities of strict use (StUCUFs), in current climatic scenario. The inset figures from 1 to 6 show the species richness of invasive exotic species in PI CUFs from different Brazilian biomes. Black lines delimit the StUCUFs

conservation and detection tools for species may help conservationists and stakeholders better evaluate and prevent the future establishment of invasive species within CUFs. For instance, Kariyawasam et al. (2020) assessed the potential establishment of invasive plant species within CUFs in Sri Lanka under future climate change scenarios. They found out that future distribution ranges of invasive species will increase within CUFs of the country, raising concerns on how managers of these protected areas will deal with this future scenario. Bellard et al. (2013) also found that some species may be negatively affected, while others are expected to benefit from future climate change. These results are similar to ours, with species responding heterogeneously to climate change without a clear general pattern of changes. Finally, considering a Brazilian perspective, Silva et al. (2020) concluded that both human population density and road density

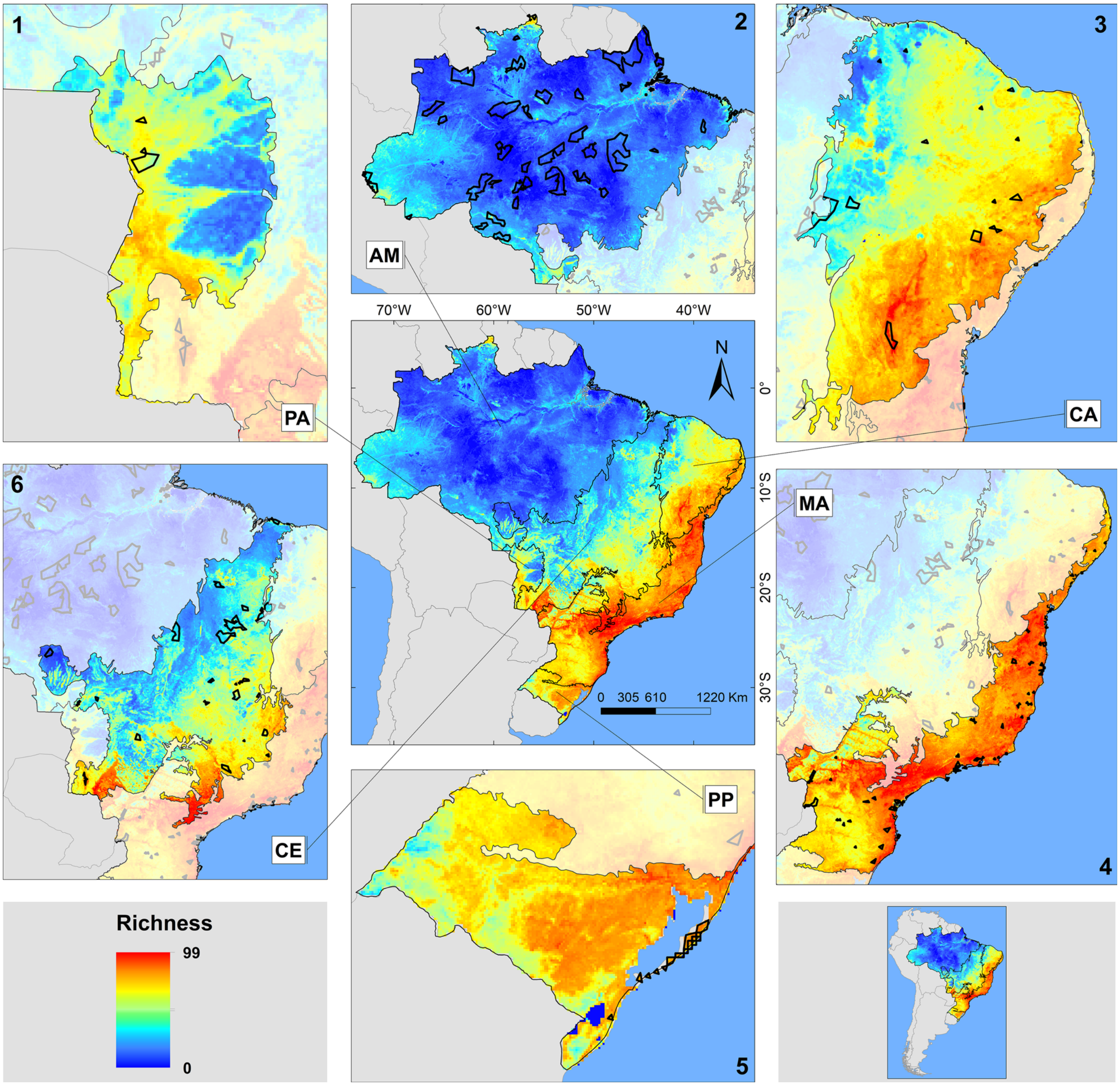

Fig. 3 Modeled species richness of invasive exotic plants within Brazilian conservation unit facilities of strict use (StUCUFs), in future climatic scenario. The inset figures from 1 to 6 show the species richness of invasive exotic species in PI CUFs from different Brazilian biomes. Black lines delimit the StUCUFs

are key factors determining the potencial invasive effects of naturalized graminoids upon CUFs within the Cerrado biome.

The poor management and control of biological invasions in Brazilian CUFs is a concerning issue (Ziller and Dechoum 2013), mainly at the Brazilian Mata Atlântica and Cerrado biomes—which we found to be more suitable for invasive species and are among the 25 biodiversity hotspots (areas with high biodiversity value and highly threatened Myers et al. 2000). Although, it is worth noting that past studies indicate that the Amazonian region may suffer savanization processes (Oyama and Nobre 2003; Malhi et al. 2008), which in this case, would make this biome more susceptible to plant invasions. Deforestation and the expansion of agricultural monocultures should accelerate this process, which may turn previously unsuitable areas suitable for establishing new

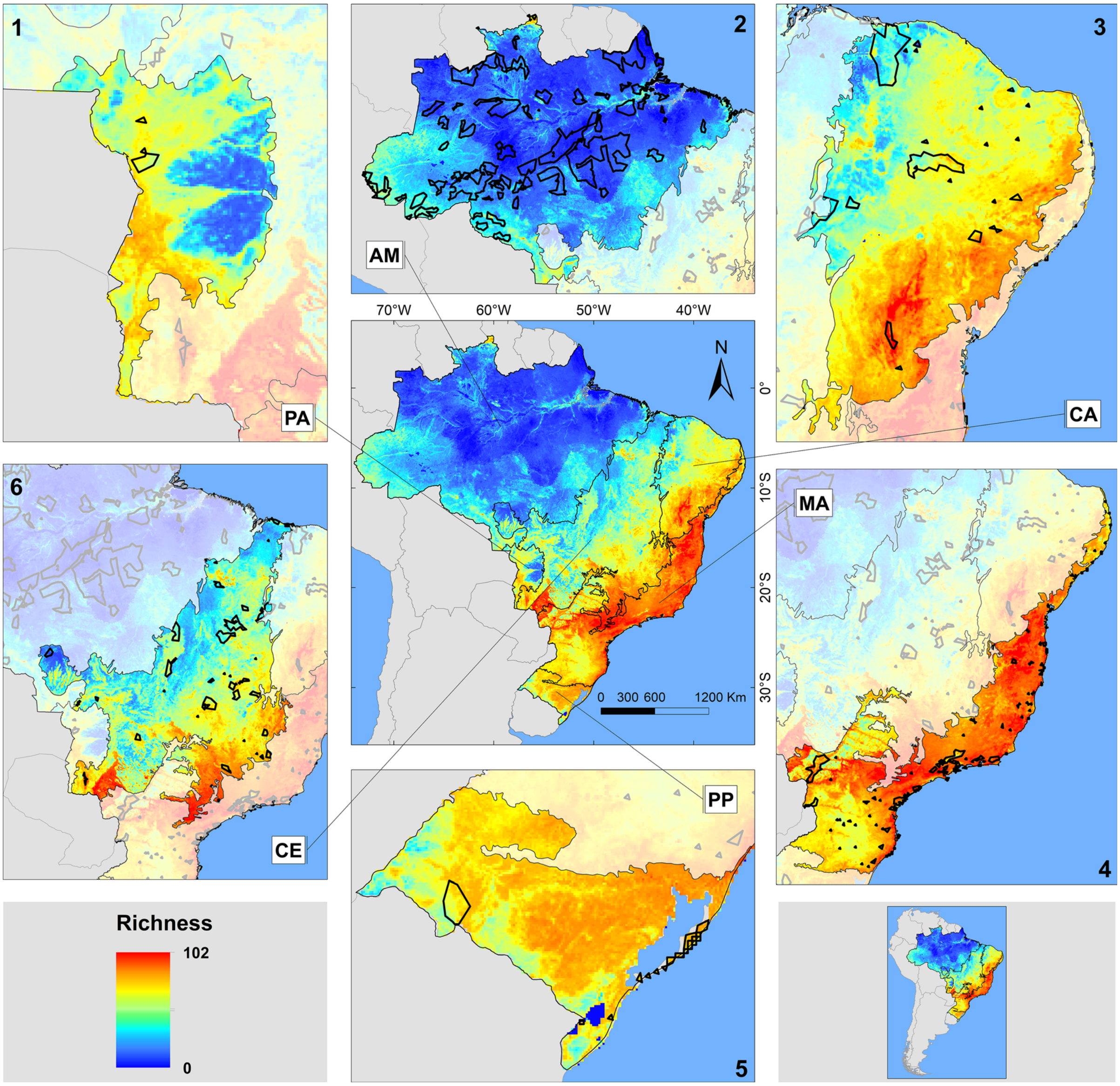

Fig. 4 Modeled species richness of invasive exotic plants within Brazilian conservation unit facilities of strict use and sustainable use (StUCUFs + SUsCUFs) in current climatic scenario. The insets 1 to 6 show the species richness of invasive exotic species in StUCUFs + SUsCUFs from different Brazilian biomes. Black lines delimit the StUCUFs + SUsCUFs

populations of invasive species—already observed for insects (Hennig and Ghazoul 2012; Braaker et al. 2014; Threlfall et al. 2017).

We note that our predictions consider solely abiotic variables, so the modeled ecological niche represents something between fundamental and realized niche—because occurrence records are already filtered by movement and biotic constraints (Peterson et al. 2011). This approach's main limitation is that models do not explicitly account for biotic interactions and dispersal capacity, probably overpredicting species distribution (Anderson 2017). Despite such limitations, as far as we are aware of, these results consist the first assessment of Brazil's plant invasion potential distribution in current and future climate scenarios.

Another critical aspect that affects species distribution is movement limitations (Barve et al. 2011). We considered the entire country accessible to the

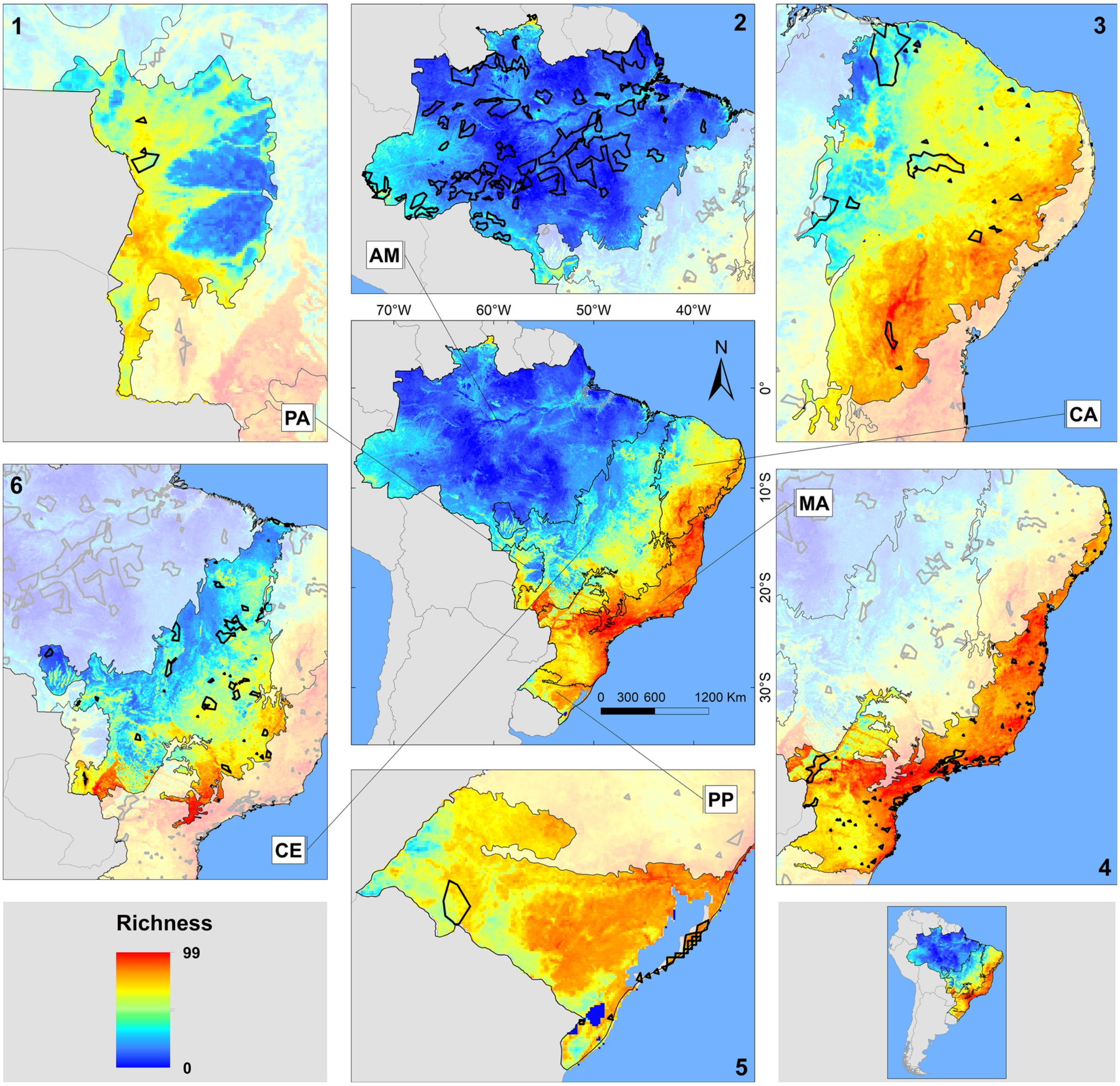

Fig. 5 Modeled species richness of invasive exotic plants within Brazilian conservation unit facilities of strict use and sustainable use (StUCUFs + SUsCUFs) in future climatic scenario. The insets 1 to 6 show the species richness of invasive exotic species in StUCUFs + SUsCUFs from different Brazilian biomes. Black lines delimit the StUCUFs + SUsCUFs

species to identify any potentially vulnerable location within the Brazilian territory. Invasive species can then spread to such locations by natural or intentional or unintentional human dispersal. For instance, many invasive plants have ornamental value and are commonly spread by commercial routes (*e.g.,* Richardson 1999). In Brazil, the highest human density, economic activity, and commerce routes—that can increase invasive plant dispersal—are precisely located in the areas that we expect to be more suitable for invasive plants. Suitability and high dispersal by humans may together amplify the risk of this region.

The lack of proper biological and ecological knowledge regarding the invasive exotic plant species colonizing Brazil, as well as their impacts, are still underestimated and prone to sampling biases that affect the available databases (e.g., literature data, museum data, citizen data; Reddy and Dávalos 2003;

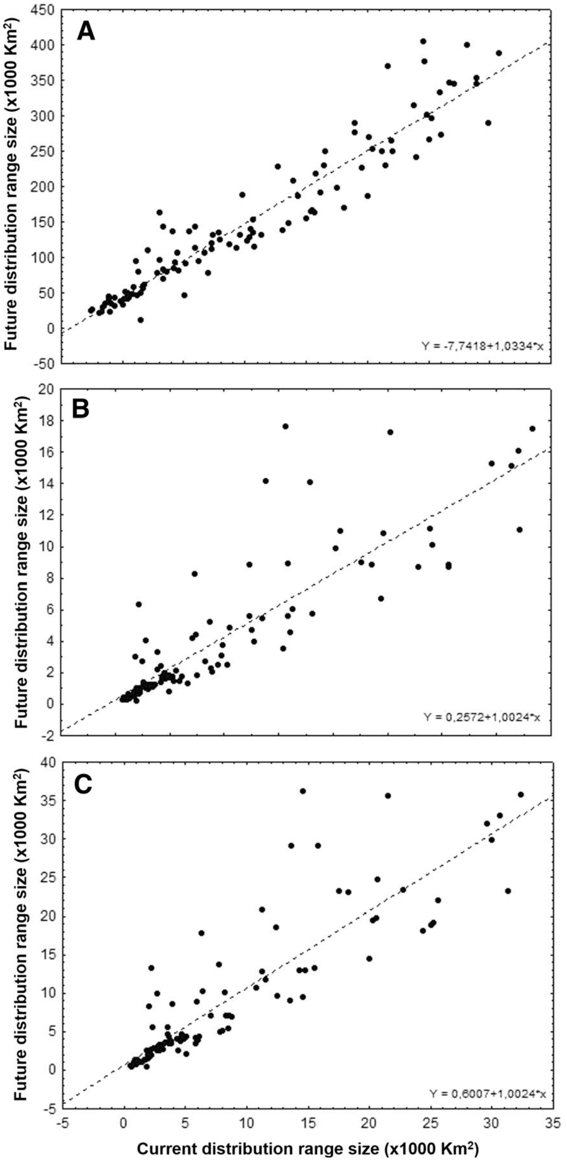

Fig. 6 Pearson's correlation between the potential distribution range size of each species in the current scenario with its distribution range size in the future scenario in Brazil (**A**), in the strict use (StUCUFs) conservation units (**B**), and the strict use plus the sustainable use (StUCUFs + SUsCUFs) conservation units (**C**)

Pyke and Ehrlich 2010; Oliveira et al. 2016). Consequently, their known geographical occurrences and potential distributions may also follow a biased pattern (Kramer-Schadt et al. 2013). For instance, past sampling efforts in Brazil were always more frequent in the Atlantic coast region and areas with high human densities (Patterson 1994; Bernard et al. 2011; Sousa-Baena et al. 2014). On the other hand, countryside areas with low human densities end up undersampled and affect the target species detectability and, consequently, species distribution models. Such pattern was already observed for Brazilian native plant species in the country (Sousa-Baena et al. 2013) and, indeed, also happens with the modeled species in our study.

Data problems could be related to reasons such as identification issues, incorrect sampling design, researchers' preference bias for some areas or biological groups, among others (Reddy and Dávalos 2003; Sastre and Lobo 2009; Newbold 2010; Pyke and Ehrlich 2010). The majority of the known occurrences of invasive exotic plant species in Brazil are related to human activities and road proximity (Zenni and Ziller 2011; Oliveira et al. 2016). The high frequency of universities in highly populated areas and the more substantial influence of research activities on the Brazilian coast may also bias the data distribution. Besides, invasive exotic species usually do not attract researchers' attention, and the effects and occurrence of these species are generally neglected and overlooked, affecting the effectiveness of management and control actions against them (Zenni et al. 2009; Zenni and Ziller 2011).

The ENMs have been widely used to fill out knowledge gaps (Guisan and Thuiller 2005; Elith and Leathwick 2009) and enhance our understanding of the bioinvasion processes (Guisan et al. 2013). Nevertheless, future research must amplify the geographical cover of sampling efforts to improve invasive species model predictability (Sastre and Lobo 2009). Field research involving invasive exotic plants (and other groups) is deeply needed (Wilson 2017), so a better risk assessment of Brazil's invasibility by these exotic species can be performed.

Finally, although we did not find an increase in the range of current invasive plants or the vulnerability of Brazilian conservation units in the future, it is worth noting that we expect new species' invasions to increase worldwide under climate change. We advise special attention to the Brazilian east coast's high potential environmental suitability (mainly at southern portions) to invasive plants. Therefore, we believe that the Brazilian biomes that occur in this region (i.e., Caatinga, parts of Cerrado, Mata Atlântica, and Pampa) are potentially the most vulnerable to the invasion, persistence, and increasing effects of the invasive plant species analyzed in this study.

Therefore, conservation unit managers from these regions and biomes should actively engage in monitoring and controlling invasive plants' presence.

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Data availability The data used in this manuscript are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interests The authors declare there is no conflict of interest.

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