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ECOSYSTEMS

Review of Ecological Restoration in the Brazilian Pampa

THAIS MICHEL & GERHARD OVERBECK

Abstract: Ecological restoration is crucial to counter global ecosystem degradation. The Brazilian Pampa, home to significant biodiversity, has been overlooked in research and conservation policies. This study involved a comprehensive literature review of 26 articles on restoration in the Brazilian Pampa, including 17 on grasslands and nine on forests, to understand the current state of knowledge on the subject. In grassland areas, the primary challenges were the invasion of exotic species and the lack of native seed or plant material. For forest restoration, the main issue was the conversion of forested areas to pastures, with challenges including the limited availability of nurseries for native species seedlings. Despite recent increases in research and some promising results, effectively guiding restoration efforts requires more research across the ecosystems of the Pampa, stronger networks for seedling and seed production, and concrete actions to achieve national restoration policy goals. The Pampa's potential for sustainable grassland use offers a unique opportunity to promote biodiversity conservation alongside economic development, making restoration efforts especially attractive.

Key words: biodiversity conservation, grasslands, Pampa, restoration ecology, seed production, species introduction.

INTRODUCTION

Global trends of conversion and degradation of ecosystems emphasize the importance of ecological restoration in environmental policies (Dobson et al. 1997, Krob et al. 2021, Lyons et al. 2023). Brazil has made considerable advancements in the knowledge necessary for ecological restoration, but the focus has primarily been on forest recovery, overlooking open ecosystems such as grasslands, despite their biodiversity and their important contributions to ecosystem services (Overbeck et al. 2013, Buisson et al. 2020, Guerra et al. 2020). Recognizing the unique challenges of each ecosystem is crucial to ensure that all natural systems are considered in the policies of the United Nations Decade on Ecosystem Restoration (UN 2019), as highlighted by Silveira et al. (2020). In 2017, Brazil committed to restoring 12 million hectares of native vegetation by 2030 through the National Plan for Native Vegetation Recovery (PLANAVEG), including 300.000 hectares in the Pampa (PLANAVEG 2017).

The Pampa corresponds to the northern portion of the grassland region of the Rio de la Plata (Andrade et al. 2018) that includes 63% of the Brazilian state of Rio Grande do Sul (i.e. the Brazilian Pampa biome, IBGE 2019), as well as northeastern Argentina and the entire country of Uruguay (Andrade et al. 2018). The natural landscapes of the Brazilian Pampa, the focus of our study, are dominated by grassland areas that historically have been shaped by fire and herbivory and support extensive livestock production on native grasslands (Overbeck et al. 2022). Alongside grasslands, the region holds a diversity of other vegetation types, including

shrublands, forests (principally but, not only, on slopes and along river courses), coastal restinga scrub and forests, wetlands and other ecosystems, such as palm groves (Overbeck et al. 2022, Andrade et al. 2023). The Pampa holds approximately 9% of Brazilian biodiversity in an area of little more than 2% of Brazil's total land, totaling 12.503 species (Andrade et al. 2023). This diversity has long been neglected in the national conservation debate (Overbeck et al. 2007, 2015). Currently, the Pampa region is experiencing rapid conversion of natural ecosystems into anthropogenic areas, with greater loss of native vegetation compared to other Brazilian biomes (Souza et al. 2020, Krob et al. 2021). Between 2008 and 2018, over 1 million hectares of grasslands were converted to other uses (MapBiomas Project 2022). Currently, only 3.23% of the Brazilian Pampa is protected by Integral Protection and Sustainable Use areas; however, even within these protected areas, approximately 20% are degraded (Ribeiro et al. 2021). Based on the rate of conversion and the degree of protection, the Pampa can be considered the most threatened of all Brazilian regions (Overbeck et al. 2015).

In the recent past, large restoration projects with a focus on grasslands have been started in the region, such as projects supported by the Brazilian federal government, which together aim to restore over 3.300 hectares of degraded lands (see discussion). However, as evidenced by Guerra et al. (2020) in their review on restoration studies across Brazil, the Pampa has received little attention in terms of scientific research (only 1% of ecological restoration studies conducted in Brazil). Here, we aim to take a more detailed look at the current scientific knowledge regarding restoration in the Pampa. For this, we conducted a bibliographic review on ecological restoration in the Brazilian Pampa region and additionally evaluated the literature from the adjacent parts of the Rio de La Plata region, encompassing the Argentine and Uruguayan Pampas, as knowledge from there should be relevant for ecological restoration of the Brazilian Pampa. The retrieved data allows us to discuss knowledge gaps regarding ecological restoration in the Pampa and to identify key topics that are of high relevance to reach the existing ambitious restoration goals (e.g. in PLANAVEG).

MATERIALS AND METHODS

Literature search

We conducted a systematic literature review using electronic databases, with a primary focus on the Web of Science platform, supplemented by a search on Scielo and on Google Scholar. The article search was performed using the following search string: Title ALL=(restor* OR recover* OR reclam* OR reclaim* OR revita* OR rehabil* OR rewet* OR reforest* OR restaur* OR recup* OR reflor* OR regener*) AND ALL=(ecolog* OR ecosyst* OR ecossist*) AND ALL=("rio grande do sul"). The search included articles published up to 28/01/2024. Our literature search used a method similar to the one employed by Kollmann et al. (2016) and Guerra et al. (2020). Considering that the Pampa region in the broader sense, i.e. Rio de la Plata grasslands, extends beyond the borders of Brazil, and that knowledge from these regions is relevant for restoration in the Brazilian Pampa, we conducted an additional search to include the adjacent parts of Uruguay and Argentina, with the help of the search string ALL=(restor* OR recover* OR reclam* OR reclaim* OR revita* OR rehabil* OR rewet* OR reforest* OR restaur* OR recup* OR reflor* OR regener*) AND ALL=(ecolog* OR ecosyst* OR ecossist*) AND ALL=(pampa).

Eligibility criteria

In the article selection, we retained only those that reported studies conducted in the Brazilian Pampa region or – in an additional table – those conducted in the Argentinean and Uruguayan parts of the Rio de la Plata region, excluding articles unrelated to the topic of ecological restoration. We focused on articles that evaluated restoration techniques or vegetation management in a restoration or recovery process, either through experiments or observational studies in previously managed areas, and did not consider theoretical works, such as Overbeck et al. (2013).

Bibliometric analysis

In a bibliometric analysis, we characterized our dataset by considering the number of publications per period, type, language, keywords, publication location, research institutions, and funding agencies involved.

Bibliographic classification

For the classification of selected articles, the following criteria were used: type of ecosystem considered; groups of organisms involved; degradation factors; restoration methods, species used and management techniques (depending on the study, one or more of these criteria applied); type of restoration monitoring; duration of monitoring; use of reference areas; and outcomes (successful or not). We divided our dataset into two main ecosystem types: grasslands and forests.

RESULTS

Bibliometric analysis

The Web of Science search for Papers on the Brazilian Pampa initially yielded 541 articles; the vast majority of articles was from outside the ecological restoration context. In total, only 26 articles directly focused on actions contributing to the restoration of ecosystems located in the Brazilian Pampa. The search on Scielo and Google Scholar did not result in any articles not found on Web of Science. The articles were published between March 2008 and November 2023, showing an increase in publications and citations in recent years. 65% (17) were published in international journals, 35% (9) in national journals, with 77% (20) published in English. The authors belonged to sixteen institutions, with Universidade Federal do Rio Grande do Sul (UFRGS) and Universidade Federal de Santa Maria (UFSM) as the most prominent contributors, accounting for 35% (14) and 20% (8) of the published studies, respectively. The main funding sources included the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ), supporting 30% (21) and 23% (16) of the research projects, respectively.

Bibliographic analysis

Among the 26 articles, 17 focused on restoration of grassland, while nine addressed forest restoration. The studies took place in 18 municipalities in the Pampa region of Rio Grande do Sul (Figure 1). Some of the articles pertained to studies conducted in the same locations but with different assessments, hence they were tallied separately for the analysis of restoration data.

In the complementary analysis, which included studies conducted in the Argentine and Uruguayan Pampas, five publications were found that met our criteria, all from Argentina, and all on grassland. No studies conducted in the Uruguayan Pampa were found to meet the criteria used in the review.

The selected studies conducted in the Brazilian Pampa revealed that the presence of

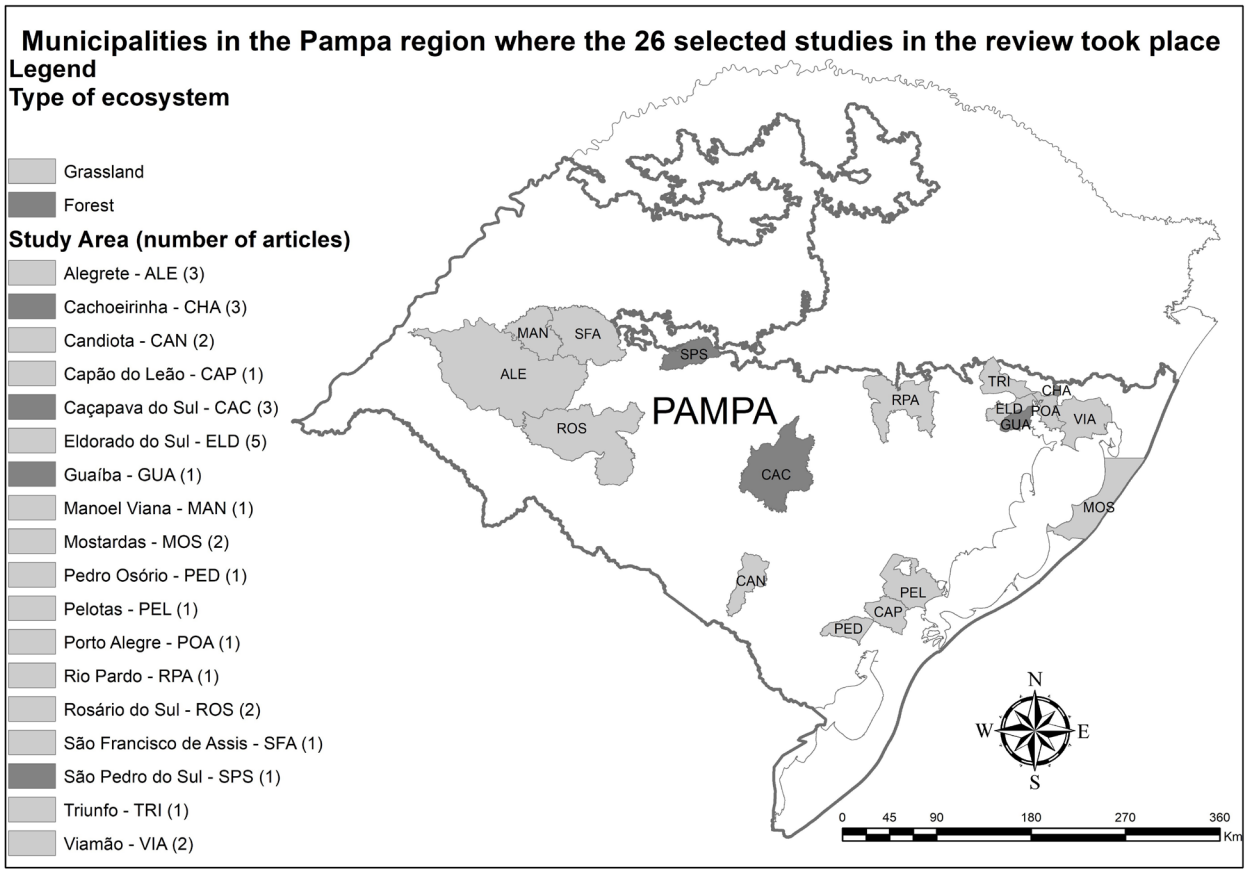

Figure 1. Map highlighting the municipalities in the Pampa region where the 26 studies selected in the review were conducted.

invasive exotic species was the main degradation in grassland areas and conversion to pasture in forested areas (Figure 2).

Regarding the type of restoration interventions, active restoration was the primary form of intervention, both in grassland and forest areas (Figure 3). The introduction of native species emerged as the most common restoration strategy (Figure 4).

The average monitoring period after method implementation was approximately one and a half years. In 10 out of 26 studies, data were recorded at a single sampling event. Only in half of the articles (13 out of 26), the areas with interventions were compared with reference areas or had a control treatment.

Studies in grassland ecosystems

Of the 17 articles that focused on grassland restoration, 10 reported experiments on the effectiveness of different restoration practices in degraded areas (Table I). Five articles evaluated ongoing restoration projects, investigating various aspects of the implemented practices, including active restoration techniques and natural regeneration. Two articles presented the results of experimental studies involving seeding and the use of hay for species introduction. The set of works covered different species introduction practices for restoration, with eight articles dealing with direct seeding, two on seedling planting, and three on hay transfer. Among the species used, highlighted in Figure 5a, were tested through direct seeding and planting.

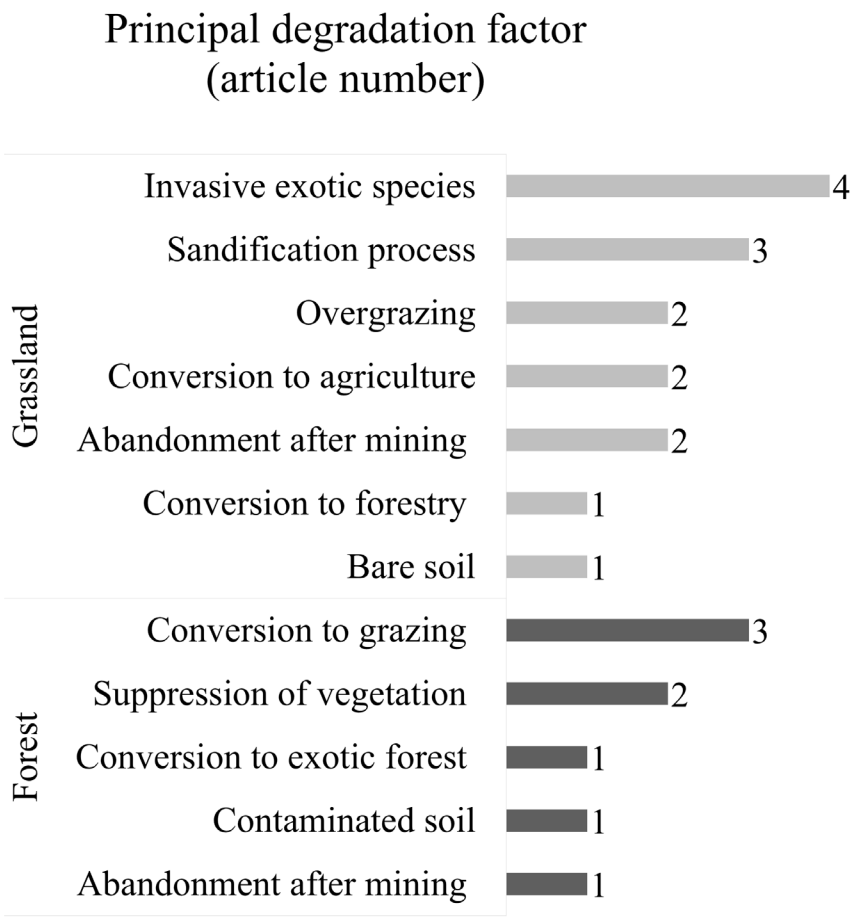

Figure 2. Main degradation factors described in the articles selected in this review.

Five articles reported results related to the use of exotic forage species, including invasive species such as *Cynodon dactylon*, *Urochloa decumbens* and *U. brizantha*. One article evaluated the planting of *Eucalyptus tereticornis* and *Pinus elliottii*, exotic and invasive forest species. Two articles investigated the potential of hay transfer to introduce a mixture of native species in restoration areas. Four articles presented results of attempts to control invasive exotic plant species, using methods such as manual removal, cutting, herbicide application, and controlled burning. Three studies experimented with the introduction of native and/or exotic species after soil preparation using techniques such as subsoiling, harrowing, fertilization, and liming. Grazing intensity control practices or temporary exclusion were tested in areas degraded by overgrazing or converted to agriculture, as well as in natural regeneration after the cutting of commercial plantations. Additionally, one study evaluated the potential of increasing seed rain with the help of physical barriers, such as tree logs, to prevent human use in degraded areas.

Studies in forest ecosystems

Of the nine studies addressing forest restoration, six articles examined ongoing restoration projects, assessing a variety of restoration practices, including active species introduction and natural regeneration, to mention the two most frequent approaches (Table II). Among the tested methods, seven studies utilized species introduction through planting native forest seedlings (Figure 5b). Three studies examined the regeneration process in an area (the same

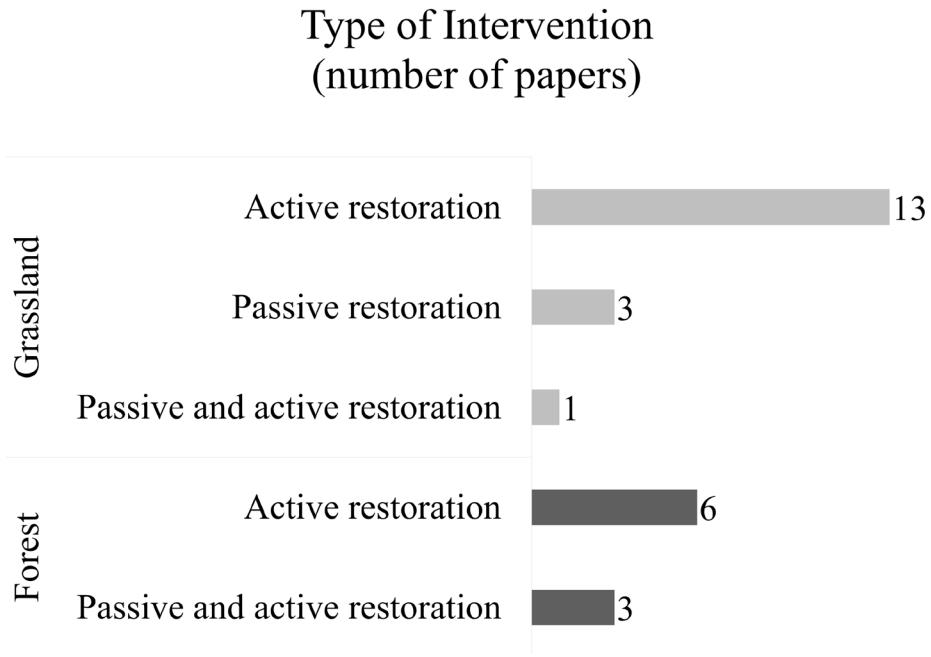

Figure 3. Type of intervention in the studied areas described in the selected articles in this review.

area for all three articles) with a history of cattle grazing, comparing the areas after 10 years of planting with reference areas. Three articles evaluated the results of natural regeneration and nucleation planting compared to a reference forest. One study assessed the effectiveness of branch transposition as a technique used to create wildlife- attractive environments and to increase seed dispersal in the area. Finally, in a forest area degraded by clay extraction, one study analyzed recovery using bioremediation (introduction of microorganisms) to decontaminate the soil with the presence of Polycyclic Aromatic Hydrocarbons (PAHs).

DISCUSSION

Current scientific knowledge on ecological restoration from the Brazilian Pampa

As expected, our literature review revealed a small scientific basis for ecological restoration in the Brazilian Pampa, with only 26 articles specifically dedicated to the evaluation of restoration techniques in the region. The expansion of research into the Pampa region in Argentina and Uruguay resulted in only a slight increase in the number of studies, with only five articles found on grassland restoration in Argentina and none in Uruguay. This highlights that, in recent decades, ecological restoration in these countries has been even less addressed than in the adjacent part of Brazil. For the Brazilian Pampa, we observed a recent increase in publications, suggesting a growing recognition of the relevance of ecological restoration in science and increasing research activities.

It is worth noting that some of the selected articles, although presenting information that contributes to the restoration of the Pampa, still presented considerable limitations. In ecological restoration, the aim is to guide the ecosystem towards its natural trajectory, considering its historical trajectory or reference conditions based on ecological data and indicators, thus demonstrating the importance of reference areas for the restoration process (Rodrigues et al. 2009b). However, not all studies included control or comparison to reference areas, which

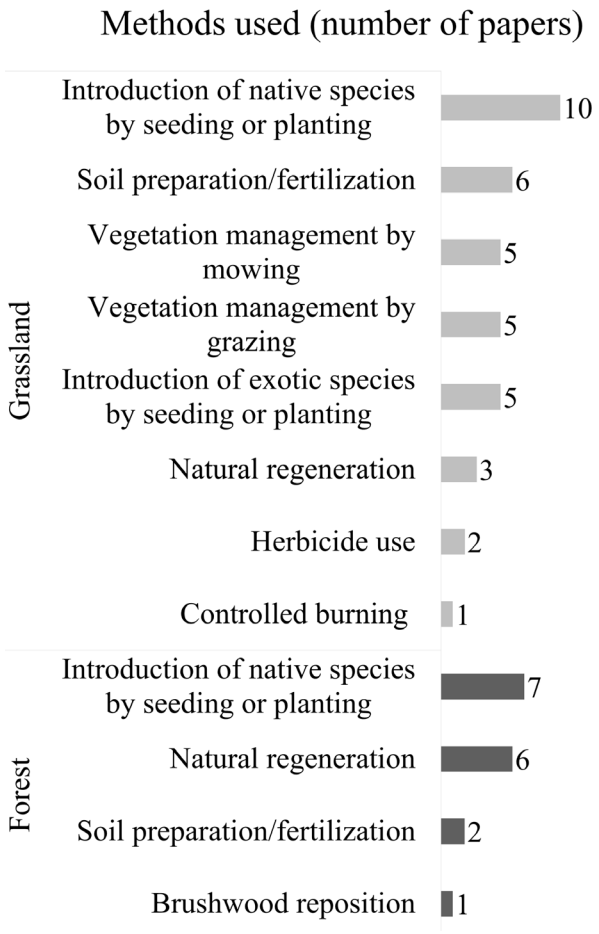

Figure 4. Main methods used in the studied areas described in the selected articles in this review.

is a drawback not only for the development of scientific knowledge, but also for the evaluation of restoration practices. Further, the average monitoring period after method implementation in the Brazilian Pampa was only about a year and a half. Long-term monitoring is considered a key issue in ecological restoration (Viani et al. 2017, Prach et al. 2019, Buisson et al. 2020) and lack of it impedes recognizing if an ecosystem was in fact restored or not. In the Argentinean Pampa, despite the limited number of reviewed publications, the studies delved deeper into monitoring, with three out of the five studies in the Argentine Pampa being monitored for an average of 9 years (references provided). These results may also be indicative of the fact that most studies are on scientific experiments, and not conducted within the context of real-world restoration.

We acknowledge that scientific knowledge needed for restoration of Pampa ecosystems does not necessarily have to be developed only in the Pampa itself. Research on restoration of highland grasslands in the Atlantic Forest region, savannas in the Cerrado, and different forest physiognomies of the Atlantic Forest (e.g., Thomas et al. 2019a, Sampaio et al. 2015, Rodrigues et al. 2009a) offer valuable insights, e.g. on successful methods of species introduction, that can benefit Pampa restoration as these systems share many ecological characteristics with ecosystems in the Pampa. Studies conducted in temperate regions of North America and Europe (e.g., Packard & Mutel 2005, Buisson et al. 2019) also provide information on potentially useful techniques for restoration in the Pampa region (see also Overbeck et al. 2013). However, care needs to be taken to consider specificities of different ecosystems: for instance, in grassland, distinct proportions of C3 and C4 grasses may lead to differences in ecological dynamics that also reflect in the need to develop region-specific restoration interventions.

Andrade et al. (2019) identified six subtypes of grassland formations within the Pampa, distinct from high-altitude grasslands in the Atlantic Forest biome. Similarly, forest formations in the Pampa differ from those of the Atlantic Forest due to climatic conditions, as shown by Oliveira-Filho et al. (2015). Additionally, the socioeconomic context in the Pampa differs from that of other regions, just as land use history and pressures. Thus, there is a need to expand scientific knowledge specifically tailored to the Brazilian Pampa and its ecosystems. In this context, it is worth noting that studies related to livestock production, such as those on

Table I. Main topics covered in each selected article from studies conducted in grassland areas.

References	Approach	Principal degradation factor	Type of intervention	Methods used
Arend da Silva et al. (2020)	Experimentation outside of a degraded situation	Not part of the research	Active restoration	Introduction of native species (seed planting)
Becker et al. (2019)	Assessment of ongoing recovery process	Post-mining area	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting); Introduction of exotic species (seed planting)
Fedrigo et al. (2018)	Experimentation in a degraded situation	Overgrazing	Passive restoration	Different grazing intensities (stocking rate adjustment); Grazing exclusion (deferment)
Fedrigo et al. (2022)	Experimentation in a degraded situation	Overgrazing	Passive restoration	Different grazing intensities (stocking rate adjustment); Grazing exclusion (deferment)
Guido & Pillar (2017)	Experimentation in a degraded situation	Invasion by *Eragrostis plana*	Active restoration	Above-ground biomass cutting (mowing); Herbicide application; Removal by uprooting
Medeiros & Ferreira (2011)	Experimentation in a degraded situation	Invasion by *Eragrostis plana*	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting); Introduction of exotic species (seed planting)
Porto et al. (2022a)	Experimentation in a degraded situation	Invasion by *Pinus elliottii*	Active restoration	Litter removal; Controlled burning (fire); Introduction of native species (hay transposition)
Porto et al. (2022b)	Assessment of ongoing recovery process	Bare soil	Active restoration	Natural regeneration with the use of physical barriers (logs)
Rovedder & Eltz (2008a)	Experimentation in a degraded situation	Advanced sandification process	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting); Introduction of exotic species (seed planting); Introduction of exotic species (seedling planting)
Rovedder & Eltz (2008b)	Experimentation in a degraded situation	Advanced sandification process	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting); Introduction of exotic species (seed planting).
Rovedder et al. (2010)	Experimentation in a degraded situation	Advanced sandification process	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting)
Silva & Fontana (2020)	Assessment of ongoing recovery process	Conversion to agriculture (soybean) and absence of disturbance	Active restoration	Above-ground biomass cutting (mowing); Different grazing intensities (stocking rate adjustment); Grazing exclusion (deferment)

Table I. Continuation.

Silva & Fontana (2021)	Assessment of ongoing recovery process	Conversion to agriculture (soybean) and absence of disturbance	Passive e active restoration	Natural regeneration; Above-ground biomass cutting (mowing); Different grazing intensities (stocking rate adjustment); Grazing exclusion (deferment)
Stumpf et al. (2016)	Experimentation in a degraded situation	Constructed soils in mined areas	Active restoration	Soil preparation; Soil fertilization/ correction; Introduction of native species (seed planting); Introduction of exotic species (seed planting); Introduction of exotic species (seedling planting)
Thomas et al. (2019b)	Experimentation in a degraded situation	Invasion by *Urochloa decumbens*	Active restoration	Topsoil removal; Above-ground biomass cutting (mowing); Herbicide application; Introduction of native species (seed planting); Introduction of native species (hay transposition)
Thomas et al. (2023)	Experimentation outside of a degraded situation	Not part of the research	Active restoration	Introduction of native species (hay transposition)
Torchelsen et al. (2019)	Assessment of ongoing recovery process	Conversion to forest planting	Passive restoration	Natural regeneration in grazed areas

pasture management in native grasslands, are also significant for the ecological restoration of Pampa grasslands, not only in terms of ecosystem ecology but also due to their relationship with local social and economic development, as livestock farming is the main activity historically carried out by local populations. Although the diversity of native grassland species with forage characteristics is recognized, the potential of native grasslands in the Pampa for animal production is still not sufficiently recognized (Nabinger et al. 2009, Jaurena et al. 2021). This potential can be leveraged for the restoration of Pampa grassland areas, as restoring native grassland areas for livestock production ensures the long-term viability of economic activity, involving rural producers and local communities in the process.

The Pampa region is not only characterized by grassland and forest but hosts a considerable diversity of other ecosystems. However, no studies on the restoration of these systems were found in our review, highlighting the lack of a specific scientific basis for research conducted in these distinct locations. Just as in the case of grasslands and forests, regional particularities may hinder the application of techniques that are more widely used in regions beyond the Pampa. To our knowledge, only for wetlands restoration experiments have been undertaken (Silva et al. 2022, a study on the restoration of wetlands converted for irrigated rice production that was not retrieved by our review). In the case of *Butia* palm groves – where degradation has been mapped (Sosinski et al. 2022) - and the Espinilho, first restoration activities have recently been started in the context of the GEF Terrestre (see below), but so far no specific scientific studies are available.

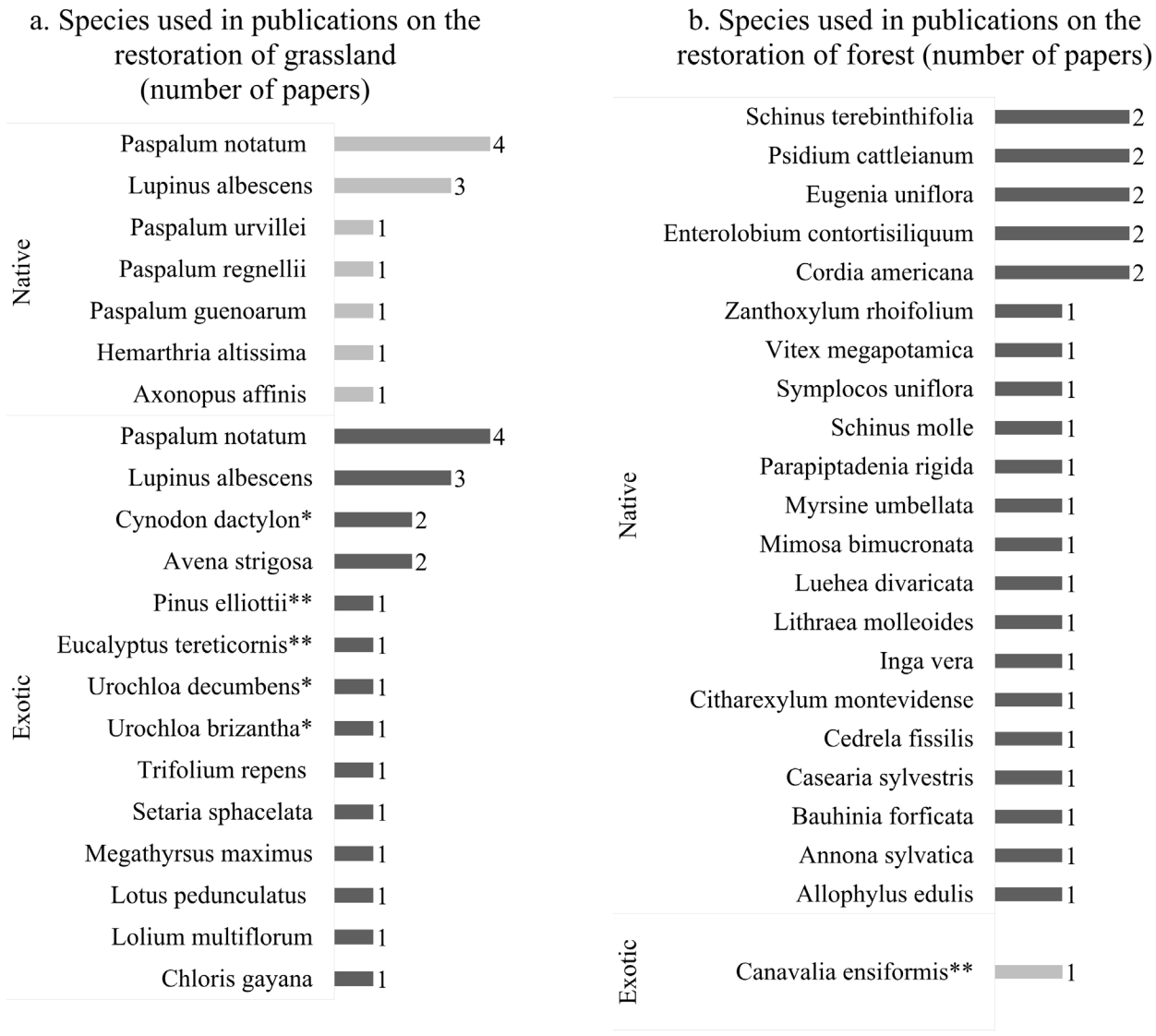

Figure 5. Species used in publications on the restoration of grassland (a) and forest (b) environments found in the review.
***Species listed** on the state list of invasive exotic species (RS 2013). Species marked with ** are invasive exotic species that are used in restoration of grassland areas. And with *** are cultivated species native to Central America used as green manure in forest.*

Overall, the few articles found (26 for the Brazilian Pampa, five for the Argentine Pampa, and zero for the Uruguayan Pampa) that either conducted scientific evaluation of restoration processes – active or not – or implemented experiments with different restoration techniques are indicative of a slow pace of scientific production compared to the rapid conversion of natural ecosystems in the Pampa.

This limited investment in ecological restoration research in the Pampa may stem from the historical neglection of non-forest environments in conservation policies in Brazil (Overbeck et al. 2015, 2022). However, our

Table II. Main topics covered in each selected article from studies conducted in forested areas.

Article	Approach	Principal degradation factor	Type of intervention	Methods used
Da Fonseca et al. (2017)	Assessment of ongoing recovery process	Conversion to grazing area	Active restoration	Planting and natural regeneration
De Sousa Pohren et al. (2016)	Experimentation outside of a degraded situation	Contaminated soil	Active restoration	Soil bioremediation techniques
Gazolla et. al (2023)	Experimentation outside of a degraded situation	Not part of the research	Active restoration	Introduction of native species (direct seeding and green manure)
Piaia et al. (2020)	Assessment of ongoing recovery process	Suppression of vegetation and conversion to grazing	Passive e active restoration	Natural regeneration; Nucleation planting
Procknow et al. (2020)	Assessment of ongoing recovery process	Suppression of vegetation	Passive e active restoration	Natural regeneration; Nucleation planting
Procknow et al. (2023)	Assessment of ongoing recovery process	Suppression of vegetation	Passive e active restoration	Natural regeneration; Nucleation planting
Rosenfield & Müller (2017)	Assessment of ongoing recovery process	Conversion to grazing and eucalyptus planting	Active restoration	Planting and natural regeneration
Rosenfield & Müller (2019)	Assessment of ongoing recovery process	Conversion to grazing area	Active restoration	Planting and natural regeneration
Toso et al. (2020)	Experimentation outside of a degraded situation	Mining area (abandoned)	Active restoration	Brushwood transposition as an attractant for wildlife

review also revealed a lack of studies on forest restoration in the Pampa: only nine articles were found. Furthermore, more than half of the studies (14 out of 26 articles) resulted from more than one paper developed on the same study areas, as observed in cases such as Silva & Fontana (2020, 2021); Fedrigo et al. (2018, 2022); Rovedder & Eltz (2008a, b) and Rovedder et al. (2010); Stumpf et al. (2016) and Becker et al. (2019); Da Fonseca et al. (2017), Rosenfield & Müller (2017, 2019); and Piaia et al. (2020), Procknow et al. (2020, 2023). While this means that researchers are efficient in making scientific benefit out of experiments or restoration management, it also indicates that the actual number of experiments or studies is lower than suggested by the number of papers as such. Overall, our review thus supports Guerra et al. (2020) findings that the Pampa, along with the Pantanal and Caatinga, lacks sufficient knowledge in ecological restoration.

Scientific knowledge for the restoration of Pampa grasslands

A total of 17 articles addressed the restoration of grasslands. The control of invasive exotic species in grasslands was a key research activity, documented in four articles – a small number considering that biological invasions are considered the second leading cause of global biodiversity loss (Pyšek et al. 2020) and a significant threat also to grasslands of the Pampa (RS, 2018, Guido et al. 2016). Similarly,

studies from the Argentinean Pampa show that exotic and invasive species are a key challenge in vegetation recovery after other land uses (Tognetti et al. 2010, Tognetti & Chaneton 2012). The severe impact in particular of *Eragrostis plana* (capim-annoni), has been evidenced in several studies, considering both biodiversity (Dresseno et al. 2018) and rangeland productivity (Medeiros & Focht 2007). A 2017 study estimated that *E. plana* was present in one million hectares of native grasslands in the state (Medeiros & Focht 2007). However, only two papers were retrieved that worked on control of the species (Medeiros & Ferreira 2011, Guido & Pillar 2017). Despite some positive results on the short term, these studies did not lead to satisfactory results, i.e., complete control of *E. plana*, evidencing the need for further studies and more experimentation with different techniques. A longer established method for the control of *E. plana*, but not retrieved by our study as no journal publication on it exists, is the "Mirapasto – Integrated Pasture Recovery Method" developed by Embrapa Pecuária Sul (Perez 2015). This method involves selective herbicide application and equipment use and is widely used, but its effectiveness has not been presented in detail to the scientific community. Importantly, the suggested protocols promote the introduction of non-native forage species, which does not contribute to native vegetation recovery even if the invador has been controlled, which is, needless to say, an important first step. Although other studies on the control of *E. plana* are available (e.g. Bettega & Trevisan 2022 on biological control), they also are not concerned with the restoration of invaded sites, but only with control of the species.

Several other invasive or potentially invasive exotic species occur in the Pampa, such as *Ulex europaeus* (León Cordero et al. 2016) or *Cytisus scoparius* (Cordero et al. 2016), to cite only two examples, but so far, no studies on the restoration of the sites where they occur have been conducted. Often, the impact of exotic species has been assessed only locally, as the case of *Urochloa decumbens* (Cezimbra et al. 2019), which is widely distributed among roadsides in the region. In the case of *Pinus* sp., control technically appears to be the easiest (cutting of treats, manual removal of seedlings, removal of seeds in the litter layer by fire; see Dechoum & Ziller 2013, Porto et al. 2021), however, these methods are not implemented on a larger scale, likely due to lack of enforcement of legislation (for example, for control in areas adjacent to planting) or even due to the immense magnitude of the problem; this means that degradation may spread over wider areas. Removal of the degradation cause, for example, of invasive species, is only a first step of a restoration process. Active restoration of grassland ecosystems often requires species addition (e.g., Kiehl et al. 2010), but southern Brazil, including the Pampa region, still lacks a native seed market for grassland species (Rolim et al. 2022). An initial list of priority plant species for restoration in the Pampa has been developed (Guarino et al. 2018), however, most species have not been evaluated concerning their potential use (e.g. how and when to introduced) and their seeds are not available on the commercial market. Studies like the one conducted by Arend da Silva et al. (2020) that aimed to identify species with high potential for ecological restoration, thus are of high relevance and, together with a better understanding of the reproductive ecology of native Pampa species (e.g., Martins et al. 2020, for a detailed study) a first step for a institutionalized seed market, today still a distant reality. In other Brazilian regions, initiatives such as the Xingu Seeds Network and the Cerrado Seeds Network provide models for establishing seedling and seed

production networks (see Sanches & Futemma 2019, Schmidt et al. 2019) that – with adaptations primarily due to socioeconomic differences – could also be developed for the Pampa region. This is necessary due the low capacity of spontaneous recovery of the natural vegetation after degradation (e.g. Torchelsen et al. 2019), in consequence of the low contribution of the grassland soil seed bank to naturally restore plant populations after land use conversion (Vieira & Overbeck 2020). Overall, our review indicates that the use of native species – by different introduction techniques including direct seeding and hay transfer – has entered into the focus of research, even though earlier studies used exotic species, including, in one study, the invasive *P. eliottii* for revegetation of a grassland site degraded by desertification (Rovedder & Eltz 2008a). However, two more recent studies evidence that, in restoration practice, use of exotic, and sometimes even invasive species, still occurs (Stumpf et al. 2016, Becker et al. 2019), this does not allow for full recovery of the degraded ecosystem (as seen in Becker et al. 2019 for grassland birds). While establishing a vegetation cover is a crucial step in any recovery process of degraded ecosystems, true ecological restoration requires the use of native species, and invasive exotic species clearly should be avoided as they may lead to degradation at other sites.

Several studies retrieved by our review evaluated the potential use of different management strategies of grasslands in the restoration process. Although overgrazing can contribute to grassland degradation, adequate grazing management is recognized as compatible with conservation of grasslands and their diversity due to its role in maintaining grassland diversity, controlling dominant plant biomass, and preventing woody species encroachment (Overbeck et al. 2007). The studies conducted in areas that suffered overgrazing showed that practices like seasonal exclusion of grazing and grazing intensity adjustments can increase species richness (Fedrigo et al. 2018, 2022) and be beneficial for organic carbon stocks in the soil (Vecchio et al. 2018). Altered management may also lead to the reduction of invasive species, as shown by Medeiros & Focht (2007). Positive results in terms of vegetation composition, plant diversity and productivity were also observed for rotational grazing (Boavista et al. 2019) a strategy widely used in recent restoration projects (see below). Importantly, seed dispersal by cattle has been shown to have potential for restoring native grasslands (Minervini Silva & Overbeck 2021).

Taken together, these studies also indicate that the vast knowledge on grazing ecology for grasslands in the region can be made useful for restoration of grasslands. Nonetheless, research addressing the potential of grazing in the restoration of specific situations of degradations are missing, just as are more detailed studies on the use of fire that is known, from ecological studies, to be important for maintenance of natural grasslands, especially where not under grazing (Müller et al. 2007, Fidelis et al. 2010). Also, it is well established that fire helps to control woody species (Ferreira et al. 2010, Fidelis et al. 2012, Joner et al. 2021). Extended fire-free intervals can reduce populations of typical grassland species (Fidelis et al. 2012), making fire a valuable restoration technique after longer periods without management, as seen in other biomes worldwide (e.g., Collins & Wallace 1990, Smith et al. 2010, Durigan 2011, Sampaio et al. 2015, Duchardt et al. 2016, Zanzarini et al. 2019). However, no specific studies on using fire for the restoration of Pampa grasslands have been published so far.

The large majority of studies was concerned principally with plant community cover and

composition, or fate of introduced species. Becker et al. (2019) and Silva & Fontana (2021) used the avifauna as indicator for restoration success, with contrasting results which might be related to the land use history (mining vs. agricultural use), but also the restoration approaches (seeding of exotic species vs. assisted recovery of native vegetation). More studies using specific groups of the fauna as indicators for restoration seem interesting, as functioning ecosystems obviously are much more than just vegetation. The potential role as indicators of some species groups for habitat quality is well known (e.g., Dröse et al. 2021). Experiments conducted with indicators assessing plant-pollinator interactions have been conducted to guide the selection of plant species for restoring grassland areas in the Argentinean Pampa (Sabatino et al. 2021a, b). These studies evaluated the attractiveness of plants to pollinators in areas undergoing restoration, demonstrating that, despite the ecological importance of certain plant species for functional attribute restoration, they may prove challenging to propagate, rendering them unsuitable for grassland restoration.

Scientific knowledge of forest restoration in the Pampa

Forest restoration has been a long-standing field of research in Brazil, with a well-established history of scientific studies and enduring interest from the academic community. Pampean forests are considered the southernmost extension of the Atlantic Forest, albeit with a reduced species diversity (Oliveira-Filho et al. 2015). Thus, it is reasonable to consider that the numerous restoration experiences in the Atlantic Forest (see Guerra et al. 2020) should also support the restoration of Pampa forests. In the context of our review, we had expected that a major portion of restoration efforts and studies, even within the grassland-dominated Pampa, would be primarily focused on forest formations. However, the bibliographic analysis revealed only nine articles that addressed the topic of forest restoration in the Brazilian Pampa, with no articles found on forest restoration in the Argentinean and Uruguayan part of the Rio de la Plata region.

Today, forests within the grassland landscape may be negatively affected by grazing animals that enter the forest in search of water and shade (Sampaio & Guarino 2007, De Moraes Stefanello et al. 2021). This indicates that conservation and restoration planning in forest-grassland mosaics requires specific attention to the different components of the mosaics: while, as discussed above, cattle can be an important agent of grassland restoration, it can lead to degradation in forests, necessitating restoration. However, in practice, the use of fences can easily resolve this conflict.

Among the articles identified in the review, three studies assessed an area with a history of cattle grazing, in which seedlings of native species were planted for restoration purposes. Ten years after planting, the vegetation in the area was evaluated, addressing different aspects of planting and natural regeneration (Rosenfield & Müller 2017, 2019, Da Fonseca et al. 2017). Although the regeneration of the areas was observed, the results indicated that the forests in the restoration process had not yet fully achieved the structure and functionality of the reference ecosystems. While natural regeneration proves to be a practice with more positive long-term results and lower application costs (Crouzeilles et al. 2020), severely degraded areas often require species introduction.

However, seedling planting is limited by high costs, and on the long-term, seedling introduction may interfere with the desired trajectory of restoration when compared

to a reference area (Rosenfield & Müller 2017). Nucleation (i.e. planting of seedlings only in parts of the degraded area) aims to recreate micro-habitats to facilitate ecological succession, i.e. natural recovery processes (Piaia et al. 2020). The studies by Piaia et al. (2020) and Procknow et al. (2020, 2023) assessed the same areas undergoing restoration, monitoring various indicators that revealed that, although both restoration through regeneration and nucleation are gradual processes, nucleation proved to be a more effective method for forest restoration. However, similar to grasslands, the availability of seedlings and seeds can also be a limitation in the Pampa, which does not have sufficient forest nurseries to meet restoration demands (Moreira et al. 2016). More research on seed quality, appropriate timing of seeding and optimal seeding density and depth were pointed out as necessary in a study involving direct seeding (Gazzola et al. 2023). Two studies tested practices involving the creation of habitat for fauna (transposition of woody debris; Toso et al. 2020) and the improvement of soil conditions (use of bioremediation for soil decontamination; De Souza Pohren et al. 2016), both with positive results. However, the studies had a very local focus, impeding generalizations, and the efficiency of the techniques needs to be evaluated within the restoration process as a whole. We can conclude that, despite the positive results found in the recovered articles, research on forest restoration in the Pampa still is very incipient.

Future directions

While there are initiatives for the restoration of grasslands and forests in the Pampa region conducted by universities, research institutions, companies, and private organizations, our review revealed that only a few of them lead to scientific publications available in widely used databases, such as Web of Science and Scielo. Certainly, more information is available in so-called 'gray literature', including in academic works or in publication series e.g. of Brazilian Agricultural Research Corporation Embrapa (Guarino et al. 2018), but these may not have passed through the scrutiny of peer review. The lack of scientific studies slows down the development of validated restoration protocols, and thus has direct impacts on restoration practice. This is especially evident in the case of species introduction for restoration of grasslands which, in practice, still does not include native species; it is hard to imagine that use of native species will become more common without scientific studies that show the viability of their use, and how they best be introduced.

The Pampa has seen several large projects aimed at understanding the diversity ecosystems that make up the region, some of them still ongoing. Important examples include the RS Biodiversity Project (2011 to 2016), the Long-Term Ecological Research Network in the grassland of the Pampa and Atlantic Forest biomes (PELD Campos Sulinos, initiated in 2010 and ongoing, e.g. Ferreira et al. 2020), and the PPBio Campos Sulinos network (Menezes et al. 2022; ongoing). While these projects did not focus on restoration-related questions, they do provide important baseline data for restoration, i.e., contribute for the definition of reference areas for restoration (Menezes et al. 2022). Since 2018, a major restoration effort has been taking place in the Pampa through the Strategic Project for the Conservation, Restoration, and Management of Caatinga, Pampa, and Pantanal Biodiversity – GEF Terrestrial, a project of the Brazilian Federal Government aimed at promoting the conservation of Caatinga, Pampa, and Pantanal biodiversity. In the Pampa, four projects are being carried out under GEF Terrestrial (see Pro-Apa Sustentável, Restaurapa, Restaurapampa, and

Rota dos Butiazais, see link https://l1nq.com/TASsS), totaling over 3.300 hectares managed for the conservation and restoration of the Pampa. These initiatives involve research institutions, extension services, public managers, and rural producers and will, besides initiating restoration processes, also generate important data for conservation of the Pampa. They represent applied restoration experiences on a scale that had not been worked on so far, but also suffer from the limitations in terms of available knowledge on best techniques and seed material that were discussed above. However, in all of them is, besides participation of extension and conservation specialists, active participation from research institutions, and experimentation with new or little tested techniques is part of these projects, so that we can expect advances in studies on the restoration of the Brazilian Pampa. Nonetheless, restoration initiatives in the Pampa still do not keep pace with the conversion of natural areas in the region (see e.g., Overbeck et al. 2015, Porto et al. 2021), and the recent climatic extreme events that affected 6.7% of the Pampa region are indicative of the rising demand in restoration due to climate change (MapBiomas Project 2022). This reinforces the urgent need for more research and experimentation with restoration techniques, from the control of exotic species to plant introduction and to restoration management. Ideally, these activities should be conducted in network of collaboration and knowledge exchange with researchers and institutions within the region and from other regions of Brazil and around the world, especially those facing similar challenges in the restoration of non-forest environments. The recently founded 'Rede Sul de Restauração Ecológica' (see link https://acesse.one/oWyUn) is an important step towards more involvement of different sectors of society and towards the development of partnerships and integrated efforts that are essential for success in Pampa restoration and conservation. Importantly, the necessary research activities also need funding: given the urgency and importance of the topic, specific calls by funding agencies seem important. If the ambitious aims of the PLANAVEG for the Pampa are to be met by 2030, we clearly need to gain speed not only in restoration practice, but also in the research that is needed to support it.

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THAIS MICHEL
https://orcid.org/0000-0002-4344-1135

GERHARD OVERBECK
https://orcid.org/0000-0002-8716-5136

Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Ecologia, Av. Bento Gonçalves, 9500, 91501-970 Porto Alegre, RS, Brazil

Correspondence to: **Thais Michel**
E-mail: thais.michel@ufrgs.br

Author contributions

GERHARD OVERBECK contributed to conception of the study. THAIS MICHEL contributed to the conception of the study, collected and analyzed data and led writing of the manuscript. Both authors reviewed the manuscript.