Programa de Pós-Graduação em Ecologia, Conservação
e Manejo da Vida Silvestre
Instituto de Ciências Biológicas
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RESTORATION PRACTICES AND STUDIES IN THE BRAZILIAN CERRADO

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Dissertação apresentada ao Programa de Pós-graduação em Ecologia, Conservação e Manejo da Vida Silvestre, do Instituto de Ciências Biológicas da Universidade Federal de Minas Gerais, como requisito para obtenção do título de Mestre.

Orientador: Prof. Dr. Ricardo Ribeiro de Castro Solar

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ABSTRACT

Ecological restoration is a key process to avoid further degradation and biodiversity loss of degraded ecosystem. However, multiple interests should be matched to achieve ecological restoration, and solid ecological knowledge can play a significant role in ensuring efficient use of natural and financial resources. Different ecosystems usually demand distinct restoration approaches and interventions due to their specific resilience and resistance capacities. Thus, the understanding of how ecosystems react to multiple sources of disturbances may enhance our ability to carry-out suitable restoration actions. The Cerrado hotspot is a Brazilian phytogeographic domain dominated by savannas, which is seriously threatened by anthropogenic disturbances. We conducted a comprehensive systematic review to assess if we have accumulated sufficient ecological knowledge that could ensure proper restoration practices for all different ecosystems of the Cerrado. We found that the current ecological knowledge is minimal and argue that it is insufficient to guarantee the success of large-scale restoration efforts. First, most of Cerrado restoration studies focused primarily in two Cerrado vegetation types, *cerrado sensu stricto* (typical savannah) and riparian forest. Besides, as in many other fields, we found that studies lack a standardized and systematic evaluation of restoration outcomes. We also found a high degree of negligence in selection of plant species for restoration programs, which mostly disregards their original occurrence and proportion of plant growth forms. In this context, we advocate for improvement of ecological knowledge to assist the successful restoration of the Cerrado. Therefore, we encourage investigations on ecological dynamics and natural regeneration of the different vegetation types of the Cerrado as well as the standardization of research based on a scientific approach. We also strengthen that Cerrado restoration research and project efforts need to explicitly define the reference ecosystem and use its structure and composition as guidance for ecological restoration. To improve the effectiveness of ecological restoration efforts in the Cerrado and ensure its conservation we need to advance the ecological knowledge about this phytogeographic domain.

Key-words: Cerrado hotspot, Brazilian savanna, ecological restoration

RESUMO

A restauração ecológica é um processo fundamental para evitar futuras degradações e perda de biodiversidade. No entanto, interesses múltiplos devem ser combinados para se atingir a restauração ecológica, e um conhecimento ecológico pode ser significativo na garantia do uso eficiente de recursos naturais e financeiros. Ecossistemas diferentes geralmente demandam distintas abordagens de restauração e intervenção, devido à especificidade de suas capacidades de resistência e resiliência. Portanto, entender como os ecossistemas mudam em função de múltiplas fontes de distúrbios pode aumentar nossa habilidade de aplicar ações adequadas. O *Hotspot* Cerrado é um domínio fitogeográfico brasileiro dominado por savanas, o qual já é ameaçado por distúrbios antrópicos. Nós realizamos uma revisão sistemática abrangente para avaliar se o conhecimento ecológico que nós acumulamos é suficiente para assegurar práticas de restauração adequadas a todos os tipos de vegetação do Cerrado. Descobrimos que o conhecimento ecológico atual é mínimo e insuficiente para garantir o sucesso dos esforços de restauração em larga escala. Primeiro, a maioria dos estudos de restauração do Cerrado focou principalmente em dois tipos de vegetação do Cerrado *cerrado sensu stricto* (cerrado típico) e mata ripária. Além disso, como em muitas outras áreas de estudo, descobrimos que os estudos não avaliam os resultados da restauração de forma padronizada e sistemática. Nós também encontramos um elevado grau de negligência em relação à forma pela qual as espécies de planta têm sido usadas, desconsiderando sua ocorrência original e a proporção de formas de vida das plantas. Nesse contexto, nós sugerimos que a melhoria do conhecimento ecológico é necessária para auxiliar o sucesso dos esforços de restauração do Cerrado. Por isso, encorajamos investigações sobre dinâmica ecológica e regeneração natural dos diferentes tipos de vegetação do Cerrado bem como a padronização de pesquisas baseadas em uma abordagem científica. Nós também reforçamos que os esforços de pesquisa e projetos de restauração do Cerrado precisam explicitar o ecossistema de referência e usar sua estrutura e composição como guia para a restauração ecológica. Para melhorar a eficácia dos esforços de restauração ecológica do Cerrado e garantir sua conservação, precisamos avançar o conhecimento ecológico sobre este domínio fitogeográfico.

Palavras-chave: Cerrado *hotspot*, savana brasileira, restauração ecológica

1. Introduction

The current expansion of human activities has led to unprecedented conversion, degradation and fragmentation of native ecosystems[1,2] with dreadful consequences to biodiversity and ecosystem functions worldwide[3–5]. As a response, conservation initiatives aiming to maintain native vegetation have been increasingly fostered throughout the globe, but it is disputable if they will be enough and in time[6]. The ramping rates of degradation and fragmentation require multiple actions to fully conserve biodiversity and ecosystems, including ecological restoration of degraded ecosystems[7]. Nevertheless, the practice of ecological restoration is hindered by several issues such as the need to integrate political incentives, society engagement, cost-effective techniques, and ecological knowledge[8–10]. Besides the challenge to conciliate the interests of different stakeholders, the low predictability of successional trajectories[11] turns ecological restoration into a much more complex challenge. To face such challenge, restoration practitioners and policy-makers can take advantage of ecological theoretical underpinnings in order to better guide restoration practice, enhancing its effectiveness and moving it from trial-and-error to a science-based approach.

Solid ecological knowledge at different temporal and spatial scales is important for efficient use of natural resources and financial support to ensure a well-planned restoration[12,13]. Moreover, restoration actions must be guided towards a previously established reference ecosystem, which is usually represented by a non-degraded version of the target ecosystem. Appropriate restoration actions should consider the structure and composition of the reference ecosystem, as well as the degradation level of the ecosystem to be restored[8]. Diverse drivers and threats can lead to reductions in the ability of ecosystems recover from natural and anthropogenic disturbance resulting in different levels of degradation[8]. The degree to which ecosystems change due to disturbances is related to their resistance (ability to tolerate or adapt during the disturbance) and resilience (ability to recover after softening the disturbance) capacities[15]. These capacities should be variable among ecosystems with different characteristics and evolutionary histories. In this context, each type of ecosystem requires specific restoration approaches and interventions. Therefore, understanding the resistance and resilience capacities of the target ecosystem can help guide restoration in a more sustainable way, diminishing or eliminating the need for active interventions in cases when these capacities are high[16].

The restoration of many ecosystems, for example grasslands and savannas, has been a challenge since most of the past restoration efforts were focused on forests[17]. Furthermore, some practices commonly used to reverse forest ecosystem degradation could not be directly applied to other ecosystems as they can jeopardize their biodiversity and ecosystem functioning[18,19]. One of these widely applied, yet inappropriate practice is planting trees in ecosystems that have originally-open vegetation[20]. Such practice, known as afforestation, can lead to the loss of grassland species because of different ecosystem functioning and both direct and indirect species interference (i.e.[20,21]). Moreover, the use of exotic species has also been extensively applied although it can change native community composition and ecosystem dynamics[18,22]. Hence, it is urgently necessary to design appropriate conservation and restoration solutions that are specific to each ecosystem type[21].

The Cerrado, in Brazil, is a phytogeographic domain that includes a variety of ecosystems such as savannas, seasonally dry tropical forests and grasslands[23]. Because savanna formations are the dominant vegetation type, the Cerrado is widely known as the 'Brazilian savanna'. The Cerrado hosts more than 300,000 animal species and 13,000 plant species[24], with many endemic species (ie. 44% of plant species are endemic to the Cerrado)[25] Moreover, it has lost almost half of its native vegetation cover, being considered a biodiversity hotspot[25,26]. The loss of vegetation cover is expected to increase because Cerrado is located in the core of one of the most active agricultural boundaries and the Brazilian federal government has encouraged agricultural expansion as a way to economic development[27,28]. Furthermore, even if Brazil's Forest Code laws are properly enforced, a potential legal loss of native habitats is expected to occur resulting in unprecedented species extinction crises. It can also cause a water supply crisis since more than 70% of intermittent springs are in areas that could be cleared[28]. Preventing the loss of biodiversity and ecosystem services in the Cerrado are not an easy task but restoration incentives are key to achieving it.

The success of restoration initiatives in the Cerrado will eventually depend upon our ability to efficiently and effectively implement ecological restoration programs[8,13]. Therefore, it is imperative to know if the knowledge that we possess can actually promote ecological restoration in face of the political, social, and economic issues. Considering a hypothetical scenario in which we have appropriate restoration investment, we are asking: with the current ecological knowledge accumulated, are we able to inform proper restoration practices to the Cerrado? We aimed to respond to this question through a comprehensive systematic review of restoration studies among all Cerrado

vegetation types. In our review, we assume that restoration initiatives and management strategies must differ among different ecosystems because of their specific ecological features and functioning. Our purpose is to draw a panorama of how Cerrado have been restorated by summarizing what is known from previous studies and then provide some recommendations for future research and restoration practice. Specifically, we will address the following questions: (a) how restoration practices and studies have been done in the Cerrado? (b) are the identity and growth forms of plant species taken into consideration in the ecological restoration of the Cerrado?

2. Methods

2.1 Definitions

Here, we adopted "restoration" to refer to the restoration field of study as a whole and tried to cover all studies that aimed to recover a degraded, damaged or destroyed ecosystem by improving its state and/or functionality[8]. Furthermore, we assumed that "ecological restoration" occurs only when a degraded ecosystem has assistance to recover aiming to reestablish the native ecosystem[8]. The "natural regeneration approach" takes place when causal factors of degradation are removed, and plant individuals increase without direct intervention through seeding or planting. On the other hand, if ecological restoration depends upon active intervention (i.e., control of exotic species, reintroductions, habitat conditioning, reapplying ecological disturbance regimes), we classified it as an "assisted regeneration approach" [8]. Different ecological restoration approaches can be adopted upon the ecosystem degradation level and its resilience capacity[29]. Hence, studies of recovery, rehabilitation, recomposition, revegetation or reforestation were considered as ecological restoration projects if their main goal was the reestablishment of the native ecosystem[8].

In this review, Cerrado was considered the phytogeographic domain that includes a wide range of vegetation types following Ribeiro & Walter[23] classification. The dominant vegetation of Cerrado was considered as old-growth savanna[30] comprising a gradient of tree cover density from open grasslands to dense woodlands: *campo limpo* (grassland predominance without trees), *campo sujo* (grassland with a few shrubs and small trees), *campo cerrado* (tree cover of 5-20% with average tree height of 2-4m that do not form a continuous canopy), *cerrado sensu stricto* (tree cover of 20-50% with average tree height of 3-6m that do not form a continuous canopy) and *cerradão* (tree

cover of 50-90% with average tree height of 8-15m). When the studies mentioned only "Cerrado" we classified it as *cerrado sensu lato* as it usually comprises all types of old-growth savanna vegetation. Moreover, we also considered other vegetation types as part of the Cerrado phytogeographic domain: riparian forests, *vereda*, seasonally dry forest, semideciduous tropical forest, rupestrian grasslands, ironstone outcrops and transitional vegetation found between Cerrado and other domains. Riparian forests are forested vegetation found alongside streams and rivers (tree cover of 50-95% with average tree height of 20-30m), and *vereda* are valley-side marshes. Seasonally dry forests (or *mata seca* – tree cover of 50-95% (rarely less than that) with average tree height of 15-25m) are forested formations associated to fertile soils while semideciduous tropical forest (or *floresta estacional semidecidual*) are forested formations associated to more humid areas. Finally, the rupestrian grasslands (or *campo rupestre*) are grassland vegetation with few shrubs and small trees that are associated to quartzite soils, and ironstone outcrops (or *canga*) that are associated to ferruginous soils.

2.2 Literature review

To compile the state of art of restoration in the Cerrado, we performed a systematic review that considered all experimental and observational studies published on the subject from 1945 to 2017. We selected journal articles, theses and dissertations in English and Portuguese languages that comprised relevant and applied information on the restoration of any of the Cerrado vegetation types. We used different databases to include all the available literature about the subject: a worldwide database (Web of Science), a Latin database (Scielo) and the Brazilian theses and dissertation bank of CAPES. To do the search, we selected three groups of keywords (Figure 1) and used combinations of keywords in the following way: we selected and fixed one keyword from each of two groups, while we changed the keyword from the third group until we reached all possible permutations (i.e. savanna AND restoration AND environmental; savanna AND restoration AND degraded area; savanna AND restoration AND ecological; savanna AND restoration AND ecology).

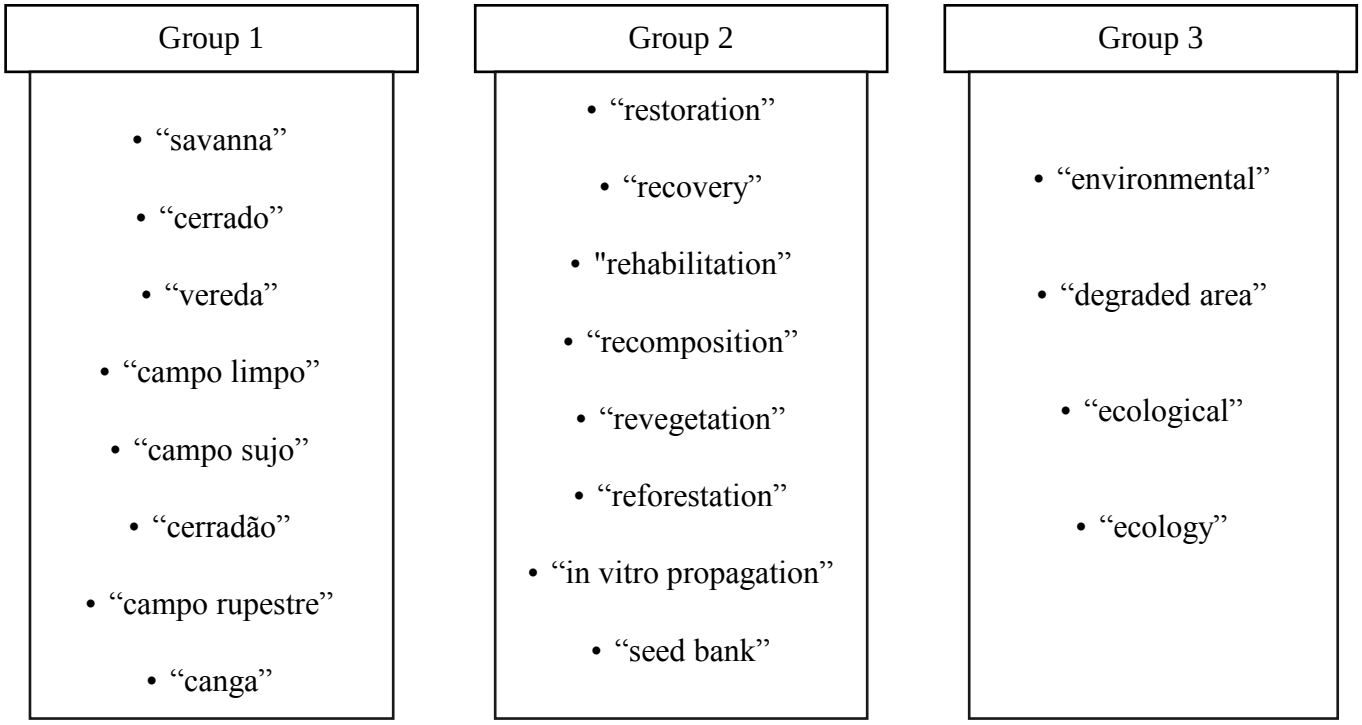

FIGURE1. GROUPS OF KEYWORDS USED TO DO THE SYSTEMATIC SEARCHES. WE USED DIFFERENT COMBINATIONS OF WORDS FROM EACH GROUP UNTIL WE REACH ALL POSSIBLE PERMUTATIONS.

We submitted all publications found in our searches to a first screening that examined the title and abstract. Then, we conducted the selected publications to a second screening carefully analyzing their integral text. We excluded publications that (i) did not have information about the vegetation of the study area; (ii) did not study any vegetation that belong to the Cerrado; (iii) did not have focus and conclusions on recovering a degraded ecosystem within the “restoration” definition adopted here (see section 2.1); (iv) did not have the full text available. From each of the remaining publications, we extracted information on the publication accessibility and on the research characteristics (Table 1). The publication accessibility is important for exchanging information as well as including the Cerrado in the international panorama of savannas. Moreover, we want to understand where and which kind of vegetation type have been restored, and to verify how research have been done considering the evaluation of outcomes and the reliability of the results (ie. how results have been analyzed).

TABLE1. INFORMATION EXTRACTED FROM THE SELECTED PUBLICATIONS

Information assessed	Description
Publication accessibility	The type of publication (journal article or dissertation/thesis), language used (English or Portuguese) and the article's Journal
Geographical location	Where the research was conducted (coordinates)
Native vegetation type	The native Cerrado vegetation type that previously occurred in the degraded studied area (see section 2.1)
Land use	The previous land use type of the area on restoration (agriculture, abandoned pasture, mining, etc.)
Monitoring activity	If the research had any monitoring activity and how frequently it was done
Analysis	If the study used any statistical analysis (frequentist, index, modelling) or not (descriptive or review)
Restoration objective/perspective	If the research had a "ecological restoration" (see section 2.1) objective, or perspective, or if it did not intend to recover the native ecosystem
Restoration approach	The restoration approach (see section 2.1) used on the publications that had a "ecological restoration" objective or perspective

2.3 Plants Database

We created a database for the plant species used in the selected publications in order to know what plant species have been used to restore the Cerrado. We recorded all plant species used as reference or in restoration. Hence, we considered only plant species that for some reason have been chosen to inform recovery progress or to improve the ecosystem recovery and did not consider plant species found at floristic surveys. Then, we obtained complementary information for the plant species from Reflora virtual herbarium[31,32]: family, growth form (or habit), occurrence and if the plant was native or exotic to the Cerrado.

2.4 Data analysis

2.4.1 The practices and studies in the Cerrado

We used publication quantity to evaluate information accessibility and analysis used, as well as to categorize the study objective/perspective and the restoration approach adopted in cases of studies that aimed to ecological restoration. The other analysis were done considering the research effort rather than publication quantity since some publications evaluated more than one restoration practice (ie. used more than one technique, did more than one type of monitoring). We used 'ggplot2' package of R software 3.5.0 [33] to make bar-plot graphs and present the characteristics of the research: the monitoring activity (periodical measurements of indicators); the native vegetation type, and the previous land use of the study area; and the analysis used. The geographical location of the studies was used to generate a heatmap to show where the majority of the studies about Cerrado restoration were done.

2.4.2 The plant species used in ecological restoration of Cerrado vegetation types

We used the information from plants database to build a multilayer and a weighted networks, using Pajek®. The multilayer networks are formed by coexisting and interacting networks in which links represent different relations/interactions in each network. The weighted networks are formed by links with weights that represent their strength. We built the networks to evaluate whether identity and growth forms of plant species were taken into consideration in the ecological restoration of the Cerrado ecological restoration. For this, we conducted a further screening on the selected publications that had an ecological restoration objective or perspective (see section 2.1). We considered the research effort rather than publication quantity and selected only research that were done in the field and used some plant species as a reference or research object (Figure 2). We also excluded from the network analysis plant species with incomplete information or lacking species identification on the plant database that we used.

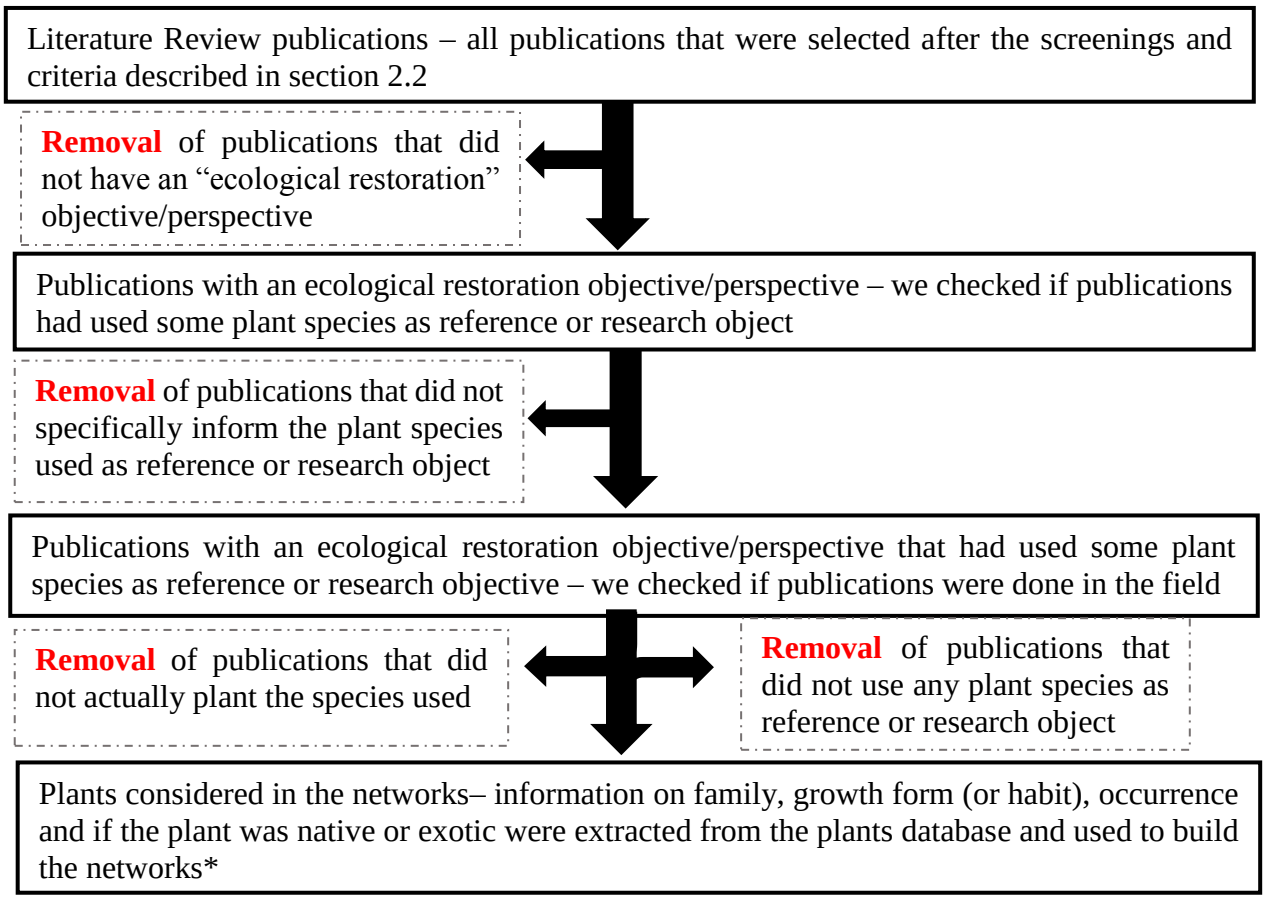

FIGURE 2. STEPS OF THE SELECTION OF THE PLANT SPECIES CONSIDERED FOR THE EVALUATION OF HOW PLANT SPECIES HAVE BEEN USED FOR ECOLOGICAL RESTORATION IN THE CERRADO

*ONE PUBLICATION ABOUT INVASIVE SPECIES CONTROL WAS EXCLUDED IN THE END OF THE EXCLUSION PROCESS

We built the weighted network to visualize whether the proportion of growth forms used in the restoration of a certain vegetation type corresponded to its original proportion (according to Ribeiro & Walter [23] definitions) and whether most of the plant species used were native from the Cerrado. We organized data as an adjacency matrix, with plant species growth forms listed as rows and Cerrado vegetation types listed as columns. We filled each cell with the number of plant species of growth form *i* used to restore vegetation type *j*. Therefore, the matrix was weighted with frequencies of plant species in each kind of growth form that was used to restore each vegetation type.

We used a multilayer network to visualize if a given plant species was used to restore its original vegetation type (correct use). To determine this, we considered the species occurrence[30,31] and the vegetation type indicated in the studies (we assumed that they were the reference ecosystem)

of the plant species most commonly used to restore the Cerrado. The multilayer network was composed by two layers (subnetworks): one layer connected plant species that were correctly used to restore the Cerrado and the other layer connected plant species wrongly used, which means that these plant species were used to restore vegetation types that they are not originally from. We organized the datasets for each of the subnetworks as adjacency matrices, with plant species listed in the rows and Cerrado vegetation types in the columns. Each cell was filled with '1' if plant species *i* was used to restore vegetation type *j*.

3. Results

3.1 The practices and studies in the Cerrado

We selected a total of 154 publications to assess the Cerrado restoration panorama along the 42 years (see Appendix 1). The majority of the selected publications were in Portuguese (63%) while 34% of the publications were in English and only 3% were in both languages (theses or dissertations with Portuguese and English chapters). We also found a great proportion of dissertations and theses (42%) and most of the selected journal articles have been published in Brazilian journals (64%). Over the years, the number of publications in peer-reviewed as well as in international journals has been increasing (Figure 3).

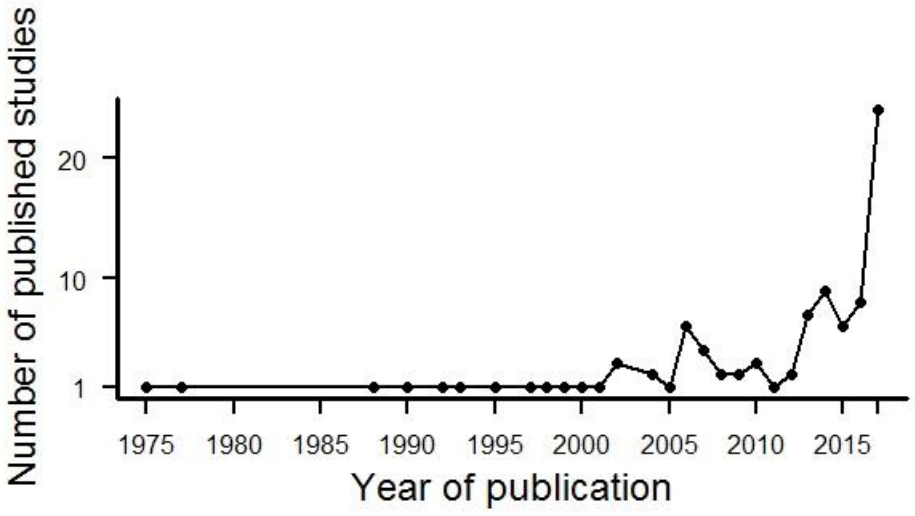

FIGURE 3. NUMBER OF PUBLICATIONS ON RESTORATION OF THE CERRADO IN PEER REVIEWED JOURNALS FROM 1975 TO 2017

We found that research efforts were highly concentrated in the Federal District and in specific locations of the states of Goiás, São Paulo and Minas Gerais, while just a few research had been developed in other states (Figure 4). There was also a predominance of research efforts around few research groups from some public institutions such as the Universidade de Brasília (UnB), Universidade Estatual Júlio Mesquita (Unesp - Assis), Universidade Estadual de Campinas (Unicamp) and Escola Superior de Agricultura Luiz de Queiroz (ESALQ-USP). However, some publications were not shown in the map (Figure 4): two publications that focused on the Cerrado as a whole; six publications that focused on restoration of native ecosystems of Brazil; and three publications conducted in Bacia do Rio Paranã (Goiás and Tocantins states) that did not provide the specific geographic location. Furthermore, most of the research efforts had an ecological restoration goal (only 26% of publications had a different goal such as rehabilitation of degraded pastures to keep agribusiness activities) with the assisted regeneration approach being more common (77%) than the natural regeneration approach (23%).

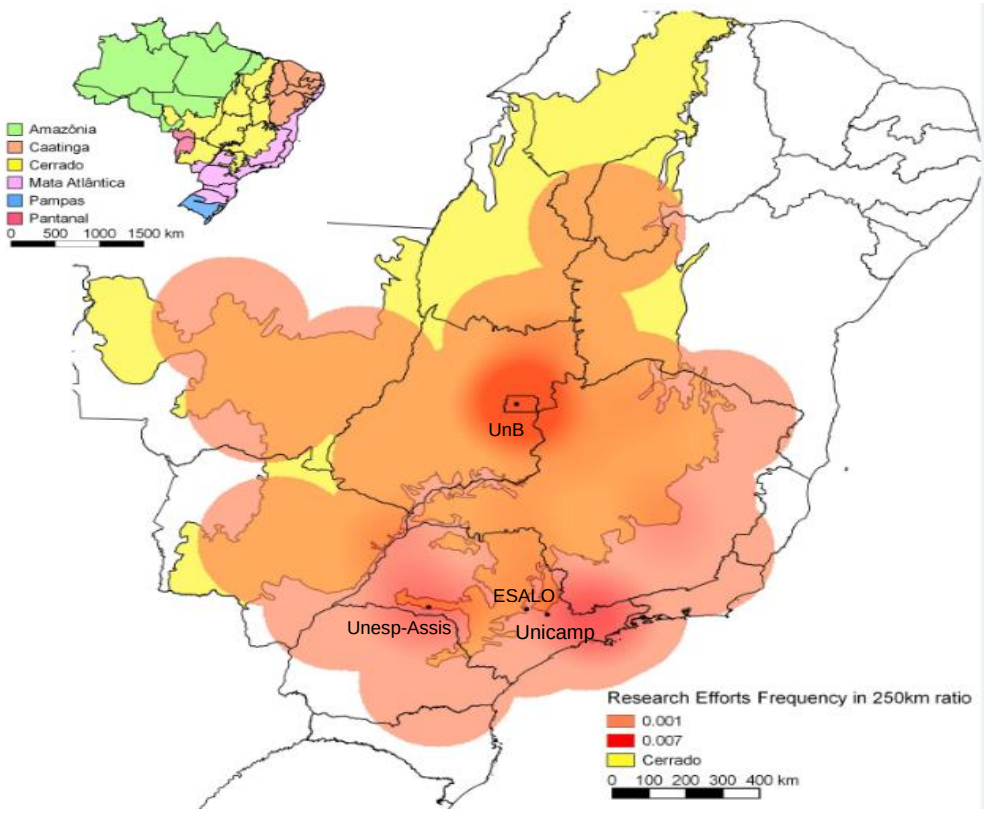

FIGURE 4. THE CONCENTRATION OF RESEARCH EFFORTS OF CERRADO RESTORATION REPRESENTED IN A KERNEL MAP. THE INTENSITY OF RED CIRCLES INCREASES AS THE NUMBER OF

RESEARCH EFFORTS INCREASE. SOME RESEARCH GROUPS OF PUBLIC UNIVERSITIES ARE POINTED: UNIVERSIDADE DE BRASÍLIA (UNB), UNIVERSIDADE ESTATUAL JÚLIO MESQUITA (UNESP - ASSIS), UNIVERSIDADE ESTADUAL DE CAMPINAS (UNICAMP) AND ESCOLA SUPERIOR DE AGRICULTURA LUIZ DE QUEIROZ (ESALQ-USP).

We evaluated the monitoring activity of the selected publications and found that 44% did not do monitoring or it was not applied to them (theoretical research). Even though most publications had presented some monitoring activity we did not find any monitoring pattern (Figure 5) and 3% of the research did not inform the periodicity of monitoring. Moreover, we also found that most publications had used some statistical analysis while 10% of them were descriptive and 5% were reviews. The most common type of statistical analysis used was frequentist and the less used was modelling (5%), as shown in Figure 6. There were two publications that used map overlay and were not considered as statistical analysis, descriptive or review[34,35].

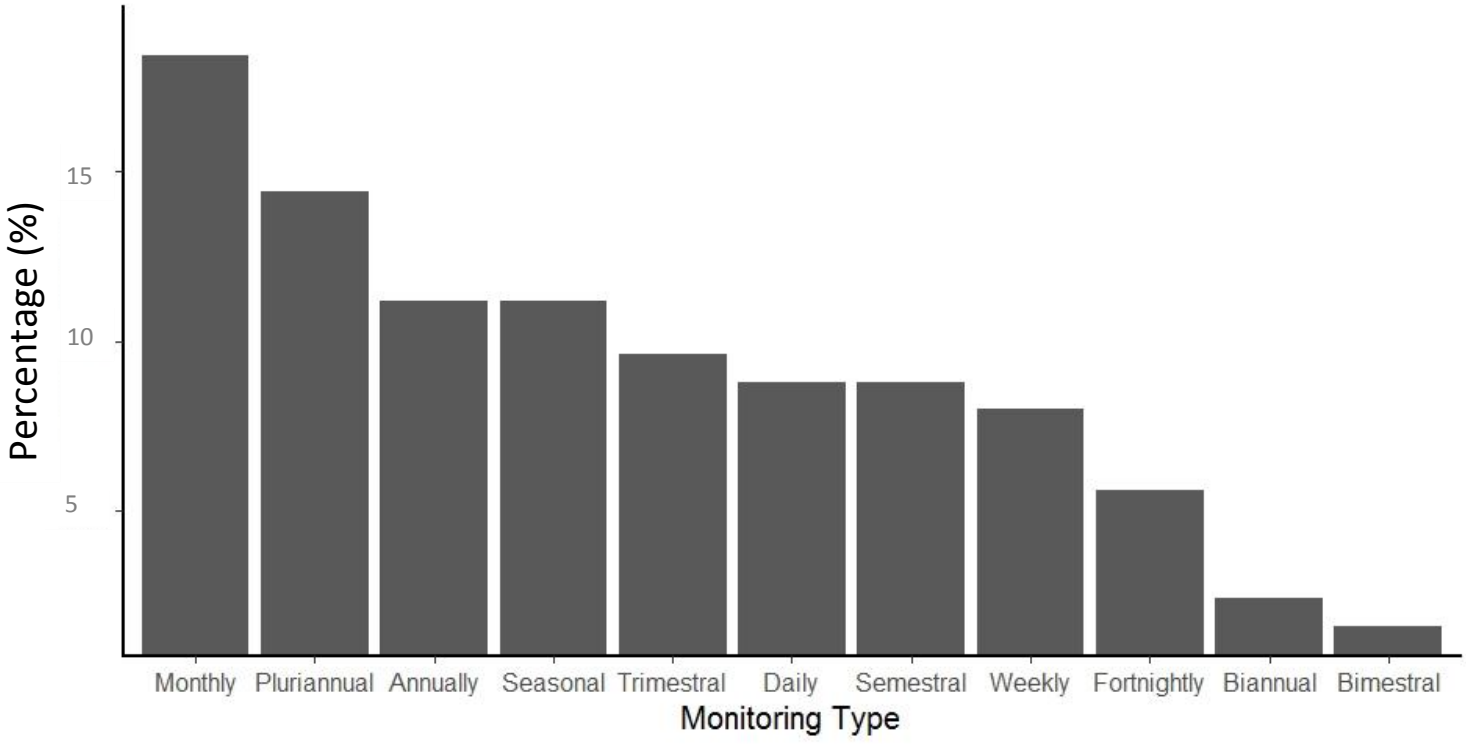

FIGURE 5. THE PROPORTION OF MONITORING ACTIVITY, OR PERIODICAL MEASUREMENTS OF INDICATORS, IN RESEARCH EFFORTS OF RESTORATION OF THE CERRADO

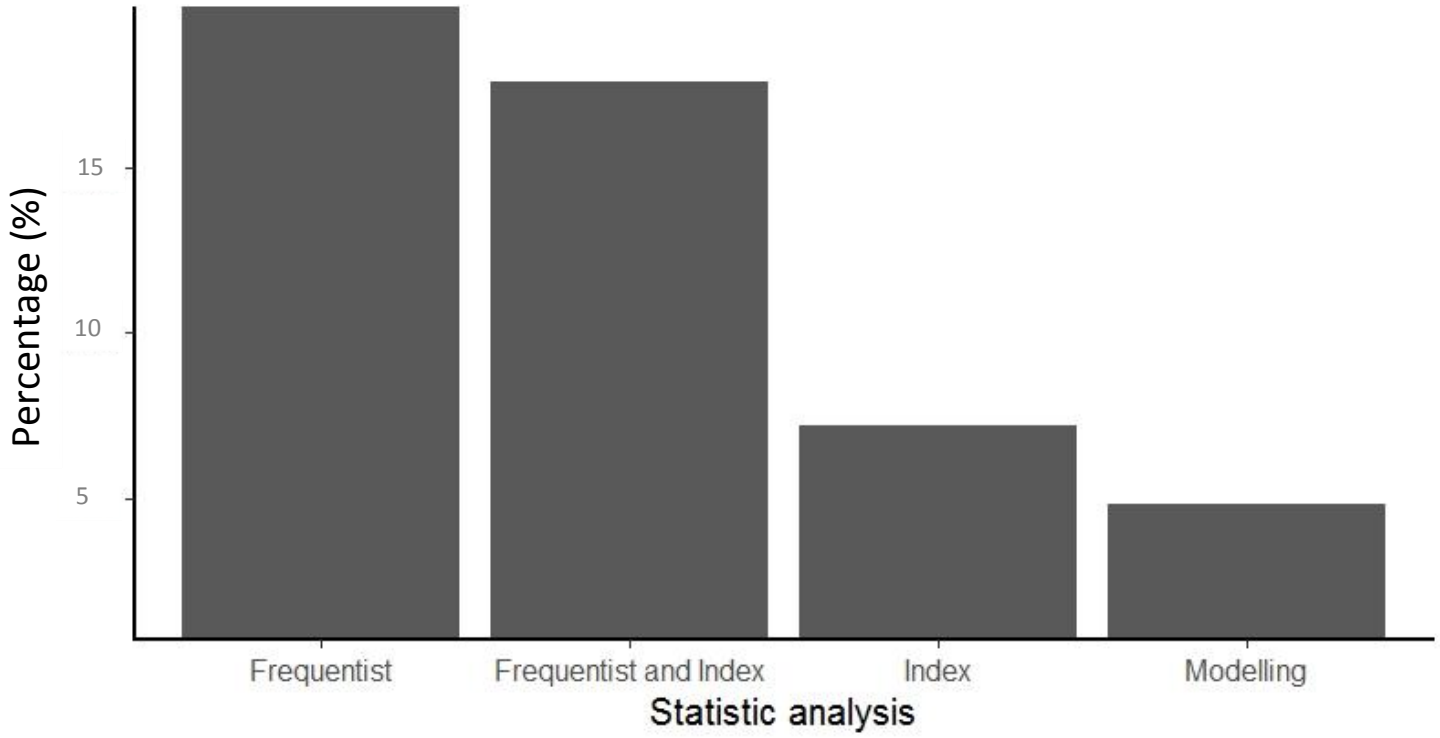

FIGURE 6. THE PROPORTION OF STATISTIC APPROACHES IN RESTORATION RESEARCHES OF THE CERRADO

We found that many vegetation types were relatively underrepresented in restoration research efforts reported in the literature with the exceptions of riparian forest and *cerrado sensu stricto* (Figure 7). *Campo limpo* did not even appear in any research while much of the research did not specify which vegetation type was going to be restored making *cerrado sensu lato* the most common vegetation type. Furthermore, some research had a focus in Brazil or in Cerrado as a whole (2%). The main previous land use of areas under restoration were pasture and agriculture (Figure 8). We could not find information about the previously land use for 13% of the studies. Additionally, we did not apply 'land use' categorization for 14% of the studies as they were theoretical.

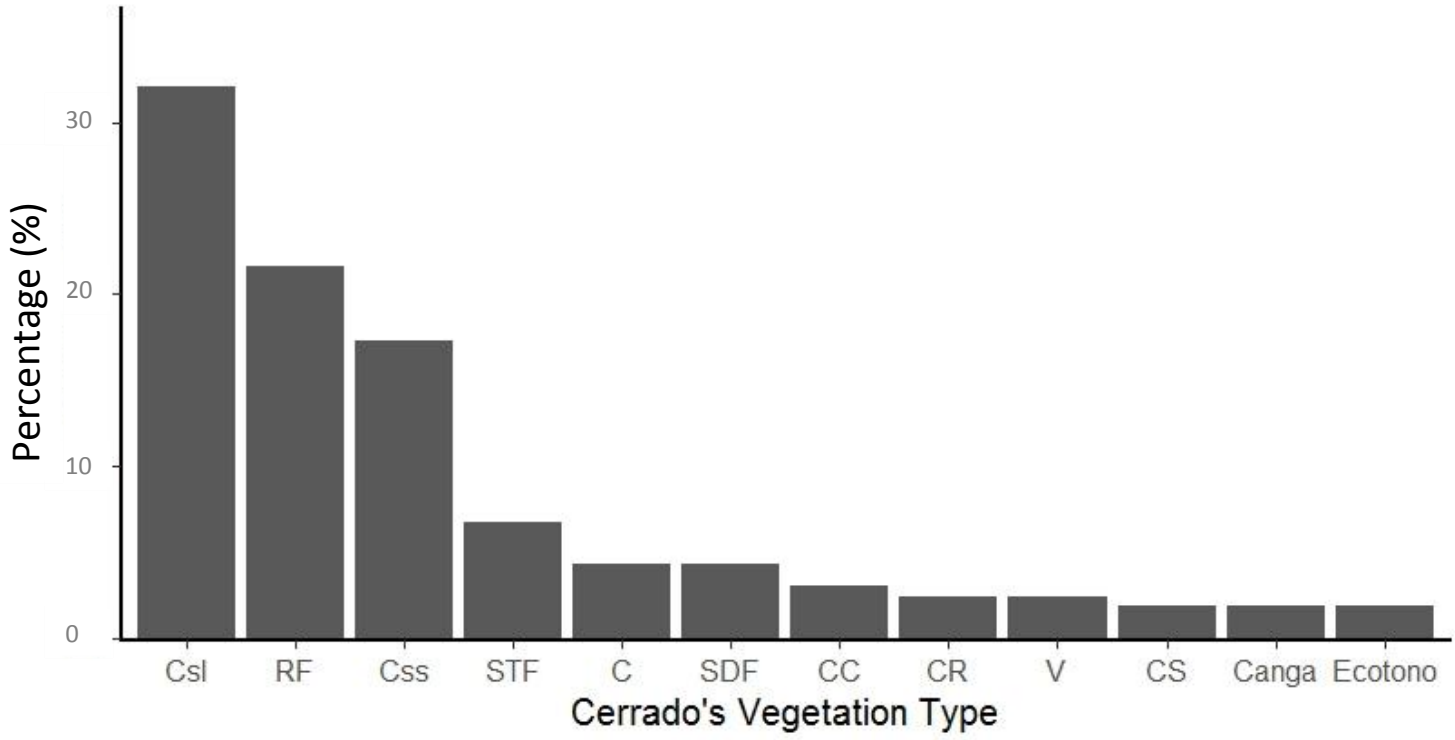

FIGURE 7. THE PROPORTION OF VEGETATION TYPES CONSIDERED AS REFERENCE ECOSYSTEM* FOR RESTORATION OF THE CERRADO: CERRADO SENSU LATO (CSL), RIPARIAN FOREST (RF), CERRADO SENSU STRICTO (CSS), SEMIDECIDUOUS TROPICAL FOREST (STF), CERRADÃO (C), SEASONALLY DRY FOREST (SDF), CAMPO CERRADO (CC), CAMPO RUPESTRE (CR), VEREDA (V), CAMPO SUJO (CS), CANGA AND ECÓTONO CERRADO-MATA ATLÂNTICA (ECÓTONO).

***WE CONSIDERED THE VEGETATION TYPE MENTIONED BY THE PUBLISHED STUDY AS THE REFERENCE ECOSYSTEM, EVEN THOUGH THEY DID NOT MENTIONED IT CLEARLY**

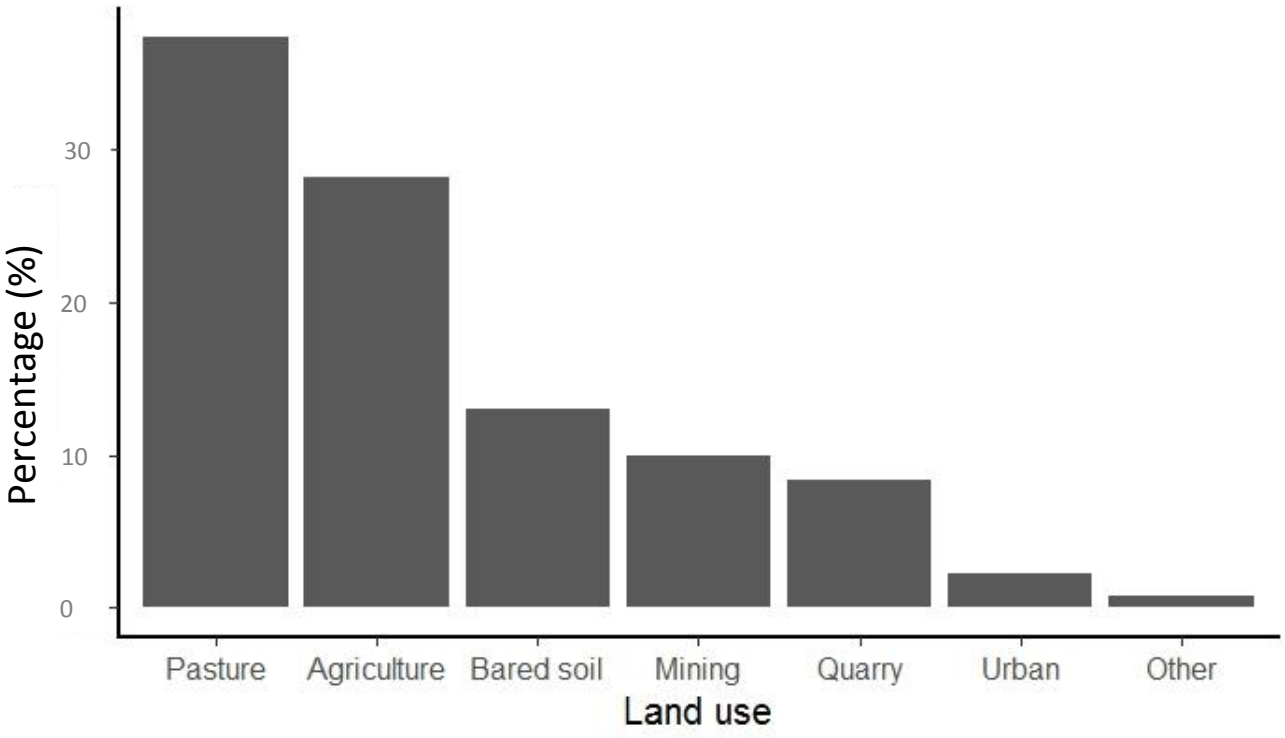

FIGURE 8. PROPORTION OF PREVIOUSLY LAND USE OF RESTORATION AREAS OF THE CERRADO. WE CLASSIFIED ONLY ONE STUDY AS 'OTHER' BECAUSE IT STUDIED CONTAMINATED LAND[36].

3.2 The plant species used in ecological restoration of Cerrado vegetation types

We found a diversity of 510 plant species that have been used for ecological restoration of the Cerrado and most of them were native (7.3% exotic and 6.5% could not be classified) to the phytogeographic domain. We found that only riparian forest has been restored using a relatively great proportion of exotic tree species (Figure 9). Moreover, only 198 plant species have been used in more than one research or restoration project; 60% of them were trees (111 plants) and 24% could have a tree or shrub growth form (45 plants). We also found that the concern about the proportion of growth forms used for ecological restoration varies according to Cerrado vegetation types (Figure 9). For instance, at "cerradão" (a forest formation) herbaceous plant species reached a proportion that did not match the original characteristic of this vegetation [type23]. Nevertheless, some vegetation originally characterized by the tree (semideciduous tropical forest, riparian forest and seasonally dry forest) or ground layer dominance (*campo rupestre* and *campo-cerrado*) were mainly restored by trees or herbaceous plants, respectively.

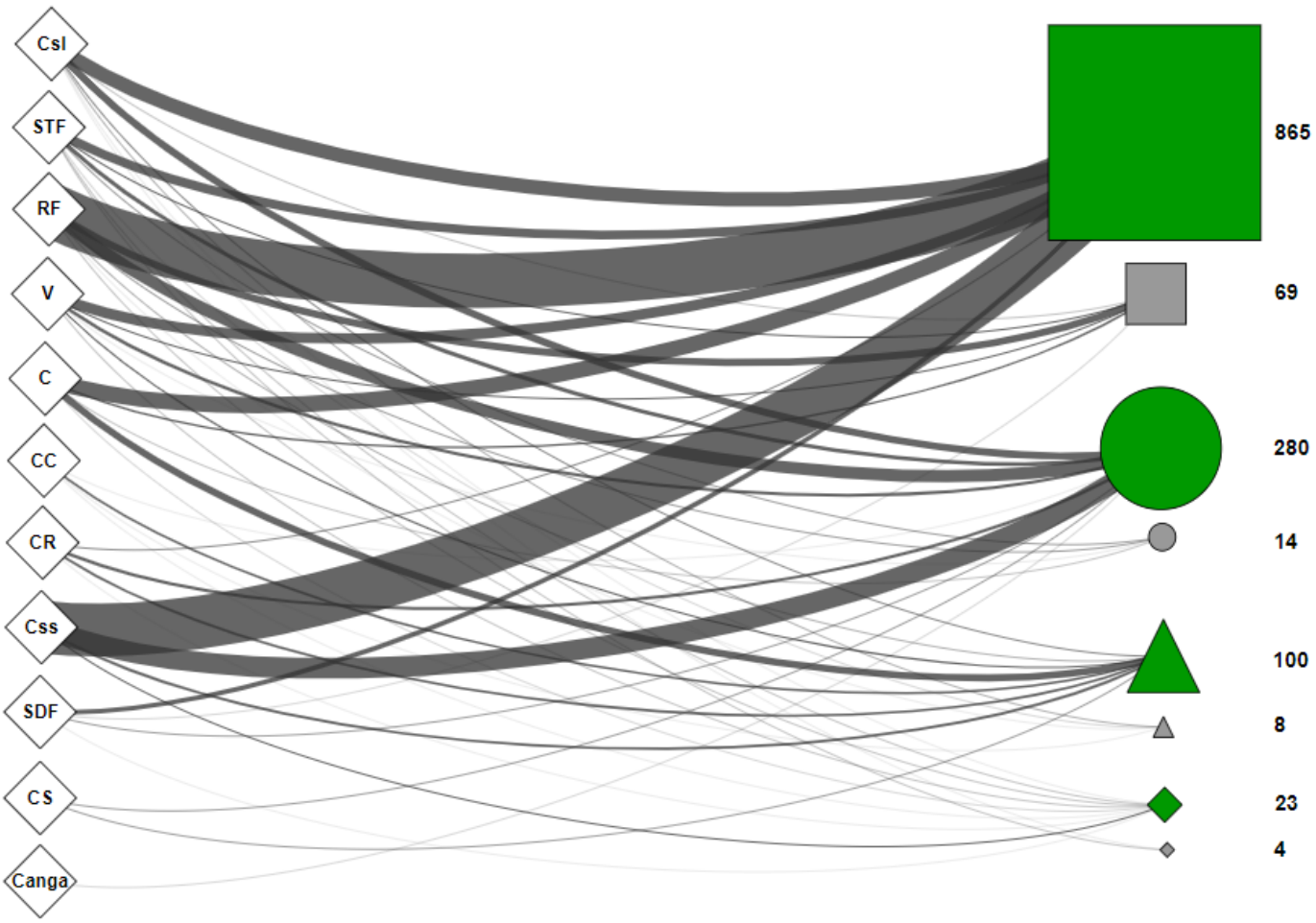

FIGURE 9. PROPORTION OF NATIVE AND EXOTIC PLANT SPECIES AND GROWTH FORMS USED TO RESTORE EACH VEGETATION TYPE OF CERRADO. THE WIDTH OF THE LINES REPRESENTS THE PROPORTION OF THE GROWTH FORM USAGE TO RESTORE THE VEGETATION TYPE. NATIVE PLANT SPECIES ARE GREEN AND EXOTIC SPECIES ARE GRAY (RECTANGULES = TREES; CIRCLES = SHRUBS; TRIANGLES = HERBS; DIAMONDS = CLIMBERS.) THE VEGETATION TYPES OF CERRADO ARE REPRESENTED BY WHITE DIAMONDS (CSL = CERRADO SENSU LATO; STF = SEMIDECIDUOUS TROPICAL FOREST; RF = RIPARIAN FOREST; V = VEREDA; C = CERRADÃO; CC =CAMPO-CERRADO; CR = CAMPO RUPESTRE; CSS = CERRADO SENSU STRICTO; SDF = SEASONALLY DRY FOREST; CS = CAMPO-SUJO; CANGA). THE NUMBERS ASSOCIATED WITH THE SYMBOLS REPRESENT THE TOTAL NUMBER OF PLANTS OF EACH GROWTH FORM.

Most plant species used to restore the Cerrado were used only a few times, thus, we considered that species used more than ten times were the most used ones: *Copaifera langsdorffii*, *Enterolobium contortisiliquum*, *Cedrela fissilis*, *Dipteryx alata*, *Anadenanthera colubrin*a, *Schinus terebinthifolius*, *Astronium fraxinifolium*, *Hymenaea courbaril*, *Peltophorum dubium*, *Eugenia dysenterica*, *Genipa americana*, *Guazuma ulmifolia* and *Myracrodruon urundeuva*. Those plant species have been used in Cerrado vegetation types that they did not originally occur (Figure 10).

All of the most used plant species were native to the Cerrado phytogeographic domain and had a tree growth form. However, *A.colubrina*, *S.terebinthifolius*, *E.dysenterica* and *G.americana* can also be shrubs.

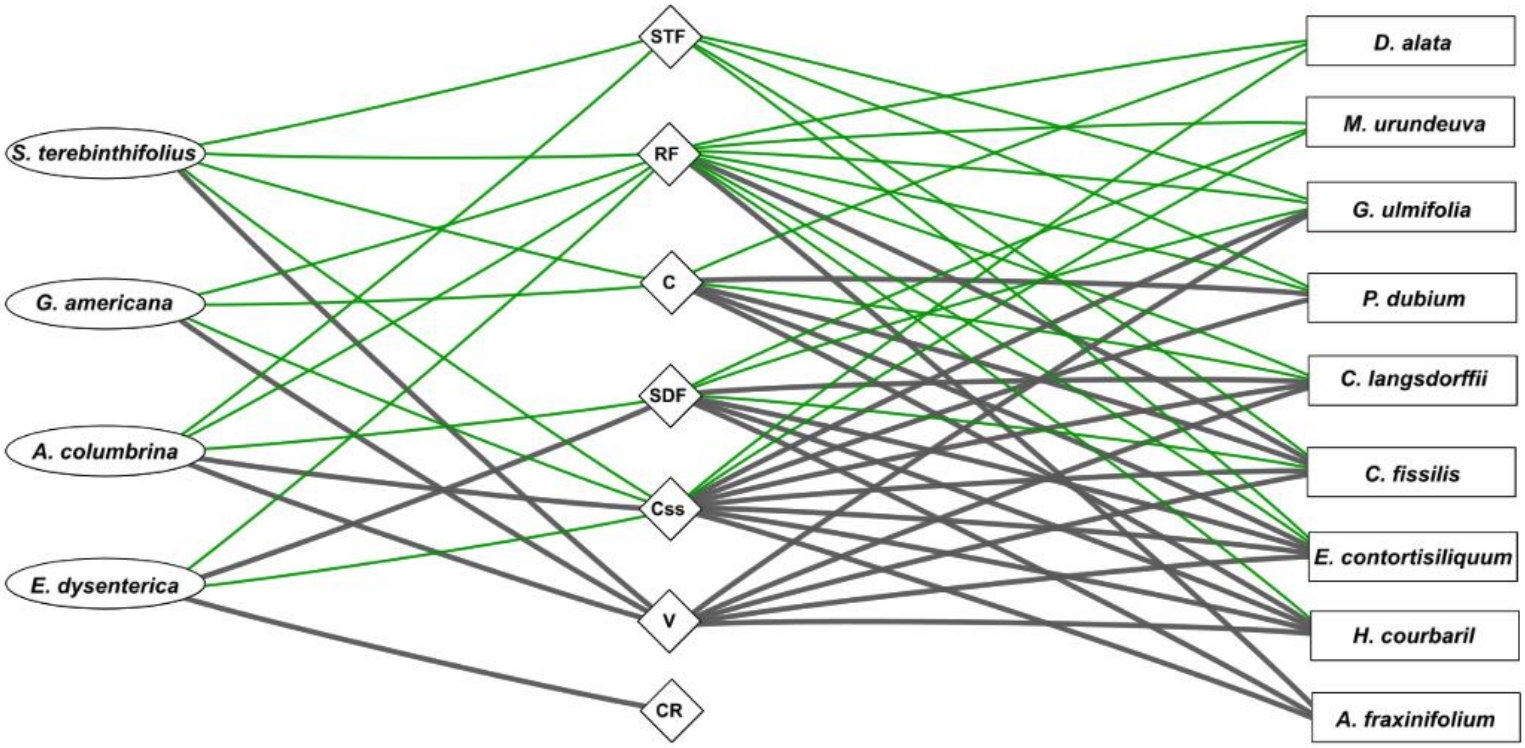

FIGURE 10. THE MULTILAYER NETWORK OF ORIGINAL OCCURRENCE AND RESTORATION USAGE OF THE PLANT SPECIES MOST USED TO RESTORE THE CERRADO PHYTOGEOGRAPHIC DOMAIN. GREEN LINES CONNECT PLANT SPECIES TO VEGETATION TYPES WHERE THEY ORIGINALLY OCCUR AND WERE ALSO USED FOR RESTORATION. THE GRAY LINES CONNECT PLANT SPECIES TO VEGETATION TYPES WHERE THEY DID NOT ORIGINALLY OCCUR BUT WERE USED FOR RESTORATION. ALL PLANT SPECIES ARE NATIVE TO CERRADO: RECTANGLES REPRESENT PLANT SPECIES WITH A TREE GROWTH FORM AND ELLIPSES REPRESENT SPECIES THAT CAN HAVE A TREE OR A SHRUB GROWTH FORMS. THE VEGETATION TYPES OF THE CERRADO ARE REPRESENTED BY DIAMONDS (STF = SEMIDECIDUOUS TROPICAL FOREST; RF = RIPARIAN FOREST; C = CERRADÃO; SDF = SEASONALLY DRY FOREST; CSS = CERRADO SENSU STRICTO; V = VEREDA; CR = CAMPO RUPESTRE).

4. Discussion

Our review of the Cerrado restoration indicates that research have not followed the recommendations established by ecological knowledge literature. We cannot deny that there is an increasing interest and/or awareness towards restoration of the Cerrado phytogeographic domain. However, we found that studies are concentrated around only four research groups and focused mainly on two Cerrado vegetation types (*cerrado sensu stricto* and riparian forest). We also found

that we still lack a standardized and systematic form of evaluating the outcomes of restoration studies as we found that most of them have been monitored in a case-specific way. Furthermore, plant species have been used regardless the reference ecosystem when we consider the original occurrence and proportion of plant species growth forms. This highlights the need to clearly define the reference ecosystem and respect its characteristics while planning and doing the restoration of the Cerrado. Therefore, we should apply the ecological knowledge that we possess into restoration practices. Besides, although we have gained some insights and perspectives into the restoration of the Cerrado, successful restoration efforts to many Cerrado vegetation types will depend on the improvement of knowledge related to their natural regeneration and dynamics as well as to native plant species cultivation.

Our ability to effectively restore the Cerrado can be enhanced by exchanging information about restoration outcomes, especially about restoration of the Cerrado and/or savannas worldwide. This exchange of information could only be possible if research are accessible and done in a standardized and systematic form. In this context, we found that 42% of publications were dissertations and theses (only 15% and 9% of them were eventually published in scientific journals, respectively) that have more limited access and could also have their information altered/improved through the peer-review process. Moreover, the predominance of Portuguese and national journals publications found for Cerrado restoration also results in access limitation. However, we acknowledge a current increase in international publications and highlight that we should keep encouraging researchers to publish their data in English and in international journals to facilitate access and interchange of ideas.

4.1 The practices and studies in the Cerrado

The research efforts to restore the Cerrado were unevenly distributed and mostly related to pasture and agricultural impacts as well as to research groups from some Brazilian public universities. In general, research efforts to restore the Cerrado have not respected literature recomendations[8]. The major issues we could detect are the lack of a systematic monitoring and the unawareness of the differences and specificity of Cerrado vegetation types. We found that a great number of restoration efforts was monitored even though monitoring activities were done in a case-specific way. We also found that most restoration studies have trustworthy results as they were supported by statistical analysis. However, some useful statistical approaches that could advance

our knowledge and efforts (e.g. modelling) were rarely used. Furthermore, although we know that Cerrado comprises a variety of vegetation types, we found that a majority of these vegetation types have only few restoration efforts reported (i.e. *campo cerrado, campo rupestre, vereda, campo sujo, campo limpo, canga*). We also found that most of the research (31.3%) did not even mention what vegetation type was intended to be restored.

The concentration of restoration efforts was related to agribusiness impacts, which can disrupt soil's physical and chemical structure as well as influence soil's fauna and seed bank. Such impacts are probably easier to face when compared to restoration challenges of areas impacted by mining, quarry or by the construction of hydroelectric power[14,37]. Furthermore, although the objective of restoring degraded pastures and cultivated areas can be related to the rehabilitation of land quality which improve agribusiness profit[38,39], we found that most of the research aimed to reestablish the native ecosystem and mainly used the assisted regeneration approach. These may indicate that environmental legislation is playing a role in stimulating ecological restoration as landowners are investing to restore natural ecosystems, especially in those areas nearby water courses[40]. Furthermore, ecological restoration through assisted regeneration may not be financially viable for many landowners or on a large scale. Prioritizing natural regeneration in areas with a low level of degradation or near native ecosystem patches could allow limited budgets to be redirected to other areas and maximize restoration efforts[41]. The landscape approach should be adopted when designing cost-effective restoration strategies for the Cerrado, especially considering the agribusiness dominance of its current landscape. Models that can estimate cost-effective scenarios for upscale Cerrado ecological restoration are an essential attempt to reverse the historical degradation[26,42].

The existence of research groups focused on Cerrado restoration is fundamental for supporting upscale its ecological restoration and conservation. However, Cerrado has been neglected as a conservation and restoration priority. Efforts have been mainly devoted to forest restoration[43] and as an old-growth savanna, the Cerrado has been misrecognized as severely degraded vegetation. Moreover, the facility to turn Cerrado's land into pastures or cultivations has made this phytogeographic domain an easy target for agribusiness. In this context, it is really important to have research groups dedicated to the Cerrado and we could detect some from Brazilian public universities that have been focused in restoration of the Cerrado. Nevertheless, research

attempts from dedicated but few and isolated groups will not move the Cerrado restoration forward as ecological restoration knowledge may be restricted to some specific areas and/or techniques. Hence, we suggest that collaboration networks between Brazilian research groups should be increased and strengthened as a way to joint restoration initiatives and encompass all Cerrado vegetation types[44]. Moreover, we also advocate for overseas collaborations since restoration practices and ideas from other savannas with similar structure and function could be applied to the Cerrado.

The differences and specificity of Cerrado vegetation types should be considered in restoration research and practices, however, we did not find such awareness. Challenges such as the lack of concern in determining the vegetation type to be restored should be faced. Determining the vegetation type to be restored is imperative because it represents the reference ecosystem used as a guidance to achieve ecological restoration[8]. Moreover, it is urgently needed to raise the concern about the insufficient efforts towards vegetation types. The representativeness of many vegetation types must increase in order to comprise the diversity of the Cerrado ecosystems[23]. Nevertheless, limited or scarce knowledge on natural regeneration, especially for some vegetation types[45], may hamper attempts to ecologically restore the natural heterogeneity of the Cerrado. Besides, the lack of knowledge about requirements of native species cultivation may hinder the development of seedlings[46,47] and create barriers to ecological restoration. Therefore, improvements on ecological foundation about each vegetation type as well as determining which vegetation type is going to be restored must be done to allow effectively ecological restoration of the Cerrado.

Another challenge that we must face is the shift from a non-standardized form of tackling restoration outcomes to a systematic form. It is well known the importance of periodically measure ecosystem indicators to assist decision-making about the requirement of management activities and/or to assist future restoration initiatives[8,48]. However, as in many other study areas, we found that monitoring of restoration initiatives of the Cerrado was not systematically done hampering comparisons among research as well as effective support to decision-making. In this context, the determination of appropriate monitoring measures is crucial as well as the feasibility of low-cost standardized methods[49]. Moreover, because restoration results can change over time, the evaluation of restoration progress should include long-term monitoring[50]. The absence of a regular and consistent monitoring may be related to relative abandonment of restoration areas mainly due to

short-period investments[48] and/or insufficient community involvement[51]. Hence, we highlight the importance to combine of short- and long-term monitoring of biophysical outcomes alongside with monitoring of socio-economic outcomes in order to evaluate success and failures of restoration efforts and managements[48,49].

The standardization of research will allow available tools, frameworks and approaches to be explored in order to enhance knowledge and ability to restore the Cerrado. Results of restoration research and their monitoring are validated by statistical analysis. Excluding reviews, most of the restoration research in the Cerrado were statistically analyzed by frequentist or indices analysis and only a few research have used modelling. Desirable analysis, such as modelling, might be worthwhile when planning landscape designs for ecological restoration[42,52]. Moreover, because landscape modelling has already been used to set conservation priority areas, we encourage stakeholders to joint conservation and restoration planning efforts. Models can also be used to predict management effects[54] like those related to different fire managements[55] or to control invasive species (i.e. [56]). Furthermore, many Cerrado restoration projects are developed by landowners who tend to have limited amounts of money and modelling resource allocation could help decision-making on how to best invest the money to obtain better outcomes[42,57,58].

4.3 The plant species used in ecological restoration of Cerrado vegetation types

The diversity of native plant species used in ecological restoration of the Cerrado have been regardless used considering the literature recommendations and the reference ecosystem. We found that plant original occurrence and plant community features of the reference ecosystem have not been respected. The most used plant species have been used everywhere and not only where they originally occur. Besides, there was a predominance of tree species, which can hamper spontaneous regeneration of native herbaceous grassland species[21] and impair old-growth savannas restoration, which are the dominant vegetation types of Cerrado. We highlight that the usage of shrubs and herbaceous plant species should be increased and the proportion of plant growth forms in each vegetation type should also be respected. Moreover, the genetic diversity of restoration efforts should also be considered, even though it was overlooked in our study. Changes in vegetation genetics, structure and phenology could result in biodiversity loss and ultimately compromised ecosystem services such as pollination and dispersal. For instance, failures in re-establishment and maintenance of grass layer in *cerrado sensu stricto* have been pointed as a reason for different

compositional and functional diversity of ant communities at restored sites[59]. Therefore, the way that plant species have been used should be improved in order to achieve ecological restoration of the Cerrado. Planning of future ecological restoration projects must continue to preferably use native species, but with an increased concern about plant species identity and growth form. We believe that the selection of plant species should be guided by the reference ecosystem, respecting the original proportion of growth forms as well as the original occurrence of the plant species.

Inadequate practices can occur if the reference ecosystem is not respected or determined. For instance, afforestation practice has been stimulated in the Cerrado and monocultures of pines and eucalypts have been threatened its ecosystems functioning as well as its biodiversity. Afforestation practice should be carefully analyzed (and probably avoided) as it can cause negative impacts at local and regional scales[20]. Besides, some exotic species have been used to restore the Cerrado because they propagate easier and outcompete native species. At first glance, the use of exotic species may seem like a good option[60] because they can ameliorate ecosystem conditions[61]. However, exotic species may become a problem to restoration as they prevent native species development[62,63]. Moreover, invasive grasses can change Cerrado's fire regime and impact native species survival[64]. Negative consequences to native plants can occur, although they are well adapted to fire, because invasive grasses can increase fire frequency and/or intensity due to more biomass accumulation. Therefore, considering the risk of threats by exotic species[22,63,64] and the economic costs of controlling them[65], we strengthen the choice for native plant species in restoration actions.

5. Concluding remarks

The challenge of reducing biodiversity loss and ecosystem degradation rates calls for effective conservation and ecological restoration actions, especially regarding threatened non-forest ecosystems. This review is among the first attempts to capture how restoration research of the Cerrado have been conducted and reveals that we still have a long way to go through to restore the diversity of these phytogeographic domain. We should start by following the recommendations established in the ecological restoration literature. Investigations on ecological dynamics and natural regeneration of the different vegetation types of the Cerrado should be encouraged in order to build a solid ecological knowledge base. Moreover, to better support decision-making, new tools and frameworks (ie. modelling approach) could be explored and improvements of native plant species

cultivation should be done. Basic and applied research should be developed in a standardized and scientific-based approach. This will allow more precise comparisons and consequently will promote a shift in restoration studies from a case specific approach (i.e. trial and error) to a more applicable and evidence-based science. Furthermore, restoration efforts should keep using mainly native plant species, but concern about which and where plant species will be used should be increased. The proportion of growth forms and their original occurrence should be considered when planning the ecological restoration of each Cerrado vegetation type. Finally, we argue that restoration research in the Cerrado should receive more support to allow those knowledge advances mentioned above. This support is important to encourage theses and dissertations to become journal articles as well as to attract more researchers into the field.

The growing awareness towards the restoration of the Cerrado may contribute to the improvement of restoration practitioners' ability of efficiently and effectively implement the ecological restoration successfully. However, some challenges must be faced as many of the results of the Cerrado restoration cannot be generalized. Furthermore, because natural and human systems are coupled, there must be an integration of political, social and economic features with ecological concerns. In this context, we argue that the usage of native species can be recommended even when ecological restoration is not the restoration goal. Community engagement can be greater as the use of native species might value popular knowledge and products provided by native plant species, such as fruits and timber, can economically attract landowners. We advocate that the effectiveness of ecological restoration efforts will be improved by advancing ecological knowledge about the Cerrado as well as considering the limited budgets, community engagement and compliance of environmental laws.

5. Future perspectives

Although it is a difficult task, the ecological restoration of the Cerrado must include all dimensions of its diversity and not only focus on species compositional diversity. Research efforts directed towards genetic, compositional, functional, and phylogenetic diversity are essential to understand and (re)establish the Cerrado biodiversity. Moreover, the relationship between diversity and invasion resistance can also be explored in order to provide better guidance to decision-making. Monitoring will be key in such research, and thus, it is important to implement them in a

standardized form. Furthermore, when we looked into the functional diversity component, we could detect that some growth forms - like herbs - were not commonly used even though they are important portion of the Cerrado. This is a reflection of the difficulties involving herbaceous seedling cultivation[47,66] and highlights the need to develop research that aim to understand and replicate herbaceous reproduction. Besides, questions related to the impacts of large-scale restoration and biodiversity remain unsolved[67]. Finally, we advocate that a free database encompassing information about restoration actions and outcomes should be built as it can gather information that could help future decision-making.

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APENDIX 1

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