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REVIEW

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Controlling invasive plant species in ecological restoration: A global review

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Abstract

1. Invasive plant species can hinder the establishment and growth of native plants and impact several ecosystem properties, such as soil cover, nutrient cycling, fire regimes and hydrology. Controlling invasive plants is then a necessary, yet usually expensive, step towards the restoration of an ecosystem. A synthesis of literature is needed to understand variation in invasive plants' impacts and their practical control in restoration contexts, and to identify associated knowledge gaps.
2. We reviewed 372 articles published from 2000 to 2019 covering the control of undesirable plants (both exotic invasive and overabundant native plant species) in ecological restoration to gather information on the main plants being controlled and methods used, and considering the distribution of studies among biomes and countries grouped according to the Human Development Index (HDI).
3. Grasses and forbs were the most-studied invasive plant species in restoration sites, but invasive trees were well studied in the tropics. *Poaceae* and *Asteraceae* were the most studied families of invasive plants. Non-chemical interventions (mostly mowing and prescribed fire) were used in more than half of the reviewed studies globally, but chemical methods (mainly glyphosate spraying, used in 40% of projects using herbicides) are also common. The reviewed studies were mostly performed in countries with very high HDI. Countries with low and medium HDI used only non-chemical methods.
4. *Synthesis and applications*. Decisions about which control method to use depend heavily on the invasive plant species' growth forms, the local economic situation where the restoration sites are located and resources available for control. More developed countries tend to use more chemical control, whereas less developed ones use mainly non-chemical methods. Since most of the reviewed studies were performed in countries with very high HDI, we lack information from developing countries, which concentrates global hotspots for biodiversity conservation and global commitments of forest and landscape restoration.

KEYWORDS
biological invasions, chemical control, exotic species, glyphosate, herbicides, mechanical control, non-chemical control, non-native species

1 | INTRODUCTION

Invasive plant species threaten natural habitats worldwide, and are reported to be one of the main causes of biodiversity loss (Vitousek, D'Antonio, Loope, Rejmánek, & Westbrooks, 1997). Invasive plant species can interfere in the establishment of native species, and consequently affect plant community structure and assembly (Pearson, Ortega, Eren, & Hierro, 2018). They can threat biodiversity leading to extinctions (Bellard, Cassey, & Blackburn, 2016; Powell, Chase, & Knight, 2011), and change soil properties (Castro-Díez et al., 2019), nutrient cycling (Vilá et al., 2011), fire regimes (Brooks et al., 2004) and hydrology (Levine et al., 2003), ultimately compromising both biodiversity conservation and human well-being (Pejchar & Mooney, 2009). Invasive plant species can not only alter natural community assembly but also represent one of the most critical barriers for restoring native ecosystems (D'Antonio & Meyerson, 2002).

Ambitious restoration pledges have been made by countries worldwide, which have committed so far to promote forest landscape restoration in 170 million hectares by 2030 (Chazdon & Brancalion, 2019). In parallel, the United Nations announced that the 2021–2030 period will be the decade on ecosystem restoration, which may also contribute to mainstream global investments to upscale restoration of different native ecosystem types. Controlling invasive plants is one of the most common (and sometimes the most important) restoration intervention (D'Antonio, August-Schmidt, & Fernandez-Going, 2016), as these plants may hinder the development of a native plant community in a degraded area (Brancalion, Campoe, et al., 2019; Kettenring & Adams, 2011; Prior, Adams, Klepzig, & Hulcr, 2018). On the other hand, using active approaches to re-establish native vegetation communities in areas where invasive plants were controlled can help reducing the chances of invasive plant species recolonization (Schuster, Wragg, & Reich, 2018), so there are mutual benefits between invasive plants control and ecological restoration. However, the methods employed to control invasive plants in restoration may not always result in the expected outcomes, as the same or even new invasive plant species may colonize the site while native species recovery can be insufficient (Reid, Morin, Downey, French, & Virtue, 2009). Effective control of invasive plant species in restoration may also require long-term investments (Norton, 2009) which are rarely available for restoration projects (Brancalion, Meli, et al., 2019), or rely on chemical methods that are of major environmental concern (Wagner, Antunes, Irvine, & Nelson, 2017). Controlling invasive plants in restoration can thus be an expensive, long lasting and uncertain process, which may compromise the implementation of the global restoration agenda.

Many methodologies can help to control invasive plant species in restoration sites. Which approach is best depends on several factors such as the species being controlled, financial resources available (Kettenring & Adams, 2011), legislation (Dechoum, Sampaio, Ziller, & Zenni, 2018; Wagner et al., 2017) and even personal beliefs when it comes to chemical control. Each invasive plant species control method has many pros and cons, so expanding knowledge of this issue is critical to guide restoration decision-making. Herbicides are largely used for the control of invasive species because of their scalability and reduced costs (Kettenring & Adams, 2011), two issues critical for the ambitious restoration commitments planned for the coming years (Brancalion, Niamir, et al., 2019). Some herbicides can permanently control competing plants, whereas non-chemical methods only remove plants' shoots and can fail to prevent re-sprouting from below-ground structures (Espeland et al., 2017; Tognetti & Chaneton, 2015). However, herbicide use in restoration raises concerns of potential water contamination, direct and indirect impacts on non-target organisms, and intoxication of field labourers (Davoren & Schiestl, 2018; Van Bruggen et al., 2018).

Successful control efforts have generally benefited biological diversity (Zavaleta, Hobbs, & Mooney, 2001). However, there is also evidence that successful eradications can have unexpected impacts on native species and ecosystems. For example, the removal of an invasive plant species can reduce the resources available for native fauna if the control is not followed by other restoration strategies (Zavaleta et al., 2001). Additionally, some invasive plant species can keep affecting the system after their removal due to their legacy effects on soil microbial community and root symbionts (D'Antonio & Meyerson, 2002; Koziol et al., 2018; Lankau, Bauer, Anderson, & Anderson, 2014). The type of species being removed, the degree to which it has replaced native species and the presence of other non-native species can affect the eventual impact of removing an invasive plant species (D'Antonio & Meyerson, 2002; Zavaleta et al., 2001).

Despite the abundance of studies on biological invasion, relatively little is known about the current status of invasive plant species in restoration sites worldwide or which methods have been used to control these plants (but see Kettenring & Adams, 2011). More information is needed to improve current methodologies and propose efficient and effective invasive plant species control strategies with low environmental impacts and operational costs. Reviewing existing literature is a useful tool to understand the global panorama of control technologies in restoration projects. Organizing basic information on the reality of biological invasions in ecological restoration studies worldwide is essential to (a) guide research and development of new models, (b) elaborate cost-effective and feasible strategies to control invasive plant species in restoration sites, especially for large-scale projects and (c) understand the potential and limitations of alternative control methods in restoration projects preferring to avoid using herbicides. Thus, science can help to fill knowledge gaps in restoration, guiding the development of cost-effective and functional restoration strategies to supress invasive plant species to successfully restore ecosystems and conserve targeted species.

Considering that invasive plant species are commonly controlled in restoration projects using chemical methods, and that these projects are normally located in vulnerable areas (e.g. riparian buffers, protected areas, habitat of endangered species), we were particularly interested in identifying to what extent chemical methods are used, and what alternative non-chemical methods are employed in restoration. Thus, to advance our understanding of practical invasive species control in restoration contexts, we reviewed existing literature about control of invasive plant species in ecological restoration to gather information on the main invasive plant species being controlled and methods used, and how they are distributed among biomes and countries with different Human Development Index (HDI) scores. While the systematic review performed by Kettenring and Adams (2011) evaluated which control methods most successfully translate into effective restoration, ours focuses on quantifying targeted invasive species groups and the methods used to control them in different socio-ecological contexts.

2 | SURVEY METHOD

We systematically reviewed papers about invasive plant species control in restoration contexts found in the Web of Science (Table S1). For an article to be selected, it had to contain at least one keyword from each of the following groups: (a) 'restoration' and 'rehabilitation'; (b) 'alien species', 'invasive species', 'weed', 'grass' and 'non-native species' and (c) 'herbicide', 'mowing', 'hand-pulling', 'chemical control', 'mechanical control' and 'fire'. We focused in keywords associated to the most common methods of invasive plants control used in large-scale restoration, to avoid the myriad of other methods used experimentally. In particular, we did not included methods associated to biological control because, although they can be effective in controlling invasive plants (Clewley, Eschen, Shaw, & Wright, 2012), they are not used yet at large scale in restoration. We included 'weed' and 'grass' as search terms because these groups of plants are the most abundant where we develop restoration projects (i.e. tropical forests of Brazil), so we were particularly interested on them. Terms referring to other growth forms (e.g. trees, shrubs, vines) were not included in the final search, as they largely increased the number of retrieved articles and most of them were not about invasive plants control in restoration. We recognize, however, that such decisions may have biased our results, so it is important to note that the importance of biological control and non-grasses plants may have been someway underestimated in our review. Our survey addressed English-language primary literature (excluding Review papers), published between January 2000 and April 2019. We selected the first 15 journals with the largest number of articles (Table S2), which are the ones that included more than one paper with those keywords.

A total of 655 articles were found based on the search described above, and their abstracts were reviewed. To be included in the analyses, the studies had to address (a) areas under restoration and (b) present at least one invasive species control method. Silvicultural plantations, mesocosm and greenhouse experiments were excluded. Rather than pre-adopting a conceptual definition of invasive species (Pyšek et al., 2004) or overabundant, undesirable native species (Essl et al., 2019), we considered in the context of our review 'invasive' all undesirable plant species controlled in a restoration project, which were mostly called as 'invasive species' in the papers reviewed. Thus, we included all papers describing the control of an undesirable (exotic and spreading native) plant species in restoration, adopting a more practical than conceptual definition of invasive species to select articles. These criteria resulted in 372 articles which were categorized by growth form (liana, tree, shrub, grass or forb) and control method (chemical or non-chemical), according to the biome, continent and human development index (HDI). Biome information was obtained by looking up geographical coordinates or the name of the city in the 'BioInteractive' app (HHMI BioInteractive, n.d.) according to Olson et al. (2001). We excluded Alpine and Boreal biomes because there was only one study for each.

3 | SOCIO-ECOLOGICAL DISTRIBUTION OF STUDIES

This review included studies from 10 biomes. The best studied biomes (i.e. with higher proportion of papers included in the review) were temperate deciduous forest (31.1%) and temperate grassland (21.2%), followed by temperate coniferous forest (13.1%), desert (11.2%), chaparral (9.5%), tropical rain forest (7.1%), savanna (4.3%) and tropical dry forest (1.6%). The over-representation of temperate ecosystems is due to a big majority of the studies having been performed in the United States (70.4% of the papers reviewed), followed by Australia (7.0%), Canada (3.2%) and 22 other countries with <2% each. Within the biomes, the reviewed studies also involved invasive plant control in wetlands, showing, for example, that native forest floodplain recolonization can be (Reinhardt Adams, Wiese, & Lee, 2015) or not (Smith, Reinhardt Adams, Wiese, & Wilson, 2016) fostered by the chemical control of invasive species. Countries in the highest HDI category comprised 94% of the reviewed studies. The geographical representation of studies of invasive plant species control in ecological restoration was similar to other reviews on restoration (e.g. Aronson et al., 2010 for a socio-economic review), in which the studies were mostly performed in developed countries, especially the United States.

4 | WHICH INVASIVE PLANT SPECIES ARE CONTROLLED IN RESTORATION SITES?

The proportion of the main plant groups being controlled in restoration projects was surprisingly similar among contrasting biome types: 46.0 ± 5.8% grass, 24.1 ± 9.0% forb, 14.6 ± 7.1% shrub, 12.1 ± 3.5% tree and 3.2 ± 3.1% liana (mean ± standard deviation of all biomes; Figure 1). Poaceae was the most frequently controlled family in all biomes (Table 1), showing that problems related to exotic grasses are a global issue. Asteraceae was the second most common, followed by Fabaceae, Pinaceae, Brassicaceae and Rosaceae (Table 1).

Restoration projects in desert, temperate and chaparral biomes have mostly controlled grasses from the genus *Bromus* (Table 1) which are a well-known invader in North America and more recently also in South America (Speziale, Lambertucci, & Ezcurra, 2013). *Bromus* is the most documented and one of the most significant invasive plant genera in North America (Vitousek et al., 1997) and has the negative impact of increasing the frequency and intensity of fires (Brooks et al., 2004). Species of this genus have invaded around 20% of the sagebrush-steppe ecosystems in the US Great Basin that was previously dominated by native shrubs and native perennial grasses (Knapp, 1996).

Invasive grasses from the genus *Urochloa* (formerly *Brachiaria*) were the most controlled in tropical rainforest restoration sites (Table 1). They are native to Africa and were introduced for fodder throughout the Neotropics, are highly competitive and quickly produce biomass which stimulates fires and hinders the growth of both planted and regenerating native trees (Campoe, Stape, & Mendes, 2010; Holl et al., 2011; Pilon, Buisson, & Durigan, 2017; Sobanski & Marques, 2014). According to Holl (2002), invasive grasses strongly impact tree seedlings' survival and development through shading, below-ground competition for water and nutrients, and allelopathic chemicals.

The family *Asteraceae* was the second most controlled group of invasive plant species in restoration in all biomes except tropical dry forest, where Rosaceae was the second (Table 1), with high frequency of invasive plant species from the genera *Cirsium*, *Centaurea* and *Senecio* (Gramig & Ganguli, 2015; Larson, Bright, Drobney, Larson, & Vacek, 2017). The genus *Cirsium* has some of the most invasive plants worldwide. They are considered a threat in the four continents where they have been unintentionally introduced (Guggisberg et al., 2012). *Centaurea* species are known for their allelopathic effects (Hierro & Callaway, 2003), while *Senecio* species are considered fast invaders possibly due to their ability to colonize a wide range of ecological habitats (Bossdorf, Lipowsky, & Prati, 2008; Lachmuth, Durka, & Schurr, 2010).

The genus *Pinus* was the most common group of invasive trees reported in restoration (Table 1), with at least 19 species observed invading natural ecosystems in the southern hemisphere (Cóbar-Carranza, García, Pauchard, & Peña, 2014; Richardson, 1998). A recent review on the ecology and management of *Pinaceae* worldwide showed that chemical and mechanical interventions are the most used methods, and, as expected, the older the invasion is, the more difficult and expensive to control it (Nuñez et al., 2017). *Ailanthus altissima* was one of the most common invasive angiosperm trees, threatening natural ecosystems in the United States, Australia and Europe, quickly forming homogeneous populations that hamper natural succession (Kowarik & Säumel, 2007).

5 | HOW ARE INVASIVE PLANT SPECIES CONTROLLED?

Worldwide, non-chemical methods were the most common approach to invasive plant species control in restoration, representing 100% in Africa and overall 62.8 ± 12.9% in the other continents, followed by chemical methods with 37.2 ± 12.9% (Figure 2a). Chemical methods predominated in countries with higher HDI and non-chemical methods in those with lower HDI (Figure 2b). Overall, chemical control predominated in countries with large-scale production of agricultural commodities, and Brazil was the developing countries with highest herbicides use (38.4%), whereas in countries with reduced access to machines, herbicides and cheaper labour, non-chemical methods predominated. Overall, the proportion of use of chemical (42.3 ± 5.8%) and non-chemical (57.7 ± 5.8%) methods was similar in most biomes (Figure 2c). We also found a few studies that combined non-chemical

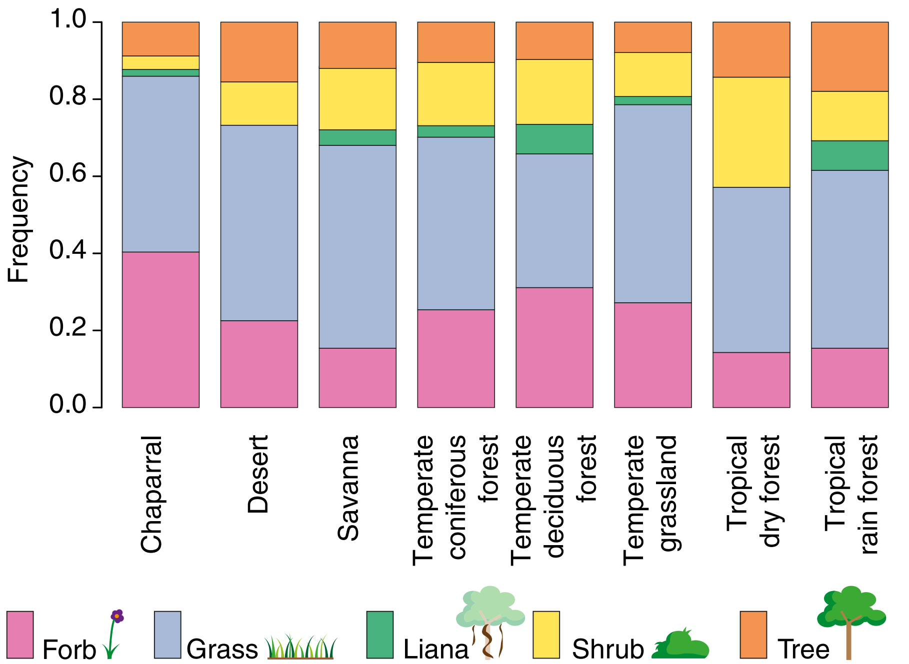

FIGURE 1 Distribution of invasive species growth forms in each biome described in the systematic review

TABLE 1 Most frequent families of invasive plant species found in each biome. Studies where native species were considered invasive (overabundant) in natural ecosystems were included in the review if they were controlled by practitioners. Biomes names are a shorter version of Olson et al. (2001) classification

Biome	Family	Genus	Species
Chaparral	Poaceae, 45.76%	*Bromus*	*Bromus diandrus*
		Avenna	*Avenna* sp.
	Asteraceae, 16.94%	*Centaureae*	*Centaurea melitensis*
		Hypochaeris	*Hypochaeris glabra*
	Brassicaceae, 9.03%	*Brassica*	*Brassica nigra*
		Hirschfeldia	*Hirschfeldia incana*
Desert	Poaceae, 38.27%	*Bromus*	*Bromus tectorum*
	Asteraceae, 9.25%	*Lactuca*	*Lactuca serriola*
	Brassicaceae, 8.64%	*Sisymbrium*	*Sisymbrium altissimum*
	Pinaceae, 6.79%	*Pinus*	*Pinus edulis*
Savanna	Poaceae, 61.22%	*Urochloa*	*Urochloa decumbens*
		Dichanthium	*Dichanthium annulatum*
		Andropogon	*Andropogon* sp.
	Asteraceae, 8.16%	*Ageratum*	*Ageratum* sp.
		Lactuca	*Lactuca* sp.
		Lepidaploa	*Lepidaploa* sp.
		Senecio	*Senecio* sp.
Temperate coniferous forest	Poaceae, 42.33%	*Bromus*	*Bromus tectorum*
		Poa	*Poa pratensis*
		Dactylis	*Dactylis glomerata*
	Asteraceae, 14.11%	*Centaurea*	*Centaurea stoebe*
		Cirsium	*Cirsium arvense*
	Pinaceae, 4.29%	*Pinus*	*Pinus* sp.
Temperate deciduous	Poaceae, 24.46%	*Bromus*	*Bromus hordeaceus*
		Microstegium	*Microstegium vimineum*
	Asteraceae, 20.03%	*Conyza*	*Conyza canadensis*
		Cirsium	*Cirsium arvense*
		Senecio	*Senecio jacobae*
	Fabaceae, 7.22%	*Trifolium*	*Trifolium dubium*
			Trifolium pratense
			Trifolium repens
		Vicia	*Vicia sativa*
Temperate grassland	Poaceae, 42.23%	*Bromus*	*Bromus inermis*
			Bromus tectorum
		Poa	*Poa pratensis*
		Agropyron	*Agropyron cristatum*
	Asteraceae, 16.77%	*Cirsium*	*Cirsium arvense*
		Taraxacum	*Taraxacum officinale*
	Fabaceae, 5.90%	*Medicago*	*Medicago lupulina*
		Melilotus	*Melilotus officinalis*
Tropical dry forest	Poaceae, 44.00%	*Pennisetum*	*Pennisetum setaceum*
	Rosaceae, 16.00%	*Rubus*	*Rubus rosifolius*
Tropical rain forest	Poaceae, 41.74%	*Urochloa*	*Urochloa decumbens*
			Melinis minutiflora
	Asteraceae, 13.59%	*Ageratum*	*Ageratum conyzoides*

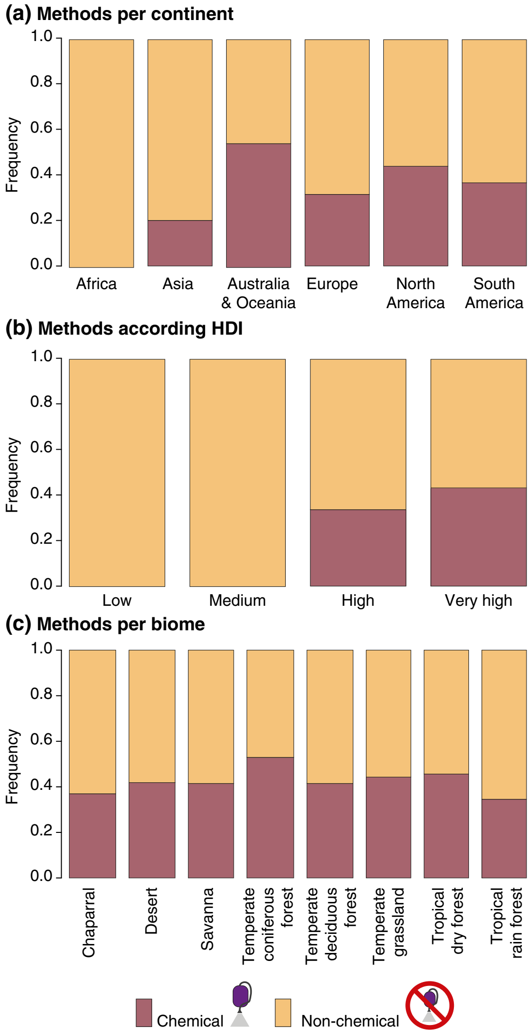

FIGURE 2 Distribution of chemical and non-chemical control methods found in the systematic review by (a) continent, (b) national Human Development Index (HDI) and (c) biome

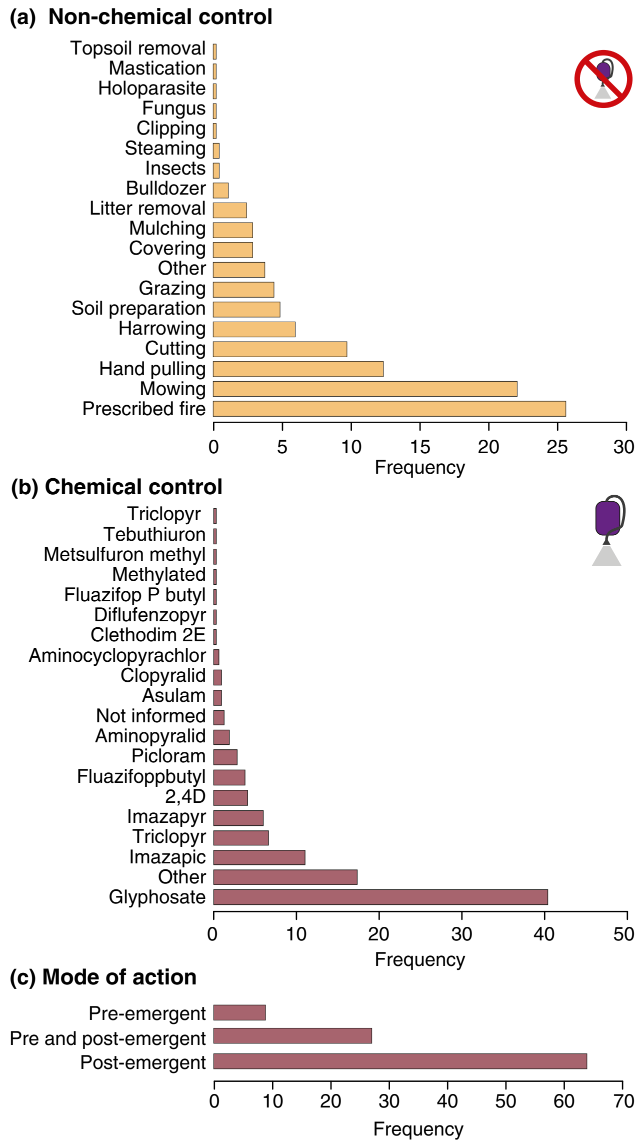

FIGURE 3 Frequency of (a) non-chemical and (b) chemical control methods used in the studies reviewed, as well as (c) the herbicide mode of action

and chemical methods, as well as combinations of two chemical or two non-chemical interventions (such as mowing and prescribed fire).

5.1 | Non-chemical control

Non-chemical control accounted for 57.7% of the total number of interventions described in the articles. Prescribed fire and mowing were the most frequent no-chemical interventions used in all articles reviewed (25.6% and 22.7% respectively), followed by hand-pulling (12.3%), cutting (9.7%) and harrowing (5.9%; Figure 3a).

Invasive plant species in chaparral, savanna and tropical rainforest restoration projects were mainly controlled by mowing. Fire was the most common non-chemical method used to control invasive plant species in deserts and temperate coniferous and deciduous forests as well as in temperate grasslands. Besides being used as a restoration tool, fire is also a management strategy to maintain fire-dependent ecosystems and species (Lehmann et al., 2014; Overbeck et al., 2013; Overbeck, Müller, Pillar, & Pfadenhauer, 2009). Temperate coniferous forests, most of which are fire adapted, had big ecological changes in structure and composition due to the exclusion of fires by environmental policies, reducing biodiversity and favouring invasion by exotic species, leading to the need for control interventions (Hessburg, Agee, & Franklin, 2005; Keane et al., 2002). The cerrado biome (the Brazilian savanna) was also affected by policies restricting fire management that do not help in establishing an adequate fire regime for maintaining its diversity (Durigan & Ratter, 2016). Thus, proper training and clarification of the benefits of prescribed burning for conservation would demystify the use of fire and make this practice more common also as a restoration tool to control invasive plant species.

Hand-pulling methods were more common in smaller restoration projects, since labour costs are prohibitive at larger scales (Ganem et al., 2020; Ray, Sherman, Godinho, Hanson, & Parker, 2018).

Cutting was more frequent in tropical biomes where invasive shrubs and trees were more common (Hooper, Condit, & Legendre, 2002; Zamith & Scarano, 2006). The more frequent methods are logically associated with the growth form of plants invading a particular biome. Grasses were the most controlled type of invasive plant; thus, mowing and fire were the most common non-chemical methods, while in tree-dominated sites cutting was more frequent.

Grazing was a common method in temperate grasslands (Doll, Haubensak, Bouressa, & Jackson, 2011; Jackson, Paine, & Woodis, 2010; Smythe & Haukos, 2010; Teague et al., 2010). Few studies showed that organisms such as fungi (Harris, Cannon, Smith, & Muth, 2013) and insects (Cutting & Hough-Goldstein, 2013) were used as biological agents to control invasive plant species in restoration. A recent global review on how safe is biological control showed that <1% of all intentional releases have the potential to lead to negative impacts (Hinz, Winston, & Schwarzländer, 2019). However, studies show that biological control can have variable effectiveness (see Hulme, 2006 for an example of low and Clewley et al., 2012 for an example of high effectiveness), and should be subjected to rigorous cost–benefit analysis, weighting the benefits, costs and ecological outcomes (Culliney, 2005; Louda & Stiling, 2004).

The variety of non-chemical methods used shows that the management of competing species varies according to biome characteristics and local particularities. In countries with very high HDI prescribed burns were the main non-chemical control, while mowing was the dominant method in lower HDI countries. Non-chemical interventions, such as mechanical control, are expensive and often ineffective (Brancalion, Campoe, et al., 2019; Jardine & Sanchirico, 2018), as well usually limited to smaller-scale projects (Rodrigues et al., 2011). However, as non-chemical methods represent the lowest technological added value for controlling invasive plant species, they may be the best (and sometimes the unique) option in low-income regions. Thus, innovative methods such as modular plant protections (an apparatus to cover the ground around planted seedlings to supply water and avoid invasive species growth; Pagnoncelli & Pagnoncelli, 2019) are promising and should be further tested in restoration. Even though our review shows the predominance of non-chemical control, a significant amount of areas under restoration, especially in tropical regions, have been managed with herbicides (Brancalion et al., 2016; Wagner et al., 2017).

5.2 | Chemical control

Chemical control accounted for 42.3% of the total number of interventions found in the articles. The most common active ingredient of herbicides used in chemical control was glyphosate (40.4%) followed by imazapic (11.4%), triclopyr (6.6%) and a variety of other types (Figure 3b). Sixty-four per cent of the herbicides used have a post-emergent mode of action (i.e. applied directly on the targeted plants), whereas 8.8% have a pre-emergent mode of action (i.e. applied in the soil to prevent seedling emergence from soil seed bank) and 27.1% used both (Figure 3c).

Besides its effectiveness for controlling targeted plants and lower costs, chemical control methods can cause environmental pollution and human health problems that need to be considered and evaluated. This is particularly the case of glyphosate, the most used herbicide in restoration areas (Cornish & Burgin, 2005; Wagner et al., 2017). Although glyphosate has been formally classified by regulatory agencies and researches as having low environmental risks (e.g. Hagner, Mikola, Saloniemi, Saikkonen, & Helander, 2019), its negative impacts in nature and humans are still highly controversial and have been debated worldwide. A recent assessment of glyphosate use showed low but pervasive contamination hazard in almost all agroecosystems globally (Maggi, Cecilia, Tang, & McBratney, 2020), and medical science studies are linking glyphosate with human diseases (Zanardi et al., 2020). From a rhizosphere perspective, while some studies found that a proper dose of glyphosate had no evidence of detrimental changes in microbial community structure (Araújo, Monteiro, & Abarkeli, 2003; Ratcliff, Busse, & Shestak, 2006), others showed that glyphosate negatively affected below-ground interactions between earthworms and mycorrhizal fungi (Zaller, Heigl, Ruess, & Grabmaier, 2014). Researchers have also warned that cascading effects of glyphosate are difficult to preview and then its use demand caution (Helander, Saloniemi, & Saikkonen, 2012).

Glyphosate mobility in soils is limited but can be affected by soil acidity and type (Berzins et al., 2019; Sprankle, Meggitt, & Penner, 1975). The role of infiltration and runoff in spreading it into surface waters (Daouk, Alencastro, & Pfeifer, 2013) is an important issue when glyphosate use is considered in restoration sites. Alternatives such as vegetative buffers, used mainly in USA and Europe, can reduce herbicide horizontal distribution (Krutz, Senseman, Zablotowicz, & Matocha, 2005; Rasmussen, Baattrup-Pedersen, Wiberg-Larsen, McKnight, & Kronvang, 2011; Reichenberger, Bach, Skitschak, & Frede, 2007). Since ecological restoration aims to provide the recovery of an ecosystem with respect of its health, integrity and sustainability (SER, 2004), using agrochemicals in restoration practices can be controversial and should, whenever possible, be avoided. However, non-chemical methods to control invasive plants in restoration will only be widely used (as glyphosate has been) if their effectiveness is increased and costs reduced, which requires the improvement of non-chemical techniques together with innovation and technological development to create new methods.

Invasive plant species have been controlled in wetlands ecosystems mainly by herbicide spraying, but non-chemical methods have also been used in some regions. Aiming to verify the effectiveness of aerial application of herbicide in hindering invasive species in New Zealand wetlands, Burge et al. (2017) found that glyphosate was efficient in restoring native vegetation trajectory, while Griffiths et al. (2018) suggest that it was effective to initiate the restoration but did not last long enough to avoid reinvasion. Holl et al. (2014) tested chemical and non-chemical control methods to restore coastal prairie grasses in California and found that chemical control was effective but required monitoring after 3 years. Considering that wetlands are ecosystems flooded by water, non-chemical control methods should be prioritized, and when chemical control is needed, it must consider the biology of the target species, the likelihood of non-target impacts on site and environmental conditions (Euston-Brown, Rathogwa, & Richardson, 2007). Richardson et al. (2007) suggest several non-chemical control strategies (such as control of regenerating aliens, clearing alien stands, introduce biological control, fire and grazing) as main management actions to facilitate restoration of riparian plant communities.

6 | PERSPECTIVES

We have presented an overview of studies on invasive plant species control in ecological restoration. Overall, our systematic review showed some general patterns. First, we found that most of the invasive plant species being controlled in restoration sites were grasses and forbs, but invasive trees were also important in the tropics. Second, non-chemical methods (mowing and prescribed fire) were found to be the most used ones to control invasive plant species, but chemical methods (mainly glyphosate spraying) are also a very common practice. Third, most of the reviewed studies were performed in countries with very high HDI, showing that we lack information from developing countries, which harbour most of the global biodiversity hotspots and global commitments of forest and landscape restoration (Brancalion, Niamir, et al., 2019), possibly due to financial limitations to control and study invasive plant species. However, this result may be biased by the fact that countries with lower HDI may publish papers in their own language (and here we limited the review to English). Finally, the decision on which control method to use seems to be highly dependent on the invasive plant species growth form, as well as on the economic situation of the country where the restoration sites were located and resources available for control.

Innovation in controlling invasive plant species is critically needed to upscale restoration projects, as a consequence of the negative impacts of these species on restoration success and costs. Our review also allows us to suggest some research priorities. Since we found that economic realities play a role in the control method chosen, there is an urgent need to come up with easy-to-use and inexpensive solutions to implement restoration plantings to increase the likelihood that native species will not be harmed by invasive plant species. Considering the unbalanced distribution of studies reviewed worldwide (mostly in English-speaking countries), we need to know what developing countries have been doing to deal with biological invasions in restoration contexts. Additionally, we suggest moving beyond traditional control methods, to look for alternative ways not only to control or suppress but also to avoid invasive plant species establishment. We need more research into how manipulating competitive relations in restoration can reduce the establishment of exotic invasive (Young, Stuble, Balachowski, & Werner, 2017), and the role of initial plant community composition in promoting facilitation and avoiding competition to supress invasive plant species (Lang, Hanslin, Kollmann, & Wagner, 2017; Vaughn & Young, 2015). For instance, invasive grasses have proliferated at the early stages of restoration projects in the tropics because of the high availability of light. Mowing and herbicides have been used to control invasive species in the first years of forest restoration until trees grow enough to outcompete grasses through shading (Evangelista, Michelan, Gomes, & Thomaz, 2017; Maron & Connors, 1996; Ross et al., 2019). A restoration method successfully used in Brazil to outcompete invasive grasses is sowing green manure species (usually exotic, but non-invasive, legume shrubs for producing biomass that have positive effects on soils) in between the planting lines of native trees (César, Brancalion, Rodrigues, Oliveira, & Alves, 2013; Durigan, Guerin, & da Costa, 2013). These species grow faster than native trees and anticipate the occupation of the ecological niche of C_4 grasses, reducing the recolonization of restoration plantations by these undesirable species. Green manure has been an alternative to reduce the use of herbicides or even to eliminate it in restoration projects.

More research is also needed to improve resistance to invasion by manipulating soil biota and species diversity (Brinkman, Raaijmakers, de Boer, & van der Putten, 2017; Callaway, Thelen, Rodriguez, & Holben, 2004; Funk, Cleland, Suding, & Zavaleta, 2008; Liao, Luo, Peng, & Callaway, 2015). Finally, there is a gap between scientific and practical knowledge in finding the best methods to control invasive plant species, and this gap can be reduced by providing awareness of what is exotic, involving local people in invasive species management (Dechoum, Giehl, Sühs, Silveira, & Ziller, 2019), and profiting from this activity (Shackleton, Le, Wilgen, & Richardson, 2017), such as when invasive trees are used as firewood or invasive grasses are used as fodder for domesticated animals.

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AUTHORS' CONTRIBUTIONS

P.H.S.B. led the project; F.G.F., E.W.A.W. and T.B.S. conducted the literature survey and reviewed the papers; P.H.S.B. and E.W.A.W. led the writing, and all authors contributed to revisions and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the figshare: https://doi.org/10.6084/m9.figshare.8968004.v1 (Weidlich, Flórido, Sorrini, & Brancalion, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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