University of São Paulo
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Assessing the ecological impacts of invasive plants in Neotropical forests through evidence synthesis

Igor Nogueira Jacob

Dissertation presented to obtain the degree of Master in Science. Area: Forest Resources. Option in: Conservation of Natural Ecosystems

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Igor Nogueira Jacob
Bachelor in Environmental Management

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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

Advisor:
Profa. Dra. **DÉBORA CRISTINA ROTHER**

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1. Invasões biológicas 2. Plantas exóticas 3. Revisão sistemática 4. Tamanho de efeito 5. Espécies introduzidas I. Título

DEDICATION

I dedicate this dissertation to my beloved parents,

Maria Inês e Georges

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"Nenhum homem poderá revelar-vos nada senão o que já está meio adormecido na aurora do vosso entendimento.

O mestre que caminha à sombra do templo, rodeado de discípulos, não dá de sua sabedoria, mas sim de sua fé e de sua ternura.

Se ele for verdadeiramente sábio, não vos convidará a entrar na mansão de seu saber, mas antes vos conduzirá ao limiar de vossa própria mente.

O astrônomo poderá falar-vos de sua compreensão do espaço, mas não vos poderá dar sua compreensão.

O músico poderá cantar para vós o ritmo que existe em todo o universo, mas não vos poderá dar o ouvido que capta a melodia, nem a voz que a repete.

E o versado na ciência dos números poderá falar-vos do mundo dos pesos e das medidas, mas não vos poderá levar até lá.

Porque a visão de um homem não empresta suas asas a outro homem.

E assim como cada um de vós se mantém só no conhecimento de Deus, assim cada um de vós deve ter sua própria compreensão de Deus e sua própria interpretação das coisas da Terra."

Khalil Gibran – O Profeta (1923)

SUMMARY

RESUMO

Avaliação dos impactos ecológicos de plantas invasoras em florestas Neotropicais por meio de síntese de evidências

Presentes em todos os ecossistemas do mundo, as espécies invasoras causam impactos ecológicos negativos generalizados na composição, estrutura e funcionamento de seus novos habitat. Simultaneamente a legislações nacionais e acordos internacionais multilaterais que têm sido implementados para mitigar estes impactos, também se observou um crescimento exponencial de publicações sobre a ecologia de invasões nas últimas décadas. O aumento das evidências sobre os impactos ecológicos das plantas invasoras ao longo do tempo tem sido fundamental não só para elucidar as consequências de diferentes espécies em contextos específicos, mas também para permitir esforços de síntese sobre o conhecimento acumulado. Várias revisões no campo da biologia de invasões também destacaram a baixa proporção de pesquisas nos países em desenvolvimento da zona tropical em relação à paises desenvolvidos majoritariamente do hemisfério norte. Reconhecendo que sínteses de evidência são instrumentos vitais para informar a gestão, a política e pesquisas voltadas à conservação e ciências ambientais, a presente dissertação tem como objetivo compilar e analisar sistematicamente os impactos ecológicos das plantas invasoras nos Neotrópicos em dois capítulos complementares. Primeiro, buscamos identificar lacunas e tendências das pesquisas primárias publicadas sobre os impactos ecológicos das plantas invasoras nas florestas tropicais e subtropicais na região neotropical, seguindo uma abordagem de mapeamento sistemático. Em segundo lugar, utilizamos o conjunto de dados do primeiro capítulo para realizar uma meta-análise para estimar a magnitude e direção dos efeitos das plantas invasoras terrestres sobre espécies e comunidades de plantas nativas de florestas tropicais e subtropicais úmidas e secas nos Neotrópicos.

Palavras-chave: Invasões biológicas, Plantas exóticas, Revisão sistemática, Tamanho de efeito, Espécies introduzidas

ABSTRACT

Assessing the ecological impacts of invasive plants in Neotropical forests through evidence synthesis

Present in all ecosystems in the world, invasive species causes widespread negative ecological impacts on the composition, structure and functioning of their invaded habitats. Simultaneously with the emerging federal legislation and multilateral international agreements that have been put in place to mitigate these impacts, there has also been an exponential growth of publications on invasion ecology in the last decades. The increase of evidence on the ecological impacts of invasive plants over time has been critical not only to elucidate the consequences of different species in specific contexts but also to enable synthesis efforts on the accumulated evidence base. Several reviews in the field of invasion biology have also highlighted the low proportion of research in developing countries in the tropical zone relative to developed countries mainly in the northern hemisphere. Recognizing that evidence reviews are vital tools to inform management, policy and research in conservation and environmental science, the present research aims to systematically collate and analyze the ecological impacts of invasive plants in the Neotropics in two complementary chapters. First, we sought to identify gaps and trends in primary research published in the peer-reviewed literature on the ecological impacts of invasive plants in tropical and sub-tropical forests throughout the Neotropics, following a systematic map approach. Second, we used the dataset from the first chapter of this dissertation to perform a meta-analysis in order to estimate the magnitude and direction of the effects of terrestrial invasive plants on native plant species and communities of tropical and subtropical moist and dry Neotropical forests.

Keywords: Plant invasions, Neotropics, Biological invasion, Systematic review, Effect size, Non-native species

1. INTRODUCTION

Even though it's not a recent phenomenon in human history, the translocation of species beyond their natural geographic range has reached unprecedented magnitudes, as a consequence of the greater global connectivity associated with the expansion of flows of goods and people between countries and continents (Jenkins 1996; Perrings et al. 2002; Hulme 2009). Despite the notable economic value of some non-native species for the provision of ecosystem services that are essential for human well-being, such as food, timber and fodder (Castro-Díez et al. 2019), once these species are introduced in a novel environment they can become invasive by overcoming several barriers to their survival, reproduction and dispersal, being able to spread and establish viable populations in areas far from the site of introduction (Blackburn et al. 2011; Richardson et al. 2000). Altough a few non-native species are able to become successful invaders (Richardson et al. 2000), the ecological damages and financial costs caused by them can be substantial (Diagne et al. 2021; Bang et al. 2022).

Present in virtually all ecosystems in the world (van Kleunen et al. 2015), invasive species are known to cause widespread negative ecological impacts on the composition, structure and functioning of their invaded habitats (Vitousek et al. 1997; Simberloff 2005; Crystal-Ornelas and Lockwood 2020). Despite the exponential progress of international agreements and national policies committed to the prevention and management of invasive species (Turbelin, Malamud, and Francis 2017), the loss of biodiversity as a result of biological invasions on a global scale persists at increasing rates (McGeoch et al. 2010). For these reasons, invasive species are considered as threats to several critically endangered species of terrestrial vertebrates and birds (Bellard, Cassey, and Blackburn 2016; Dueñas et al., 2021), and is considered as one of the top five causes of biodiversity loss in the world (IPBES, 2019).

Simultaneously with the policy efforts that have been put in place to mitigate these impacts (Chandra and Idrisova 2011; De Sá Dechoum et al. 2018; Genovesi et al. 2015; Simberloff, Parker, and Windle 2005), there has also been an exponential growth of publications on invasion ecology in the last decades (MacIsaac, Tedla, and Ricciardi 2011; Pyšek and Richardson 2010). These publications have different approaches and applications, such as early detection of newly introduced species, risk assessment, management and eradication strategies, as well as the measurement of invasive species impacts (Keller, Lodge, and Finnoff 2007; Simpson et al. 2009; Wilson et al. 2011; 2013; Ziller et al. 2020). Although studies dedicated to quantify the ecological impacts of invasive species have been slower to emerge than other research foci, these studies have now achieved greater representation in the literature (Pyšek and Richardson 2010), due to their relevance in supporting the prioritization of management efforts to address the most impactful invaders (Parker et al. 1999).

The increase of scientific evidence on the ecological impacts of invasive plants over time has been critical not only to elucidate the consequences of different species in specific contexts (Wardle et al. 2011), but also to enable synthesis efforts on the accumulated evidence base (Lowry et al. 2013). Several reviews published in recent years on the impacts of invasive plants have enabled generalizations about the magnitude and direction of their effects and their variability among a wide range of environmental settings and different levels of ecological complexity (Gaertner et al. 2009; Vilà et al. 2011; Pyšek et al. 2012), as well as to provide an overview of the scientific field over time (Hulme et al. 2013; Castro-Díez et al. 2015).

Several attempts to depict the current state of knowledge in the field of invasion biology have also highlighted the low proportion of research in developing countries in the tropical zone relative to the northern hemisphere (Pyšek et al. 2008; Pyšek and Richardson 2010; Lowry et al. 2013), indicating the need for more studies conducted in tropical ecosystems where conservation efforts should be prioritized and invasive species may exert the greatest impact on biodiversity (Myers et al. 2000; Nuñez and Pauchard 2010). As a result of the economic growth of developing countries associated with the expansion of international trade and a greater pressure on natural resources, an increase in the number of introduced species in these countries and simultaneously a greater vulnerability to biological invasions is expected (Hulme 2009; Nuñez and Pauchard 2010), with a clear trend of greater pressure from invasive plants being already observed in tropical forests (Lopez 2012; Lövei, Lewinsohn, and Network 2012).

Recognizing that evidence reviews are vital tools to inform management, policy and research in conservation and environmental science (Stewart, Coles, and Pullin 2005; Roberts, Stewart, and Pullin 2006; Carpenter et al. 2009), the present research aimed to systematically collate and analyze the ecological impacts of invasive plants in the Neotropics in two complementary chapters:

Chapter 1. *Reviewing research on the ecological impacts of invasive alien plants in neotropical forests: a systematic map approach.* Here, we sought to identify gaps and trends in primary research published in the peer-reviewed literature on the ecological impacts of invasive plants in tropical and sub-tropical forests throughout the Neotropics. Following a systematic map approach, we gathered, categorized and compared characteristics from these studies in order to indicate and discuss topics that need further investigation, as well as knowledge-rich subjects that can be quantitatively analyzed in systematic reviews.

Chapter 2. *Responses of native plant species and communities to plant invasions in tropical and sub-tropical forests: a meta-analysis for the Neotropics*. Here, we used the dataset of included articles from the first chapter of this dissertation to perform a multi-level meta-analysis model to quantify the effects of terrestrial invasive plants on native plants of tropical and subtropical moist and dry forests throughout the Neotropical realm. We calculated the effect sizes to estimate the magnitude and direction of invasive plants impacts on native plants between invaded and uninvaded sites. To better understand sources of heterogeneity, we accounted for the phylogenetic relatedness of invasive species and performed moderator analyses to test whether a set of relevant categorical variables of both invasive plants and invaded sites affected our mean estimates.

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2. REVIEWING RESEARCH ON THE ECOLOGICAL IMPACTS OF INVASIVE ALIEN PLANTS IN NEOTROPICAL FORESTS: A SYSTEMATIC MAP APPROACH

Abstract

Invasive plants are known to cause broad negative ecological impacts on biodiversity and ecosystem services in many regions of the world. These effects can be intensified in fragmented ecosystems that have historically suffered drastic disturbances to their structure, composition, and function, such as tropical and sub-tropical forests. Although several studies have been published recently reporting the ecological impacts of invasive plants in tropical and subtropical forests in the Neotropics, this knowledge has not yet been systematically mapped. In this chapter, we conducted a review incorporating systematic mapping principles aiming to identify gaps and trends in primary research that has measured those impacts in Neotropical dry and moist forests. We show how these studies are geographically distributed among the tropical and sub-tropical dry, moist and coniferous forest biomes, what are the invasive alien plants studied and its growth forms, the methodological approaches employed to measure impacts, and the biological scales and impacted groups (biotic and abiotic features) assessed. The literature search yielded a total of 2870 articles after duplicate removal, of which 67 were included in the review. We tested the reproducibility of the inclusion criteria by the Kappa test, reaching a substantial agreement among two raters. Our results revealed a substantial trend of increasing publications from a period spanning 22 years of research. The majority of studies were carried out in Brazil (55.2%), followed by Argentina (19.4%) and Mexico (7.5%). Moist forests were the most studied biome (83.6%), with the remainder 16.4% in dry forests. We found a total of 44 invasive plants whose impacts were measured, being Poaceae (31.8%) and Fabaceae (20.4%) the most species-rich families. Trees (59.7%) and herbs (33.3%) were also the most studied growth forms, with few evidences for shrubs and vines. Abandoned habitats accounted for more than half of the studies (55.2%), and were the only category that had species belonging to all growth forms. Observations comparing invaded and uninvaded sites (51.35%) were the most adopted study design, with less than 18% for each of the other methods. The vast majority of studies assessed impacts at community-level, whereas ecosystem-level responses to invasions were the least studied (19.8%). In addition, only 28.4% assessed impacts at more than one biological scale. We also found a disproportionate amount of research effort on the response of native plants (57.8%) compared to other taxa and environmental variables related to ecosystem functioning. Based on our results, we fostered a discussion about knowledge-rich subsets, as well as research gaps that need further investigation to broaden our understanding of plant invasion outcomes in Neotropical forests.

Keywords: Neotropics, biological invasions, alien plants, systematic review, ecological effect, forest ecosystems

2.1. Introduction

Among the different organisms, terrestrial plants are the most representative one (32%) in the list of the 100 of the worst invasive species in the world (Luque et al. 2014). Concomitantly, most studies on biological invasions in terrestrial ecosystems are related to plant invasions (Pyšek et al. 2008; Pyšek and Richardson 2010; Lowry et al. 2013; Crystal-Ornelas and Lockwood 2020). However, there is a bias regarding the research foci in the published evidence, where studies concerned with the causes and mechanisms of plant invasions are prevalent over studies on their impacts (Pyšek and Richardson 2010). In other words, the research effort on how biotic and abiotic components of ecosystems changes following plant invasions remain less representative compared to invasibility (e.g. vulnerability of recipient ecosystems to invasion) and invasiveness studies (e.g. ability of a particular species to invade) (Van Kleunen et al. 2010).

Despite the evident and significant ecological impacts caused by invasive plants at different biological scales, whether at the population, community, or ecosystem level (Vilà et al. 2011), quantitative assessments of these impacts on a global scale have been conducted on a few subset of invasive plant species (Hulme et al. 2013), being poorly representative of the potential impacts of these species as a whole, comparing to the current 3008 unique invasive plant taxa identified (Laginhas and Bradley, 2022). It is also noted that the impacts of invasive plants tend to be less studied and less mentioned than the impacts of invasive fauna (Pyšek and Richardson 2010; MacIsaac, Tedla, and Ricciardi 2011). The reasons for such patterns are, for example, that terrestrial invertebrates (e.g. agricultural pests) are more related to economic impacts of high magnitude, having more conspicuous effects than plant invaders and thus attracting more scientific attention (Pyšek and Richardson 2010), as well as that predation by invasive vertebrates and freshwater organisms is a more significant driver of native species extinctions than competition among plants (Blackburn et al. 2004; Vilà et al. 2010).

In addition to the taxonomic bias of researches in the field of biological invasions, the uneven distribution of studies is also pronounced geographically, with a substantial clustering of research in North America and Europe (Pyšek et al. 2008; Pyšek and Richardson 2010). The low representativeness of the tropical region in relation to the volume of scientific knowledge produced about invasive plants does not mean that these species are less important in these regions neither that their impacts are of no concern (Fine 2002; Lowry et al. 2013; Pyšek et al. 2008). Tropical ecosystems harbor the vast majority of the world"s biodiversity and are vital for the provision of ecosystem services (Barlow et al. 2018). However, the tropics have experienced the highest rates of habitat degradation and conversion worldwide, such that the greatest net loss of forest cover in recent decades has occurred in the tropical dry (-95,000 km2, -8% of total biome area) and moist (-84,000 km2, -2%) forest biomes (Song et al. 2018). Such is the importance of these ecosystems that 15 of the 25 (60%) global hotspots for biodiversity conservation are located in the rainforest biome, due to their exceptional concentration of endemic species and high rates of habitat loss (Myers et al. 2000).

Given the progressive loss of primary tropical forests and the trend that structurally smaller and younger native forest stands are increasingly representative in extent (McDowell et al. 2020) secondary forests and degraded remnants emerge as key components for biodiversity conservation (Chazdon et al. 2009) and maintenance of carbon stocks in tropical landscapes (Chazdon et al. 2016). However, these forests are mostly fragmented and interspersed in degraded landscapes, usually in agricultural matrices with the predominance of introduced species, being therefore susceptible to constant biological invasions (Fine 2002; Jakovac et al. 2021). Alien plants present in the surrounding matrices can disperse to natural areas and threaten the development of native species through mechanisms such as allelopathy, competition and hybridization with native species, being able to modify biotic and abiotic features of the ecosystem and inhibit the successional path of the forest community (Blackburn et al. 2014; Catterall 2016).

Regardless of the low representativeness of research on biological invasions in the tropical region, it has been remarkable the growth of scientific publications on the issues of introduced species and their implications for biological conservation in some Neotropical countries (Pauchard et al. 2010; Frehse et al. 2016). A number of recent studies have shown that several invasive plant species in Neotropical forests can modify vegetation structure and composition (Raymundo et al. 2018; Malizia et al. 2017; Baptiste et al. 2019), litter and soil nutrient stocks (Aragón, Sardans, and Peñuelas 2014), avifauna population dynamics (Ayup et al. 2014) and hydrological cycles (Zamora Nasca et al. 2014). Similarly, invasive plants can alter successional trajectories by inhibiting the regeneration of native species (Chiba De Castro et al. 2019; Rojas-Sandoval, Meléndez-Ackerman, and Anglés-Alcázar 2016; Schmidt, Castellani, and Dechoum 2020), changing the canopy openess and light regimes (Schmidt, Castellani, and de Sá Dechoum 2020), as well as decrease biodiversity through mutualistic interactions with other invasive species (Carrera-Martínez et al. 2019).

In view of this trend, the published literature on alien species and invasion ecology in the Neotropics could be compiled and reviewed in a few papers, considering different taxa, geographic scales and research foci (Petenon and Pivello 2008; Pauchard et al. 2010; Zenni and Ziller 2011; Speziale et al. 2012; Valduga, Zenni, and Vitule 2016; Frehse et al. 2016; Ruaro et al. 2020). Despite the undoubted practical and scientific relevance of these reviews, there is still a lack of an up-to-date and comprehensive synthesis accounting for how the impacts of invasive plants have been assessed in neotropical forests, which are facing increasing and threatening levels of biological invasions (Lopez 2012; Lövei, Lewinsohn, and Network 2012).

Therefore, to promote a better understanding of how the ecological impacts of terrestrial invasive plants have been detected and measured in Neotropical forests, we performed a review following the systematic mapping methodology according to some guidelines of the Collaboration for Environmental Evidence (CEE 2018) and Haddaway et al. (2016). Systematic maps are particularly designed to describe the research effort across a broad scientific subject, based on the same reliable procedures of systematic reviews to gather and synthesize information from papers in an objective and replicable manner, aiming to reduce common biases that may arise when conducting a review (such as reporting bias, selection bias and publication bias) (Haddaway et al. 2016). But unlike traditional systematic reviews, the systematic mapping method are not restricted to closed-framed questions neither the use of quantitative techniques to combine the results of primary research. Instead, the coding process in systematic maps focuses on the extraction of each study settings that may be relevant to the topic, thus producing a searchable database of these meta-data variables (Haddaway et al. 2016).

The overview of the current evidence provided by systematic maps is useful to identify knowledge gaps (underrepresented topics) and trends (most researched topics), providing generalizations that may be relevant to advancing the science of biological invasions in the tropics (Lowry et al. 2013; Haddaway et al. 2016). Given this background, this review sets out to summarise the current state of knowledge on the species and plant growth forms studied, at what biological scales the impacts have been quantified, the methodological characteristics employed, as well as the geographical distribution of these studies in the neotropical forest biomes and the typologies of the invaded habitats. These information will be used to identify knowledge gaps and trends, aiming to contribute to the direction of future primary research in the field of invasion ecology, as well as to point out specific topics with the richest data in the evidence base (knowledge clusters) that are suitable for quantitative analysis in subsequent systematic reviews (e.g. meta-analyses) (Berger-Tal et al. 2019). To this end, we addressed the following research questions:

i. How are these studies geographically distributed in the neotropics among the tropical and sub-tropical dry, moist and coniferous forest biomes (Dinerstein et al. 2017) and what are the typologies of the invaded habitats, based on the framework proposed by Kueffer and Daehler (2009)?;
ii. What are the invasive alien plants (IAPs) studied and its growth forms, based on Engemann et al. (2016)?;
iii. What are the methodological approaches employed to quantify the ecological impacts of invasive plants, based on Kumschick et al. (2015)?;
iv. At what biological scales and biotic and abiotic groups have the impacts of invasive plant species been measured (according to the classification by Vilà et al., (2011))?

2.2. Methods

2.2.1. Literature search

The search strategy was employed in a two-step approach. The first was carried out according to the methodological proposal by Grames et al. (2019), aiming to identify the most relevant keywords on the subject of the review in an efficient and automated using the *litseachr* package in R environment (RStudio Team, 2019). Through text mining and keyword co-occurrence networks, this method makes the search strategy less biased and more comprehensive by identifying key terms and synonyms that might otherwise be omitted by the review team (Grames et al. 2019). Thus, we conducted an initial search (hereafter, naïve search) for articles in the online platforms ISI Web of Knowledge Core Collection (databases SCI-E, SSCI, ESCI) and Scopus, without restriction of time or type of document, aiming to retrieve a set of articles of high relevance to the topic of this review. The keywords considered most important were grouped in a search string using the Boolean operators "OR" and "AND" (Appendix A). A total of 386 records were retrieved from the ISI Web of Knowledge and 289 records from the Scopus database, with a total of 459 articles after deduplication. The complete bibliographic data from the naïve search were loaded into the litsearchr package in R environment, which obtained 1023 keywords that were checked and selected for inclusion in the definitive search strategy according to their relevance (see details on the script used in Appendix B).

In the second step, we performed a comprehensive definitive search for articles published in peer-reviewed literature indexed in the following electronic databases: (i) ISI Web of Knowledge Core Collection (SCI-E, SSCI, and ESCI); (ii) Scopus; and (iii) CAB Direct. The literature searches were conducted in March 2022 by combining the following search terms: "*forest*" AND "invasive" OR "invasion" OR "invader" OR "invaded" OR "alien" OR "exotic" OR "non-indigenous" OR "nonindigenous" OR "non-native" OR "nonnative" AND "plant*" OR "tree*" OR "shrub*" OR "woody*" OR "liana*" OR "vine*" OR "herb*" OR "grass*" OR "fern*" OR "forb*" OR "palm*" OR "cact*" OR "bamboo*" OR "epiphyte*" AND "effect*" OR "impact*" OR "affect*" OR "change*" OR "threat*" OR "alter*" OR "influenc*" OR "consequence*" OR "disturbance*". Since the queries retrieved an unfeasible amount of articles (n = 44.898), we then applied a geographical location filter to get only papers in Neotropical countries[1] (including the Caribbean islands), thereby yielding a total of 4,797 articles. All information about the terms, geographical filters and the search dates for each bibliographic source are reported in Table 1.

[1] We included all the Caribbean islands and did not include Chile and Uruguay because these countries aren't covered by the Tropical and Sub-tropical Moist, Dry or Coniferous Forest biomes that fits into the scope of this review. In Web of Science and Scopus, we used the platforms' own tool to apply the filters for the available countries. In the Scopus filter we also selected the "undefined" option to avoid missing relevant articles in countries of interest. After running the CAB Direct search, the platform tool to filter by Geographic Location only showed the countries with more than 49 records. Therefore, unique to this platform we have included a new combination of terms in the search string comprising the names of all countries in the Neotropical region separated by "OR" and grouped by the operator "gl", which applies the filter only to the Geographic Location field.

Table 1. Complete search strategy performed, detailing the combined terms and the geographic location filters applied. Searches were performed on 03/21/2022 and were limited to documents published in English, Portuguese and Spanish. Adapted from Romanelli et al. (2020).

Bibliographic Sources	Search terms
WEB OF SCIENCE (Core Collection: SCI-E, SSCI, ESCI; All years; All documents; TOPIC)	("*forest*") **AND** ("invasive" OR "invasion" OR "invader" OR "invaded" OR "alien" OR "exotic" OR "non-indigenous" OR "nonindigenous" OR "non-native" OR "nonnative") **AND** ("plant*" OR "tree*" OR "shrub*" OR "woody*" OR "liana*" OR "vine*" OR "herb*" OR "grass*" OR "fern*" OR "forb*" OR "palm*" OR "cact*" OR "bamboo*" OR "epiphyte*") **AND** ("effect*" OR "impact*" OR "affect*" OR "change*" OR "threat*" OR "alter*" OR "influenc*" OR "consequence*" OR "disturbance*")) **Available filters**: Brazil, Argentina, Mexico, Colombia, Panama, Ecuador, Uruguay, Costa Rica, Venezuela, Bolivia, Peru, Cuba, Trindad Tobago, Bahamas, French Guiana, Guyana, Jamaica, Dominica, Dominican Rep, Haiti, Honduras, Paraguay, St Kitts Nevi, St Lucia. **Total number of records:** 11.794 **Filtered records:** 1.409

SCOPUS (All years, All documents and Access type; TITLE-ABS-KEY)	(TITLE-ABS-KEY ("*forest*") **AND** TITLE-ABS-KEY ("invasive" OR "invasion" OR "invader" OR "invaded" OR "alien" OR "exotic" OR "non-indigenous" OR "nonindigenous" OR "non-native") **AND** TITLE-ABS-KEY ("plant*" OR "tree*" OR "shrub*" OR "woody*" OR "liana*" OR "vine*" OR "herb*" OR "grass*" OR "fern*" OR "forb*" OR "palm*" OR "cact*" OR "bamboo*" OR "epiphyte*") **AND** TITLE-ABS-KEY ("effect*" OR "impact*" OR "affect*" OR "change*" OR "threat*" OR "alter*" OR "influenc*" OR "consequence*" OR "disturbance*")) **AND** (LIMIT-TO (AFFILCOUNTRY , "Brazil") OR LIMIT-TO (AFFILCOUNTRY , "Argentina") OR LIMIT-TO (AFFILCOUNTRY , "Mexico") OR LIMIT-TO (AFFILCOUNTRY , "Colombia") OR LIMIT-TO (AFFILCOUNTRY , "Panama") OR LIMIT-TO (AFFILCOUNTRY , "Puerto Rico") OR LIMIT-TO (AFFILCOUNTRY , "Ecuador") OR LIMIT-TO (AFFILCOUNTRY , "Costa Rica") OR LIMIT-TO (AFFILCOUNTRY , "Venezuela") OR LIMIT-TO (AFFILCOUNTRY , "Peru") OR LIMIT-TO (AFFILCOUNTRY , "Bolivia") OR LIMIT-TO (AFFILCOUNTRY , "Cuba") OR LIMIT-TO (AFFILCOUNTRY , "Jamaica") OR LIMIT-TO (AFFILCOUNTRY , "Bahamas") OR LIMIT-TO (AFFILCOUNTRY , "Trinidad and Tobago") OR LIMIT-TO (AFFILCOUNTRY , "Dominican Republic") OR LIMIT-TO (AFFILCOUNTRY , "French Guiana") OR LIMIT-TO (AFFILCOUNTRY , "Guatemala") OR LIMIT-TO (AFFILCOUNTRY , "Honduras") OR LIMIT-TO (AFFILCOUNTRY , "Belize") OR LIMIT-TO (AFFILCOUNTRY , "Bermuda") OR LIMIT-TO (AFFILCOUNTRY , "Dominica") OR LIMIT-TO (AFFILCOUNTRY , "Guadeloupe") OR LIMIT-TO (AFFILCOUNTRY , "Guyana") OR LIMIT-TO (AFFILCOUNTRY , "Haiti") OR LIMIT-TO (AFFILCOUNTRY , "Undefined")) **Total number of records:** 12.748 **Filtered records:** 1.689

CAB DIRECT (All years, All documents; All Fields)	"*forest*" **AND** "invasive" OR "invasion" OR "invader" OR "invaded" OR "alien" OR "exotic" OR "non-indigenous" OR "nonindigenous" OR "non-native" OR "nonnative" **AND** "plant*" OR "tree*" OR "shrub*" OR "woody*" OR "liana*" OR "vine*" OR "herb*" OR "grass*" OR "fern*" OR "forb*" OR "palm*" OR "cact*" OR "bamboo*" OR "epiphyte*" **AND** "effect*" OR "impact*" OR "affect*" OR "change*" OR "threat*" OR "alter*" OR "influenc*" OR "consequence*" OR "disturbance*" **AND** **gl:** ("Anguilla" OR "Antigua" OR "Argentina" OR "Aruba" OR "Bahamas" OR "Barbados" OR "Barbuda" OR "Belize" OR "Bermuda" OR "Bolivia" OR "Brazil" OR "British Virgin Islands" OR "Cayman Islands" OR "Costa Rica" OR "Cuba" OR "Colombia" OR "Dominica" OR "Dominican Republic" OR "Ecuador" OR "El Salvador" OR "Falkland Islands" OR "French Guiana" OR "Grenada" OR "Guadeloupe" OR "Guatemala" OR "Guyana" OR "Haiti" OR "Honduras" OR "Jamaica" OR "Martinique" OR "Mexico" OR "Montserrat" OR "Netherlands Antilles" OR "Nicaragua" OR "Panama" OR "Paraguay" OR "Peru" OR "Puerto Rico" OR "Saint Kitts and Nevis" OR "Saint Lucia" OR "Saint Martin" OR "Saint Vincent and the Grenadines" OR "Saint-Barthélemy" OR "Suriname" OR "Trinidad and Tobago" OR "Turks and Caicos Islands" OR "United States Virgin Islands" OR "Venezuela") **Total number of records:** 20.356 **Filtered records:** 1.699

The complete bibliographic data of the searches were downloaded in .bib format and the duplicates were removed by title and DOI, using the revtools package in RStudio (RStudio Team 2019; Westgate 2019; Appendix C). The output is a spreadsheet containing all the bibliographic information of the deduplicated articles and was further used to screen the articles by title and abstract.

2.2.2. Article screening and study elegibility criteria

All the remaining articles (n = 2870) after duplicate removal were screened initially by titles and abstracts in order to identify the study's potential to meet the inclusion criteria and therefore be selected for the full-text screening. We structured each inclusion criteria within the PECO framework (Population, Exposure, Comparator, Outcomes), which is often used in systematic reviews to formulate objective and informative research questions and elegibility criteria (Morgan et al. 2018). To be included in the evidence base of the review, each article had to meet the following inclusion criteria:

i) Population: The study was carried out in forest ecosystems within the Neotropics comprised by the following biomes: i) Tropical & Subtropical Moist Broadleaf Forests; ii) Tropical & Subtropical Dry Broadleaf Forests; and iii) Tropical & Subtropical Coniferous Forests, according to Dinerstein et al. (2017). These are the forested biomes within the tropical and subtropical zones in the Neotropical realm. Therefore, studies on the following biomes were not eligible for this review: Boreal Forests/Taiga, Deserts & Xeric Shrublands, Flooded Grasslands and Savannas, Mangroves, Mediterranean Forests, Woodlands & Scrub, Montane Grasslands and Shrublands, Temperate Broadleaf & Mixed Forests, Temperate Conifer Forests, Temperate Grasslands, Savannas and Shrublands, Tropical & Subtropical Grasslands, Savannas and Shrublands, and Tundra. We included studies of invasions on disturbed sites undergoing early secondary succession and abandoned areas where the original vegetation was comprised by tropical or sub-tropical forests. Nevertheless, we excluded studies on anthropogenic habitats such as agricultural areas, active pastures and silvicultural plantations;

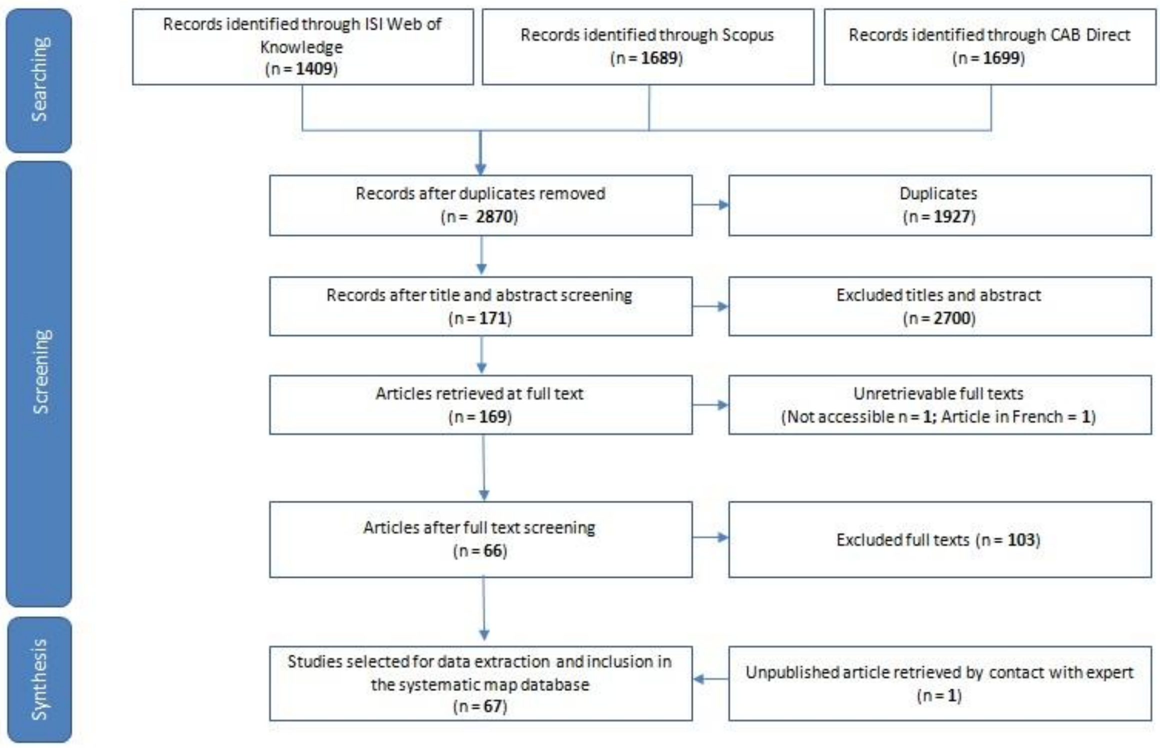
ii) Exposure: The studied species is a terrestrial invasive alien plant. For the article to be included the alien plant species must have been described as invasive by the author(s) and its scientific name provided;

iii) Comparator: As it was our interest to evaluate the study's setting and design, both observational and manipulative experimental primary research was eligible for this review. This included non-field experimental assessments (e.g. species additions in controlled environmental conditions such as greenhouses);

iv) Outcomes: The study must have assessed the ecological impact at any biological scale (i.e. population, community or ecosystem) associated with one or more terrestrial invasive plants, i.e. a measurable change in the properties of an ecosystem caused by the invasive plant, which may be positive or negative and vary in magnitude on a continuous scale (Ricciardi et al. 2013). Studies on the impact of invasive plants on other alien species (e.g. crops) will not be included, nor will studies that address the consequences of expansion or colonization of native species.

We also did not include reviews, meta-analyses and opinion articles. Completion of the screening processes left us with of 67 publications selected for data extraction and inclusion in the systematic map database (Figure 1; Appendix D.). For the sake of transparency, the list with all articles excluded by the full-text screening (n = 103) are available indicating the detailed reasons for exclusion (Appendix E.).

Figure 1. Flow diagram describing the article selection procedure on the ecological impacts of invasive plants in tropical and sub-tropical moist and dry forests in the Neotropics. Adapted from ROSES Flow Diagram for Systematic Reviews Version 1.0.



Recognizing that the inclusion and exclusion of papers can be based on subjective criteria, all articles selected for full-text screening (n = 169) were analyzed by a second rater and the decisions compared using the Cohen's Kappa agreement test (Cohen 1960). Cohen's Kappa coefficient is a statistic that is used to measure the degree of inter-rater and intra-rater reliability between proportions derived from dependent samples on categorical nominal scales (Cohen 1960; Silva and Paes 2012), being widely used in systematic reviews to evaluate the reliability of the inclusion criteria in the screening and data extraction stages (Belur et al. 2018; Park and Kim 2015; Romanelli et al. 2020). The Kappa coefficient is calculated by the Eq. (1):

$$K = \frac{P_O - P_E}{1 - P_E} \quad (1)$$

Where:

$$P_O = \text{Observed proportion of agreement among raters}$$

$$P_E = \text{Proportion of agreement expected by chance}$$

Thus, the coefficient value can be directly interpreted as the proportion of judgments in which there is agreement, after excluding the agreement expected only by chance. As a suggestion to ease the interpretation of the strength of agreement associated with the Kappa value, McHugh et al. (2012) assigned the following benchmarks corresponding to six distinct intervals:

Table 2. Benchmarks for Kappa coefficient interpretation (McHugh et al., 2012).

Value of Kappa	Level of Agreement
0.00 - 0.20	None
0.21 - 0.39	Minimal
0.40 - 0.59	Weak
0.60 - 0.79	Moderate
0.80 - 0.90	Strong
> 0.90	Almost Perfect

The Kappa test showed that there is moderate reliability among observers (k = 0.69 [95% Lower/Upper CI: 0.58 – 0.79]; agreement = 84.1%). As established in other systematic review protocols, we set the value of k ≥ 0.60 as an indicator of substantial agreement and that decisions were sufficiently repeatable (Bayliss et al. 2015; Reed, Deakin, and Sunderland 2014; Schindler et al. 2016; Martin et al. 2020; Romanelli et al. 2020). If the score obtained was lower than 0.60, the inconsistencies between the two raters would be discussed until consensus was reached, with subsequent redefinition of the inclusion criteria in order to reduce subjectivity in the decision process (inclusion or exclusion of articles).

2.2.3. Coding and data extraction

Studies included by full-text screening were coded by recording the bibliographic information and study characteristics shown below for inclusion in the review database (Table 3).

Table 3. Description of the information and classifications assigned to each study included in the systematic map database.

Category	Variable	Description
Publication details	Paper	Article unique ID
	Author	Authors' name
	Title	Publication title
	Year	Year of publication
	Journal	Journal where the paper was published
Population	Country	Country of study sites
	Coordinates	Geographic coordinates of study sites
	Biome	Tropical and Subtropical Moist, Dry or Coniferous Forests (Dinerstein et al., 2017)
	Ecoregion	Name of the Ecoregion where the study was conducted
	Typology	Abandoned Habitat, Designed Habitat (i.e. Active Restoration) or Reference Habitat, according to Kueffer and Daehler (2009). The definition of each habitat in this framework is presented in Appendix F. We also included the Forest Edge habitat classification based on our observations. Some studies were conducted in environments such as greenhouses, nurseries, common gardens and laboratories, which we coded as Non-Field.
Exposure	IAP Family	Invasive Alien Plant botanical family
	IAP Binomial	Invasive Alien Plant scientific name. We standardized the scientific name of each species based on the accepted taxon name provided by The World Flora Online (WFO 2022).
	Growth Form	Plant growth form (i.e. herb, shrub, tree, and vine) according to the global database of plant growth forms from Engemann et al. (2016)
	Time Introd	Time, in years, since the alien species was introduced into the region, if reported
	Time Inva	Time, in years, since the alien species invaded the study sites, if reported
Comparator	Method	Observational or Experimental study
	Study Design	Study design, based on Kumschick et al. (2015) classification (Appendix G): Abundance Gradient, Addition, Chronosequence of Invasion, Invaded vs Uninvaded, Removal vs Invaded, Removal vs Uninvaded, Invasive and Native Removal.
Outcomes	Biotic Abiotic	Biotic or Abiotic impacted groups
	Biological Scale	Biological scales at which the ecological impact was measured, which may be at the level of plant populations, plant communities, animal populations, animal communities, and ecosystem (Vila et al., 2011; Definitions in Appendix H.)
	Groups	Impacted groups: Plants, Vertebrates, Invertebrates,

	Microorganisms, Soil Chemistry, Soil Physics, Litter, and Fire regimes.

The geographic coordinates of each study were loaded as a point layer into QGIS 3.18.1 software to obtain the biome and ecoregion information for the study sites, based on the shapefile provided by the Ecoregions 2017© application (Dinerstein et al. 2017; QGIS.org 2021).

2.2.4. Synthesis and presentation of results

To asssess the cumulative time trend in the number of published articles, we fitted a linear regression model with the year of publication as the predictor variable, and the number of publications per year as the response variable. We removed articles from 2022 from the analysis because we did not capture all possible articles published in this year. We also prepared a thematic map in QGIS 3.18.1 - Zürich software with the geographic location of the studies, allowing us to visualize how they are distributed among countries and Neotropical biomes (QGIS.org 2021). The scientific names of the invasive plant species that have had their ecological impacts measured in tropical and subtropical forests of the Neotropics were listed along with the categorical information associated with those species, such as growth form, frequency (number of studies for each species), biomes and countries in which they were studied.

We present the results in plots prepared in the ggplot2 package in RStudio software (Wickham 2016; RStudio Team 2019), and the narrative synthesis of the evidence base was described from the identified gaps and patterns, which was discussed based on the representativeness of each category and the relationship between them. Associatedly, systematic maps also aim to produce accessible databases that integrate all the descriptive information of the studies included in the review, being a useful resource for researchers and decision makers searching for scientific evidence on a given topic (Haddaway et al. 2016).

Then, the retrieved literature will be made available in a searchable, freely accessible database upon publication, synthesizing all information from the studies obtained during the review process. The spreadsheet containing all the information from the reviewed literature will be also made available, along with an interactive map (.html) to allow free exploration of the data by interested users through the EviAtlas application (https://estech.shinyapps.io/eviatlas) (Haddaway et al. 2019). EviAtlas is an Open Access and Open Source multifunctional tool designed to produce and share static and interactive visualizations of data compiled into a systematic map, such as spatial maps, readable data tables, histograms, and heat maps, enabling users to filter and examine the data they want to query and visualize. By doing so, the app ensures that systematic map results can be easily communicated and understood (Haddaway et al. 2019).

2.2.5. Limitations

As with any research, reporting on the methodological limitations of a review is essential to ensure that readers can more critically qualify the interpretation of the results and conclusions of the evidence synthesis (CEE 2018). In this regard, due to time and resource constraints, it was not possible to follow all CEE standards and guidelines, such as publishing the review protocol before conducting the study, involving several stakeholders at the stage of defining the research question and methods, and including gray literature in the search strategy. Given the broad geographical scope of this research, the inclusion of grey literature (e.g. theses and dissertations, technical reports, and conference proceedings) would involve undertaking non-systematic search strategies in databases of regional institutions and academic repositories from several different countries. Additionally, such literature does not go through the peer-review sieve. While this is an important procedure for attempting to capture the entire existing evidence base on the review topic, the process of conducting additional searches for gray literature often demands significant time in systematic reviews (Haddaway et al. 2015).

In general, Haddaway et al. (2015) recognize that the resource demands required to strictly follow systematic review standards and guidelines can be prohibitive for researchers and organizations operating under time constraints and limited budgets, given the need to coordinate multiple reviewers, process large volumes of research findings, and involve a team of expert consultants. In this regard, the authors recommend that in cases where conducting a full systematic review is not feasible, it is possible to incorporate some consolidated methodological guidelines in order to reduce biases and substantially improve the reliability of the review (Haddaway et al. 2015). Despite the limitations stated, we incorporated several principles to enhance the objectivity, transparency, and repeatability of the review (Haddaway et al. 2015; 2016; CEE 2018), such as: (i) planning the questions and drafting the inclusion criteria before the search began and consulting with researchers who are experts on the topic; (ii) developing a comprehensive search strategy in several databases, these being Scopus, CABDirect and SCI-E, SSCI, ESCI of the Web of Science, gathering studies in English, Portuguese and Spanish languages; (iii) transparency at all stages of the literature search, with subsequent application of the Kappa agreement test between different raters in the screening stage of the studies to verify the objectivity of the inclusion criteria.

2.3. Results

Our dataset contained a total of 67 peer-reviewed papers on the ecological impacts of terrestrial invasive alien plants in Neotropical forests published between 2000 and 2022 (Figure 2A). During this period spanning 22 years of research, there was a gap of three years without publications between 2007 and 2009, from which we detected a clear and substantial trend of increasing publications over the years ($r^2 = 0.53$, $p < 0.001$), with remarkable growth from 2010 onwards (Figure 2B). With regard to geographical distribution, we found publications in eight different countries: Brazil (n = 37, 55.22%), Argentina (n = 13, 19.40%), Mexico (n = 5, 7.46%), Puerto Rico (n = 4, 5.97%), Panama (n = 3, 4.48%), Colombia (n = 2, 2.98%), Jamaica (n = 2, 2.98%) and Costa Rica (n = 1, 1.49%). The most studied biome was Tropical & Subtropical Moist Broadleaf Forests, accounting for 83.58% of the studies (n = 56), whereas Tropical & Subtropical Dry Broadleaf Forests represented only 16.42% with 11 papers (Figure 3). The region in Central and North America covered by the Tropical & Subtropical Coniferous Forests biome had no publications about the ecological effects of invasive plants. We highlight that there were only three studies in the Amazon Rainforest, with a noteworthy research focus in the Brazilian Atlantic Forest and in the Southern Andean Yungas ecoregion in Argentina.

Figure 2. Relationship between the number of articles and year of publication. A) Barplot showing the number of published studies from January 2000 to May 2022. B) Scatterplot with regression line and model results. Papers from 2022 were removed from analysis because they were retrieved before the end of the year.

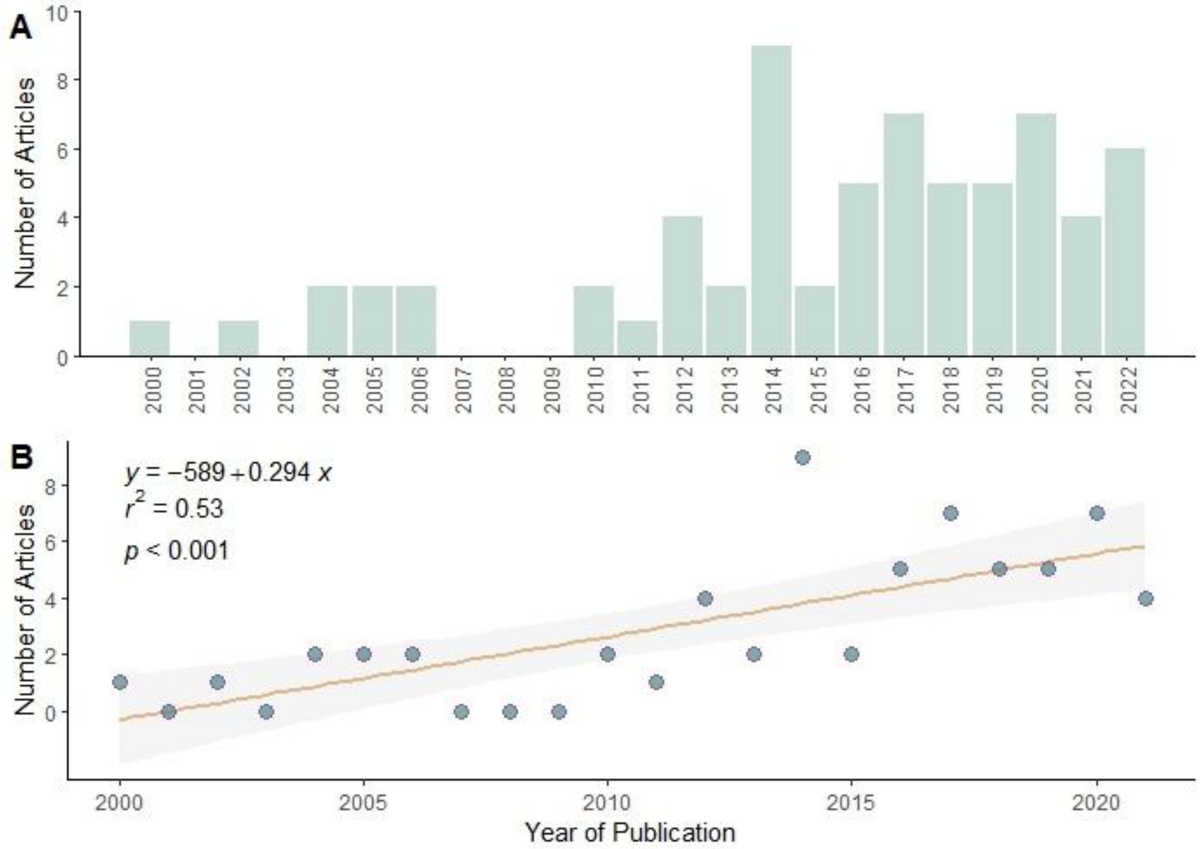
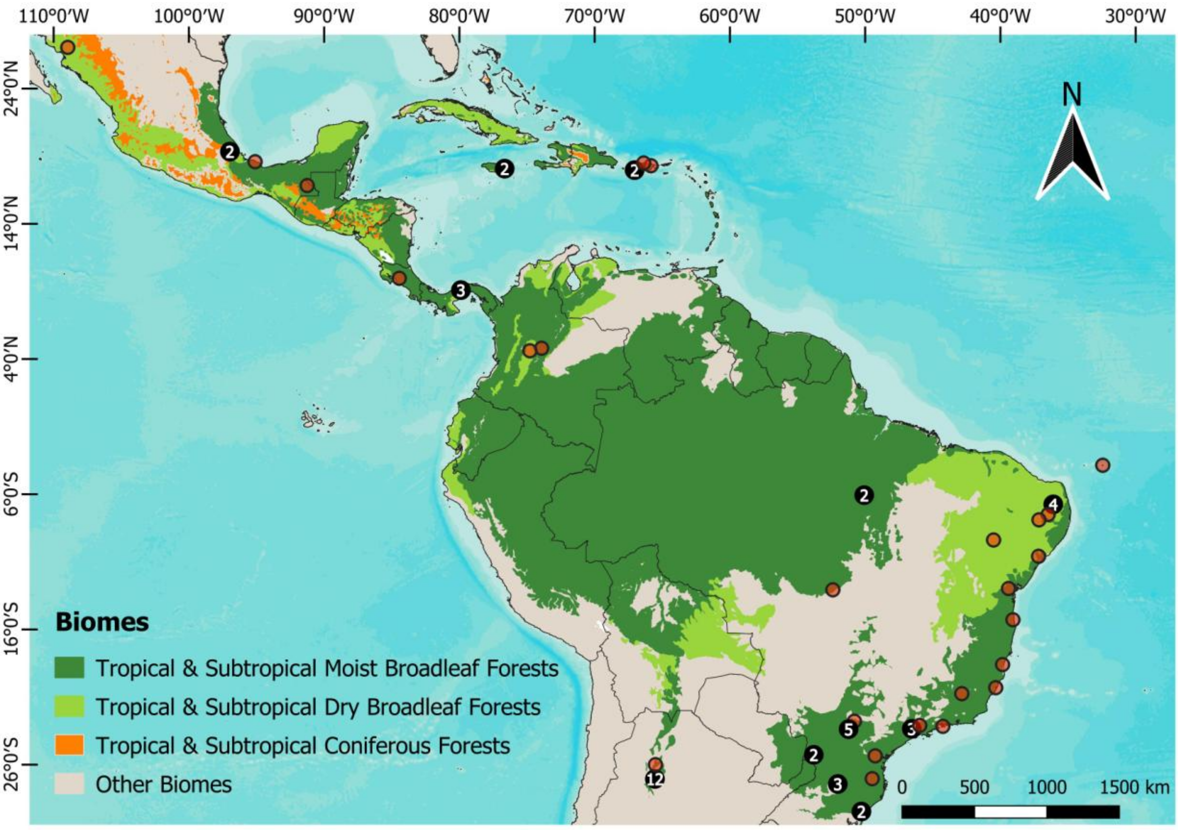


Figure 3. Distribution of sixty seven studies on the ecological impacts of invasive alien plants across tropical and subtropical moist and dry forests in the Neotropics (the symbol on the Atlantic Ocean belongs to the Fernando de Noronha archipelago). No studies were found in coniferous forests. Light red circles are single study sites and the black circles represent the number of clustered study sites in the same coordinates or spaced up to 0.5 degrees apart (map units). Biomes shapefile from Dinerstein et al. (2017) licensed under CC-BY 4.0.



In total, 44 invasive alien plants had their ecological impacts quantified and published (Table 4). The most frequently studied plant species in the reviewed publications were by far *Ligustrum lucidum* (n = 13, 19.40%), followed by *Prosopis juliflora* (n = 7, 10.45%), *Artocarpus heterophyllus* (n = 5, 7.46%), *Hovenia dulcis* (n = 4, 5.97%) and *Panicum maximum* (n = 4, 5.97%). The species *Saccharum spontaneum*, *Urochloa brizantha*, *Urochloa decumbens*, *Cynodon plectostachyus*, *Pittosporum undulatum*, *Syzygium jambos* and *Tradescantia zebrina* were targeted by 3 articles (4.48%) each. The majority of species in our dataset were represented by only one article (n = 28, 63.64%). Of the 15 plant families found, those with the greatest number of species were Poaceae (n = 14, 31.82%), Fabaceae (n = 9, 20.45 %), Arecaceae (n = 5, 11.36%) and Moraceae (n = 3, 6.82%). Myrtaceae and Oleaceae had two species each (4.54%), with the remaining 9 families being represented with only one species.

Table 4. List of invasive plant species (n = 44) whose ecological impacts have been measured in Neotropical forests and published in scientific literature, including information on the species' growth form, biome and country in which it was studied, and the number and percent of papers.

Family	Species	Growth Form	Biome	Country	Frequency
Apocynaceae	*Cryptostegia madagascariensis*	Shrub	Dry	Brazil	1 (1.49 %)
Arecaceae	*Archontophoenix alexandrae*	Tree	Moist	Brazil	1 (1.49 %)
	Archontophoenix cunninghamiana	Tree	Moist	Brazil	1 (1.49 %)
	Archontophoenix sp.	Tree	Moist	Brazil	1 (1.49 %)
	Livistona chinensis	Tree	Moist	Brazil	2 (2.98 %)

Family	Species	Growth Form	Biome	Country	Frequency
	Phoenix roebelenii	Tree	Moist	Brazil	1 (1.49 %)
Combretaceae	*Terminalia catappa*	Tree	Moist	Brazil	1 (1.49 %)
Commelinaceae	*Tradescantia zebrina*	Herb	Moist	Brazil	3 (4.48%)
Euphorbiaceae	*Ricinus communis*	Shrub	Moist	Brazil	1 (1.49 %)
Fabaceae	*Acacia auriculiformis*	Tree	Moist	Brazil	1 (1.49 %)
	Acacia farnesiana	Tree	Dry	Colombia	1 (1.49 %)
	Acacia mangium	Tree	Moist	Brazil	1 (1.49 %)
	Leucaena leucocephala	Tree	Moist	Brazil	2 (2.98 %)
	Parkinsonia aculeata	Tree	Dry	Brazil	1 (1.49 %)
	Prosopis juliflora	Tree	Dry	Brazil / Colombia	7 (10.45 %)
	Schizolobium parahyba	Tree	Moist	Brazil	1 (1.49 %)
	Sesbania virgata	Shrub	Dry	Brazil	1 (1.49 %)
	Ulex europaeus	Shrub	Moist	Colombia	1 (1.49 %)
Moraceae	*Artocarpus heterophyllus*	Tree	Both	Brazil	5 (7.46 %)
	Morus alba	Tree	Moist	Argentina	2 (2.98 %)
	Morus sp.	Tree	Moist	Argentina	1 (1.49 %)
Myrtaceae	*Syzygium cumini*	Tree	Moist	Brazil	1 (1.49 %)
	Syzygium jambos	Tree	Moist	Costa Rica/ Puerto Rico	3 (4.48%)
Nephrolepidaceae	*Nephrolepis brownii*	Herb	Moist	Mexico	1 (1.49 %)
Oleaceae	*Jasminum fluminense*	Vine	Dry	Puerto Rico	1 (1.49 %)
	Ligustrum lucidum	Tree	Moist	Argentina	13 (19.40 %)
Pinnaceae	*Pinus spp.*	Tree	Moist	Brazil	1 (1.49 %)
Pittosporaceae	*Pittosporum undulatum*	Tree	Moist	Brazil / Jamaica	3 (4.48%)
Poaceae	*Andropogon gayanus*	Herb	Moist	Brazil	1 (1.49 %)
	Bambusa longispiculata	Herb	Moist	Puerto Rico	1 (1.49 %)
	Bambusa tulda	Herb	Moist	Puerto Rico	1 (1.49 %)
	Bambusa tuldoides	Herb	Moist	Puerto Rico	1 (1.49 %)
	Bambusa vulgaris	Herb	Moist	Puerto Rico	1 (1.49 %)
	Urochloa brizantha	Herb	Moist	Brazil	3 (4.48%)
	Urochloa decumbens	Herb	Moist	Brazil	3 (4.48%)
	Cenchrus ciliaris	Herb	Dry	Mexico / Puerto Rico	2 (2.98 %)
	Cynodon plectostachyus	Herb	Moist	Mexico	3 (4.48%)
	Dendrocalamus strictus	Herb	Moist	Puerto Rico	1 (1.49 %)
	Melinis minutiflora	Herb	Moist	Brazil	1 (1.49 %)
	Melinis repens	Herb	Moist	Brazil	1 (1.49 %)

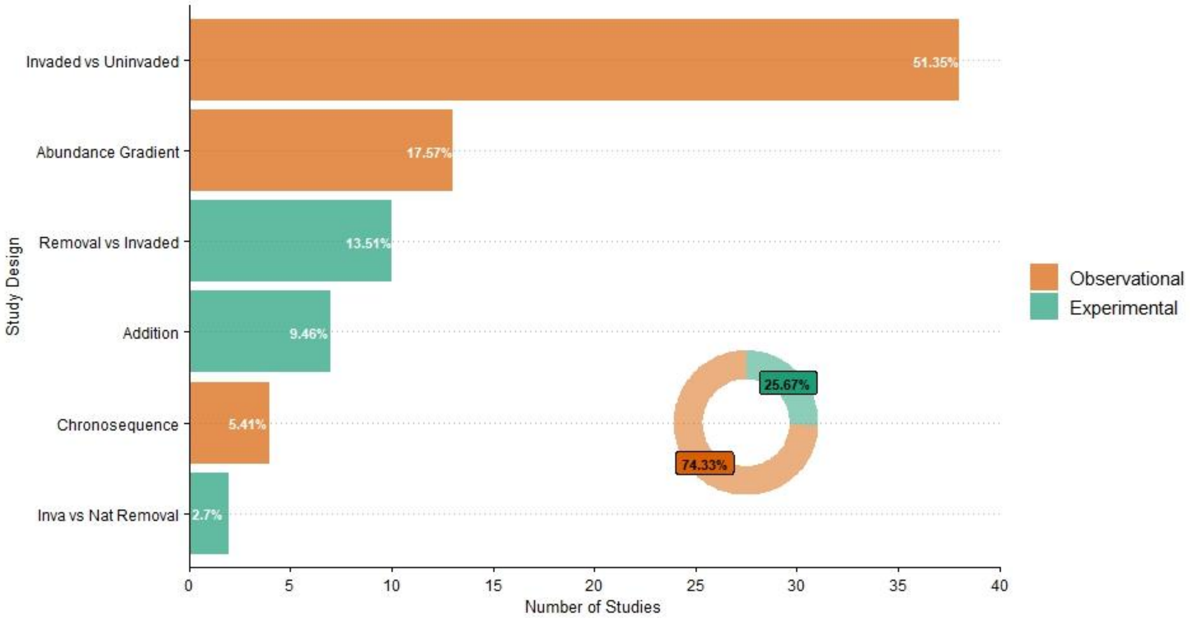
Family	Species	Growth Form	Biome	Country	Frequency
	Panicum maximum	Herb	Both	Brazil / Puerto Rico	4 (5.97 %)
	Saccharum spontaneum	Herb	Moist	Panama	3 (4.48%)
Rhamnaceae	*Hovenia dulcis*	Tree	Moist	Brazil	4 (5.97 %)
Zingiberaceae	*Hedychium coronarium*	Herb	Moist	Brazil	1 (1.49 %)

Most of the invasive plant growth forms were trees (n = 43, 59.72%) and herbs (n = 24, 33.33%), with only four evidences for shrubs (n = 4, 5.56%) and one for vines (n = 1, 1.39%), in a total of 72 case studies since a few papers addressed more than one species belonging to different growth forms. By exploring the association between growth forms and invaded habitats (see Appendix F for definitions), we found that herbs were the only growth form studied in every habitat and the only one studied in sites undergoing active forest restoration (Figure 4). Among the invaded site typologies, abandoned habitats accounted for more than half of the studies (n = 37, 55.22%), and was the only category that had studies with species belonging to all growth forms (Figure 4). The other categories were much less representative, such as reference habitats (n = 13, 19.40%), which were mostly invaded by tree species, designed habitats (n = 8, 11.94%), non-field (n = 6, 8.95%) and forest edge (n = 3, 4.48%). We were unable to assign a typology to three field studies within these categories due to the lack of detailed information on the invaded areas.

Figure 4. Heatmap showing how the invaded habitats and plant growth forms are clustered. Values are number of studies.

The majority of the papers were based on observational approaches to assess the ecological effects of plant invasions (n = 52, 74.33%), whilst experimental studies accounted for 25.67% (n = 17). Only two studies combined both field observational and experimental methods. The most commonly adopted study design was based on comparisons between invaded and uninvaded sites (n = 38, 51.35%), with less than 18% for each of the other methods (Figure 5). We did not find any studies comparing sites before and after plant invasions, nor studies comparing the invasive species removal treatment with a reference site without the invader presence. However, two studies actualy had ecological data from the study sites before the invasion took place. Looking at the invasion process, only 12 articles (17.91%) reported the approximate year when the invasion by the target species into the study area occurred. Likewise, information on the year or period when a particular non-native species was introduced to the region, considering a broader geographic scale, was provided by only 20 articles (29.85%). Surprisingly, almost half of the reviewed papers did not provide none of the above information (n = 35, 52.24%).

Figure 5. Number and percentage of studies for each observational, experimental or modeling design used to measure invasive plant ecological impacts.



Interestingly enough, trees were the only growth form studied by all the six different study design approaches found in our review, and herbaceous species just have not been addressed in chronosequence studies. However, most observational field studies comparing invaded and non-invaded areas dealt with invasive trees (62.03%), while the remainder was made up of herbaceous plants (31.65%) and shrubs (5.1%). Taking the twelve case studies that used field removal experiments (both removal vs invaded and invasive vs native removal) into account, we saw that mostly herbaceous species were addressed (n = 10, 83.33%), with only two invasive tree removal studies (16.66 %).

Looking at the biological scales at which impacts have been quantified, we revealed that the vast majority of studies are focused on biotic impacts (80.23%), with greater representation of community-level effects on both native flora and fauna compared to impacts assessed at the population level (Figure 6). Effects of invasive plants assessed at ecosystem-level accounts for 19.27% of case studies in our review. In addition, of the 67 articles, 48 (71.64%) assessed impacts at only one biological scale and 19 (28.36%) at more than one scale. Of these 19, virtually half (n =10, 52.63%) studied both biotic and abiotic impacts. Considering the biotic and abiotic groups impacted, there is a disproportionate amount of research evaluating the response of native plants (n = 48, 57.83%) compared to other taxa and environmental variables related to ecosystem functioning (Figure 7). The number of publications investigating the impact of invasive plants on organisms of different trophic levels was low and quite similar among vertebrates (7.23%), invertebrates (4.82%), and microorganisms (6.02%) groups. Ecosystem-level impact assessments are still incipient compared to those assessed on populations and communities of living organisms, being mostly studied on the litter dynamics (n = 8) and soil chemistry (n = 6).

Figure 6. Number and percentage of studies for each biological scale in which invasive plant impact was measured.

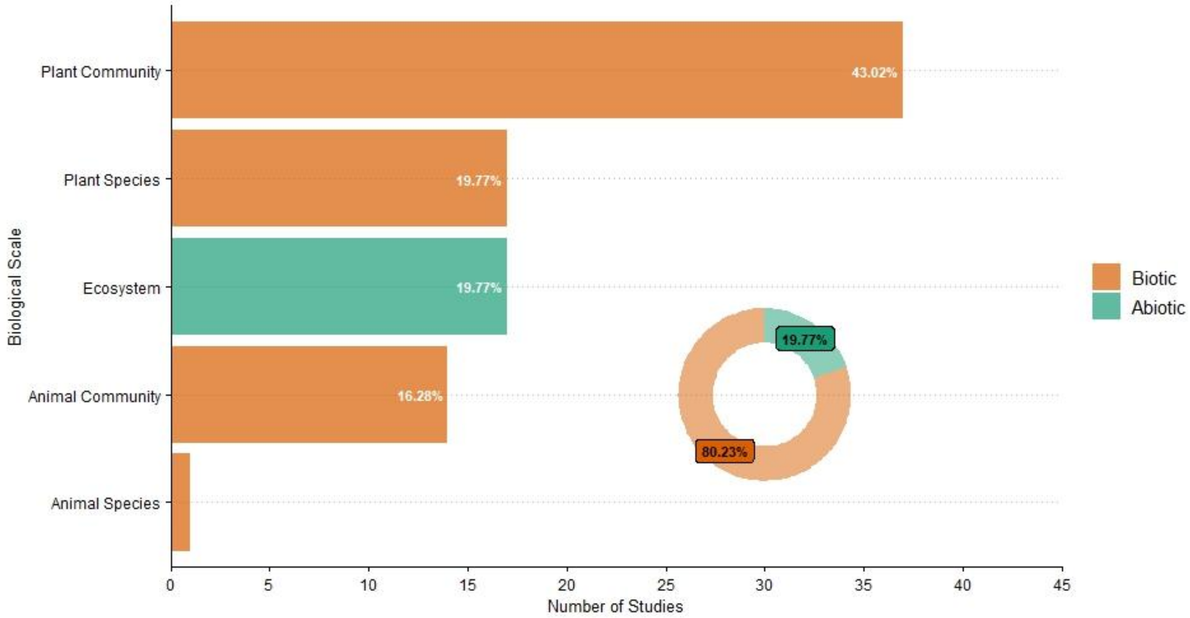
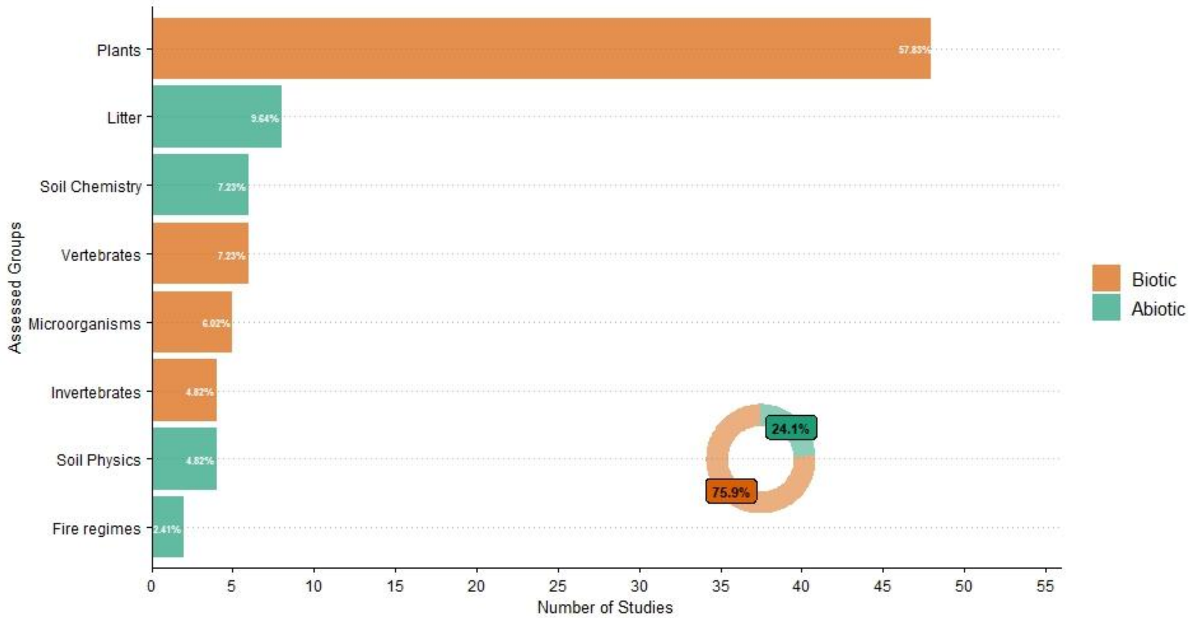


Figure 7. Number and percentage of studies for each biotic and abiotic group in which invasive plant impact was measured.



2.4. Discussion

The first paper that quantified the ecological impact of an invasive plant on a tropical forest ecosystem in the Neotropics was published exactly one year after the subject was first and broadly reviewed by Parker and colleagues back in 1999. Even though this causal relationship may not exist, it is recognized that this (frame-)work was a milestone in driving the development of new primary research on the ecological effects of invasive species (Crystal-Ornelas and Lockwood, 2020), although the substantial increase in publications that we evidenced only came about ten years later. Despite our optimism about the desirable trend of increasing knowledge on plant invasion effects, we understand that it is not exclusive to this topic and most likely mirrors the exponential increase in the production rate of scientific papers, which has been shown to be similar across different disciplines (Bornmann and Mutz, 2015) and even among several sub-fields of the biological sciences on a global scale (Pautasso, 2012).

Being the country with the especially largest area of the reviewed biomes, we already predicted to find Brazil as the leading Neotropical country with respect to available evidence on the consequences of plant invasions, especially throughout the mega-diverse and threatened Brazilian Atlantic Forest. Our results are consistent with recent work that found the Brazilian Atlantic forest to hold not only the largest volume of studies on invasive plant impacts in the country (Zenni et al., 2022), but also the largest number of invasive species (Dechoum et al., 2021) and naturalized plants (Zenni, 2015), which draws our attention to an increased likelihood of more species becoming successful invaders in the Atlantic Forest and potentially causing novel environmental damages anytime soon (Rejmanék and Randall, 2004). Surprisingly, the country with the second highest number of publications was Argentina. We did not expect this result since the extent of subtropical moist forests covers only about 2.6% of its territory. Interestingly, all studies in the country have targeted a single invader (Ligustrum lucidum) in the Southern Andean Yungas ecoregion, which had a great extent of its native subtropical montane forests cleared for agricultural and grazing, being invaded after land abandonment (Fernandez et al., 2017; Malizia et al., 2017). In addition to L. lucidum representing the species whose impacts have been studied in greater detail in our review, we highlight that Argentina has been one of the most active countries in contributing to a better awareness of the aforementioned species invasion worldwide (Fernandez et al., 2020).

The virtual absence of studies in the Amazon rainforest is likely related to the fact that these regions exhibit fewer invasive species recorded in comparison to more populated areas that have undergone a long-standing history of degradation, at least in Brazil (Zenni and Ziller, 2011; Dechoum et al., 2021). Nevertheless, the ongoing land use change marked mainly by the conversion of primary forests in the Brazilian Amazon to pastures (Nepstad et al., 2014) mean that pressure from non-native grass propagules and areas susceptible to invasion will become increasingly extensive (Balch, Nepstad and Curran, 2009). Strong evidence exists related to synergistic effects between climate change and forest-to-pasture conversion as drivers of flammable grass invasion in degraded-forest edges (D'Antonio and Vitousek, 1992; Balch, Nepstad and Curran, 2009; Veldman et al., 2009; Silvério et al., 2013), as well as the negative effects of fire on the structure and functioning of Amazon rainforests (Cochrane and Barber, 2009; Coe et al., 2013). Knowledge of the magnitude and persistence of the effects of invasion-induced wildfires in Neotropical rainforests is still lacking, particularly to disentangle whether the intensity and frequency of fires, as well as post-fire vegetation recovery differs in areas with the presence and absence of invasive grasses (Silvério et al., 2013). Thus, better understanding the mechanisms and consequences of such fire-grass feedbacks is equally important to halt losses of native forests by plant invasions that could have been avoided by precautionary management (Nepstad et al., 2008), thereby preventing the Amazon Forest from reaching a fragmentation threshold with irreversible erosion of ecosystem services and biodiversity (Alcock, 2003).

Similarly, the absence of evidence of plant invasion effects in Tropical & Subtropical Coniferous Forests is not a good sign since these ecosystems have undergone severe human-mediated disturbances, with much of its native pine-oak formations fragmented and depleted in terms of vegetation structure and species composition (Galindo-Jaimes et al., 2002). Several factors, such as harsh environmental conditions, relative low connectivity and isolation, once perceived as barriers to biological invasions in high-elevation ecosystems, are rapidly shifting as a result of climate change and anthropogenic disturbances (Pauchard et al., 2009; Pauchard et al., 2016), in the same way that the presence and negative ecological effects of invasive species have been increasingly frequent in harsh environments with theoretically high abiotic resistance (Sanderson, McLaughin and Antunes, 2012). Despite the lack of impact studies for an entire Neotropical biome, Richardson et al. (2009) has already pointed out that the impact of invasive plants on native pine forests is probably much greater than is showed in the literature, and that such impacts can probably be expected for other species and similar regions. Consistent with the review of Zenni et al. (2022) on plant invasions in South America, our work stresses that the lack of concrete evidence on the ecological impacts of invasive plants in most neotropical countries is a worrying result, because many invasive and naturalized plant species have already been detected in some of those countries and recorded in their respective national lists (Zenni et al., 2022).

Considering the invasive plants studied, we uncovered the same trend also found by Crystal-Ornelas and Lockwood (2020), whereby most species were studied only once. In other words, we still do not know most of the impacts that can potentially be caused by these under-studied species. Since the number of problematic invaders is presumably much larger than the number of those that have already been addressed (Hulme et al., 2013), there is a trade-off in which invasion biologists must weigh up whether to extend research to species for which there is little evidence or to increase knowledge about those that have already been studied. There are valid arguments that support both decisions. For example, evaluating species that have not yet been studied is crucial to ascertain if the invader does indeed threaten any context-specific ecological attribute, bringing insights into the need for further research and/or management. On the other hand, replicated measurements at multiple times or locations on a single species are necessary to make accurate inferences about their true effects (Crystal-Ornelas and Lockwood, 2020), or even to assess impacts on distinct features of the invaded site. Such information is required to allow generalization and comparison of estimates obtained from different study settings, such as in meta-analyses (Gundale et al., 2014). It should also be considered that the expenditure of research effort on extensively studied species is more relevant when they represent good model systems (Hulme et al., 2013), as is the case of Ligustrum lucidum, which is a troublesome invasive tree in many countries and presents a biological behavior that is foreseen to become more common in the Anthropocene (Fernandez et al., 2020).

Probably the most prominent example of such a model taxon in invasion ecology is the genus *Pinus*, as the plethora of studies on invasive pines worldwide has played a key role in shedding light to the field of plant invasions (Richardson, 2006; Gundale et al., 2014). Although pine invasions occur in many countries and biomes throughout South America (Pauchard et al., 2015), we had only one study on its impact in our review (Oliveira et al., 2014). This low proportion may reflect that non-native pine invasions are more conspicuous in less dense vegetation physiognomies (García et al., 2019), being a more pervasive invader in savannas (Abreu and Durigan, 2011), coastal scrubs (Mesacasa et al., 2022), mountain grasslands (Falleiros, Zenni and Ziller, 2009), as well as temperate forests and steppes (Franzese et al., 2017). However, we also believe that the impacts of the genus may have been poorly described in Neotropical moist and dry forest biomes because, in theory, invasive pines can successfully establish and develop self-sustaining populations in disturbed sites. Otherwise, the most species-rich families whose invasion impacts have been quantified in Neotropical moist and dry forests are Poaceae and Fabaceae. These results are not surprising, since these two botanical families are among the most emblematic contributors to the global naturalized (Pyšek et al., 2017) and invasive flora (Pyšek, 1998). Similarly, they are also the families with the highest number of invasive (Zenni, 2014) and naturalized plant species in Brazil (Zenni, 2015), the most representative country in our review.

The taxonomic skewness also relates to the over-representation of invasive tree and herb species, with few impact studies on shrubs and vines. This pattern may be associated with different introduction efforts. For example, shrubs were introduced on much smaller scales in Central and South America compared to tree species (Rejmánek, 2014). The most frequent and species-rich herbaceous invasive plants whose impacts were studied are perennial African grasses, which have a centuries-long history of cultivation as fodder and have long been perceived as a widespread plant cover throughout the American tropics as well as pervasive invaders (Parsons, 1972; Williams and Baruch, 2000). Although there is still no information about the history and effort of grass introductions on a global scale, it is known that the American continent is a major recipient of a high diversity of these organisms (Monnet, 2020). Observing that grasses were the only invasive plants targeted in designed habitat studies is related to the necessity of managing these plants in areas undergoing active forest restoration (Román-Dañobeytia et al., 2012; D'Antonio, August-Schmidt, & Fernandez-Going, 2016). This result is also supported by Weidlich and colleagues' (2020) review, which found that most of the invasive plants controlled in such sites were grasses and forbs. Because of traits such as high fecundity and growth rates, early germination, and efficient dispersal mechanisms (Golivets, 2014), invasive grasses are able to establish in degraded sites and outcompete both planted native seedlings (Hooper, Condit and Legendre, 2002; Román-Dañobeytia et al., 2012) and natural forest regeneration (Ferreira et al., 2016; Williams-Linera, Bonilla-Moheno and López-Barrera, 2016). Moreover, the restoration of forest ecosystems may be even more threatened due to the trend of more areas becoming prone to non-native grass invasions in South America as a result of climate change, especially in tropical regions (Barbosa, 2016). On top of that, the significant overlap of target lands for forest restoration with climatically suitable areas for some invasive trees (e.g. Heringer et al., 2019) also suggests that restoration efforts could be even more jeopardized by plant invasions in general.

Areas abandoned after economic exploitation were the most studied habitat. In general they comprise highly disturbed ecosystems that are more prone to invasions because of a greater range of empty niches no longer occupied by native plants (Hobbs and Huenneke, 1992; Hulme, 2003; Vilà, Pino and Font, 2007; Chytrý et al., 2008; Liccari et al., 2020). Under such conditions, non-native plants are more likely to form mono-dominant stands after land abandonment and therefore exhibit more conspicuous invasions. In this sense, it could be expected that there would be a greater volume of studies in these habitats and in contrast fewer studies in reference sites, because the vast majority of deliberately introduced plants have early successional life-history traits that confer them greater adaptability to anthropogenic environments (Martin, Canham and Marks, 2008). The general recognition that tropical forests with high biodiversity and vegetation cover are more resistant to invasion (Rejmanék, 1996) may be more related, therefore, to a smaller pool of current invasive plants able to tolerate shaded understories (Fine, 2002). However, one cannot consider that less disturbed forests are immune to biological invasions, since several shade-tolerant introduced plants exists and are highly invasive of more biodiverse and closed-canopy tropical forests (Martin and Marks, 2006; Martin, Canham and Marks, 2008; Assunção, 2019; Castro, 2019). And even if the invasion process in these cases is less remarkable because it spreads more slowly compared to environments with high resource availability (Rejmanék and Richardson, 1996; Martin and Marks, 2006), measuring their potential impacts in reference habitats is necessary due to the ability of invasive plants to persist throughout succession and exert long-term negative ecological impacts (Lugo, 2004).

Considering environments where biological invasions may take time to be noticed, it is of utmost importance that field monitoring campaigns in these places take into account the detection of potential disturbance drivers such as the arrival of invasive species (Rejmánek, 2001). The information of the time an area has been invaded by a particular species is crucial not only for the management and prevention of possible negative ecological impacts, but also to enable comparisons of ecological attributes before and after the invasion event as well as accurately track their progress over time (Flory and D'Antonio, 2015; Fernandez et al., 2020). For example, the very few studies in our review that had ecological data from forest sites before the invasion occurred were from permanent plot monitoring (Bellingham, Tanner and Healey, 2005; Bellingham et al., 2018), which eventually encouraged research into the role of the invasive species in the native community. Whereas time series evaluations of impact shouldn't be constrained by the lack of exact records of when the invasion occurred, proxies can be useful to deal with uncertainty and distinguish between younger and older invasions, such as the density and size of invading individuals (Mesacasa et al., 2022), dendrochronology (Xavier et al., 2021), and remote sensing techniques (Paz-Kagan et al., 2019; Kozhoridze, Dor and Sternberg, 2022; Sabat-Tomala, Raczko and Zagajewski, 2022). While the age of the invasion may not be pertinent to answering certain research questions, it is encouraged that the temporal context should be more accounted for into invasion research, as changes in ecological and evolutionary processes affect the magnitude and direction of impact estimates (Strayer et al., 2006; Barney et al., 2015; Grove, Parker and Haubensak, 2017).

Although impact assessments should go beyond single snapshots in time from comparisons between invaded and non-invaded areas (Grove, Parker and Haubensak, 2017), we couldn't spot such patterns from the studies in our review, acknowledging our limitation in not recording the number of repeated measures and study length. In this regard, it wasn't a surprise to find that pairwise comparisons between invaded and non-invaded areas were the most widely employed method to quantify the ecological impacts of invasive plants in dry and moist Neotropical forests, since observational studies correspond to the primary mode of inquiry in this topic (Stricker, Hagan and Flory and D'Antonio, 2015). Despite the clear benefits of this approach in allowing larger scale data collection in realistic environmental settings with reduced costs compared to experimental methods, it is often not possible to disentangle whether the invasive plant species are actually passengers or drivers of observed outcomes (Ricciardi, 2013; Kumschick et al., 2015; Sofaer, Jarnevich and Pearse, 2018; Stricker, Hagan and Flory, 2015). The advantages and drawbacks of impact assessment methods have already been discussed in depth elsewhere (e.g. Kumschick et al., 2015; Stricker, Hagan and Flory, 2015), with a consensus that combining observational and experimental approachs is the way forward to depict cause and effect through more reliable data. Recent work carried out by Guido and Pillar (2017) and Mesacasa et al. (2022) are good examples of how comparing removal, unmanipulated invaded, and reference uninvaded areas over time are valuable to detect not only the ecological impacts but also the ecosystem response after invasive plant control. Both results informed restoration practice by showing that invader removal alone was not enough to trigger the successional pathways required for ecosystem restoration, also revealing that a reduction in the cover of the target invader can even promote colonization of novel invaders (Mesacasa et al., 2022).

Acknowledging that the management of invasive plants is usually prompted by the restoration of native vegetation, there is a pressing need for carefully designed long-term removal experiments and further monitoring

(Kettenrig and Adams, 2011; Prior et al., 2018), since vegetation recovery in terms of structure and species composition following removal may not occur in the desired timeframe of a specific management context, or even passively fail to converge on uninvaded reference areas without the adoption of revegetation strategies (Kettenrig and Adams, 2011; Flory and D'Antonio, 2015; Mesacasa et al., 2022). Although the results of our review point to the need for further research integrating observational and experimental methods, the set-up of more robust designs implying control and monitoring at larger temporal and spatial scales is usually not feasible due to high logistical and operational costs (Barney et al., 2015). While more robust and expensive studies do not fit the budget realities of research institutions, purely observational approaches remain very valuable for identifying potential impacts. However, appropriate conclusions of causality by these approaches require that confounding factors be isolated as much as possible by comparing areas with sufficiently similar environmental characteristics and disturbance histories (Kumschick et al., 2015; Schmidt et al., 2020). Modeling methods can also be strategic in order to draw insights based on large-scale observations that would be unrealistic through field sampling (Pauchard and Shea, 2006). However, potential impact assessments in modeling studies are still poorly developed (Flory and D'Antonio, 2015), and its predictions can be challenging based on occurrence records alone, since for most species the availability of abundance data are scarce, for example (O'Neill, Bradley and Allen, 2021).

On the biological scales, there was a high skew of the impacts of invasive plants being quantified at the community scale, in particular of native plants. Such a pattern has already been revealed in the global literature of invasive species ecological impacts (Crystal-Ornelas and Lockwood, 2020), which might be explained by the general concern of invasive species as leading causes of extinctions (Gurevitch and Padilla, 2004) and even the relative simplicity of measurement of community-level metrics (Hulme et al., 2013), rather than that other scales are less affected in reality. Fewer studies addressing ecosystem-level impacts is a concern not only because understanding how invasive plants interfere with ecosystem functioning is relevant to inform policy and management (Barney et al., 2015; Stricker, Hagan and Flory, 2015), but also because severe changes in the abundance and diversity of native species are likely to induce changes in ecosystem pools and fluxes, and vice-versa (Simberloff, 2011). For these reasons, Simberloff (2011) argues that in many cases there's no true distinction of community and ecosystem impacts, showing several examples of when negative impacts to resident species fall under the "ecosystem-level impact" category. Such mechanistic links of impacts across biological scales should be more explored in further studies to differentiate direct and indirect effects as well as to unravel context-dependency (Hulme et al., 2013; Hulme, 2014). For example, in studying the invasion of Ligustrum lucidum in subtropical forests under a trait-based approach, Fernandez et al. (2021) showed that invasion outcomes in the functional structure of the community was related to a combination of different invasiveness mechanisms (i.e., niche differentiation and fitness superiority), as well as changes in ecosystem properties. Another recent research concerning an invasive tree, Hovenia dulcis, depicted significant changes in allochthonous input of organic matter and litter decomposition rates due to invasion, but no marked changes in the associated invertebrate community, and thereby no obvious effect in stream functioning (Fontana, Restello and Hepp, 2022).

In terms of organisms impacted by invasive alien plants, there was a tremendous disproportion in the amount of research focused on native plant responses compared to higher trophic levels. These findings are reflected in the global literature (Stricker, Hagan and Flory, 2015), which may imply a greater convenience in studying sessile as opposed to mobile organisms (Kumschick et al., 2015). Albeit poorly investigated in the scope of our review, the diversity, abundance, and activity patterns of native fauna can suffer detrimental effects mainly through altered habitat structure and food resource availability (Litt and Pearson, 2022; Cunningham-Minnick and Crist, 2020;

Gomes, Carvalho and Gomes, 2018). In a global meta-analysis, Schirmel et al. (2016) showed neutral impacts of invasive alien plants on resident animals in forest ecosystems in comparison to other environments, suggesting that a sampling bias may underestimate those effects since the existence of multiple vegetation layers makes it difficult to detect fauna comprehensively in forests. The study carried out by Cunningham-Minnick and Crist (2020) showed that this is particularly important to account for, because invasive plant impacts may differ according to vertical strata and, most notably, that the surveyed canopy communities were highly dependent on native plant resources and threatened by the invader. As the meta-analysis by Schirmel et al. (2016) was highly skewed towards temperate regions from the north hemisphere, we believe that this sampling effect could be even more pronounced in more stratified tropical and subtropical forests. In order to leverage the sampling effort in such cases, several taxonomic groups could be assessed through passive acoustic monitoring (Aide et al., 2013). Field deployment of recording devices coupled with machine learn classifiers could be incorporated into impact study designs, by comparing the assemblage of native vocalizing animals between invaded vs. un-invaded areas, and gradients of invasive plant abundance, for example. In a two-way street, such an approach can also be of benefit in identifying the occurrence of non-native animals (Ribeiro Jr. et al., 2022) as well as underlying disturbance factors in the sites through soundscape analysis (Pijanowski et al., 2011).

In summary, our systematic map demonstrated that the ecological impacts of invasive plants in dry and moist Neotropical forests have been increasingly addressed and reported in the peer-reviewed scientific literature. Even though several invasive alien plants have been studied, the research efforts are biased towards a few countries, plant growth forms, as well as environmental and methodological settings. The majority of studies measured the responses of native plant species and communities to plant invasions, specifically in abandoned habitats through observational comparisons of invaded vs. un-invaded sites. This relatively data-rich subset provided a unique opportunity to quantitatively analyze general patterns and sources of variation in the impacts of invasive plants on native plants in tropical and subtropical forests, which was addressed in the second chapter of our research. We also emphasize several knowledge gaps that can be filled by new primary studies, especially by: i) combining experimental and observational approaches that incorporate the temporal context of invasion; ii) monitoring and quantifying the impacts of invasions on more conserved habitats; iii) assesing the responses of native animals and ecosystem functioning to invasive plants; iv) as well as measuring how ecological impacts manifest and interact themselves across multiple biological scales. Since impacts are among the subjects that still holds less representativeness in the field of biological invasions (Funk et al., 2020), we strongly believe that many other topics of equal importance may hold a larger volume of studies compared to what we have found, and therefore deserve special attention for further synthesis efforts as well. We hope that our work will be useful in raising the scientific community's interest in new primary research and potential approaches that can contribute to a better understanding of how and to what extent invasive plants of different taxa affect tropical and subtropical forest ecosystems.

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3. RESPONSES OF NATIVE PLANT SPECIES AND COMMUNITIES TO PLANT INVASIONS IN TROPICAL AND SUB-TROPICAL FORESTS: A META-ANALYSIS FOR THE NEOTROPICS

Abstract

The synergistic effects of high rates of habitat fragmentation and increasing propagule pressure have increased the vulnerability of tropical forests to biological invasions and their negative effects. To account for the high context-dependency and heterogeneity that have been observed on the effects of invasive plants in Neotropical forests, meta-analysis emerges as a powerful tool to investigate how these impacts vary depending on the habitat conditions and specific traits of invasive taxa. Althought several meta-analysis have helped to identify and quantify some broad-scale patterns in invasion ecology, most of our understanding about these general rules is still derived mostly from studies in the northern hemisphere and outside the tropical zone. To fill this gap, we performed a multi-level meta-analysis based on 145 effect sizes to estimate the magnitude and direction of the effects of terrestrial invasive plants on native plant abundance, diversity, growth and fitness on neotropical moist and dry forests. To better understand sources of heterogeneity, we computed the I^2 statistic and accounted for the phylogenetic relatedness of invasive plants, as well as performed moderator analyses to test whether biome, invaded habitat and invasive plant growth form affected the mean estimates. Overall, we found that impacts were negative and statiscally significant for three out of the four variables assessed, with reductions of native plant diversity, abundance, and growth in invaded sites of 48,4%, 37.8% and 44.6%, respectively. Estimated results were highly heterogeneous, and we did not find evidence of a possible phylogenetic effect. The moderator analysis showed that none of the included explanatory variables influenced the magnitude and direction of impact estimates. Specifically, responses of native plants to invasive plants were not significantly different when the study location was in moist or dry forests, between different invaded habitat typologies, nor when the invasive plants were herbaceous or woody species. Although our study could not uncover potential sources of variation in the responses assessed due to data related limitations, we provide concrete evidence that the ecological impacts of invasive plants on native plant species and communities in Neotropical forests is severe and should not be underrated.

Keywords: Effect size, subtropical forest, non-native plants, invasion biology, systematic review, meta-analyses, impact

3.1. Introduction

Tropical forests have long been considered less susceptible to biological invasions than other biomes around the world (Elton 1958). This is largely due to the expectations raised by the biotic resistance hypothesis, which states that native communities with greater biodiversity tend to make better use of available resources and therefore have fewer empty niches that can be occupied by opportunistic invasives (Elton 1958; Hooper et al. 2005). In addition, because of the strong association between economic development and higher rates of biological invasions, developing countries in the tropics have historically witnessed lower levels of alien species introduction compared to developed countries in the northern hemisphere (Nuñez and Pauchard 2010). However, the synergistic effects of habitat fragmentation and increasing propagule pressure in tropical ecosystems have increased the susceptibility of tropical forests to biological invasions and their negative effects (Dawson, Burslem, and Hulme 2015; Fine 2002; Lopez 2012; Lövei, Lewinsohn, and Network 2012), especially in ecosystems subject to drastic changes in their structural characteristics and species composition such as degraded abandoned sites and secondary forests (Colón and Lugo 2006; Dechoum et al. 2015).

The tropical region where the largest forest cover on Earth (45%) is concentrated has been the target of the highest deforestation rates in the last three decades, accounting for 90% of total forest loss on a global scale (FAO and UNEP 2020). Abandoned sites targeted for restoration and areas undergoing secondary succession correspond to the majority of forest cover in the tropics and are key components in mitigating biodiversity loss and providing ecosystem services (FAO 2015; Chazdon 2008; Chazdon et al. 2016). Regeneration of these forests usually occur in degraded agricultural areas, where local disturbance factors may facilitate invasion by generalist alien species present in the landscape (Van Kleunen et al. 2010). In several countries of the Neotropics, alien species have been introduced for various purposes, such as silviculture, forage, ornamentation, urban afforestation, and erosion control (Richardson and Rejmánek 2011; Simberloff et al. 2010), and several life-history traits that are recognized to confer invasion potential are shared by these species (Padmanaba and Corlett 2014; Pyšek and Richardson 2007). Despite the fact that the vast majority of invasive alien plants have rapid growth and shade-intolerance traits that make them adapted to disturbed habitats in early successional stages (Hobbs and Huenneke 1992; Rejmánek, Richardson, and Pyšek 2013), many shade-tolerant invaders are of concern because they are able to invade undisturbed forests and persist through ecological succession, exerting long-term impacts on the native community (P. H. Martin, Canham, and Marks 2009).

In Neotropical forests, many species with distinct characteristics are able to invade and cause different types of impacts in a wide range of ecosystems. In closed-canopy forests, the invasive tree *Artocarpus hererophyllus* is reported affecting both plant and animal native communities (Fabricante et al. 2012; Gama-Matos et al. 2020), as well as the herbaceous *Tradescantia zebrina* that is commonly found in understories of protected forests (Bail et al. 2022). Accordingly, several deforested areas throughout the Neotropics are dominated by invasive grasses such as *Melinis minutiflora* and *Saccharum spontaneum,* widely known to arrest succession and restoration efforts (César et al. 2014; Hooper, Condit, and Legendre 2002). On the other hand, many alien woody plants can persist in the ecosystem after land abandonment and influence the successional trajectory of the native community, either by reducing the density and diversity of regenerants (Raymundo et al. 2018), or by favoring regeneration of native species by outshading other light-dependent invasives and hence supress the above and belowground competition (Brancalion et al. 2020).

One of the greatest challenges in invasion ecology is to discover patterns and generalizations that may exist among the wide variety of ecological impacts of invasive plants (Parker et al. 1999; Ricciardi et al. 2013), which is by no means a straightforward endeavor due to the high complexity of interactions between distinct biotic and abiotic conditions of invaded habitats and the wide range of particular traits of invasive species and their growth forms (Pyšek et al. 2012). This issue has been discussed for quite some time, with one of the milestones of this debate being the work of Parker et al. (1999), which reviewed how the ecological impacts of invasives had been empirically quantified, supporting the development of initial theories of these impacts and approaches that new research might account for in order to better generalize those measurements. Although at that time the obvious insufficiency of primary data still did not allow a comprehensive comparison considering a range of species and metrics, the period of increasing volume of publications that has been fostered since then (Crystal-Ornelas and Lockwood 2020) makes it feasible to use a statistical approach recommended by the authors for its potential in providing new insights and identifying patterns related to the ecological impacts of invasives, which is meta-analysis (Parker et al. 1999).

According to Koricheva, Gurevitch and Mengersen (2013), meta-analysis can be defined as a method of evidence synthesis that comprises a set of statistical tools used to combine and synthesize the magnitudes of the outcomes across different studies on the same topic. As a powerful approach to address sources of heterogeneity that cannot be easily assessed at site-scale observational or experimental single studies (Nakagawa and Santos 2012), several meta-analysis have helped to identify and quantify some patterns in invasion ecology, such as how impacts scale with climatic gradients (P. A. Martin, Newton, and Bullock 2017), different types of impact (Vilà et al. 2011), and different ecosystems (Gioria, Jarošík, and Pyšek 2014). However, most of our understanding about these general rules on the ecological impacts of invasive plants is still derived mostly from studies in the northern hemisphere and outside the tropical zone (Chong et al., 2021). Meta-analyses also provide an opportunity to assess relationships between the phylogenetic relatedness of invasive species and their impacts, which is often difficult in primary research since most impact studies targets a single invasive taxa (Hulme et al., 2013).

Recognizing that there is an available and recent body of evidence of these impacts for the Neotropics, we performed a meta-analysis to fill this gap and quantitatively analyze the magnitude and direction of the effects of terrestrial invasive plants on native plant species and communities of tropical and subtropical moist and dry forests throughout the Neotropical realm. Our main goal was to identify broad-scale patterns to better understand how these outcomes vary depending on the measured response variables and the characteristics of both invasive species and recipient ecosystems. To do so, in this study we addressed the following research questions:

i. What is the magnitude and direction of the overall mean effect of invasive alien plants on native species (i.e. fitness and growth) and communities (i.e. abundance and diversity) of neotropical forest ecosystems by comparing invaded and uninvaded reference sites?
ii. How much of the heterogeneity of plant invasion impacts on native plants can be attributed to the phylogenetic relatedness between invasive species?
iii. To what extent the overall mean effect sizes are explained by plant growth forms, habitat types and forest biomes?

3.2. Methods

3.2.1. Study eligibility assessment and data extraction

Rather than performing a literature search, the data collection procedure was performed on the dataset of the already systematically mapped articles from the previous chapter of this dissertation, entitled "*Reviewing research on the ecological impacts of invasive alien plants in neotropical forests: a systematic map approach*". However, since qualitative and quantitative evidence synthesis methods differ in their research questions and goals, the study's eligibility assessment must be based on distinct criteria. For example, systematic maps often answers broad research questions and provides a descriptive output. On the other hand, meta-analyses are concerned to combine the results of each study and requires great rigor to select the data for a pooled statistical analysis. For the analysis to make sense biologically, the study's settings and design must be quite similar in nature and therefore be critically appraised for inclusion and data extraction. For example, comparing studies that are completely different in terms of assumptions and assessment methods is something that should be avoided as it biases the results and their correct interpretation (CEE 2018). Thus, in addition to the inclusion criteria that were determined in the first chapter, the set of articles related to impacts on native plant species and communities (n = 55) were screened again for their eligibility in the meta-analysis based on the following additional criteria:

i. We included observational studies comparing the impact of invasive plant species in invaded vs uninvaded reference sites in natural or semi-natural (e.g. species additions in greenhouses and nurseries) ecosystems. Thus, we did not include studies where the control site (i.e. uninvaded) had the invasive plant removed due to counfounding disturbance effects (Corbin and D'Antonio 2012);
ii. In case the study addressed more than one invasive species, we included the study only if the measurements could be distinguished for each species. If the effect of several invasive plants (i.e. multi-assemblages) were pooled in a single measure the study wasn't included;
iii. When one or more response variables were measured at multiple times (i.e. repeated measures), we obtained only the last measurement. This procedure was also valid for studies with measurements in different seasons, to avoid selection bias;
iv. If a given study evaluated areas at different degrees of invasion (i.e. abundance gradient) or compared areas where invasion occurred at different times (i.e. chronosequence of invasion), we only compared the information between the most invaded areas with the least invaded ones, and the differences between non-invaded areas and areas with the longest time of the invader's presence, respectively (Vilà et al. 2011);
v. The study must have provided suitable information about descriptive statistics (i.e. means, standard deviations or standard errors) and samples sizes for the invaded and uninvaded groups, that could be obtained from text, tables, charts or online supplementary information. If the required data could not be obtained from any of the above sources the study was excluded from analysis;

A total of 21 papers with 145 effect sizes that met our criteria were included for the meta-analysis. Details about included studies and excluded studies, along with the reasons for exclusion based on full text screening are reported in Appendix I and J, respectively. Since the relevant characteristics of the studies that we used as moderator variables were already obtained in the systematic map, for the meta-analysis we only extracted the descriptive statistics (i.e. means, standard deviation or standard error, and sample sizes) reported in full text and supplementary materials to calculate effect sizes. Descriptive statistics (i.e. means and standard deviations) not readily available in texts and tables were extracted from data displayed in published plots using the metaDigitise package in R environment (Pick, Nakagawa, and Noble 2019). We tested the consistency of this method by comparing the data estimated with metaDigitise with the original data. To do so, we calculated the range of the estimation errors by comparing the obtained values from a few papers that presented both extractable plots and descriptive statistics from texts. For eight paired comparisons (four of means and four of standard deviations), the average percent error between measures was 4.21 % ± 3.22 %. Since the range of estimation errors was only 0.31 – 8.33%, we felt confident to use the data obtained from the metaDigitise package in our analyses.

3.2.2. Meta-analysis

A multi-level (hierarchical) meta-analysis model was used since its assumptions are more suitable for biological meta-analyses (Nakagawa et al. 2017), as we expect to have more than one effect size per study. Therefore, we also added the study ID and effect-size ID as random factors in a nested structure. We ran separate meta-analysis models fitted with restricted maximum likelihood (REML) by subsetting our dataset for each response variable, being abundance, diversity, fitness and growth. Similarly, multi-level meta-analysis allowed us to model sources of non-independence between effect sizes that are common in ecological and evolutionary meta-analysis (Nakagawa and Santos 2012). One of these sources of non-independence is due to the fact that effect sizes that are shared among species that are closely related in an evolutionary perspective tend to be more correlated (Nakagawa and Santos 2012). Therefore, we constructed a phylogenetic tree for the invasive species present in our dataset using the rotl package (Michonneau, Brown and Winter, 2016) in R environment. We further computed the tree branch lengths using the ape package (Paradis and Schliep 2019) and included the correlation matrix accounting for the phylogenetic relatedness between species as a random effect in our model. This approach is still poorly investigated in invasion ecology, and the majority of meta-analysis in the field did not adequately explored wether the impacts of invasive species are more similar to those of phylogenetically related species (Kumschick et al. 2015).

The response variables were standardized by calculating the natural logarithm of the response ratio (*ln*RR) as a metric of the magnitude and direction of effect sizes between exposed (i.e. invaded) and control sites (i.e. uninvaded), following the Eq. (2) (Hedges, Gurevitch, and Curtis 1999):

$$lnRR = \frac{\bar{X}_E}{\bar{X}_C} \quad (2)$$

Where X_E and X_C are the means of a response variable in the exposed group (invaded) and control group (uninvaded), respectively. The variance of lnRR were calculated following the formula in Eq. (3):

$$v(lnRR) = \frac{(SD_E)^2}{n_E(\bar{X}_E)^2} + \frac{(\mathrm{SD_C})^2}{\mathrm{n_C}(\bar{\mathrm{X}}_\mathrm{C})^2} \quad (3)$$

Where standard deviation and the sample size in the invaded group are denoted by SD_E and n_E, and the standard deviation and sample size of the control group by SD_C and n_C, respectively. We chose the lnRR to estimate effect sizes because it's less susceptible to pseudoreplication, since its point estimates (i.e. magnitude of the differences between exposure and control) are not weighted by the sample sizes such another common effect size metric used for mean differences like Hedges d' (Noble et al. 2017). Thus, the lnRR is less affected by inflated sample sizes obtained from non-independent samples within studies designs.

The results of our models were presented in orchard plots using the orchaRd R package (Nakagawa et al., 2020), which show the overall mean effects for each sub-group and its 95% confidence and prediction intervals (CIs and PIs, respectively), as well as the individual effect sizes weighted by their precision (1/SE). The effect size was considered significant if the upper and lower bounds of confidence intervals did not overlap zero. PIs are not commonly used in tradicional forest plots, but are relevant to show the extent of heterogeneity in the data and the expected range of effect sizes likely to be found in future studies (Nakagawa et al., 2020). To better communicate our results, we back-transformed the lnRR effect sizes to RR in order to show the percent change in response variables due to the presence of invasive species, following the Eq. (4).

$$(e^{lnRR} - 1) * 100 \ (4)$$

The I^2 statistic for multi-level meta-analytic models was used for assessing the heterogeneity of the results, which is the proportion of the variance that is not attributed to sampling error in the data (Nakagawa and Santos 2012). This method enabled us to obtain the partitioned heterogeneity for each of the three variance components of our models, accounting for the percent of true variance attributed to phylogeny, and to between and within-study estimates. To better understand sources of variation, we used Likelihood Ratio Tests (LRT) to compare models without moderators (i.e., explanatory variables) to models including a set of relevant categorical moderators of both invasive plant characteristics (e.g. growth forms) and environmental characteristics of the invaded site (e.g. biome and habitat typology). We made these comparisons by running separate models for each moderator if more than 10 effect sizes per factor level were available (Nakagawa et al. 2017). The explanatory power of each moderator were confirmed by the statistical significance of LRTs.

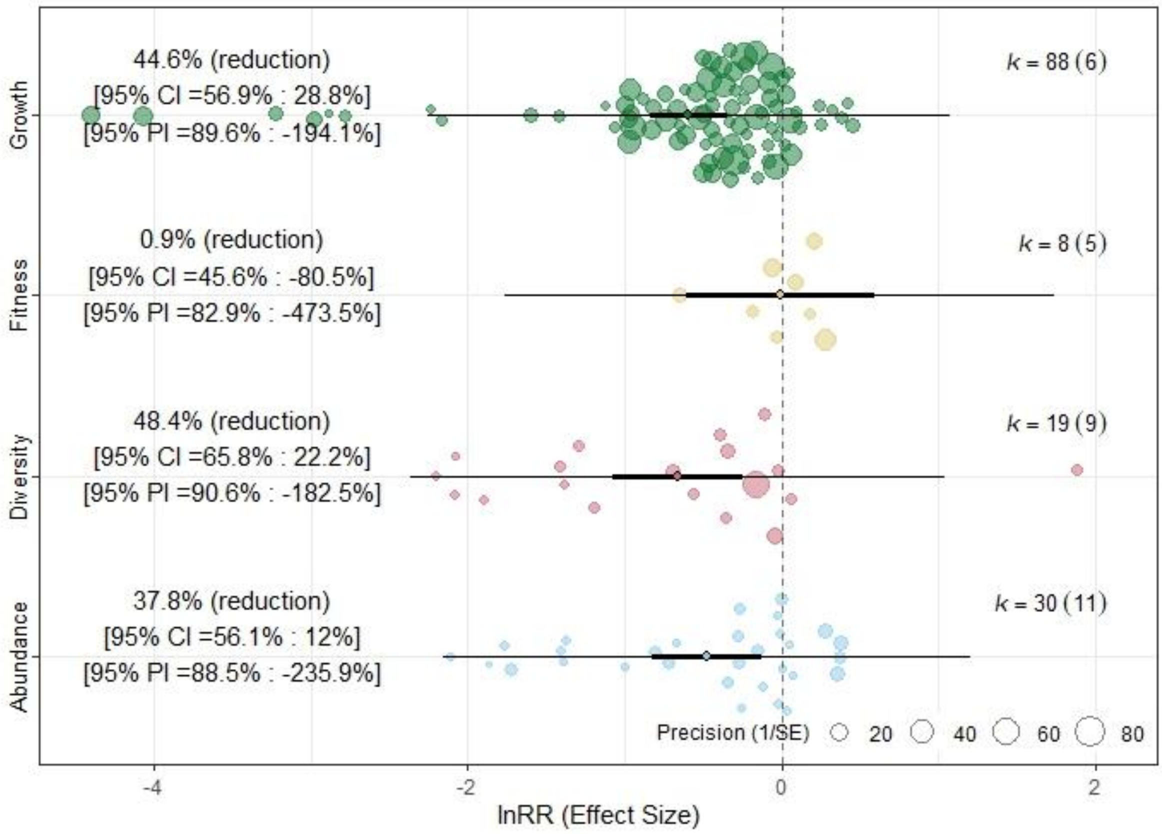
Publication bias was assessed by visually inspecting funnel plots and by measuring their asymmetry using a multi-level model version of Egger's regression, including standard error (i.e., square-root of variance - sqrt(vi)) as a moderator in our models (Egger et al. 1997). Funnel asymmetry is confirmed if the estimate obtained for sqrt(vi) is statistically significant. Since we did not account for every possible source of non-independence in our dataset, we performed a sensitivity analysis with only one randomly selected effect size per study for each model, allowing the comparison between the analysis of the whole dataset and the subset. All analyses were conducted in the RStudio environment (RStudio Team 2019) using the metafor package (Viechtbauer 2010).

3.3. Results

Overall, our meta-analysis dataset comprised a total of 145 effect sizes from 21 papers belonging to 14 different invasive alien plant species (Appendix K), with a minimum of 1 and a maximum of 38 effect sizes per article (6.9 ± 9.03). The species with the highest presence in different publications were *Ligustrum lucidum* (Oleaceae) (n = 3) and *Artocarpus heterophyllus* (Moraceae) (n = 3), followed by *Urochloa decumbens* (Poaceae), *Prosopis juliflora* (Fabaceae) and *Pittosporum undulatum* (Pittosporaceae) with two publications each. The observations of the remaining nine species came from only one article. When it comes to the number of effect sizes per species, the most representative invasive plants were *Urochloa brizantha* (n = 38), *Urochloa decumbens* (Poaceae) (n = 25), and *Prosopis juliflora* (Fabaceae) (n = 24). The majority of effect sizes came from studies carried out in Tropical and Subtropical Moist Forests (80.7%), while 19.3% from Tropical and Subtropical Dry Forests. Non-field experimental addition studies provided the most observations in our dataset, accounting for 50.35% of all effect sizes, whereas abandoned habitats, reference habitats, designed habitats and forest edge accounted for 25.52%, 7.59%, 3.45% and 2.1%, respectively. The data set showed a proportional representativeness of effect sizes between trees and herbs, with 51% and 46.9% respectively, being all effect sizes from herbaceous species from non-field studies. Similarly, the few observations from shrub species were all from forest edge habitats (2.1%). Finally, when comparing the distribution of observations by type of impact, we found that growth-related variables were the most representative (60.69%), along with abundance (20.69%), diversity (13.1%) and fitness (5.52%).

To answer our main question regarding the magnitude and direction of invasive plant impacts on different native plant response variables, we found that impacts were negative and statistically significant for three out of the four sub-groups (Figure 8). The magnitude of impacts on community-level metrics was in the order of a 48.4% reduction in diversity (lnRR = -0.66, p = 0.002, 95% CI: -1.07; -0.25) and 37.8% reduction in native plant abundance (lnRR = -0.48, p = 0.007, 95% CI: -0.82; -0.13) in sites invaded by non-native plants. For species-level metrics, we identified a 44.6% reduction in native plants growing in competition with invasive plants (lnRR = -0.59, p < 0.001, 95% CI: -0.84; -0.34). However, we did not find evidence for significant impacts for fitness responses (lnRR = -0.009, p = 0.98, 95% CI: -0.61; 0.59).

Figure 8. Orchard plot for different native plant outcomes showing their mean estimates (lnRR) and associated percent change in response to invasive plants. The plot also shows the confidence and prediction intervals (bold and fine lines, respetively), as well as individual effect sizes weighted by their precision (inverse variance) and the total heterogeneity (I^2). The number of effect sizes for each sub-group is denoted "k", with the number of unique papers in parentheses.

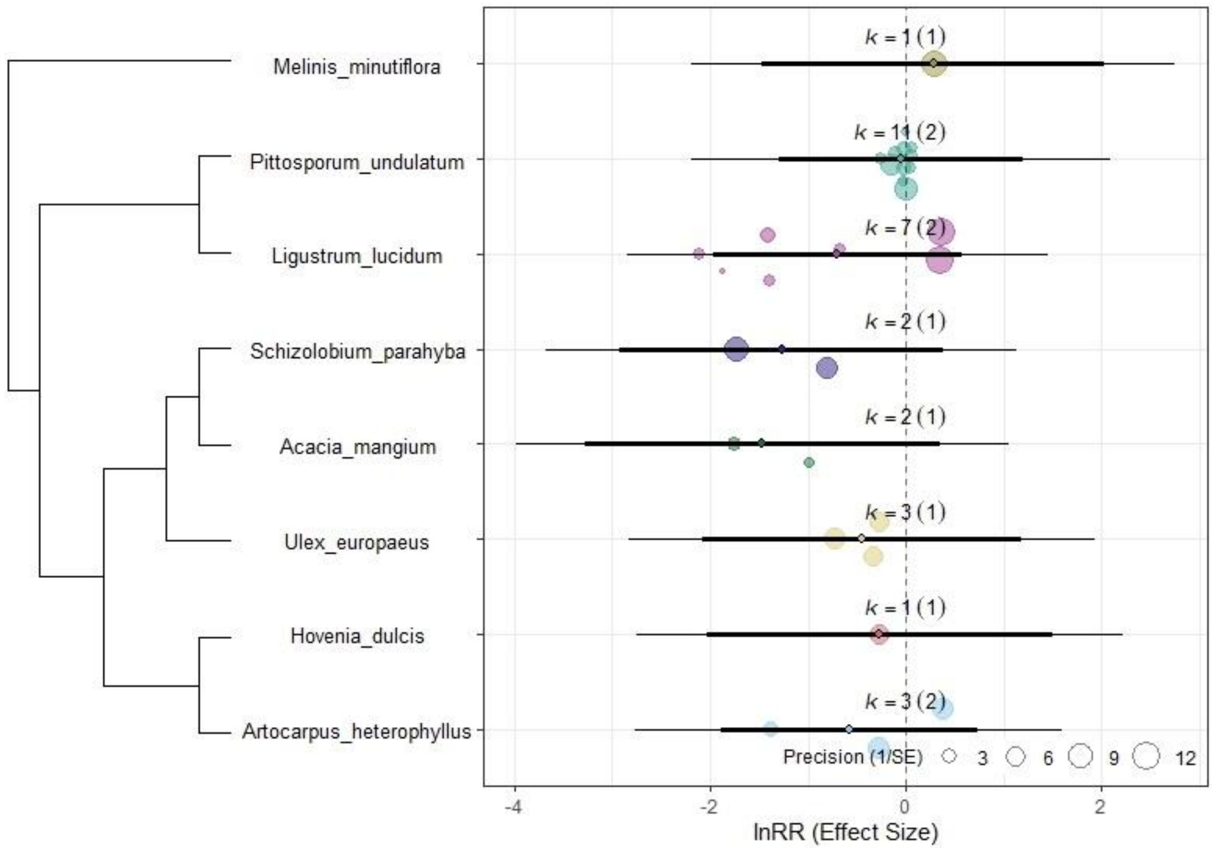


We found no significant differences between the effects of invasive plants on the assessed response variables, meaning that the impacts were relatively similar in both direction and magnitude. Moreover, all subgroups showed a high heterogeneity in the results (Table 5). We did not find evidence for an existing phylogenetic signal in any response variable. However, it was observed that the impacts of close relatives were somewhat more alike than those of distant relative species for abundance responses (Figure 9).

Table 5. Total heterogeneity (I^2 Total = percent of variance not attributable to sampling error) for the models and the partitioning of the true effect variation attributed to i) phylogeny (I^2 phylo); ii) differences among effect sizes of included studies (I^2 between-studies); iii) differences among effect sizes from the same study (I^2 within-study).

Outcome	I² Total	I² phylo	I² between-studies	I² within-study
Abundance	93.58	0.0	60.79	32.79
Diversity	98.96	0.0	0.0	98.96
Fitness	97.03	0.0	97.03	0.0
Growth	99.81	0.0	0.84	98.97

Figure 9. Phylogenetic tree and the effects of each invasive plant species on native plant abundance. The plot also shows the confidence and prediction intervals (bold and fine lines, respectively), and individual effect sizes weighted by their precision (inverse variance). The number of effect sizes for each species is denoted "k", with the number of unique papers in parentheses.



Regarding the assessment of wheter the biome, invasive plant growth forms and invaded habitats affected the estimates of native plant responses we could only test for the effect of moderators in the growth model, since the remaining response variables had only one factor level with more than 10 effect sizes for each environmental and biological category (Appendix L). Accordingly, there were no improvements in model fit with the inclusion of these characteristics, i.e., the growth responses of native plants were not different when the study location was in moist or dry forests (LRT = 0.82, p = 0.36), nor when the invasive plants were herbaceous or woody species (LRT = 0.65, p = 0.42), though our observations were highly skewed towards invasive herbs in moist forests. Moreover, these two moderators in this subset are completely correlated, with virtually all observations of tree invasions belonging to dry forests and invasive herbs in moist forests.

The outputs of the sensitivity analysis with each model fitted with only one randomly selected effect size per publication showed that the direction and magnitude of invasive plant impacts were nearly similar to the analysis of all observations, suggesting that the patterns and interpretations of our results have not quantitatively changed, except for the growth variable where the confidence intervals for the mean effect marginally overlapped zero (Appendix M). We believe that the lack of significance in this case was due to the limited number of unique articles (n = 6), resulting in a sensitivity analysis with low statistical power. In addition, the partitioning of heterogeneity for this model showed a high variability among effect sizes within each study (Table 5). That is, since each study investigated the growth response of several native species individually, in some cases belonging to different functional groups, it is expected that our dataset for these variables would be more heterogeneous. In this regard, we confidently discussed the results based on our findings with the complete data.

Visual inspection of the funnel plots with the reference line at zero revealed subjectively asymmetric patterns, except for the fitness point estimates, suggesting a possible publication bias in our meta-analysis (Appendix N). However, the Egger's regression tests perfomed separately on each of our models quantitatively suggested a lack of evidence of publication bias for growth and fitness data, with statistically significant results for abundance and diversity (Table 6). In this sense, the estimates obtained for the community-level models should be interpreted with caution, since studies indicating results with positive directions or non-significant differences may not have been published. However, it is important to note that, according to Egger et al. (1997), funnel asymmetry may exist for causes other than publication bias, such as true heterogeneity, data irregularities or even by chance.

Table 6. Outcomes of publication bias analysis using Egger's regression, including the square-root of variance (sqrt(vi)) as a moderator in each model.

Outcome	Sqrt (vi)	p-value	Lower CI	Upper CI
Abundance	-1.72	***0.02***	-3.14	-0.29
Diversity	-4.16	***0.001***	-6.73	-1.59
Fitness	-0.25	0.79	-2.08	1.58
Growth	-1.79	0.17	-4.34	0.76

Finally, to overcome the low statistical power of the subsetted moderator analyses, we tested for the effects of biome, invaded habitat and species growth form on the full dataset. Additionaly, we also performed all the analysis described in our methodology as we did for each response variable model, and decided to report the findings to check for general patterns. That said, the overall mean effect size considering all cases (n = 145) as estimated by the multi-level meta-analysis was -0.52 ($p < 0.0001$; 95% CI: -0.71; -0.32), which indicates that invasive alien plants exert negative and significant ecological impacts on native plants in Neotropical forest ecosystems, regardless of the assessed metrics. Such effect corresponds to a reduction of 40.9% in native plant attributes in the presence of invasive species. The dataset total heterogeneity was still very high (I^2 = 99.70%). Further inclusion of the phylogenetic correlation matrix as a random factor in the multi-level model did not account for any observed heterogeneity (I^2 phylo = 0.04%). Even in the full dataset analysis, none of the included moderator variables influenced the magnitude and direction of impact estimates (Table 7). Specifically, native plant responses to plant invasions did not significantly differ between biomes (p = 0.051), but the overlap of the confidence intervals for the two estimates was slight. However, higher negative effects have been recorded on dry forests (lnRR = -0.85, $p < 0.0001$) in comparison to moist forests (lnRR = -0.44, $p < 0.0001$). Likewise, whether the invasive plant growth form was woody or herbaceous, the magnitude and direction of effects did not significantly differ (p = 0.88), nor among different invaded habitat typologies (p = 0.36). The sensitivity analysis for the complete model (n = 21) also yielded similar results compared to the general output (lnRR = -0.52, p = 0.0001, 95% CI: -0.78; -0.27). The assessment of publication bias considering all cases together evidenced the possible existence of publication bias in our meta-analysis (p = 0.01). However, the bias analyses by subgroups showed that the greatest contribution to this result being significant were from community-level effect sizes.

Table 7. Significance of Likelihood Ratio Tests outputs for the inclusion of moderator variables in the full dataset (n = 145).

Moderators	df	AIC	BIC	LRT (X^2)	p-value
Biome					
Full	4	373.37	385.27	3.80	0.05
Reduced	3	375.17	384.09		
Growth Form					
Full	5	378.90	393.79	0.26	0.88
Reduced	3	375.17	384.09		
Invaded Habitat					
Full	7	352.55	372.57	4.35	0.36
Reduced	3	348.89	357.48		

3.4. Discussion

Our meta-analysis revealed overall negative and significant effects of invasive plants on native plant abundance, diversity and growth in Neotropical moist and dry forests, with neutral effects on fitness. We also showed that the magnitude and direction of impacts were very similar among the groups of variables, which was not expected since the direction of invasive plant impacts has been proven, on a worldwide perspective, to be highly variable and dependent on the ecological metric studied (Pysek et al., 2012). However, it is anticipated that comparisons undertaken on a global scale will find greater differences between estimates, especially when contrasting community and ecosystem level outcomes, which often tend to be opposite in direction (Vilà et al., 2011; Pysek et al., 2012; Torres et al., 2011). While increases in ecosystem processes such as soil properties and microbial activity are not so straightforward to be viewed as positive or negative, reductions in native abundance and diversity, on the other hand, are unambiguously detrimental to biological conservation (Barney and Tekiela, 2020).

One of the most documented consequences of numerous invasive plants around the world is the decline of native species (Fletcher et al., 2019; Hejda, Pysek and Jarosík, 2009; Morales and Traveset, 2009), especially of resident plants (Pysek et al., 2012). As a striking feature of the Anthropocene, the process of simplification of ecological communities, termed biotic homogenization, has in biological invasions one of its main causes (McInney and Lockwood, 1999). Indeed, a recent overview of this process from a set of over two hundred thousand plant species revealed that invasive species are the strongest contributors to changes in beta and alpha diversity worldwide (Daru et al., 2021). Accordingly, control of invasive plants that hinder the establishment of a diversity of native species has been raised as a necessity to overcome biotic homogenization in habitats undergoing ecological restoration (Holl, Luong and Brancalion, 2022). Although the biotic homogenization process can occur due to a series of anthropogenic pressures, the introduction of invasive alien species has also been considered one of its most determining drivers in the Brazilian Atlantic Forest (Vitule et al., 2021), a Neotropical biodiversity hotspot from which the majority of our effect sizes were derived.

The largest share of the observations in our meta-analysis corresponded to variables of native plants growing in competition with mainly invasive herb species, although they came from a small number of studies compared to the other types of impact. The high within-study heterogeneity observed for the growth model could be attributed to the fact that species-specific measurements were assessed in each unique paper, and thus are more likely to differ in either magnitude and direction (Hulme et al., 2013). For example, some native species can better allocate its resources in height to overcome dense stands formed by invasive plants (Nishimura et al., 2010), as well as perform poorly in habitats with high invasive plant cover (Castro et al., 2019). Tropical woody species responses to above and below-ground competition from invasive grasses also vary depending on species traits such as seed-size and shade-tolerance (Hooper, Condit and Legendre, 2002). Even with a narrow data set consisting of few individual studies and invasive species, our results suggest that most of the native plants from tropical forests tested have their growth impaired by the co-existence of invasive plants.

Although we did not evidence a significant effect on fitness, we believe this was mainly due to the low number of observations, since it was common for establishment and survival data to be excluded due to the lack of descriptive statistics such as standard deviation. Contrastingly, the global meta-analysis performed by Vilà et al. (2011) on the ecological impacts of invasive plants showed that impacts on fitness were of greater magnitude compared to native plant abundance, diversity, and growth, yet considerably more variable. Interestingly, the ordination of the average effects for diversity, abundance, and growth in their results was similar to what we found, with stronger effects on diversity and weaker on growth. More recently, a meta-analysis on the effects of non-native plants on the fitness of native plants clearly showed negative outcomes on many fitness components, especially survival, with a precisely adverse impact on forests and tropical biomes (Jauni and Ramula, 2015). Knowing that the establishment, fecundity, and survival of new recruits are determinants of population dynamics (Florentine et al., 2013; Jauni and Ramula, 2015), more studies are needed to broaden the understanding of how the successional trajectory of Neotropical forests is affected by different invasive plants and which native species and life cycles are more capable of competing in invaded areas.

We did not find evidence that closely related invasive species have more similar impacts. Analyzing the point estimates by species, we showed that all invasive plants had a low number of observations, with most species coming from only one study. Hence, a large overlap in both confidence and prediction intervals is observed among invasive plants, suggesting that the range of effect sizes between them are highly variable and do not differ significantly as a matter of fact. One of the main contributions of phylogenetics to studies of biological invasions has been to explain invasion success (Chabrebrie et al., 2019). For example, recent studies showed that the phylogenetic relatedness of co-occurring native and invasive species plays a crucial role in promoting invasions in different resident communities due to their similarities in environmental adaptations, supporting the environmental filtering hypothesis. (Divísek et al., 2018; Lososová et al., 2015). Although there is evidence that native plant reproduction is more impaired when the co-occurring invader shares a common ancestor (Jauni and Ramula, 2015), to what degree do ecological impacts tend to be more clustered for close related invasive species remain poorly understood.

The ecological impacts of invasive plants are extremely context-dependent, and several sources of variation affect impact estimates, such as biome (Jauni and Ramula, 2015), habitat type (Castro, 2019), differences in native and invasive traits (Martin, Newton and Bullock, 2017), and methodological differences between studies (Hulme et al., 2013). In this regard, we found a remarkably high heterogeneity in our models, which was not surprising at all, as the average value of I^2 in ecological and evolutionary meta-analyses lies above 90% (Senior et al., 2016). Although this statistic is used to validate the use of variables to predict the magnitude of effects (Senior et al., 2016), the complexity of ecological systems and the disparate nature of studies in ecology and evolution by itself is already a plausible justification. In our moderator analysis we found no evidence of differences in the magnitude and direction of invasive plant impacts across biomes, growth forms, and habitat typology. We therefore believe that the lack of evidence is not evidence of absence, because our data set was limited mainly by the unequal proportion of factor levels for all moderators (see Appendix L.), and consequently low statistical power (Cuijpers, Griffin and Furukawa, 2021). We also consider that the broad categories we have adopted may be somewhat artificial, due to the fact that the true variations may be associated with fine-scale processes (e.g., Lázaro-Lobo et al., 2021) that could not be incorporated into analysis.

Our research also ran into several other limitations commonly found in meta-analyses of ecological data (Koricheva and Gurevitch, 2014). First, we evidenced possible publication bias by quali and quantitative perspectives, even though the tests were only statistically significant for the diversity data. Inclusion of gray literature is important in evidence syntheses to deal with the fact that primary research with statistically significant and positive results in favor of a-priori hypotheses are more likely to be published in peer-reviewed journals (Dickersin 1990; Gurevitch and Hedges 1999; J. Lortie et al. 2007). In this sense, meta-analyses that do not include the gray literature tend to overestimate the values of effect sizes (Conn et al. 2003). However, since our search for articles was extensive and encompassed all the countries' languages in our geographic scope, we strongly believe it is representative of the state of the art of research on this particular topic. Second, almost a third of the non-eligible articles were because of missing data. Although this issue is beyond our control, several strategies are available to ensure a more comprehensive synthesis, such as requesting data from the authors and imputing standard deviations (Bishop and Nakagawa, 2021), performing unweighted meta-analysis (Romanelli et al., 2022), and extracting data from figures (Pick, Nakagawa and Noble, 2018). Even though we still missed potential information, the data extraction by the metaDigitise package was considered satisfactory as it managed to cover a huge number of the articles where the data were not explicitly available through texts and tables, as well as it produced accurate estimates. Third, we couldn't address every possible source of non-independence, such as correlations between studies from the same research groups (Noble et al., 2017). However, the sensitivity analysis proved the robustness of our results by obtaining results similar to those obtained by combining all effect-sizes.

Overall, our meta-analysis disclosed that plant invasions, mainly from herbaceous and tree species, exert negative and significant ecological impacts on abundance, diversity and growth of native plants of Neotropical moist and dry forests. Although the limitations of our data did not allow us to make further generalizations about potential sources of variation in impacts, we consider the estimated reductions of native plant species and communities in exposure to invasive plants as very high and biologically significant. We also recommend that authors do not fail to report detailed information in published primary research regarding descriptive statistics, ecological and historical data of the invaded and non-invaded areas, as well as the cover of the invader and approximate age of the invasion, as they can certainly contribute to future syntheses of greater predictive ability. We hope our study will be informative in the context of a paradigm shift in which plant invasions should not be considered less of a concern in tropical and subtropical forest ecosystems.

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4. CONCLUDING REMARKS

In this dissertation, we sought to fill a knowledge gap where most large-scale patterns and generalizations of plant invasion ecology are derived from studies and syntheses from temperate regions, especially from countries in the global north (Chong et al., 2021). Throughout the two chapters, we used well established methods of evidence-based research to systematically collate and quantify the ecological impacts of invasive alien plants in Neotropical dry and moist forests, therefore contributing to a better understanding of how research is developing in this field, and to what extent plant invasions are detrimental to the development of native species and communities.

In our first chapter we performed a review incorporating principles of systematic mapping to identify gaps and trends in primary research published in the peer-reviewed literature on the ecological impacts of invasive plants in tropical and sub-tropical forests throughout the Neotropics. From the collated evidence, we showed that an increasing number of researchers have been concerned with understanding and communicating how invasive plants affect forest environments, but this knowledge is still restricted to a few countries and methodological settings. Most of the available knowledge on this subject is based on Brazilian research and moist forest biomes, just as most studies measured the responses of native plant species and communities to invasions, specifically in abandoned habitats through observational comparisons of invaded vs. un-invaded sites. Our results clearly indicated that further primary research should account for combined experimental and observational approaches; measuring impact in more undisturbed habitats; as well as assessing how native fauna and ecosystem functioning is affected from plant invasions. Our findings from the mapped literature also provided the basis for the development of a meta-analysis in the second chapter.

To our knowledge, in the second chapter we performed the first meta-analysis to synthesize and quantify the ecological impacts of several invasive plants on native plants of Neotropical forests, accounting for the effects of many invasive plant species in different habitats. Our work disclosed that plant invasions, mainly from herbaceous and tree species in moist forests, exert negative and biologically significant ecological impacts on abundance, diversity, and growth of native plants. Although our study could not uncover potential sources of variation in the responses assessed due to data related limitations, we provide concrete evidence that the ecological impacts of invasive plants on native plant species and communities in Neotropical forests is severe and should not be underrated. For future synthesis to be of greater predictive power, we recommend that authors of primary research should always provide detailed information in their publications, related to ecological and historical data of the invaded and non-invaded areas, the cover of the invader and approximate age of the invasion, as well as quantitative and statistical data for every measurement undertaken.

An important message from our study is that evidence synthesis efforts can only be continuously pursued as new primary research emerges and and seeks to move beyond the knowledge frontier. As such, we hope that our study might foster new primary research capable of filling the current knowledge gaps that we highlighted, in order to increase our understanding of how and to what extent invasive plants of different taxa affect tropical and subtropical forest ecosystems.

APPENDICES

APPENDIX A. Focused naïve search employed to identify a set of articles of high relevance to the topic of this review. The searches were carried out on 17/03/2021.

Bibliographical Sources	Search terms
Web of Science (Core Collection: SCI-E, SSCI, ESCI; All years; All documents; TOPIC) **Scopus** (All years, All documents and Access type;TITLE-ABS-KEY)	(("invasive plant*" OR "introduced plant*" OR "alien plant*" OR "exotic plant*" OR "non-native plant*" OR "nonnative plant*" OR "non-indigenous plant*" OR "nonindigenous plant*" OR "plant invasion") **AND** ("impact*" OR "effect*" OR "affect*") **AND** ("secondary forest*" OR "second-growth forest*" OR "secondary succession*" OR "forest* regenerat*" OR "regenerating forest*" OR "natural* regenerat*" OR "tropical forest*" OR "rain forest*" OR "rain-forest*" OR "rainforest*" OR "dry forest*"))

APPENDIX B. R Script used in litsearchr package.

```
library(litsearchr)
library(devtools)
library(revtools)
library(stringi)
library(stringr)

getwd()

naiveimport <- litsearchr::import_results(file = c("woss.bib",
"scops.bib"), verbose = TRUE)

naiveresults <- litsearchr::remove_duplicates(naiveimport, field = "title",
                                         method = "string_osa")

rakedkeywords <- litsearchr::extract_terms(text = paste(naiveresults$title,
                                         naiveresults$abstract),
                                         method = "fakerake", min_freq =2,
                                         ngrams = TRUE,
                                         min_n = 2, language = "English")

taggedkeywords <- litsearchr::extract_terms(keywords =
naiveresults$keywords,
                                         method = "tagged",
                                         min_freq = 2, ngrams = TRUE,
                                         min_n = 2, language = "English")

all_keywords <- unique(append(taggedkeywords, rakedkeywords))

naivedfm <- litsearchr::create_dfm(elements = paste(naiveresults$title,
                                         naiveresults$abstract),
                                         features = all_keywords)

naivegraph <- litsearchr::create_network(search_dfm = as.matrix(naivedfm),
                                         min_studies = 2, min_occ = 2)

cutoff <- litsearchr::find_cutoff(naivegraph, method = "cumulative",
percent = .80, imp_method = "strength")

reducedgraph <- litsearchr::reduce_graph(naivegraph, cutoff_strength =
cutoff[1])

searchterms <- litsearchr::get_keywords(reducedgraph)

options(max.print = 2000)

head(searchterms, 2000)

write.csv(searchterms, "search_terms.csv")
```

APPENDIX C. R Script used in the *revtools* package.

```
library(tidyr)
library(dplyr)
library(stringr)
library(openxlsx)
library(revtools)

wos_1 <- read_bibliography("./wos1.bib")
wos_2 <- read_bibliography("./wos2.bib")
wos_3 <- read_bibliography("./wos3.bib")
wos_4 <- read_bibliography("./wos4.bib")

scopus <- read_bibliography("./scopus.bib")

cab_1 <- read_bibliography("./cab1.ris")
cab_2 <- read_bibliography("./cab2.ris")

wos_5 <- merge_columns(wos_1, wos_2)
wos_6 <- merge_columns(wos_3, wos_4)
wos_7 <- merge_columns(wos_5, wos_6)

cab_3 <- merge_columns(cab_1, cab_2)

names(wos_7)
names(scopus)
names (cab_3)

wos_8 <- wos_7 %>%
mutate(source = paste0("web_of_science"))

cab_4 <- cab_3 %>% rename (source = "DB")

data <- merge_columns(wos_8, scopus)
data_1 <- merge_columns(data, cab_4)

data_2 <- data_1 %>%
        arrange(title) %>%
        mutate(code = paste0("article", seq(1:4791))) %>%
        select(code, everything())

write.xlsx(data_2, file = "./planilha_total.xlsx")

write.csv(data_2, file = "./planilha_total.csv",
        row.names = FALSE,
        fileEncoding = "UTF-8")

duplicates_doi <- find_duplicates(data_2,
                                  match_variable = "doi",
                                  match_function = "exact",
                                  method = NULL)

data_3 <- extract_unique_references(data_2, duplicates_doi)

data_4 <- data_3 %>% rename(doi_duplicates = "n_duplicates")

sum(data_4$doi_duplicates)

duplicates_title <- find_duplicates(data_4,
                                  match_variable = "title",
```

```
                                          match_function = "stringdist",
                                          method = "osa",
                                          threshold = 1,
                                          to_lower = T,
                                          remove_punctuation = T)

data_5 <- extract_unique_references(data_4, duplicates_title)

data_6 <- data_5 %>% rename(title_duplicates = "n_duplicates")

sum(data_6$title_duplicates)

data_7 <- data_6 %>%
        mutate(duplicatas = title_duplicates + doi_duplicates - 1)

sum(data_7$duplicatas)

write.xlsx(data_7, file = "./final_dataset_duplicatas_removidas.xlsx")
```

APPENDIX D. List of included articles in the systematic map (n = 67) at full text screening.

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Williams-Linera, Guadalupe, Martha Bonilla-Moheno, and Fabiola López-Barrera. 2016. "Tropical Cloud Forest Recovery: The Role of Seed Banks in Pastures Dominated by an Exotic Grass." *New Forests* 47 (3): 481–96. https://doi.org/10.1007/s11056-016-9526-8.

Zamora Nasca, Lucía, Lia Montti, Ricardo Grau, and Leonardo Paolini. 2014. "Efectos de La Invasión Del Ligustro, Ligustrum Lucidum, En La Dinámica Hídrica de Las Yungas Del Noroeste Argentino." *Bosque* 35 (2): 195–205. https://doi.org/10.4067/S0717-92002014000200007.

Zangaro, Waldemar, Luis Eduardo Azevedo Marques Lescano, Enio Massao Matsuura, Artur Berbel Lirio Rondina, and Marco Antonio Nogueira. 2018. "Interactions between Arbuscular Mycorrhizal Fungi and Exotic Grasses Differentially Affect the Establishment of Seedlings of Early- and Late-Successional Woody Species." *Applied Soil Ecology* 124 (December 2017): 394–406. https://doi.org/10.1016/j.apsoil.2017.12.003.

APPENDIX E. List of excluded articles (n = 103) at full text screening along with reasons for exclusion.

Reference	Reasons for exclusion
Abarca, Camila, Marcelo Daniel Barrera, Marta Cabello, Fabricio Valdés, and María Silvana Velázquez. 2021. "Invasion of a Xeric Forest by an Exotic Tree Species in Argentina: Impacts on the Diversity of Arbuscular Mycorrhizal Fungi and Pre-Existing Mutualistic Relationships." *Acta Botanica Brasilica* 35 (2): 269–75. https://doi.org/10.1590/0102-33062020abb0095.	Not tropical forest.
Abelleira Martínez, Oscar J. 2010. "Invasion by Native Tree Species Prevents Biotic Homogenization in Novel Forests of Puerto Rico." *Plant Ecology* 211 (1): 49–64. https://doi.org/10.1007/s11258-010-9771-4.	Effects of land use history and substrate properties on tree species composition. Does not directly test the effect of the invasive species.
Aguilar-Dorantes, Karla, Klaus Mehltreter, Heike Vibrans, Martin Mata-Rosas, and Valentín A. Esqueda-Esquivel. 2014. " Repeated Selective Cutting Controls Neotropical Bracken (Pteridium Arachnoideum) and Restores Abandoned Pastures ." *Invasive Plant Science and Management* 7 (4): 580–89. https://doi.org/10.1614/ipsm-d-13-00062.1.	Effects measured on desirable pasture species (including alien plants).
Aizen, Marcelo A., Carolina L. Morales, and Juan M. Morales. 2008. "Invasive Mutualists Erode Native Pollination Webs." *PLoS Biology* 6 (2): 0396–0403. https://doi.org/10.1371/journal.pbio.0060031.	Temperate Forests.
Andrés, Pilar, Cloribel Salgado, and Josep M. Espelta. 2011. "Optimizing Nursery and Plantation Methods to Grow Cedrela Odorata Seedlings in Tropical Dry Agroecosystems." *Agroforestry Systems* 83 (2): 225–34. https://doi.org/10.1007/s10457-011-9404-5.	Competition from a native grass.
Baptiste, Alberto Jean, Pedro A. Macario, Gerald A. Islebe, Benedicto Vargas-Larreta, Luciano Pool, Mirna Valdez-Hernández, and Jorge O. López-Martínez. 2019. "Secondary Succession under Invasive Species (Pteridium Aquilinum) Conditions in a Seasonal Dry Tropical Forest in Southeastern Mexico." *PeerJ* 2019 (5): 1–16. https://doi.org/10.7717/peerj.6974.	It is not known whether Pteridium is invasive or not.
Barbosa, Karina Cavalheiro, Eduardo Luis Martins Catharino, Luiz Mauro Barbosa, Hilton Thadeu Zarate Do Couto, and Nelson Augusto Dos Santos Junior. 2021. "Potential of Natural Regeneration of a Compensatory Planting Carried out in an Urban Conservation Unit under Strong Anthropic Pressure." *Ciencia Florestal* 31 (2): 786–807. https://doi.org/10.5902/1980509843659.	Recorded a high seed rain from an invasive grass in a restoration planting, meaning that the area is still susceptible from grass invasion.
Bello, Carolina, Ana Laura P. Cintra, Elisa Barreto, Maurício Humberto Vancine, Thadeu Sobral-Souza, Catherine H. Graham, and Mauro Galetti. 2021. "Environmental Niche and Functional Role Similarity between Invasive and Native Palms in the Atlantic Forest." *Biological Invasions* 23 (3): 741–54. https://doi.org/10.1007/s10530-020-02400-8.	Not IAP impact assessment.

Braasch, Marco, Luis García-Barrios, Neptalí Ramírez-Marcial, Elisabeth Huber-Sannwald, and Sergio Cortina-Villar. 2017. "Can Cattle Grazing Substitute Fire for Maintaining Appreciated Pine Savannas at the Frontier of a Montane Forest Biosphere-Reserve?" *Agriculture, Ecosystems and Environment* 250 (August): 59–71. https://doi.org/10.1016/j.agee.2017.08.033.	Human-induced savannas managed with a focus on livestock production and non-timber products (anthropogenic).
Brandão, Jeane de Fátima Cunha, Sebastião Venâncio Martins, and Isac Jonatas Brandão. 2017. "Potencial de Regeneração de Uma Área Invadida Por Pteridium Aquilinum No Parque Nacional Do Caparaó." *Floresta* 46 (4): 543–52. https://doi.org/10.5380/rf.v46i3.41387.	It is not known whether Pteridium is invasive or not.
Calvo-Alvarado, Julio César, César Dionisio Jiménez-Rodríguez, Juan Carlos Solano, and Oscar Arias-Rodríguez. 2022. "Interception and Redistribution of Precipitation by Parkinsonia Aculeata L.: Implications for Palo Verde National Park Wetlands, Costa Rica." *Water (Switzerland)* 14 (3). https://doi.org/10.3390/w14030311.	Wetland. Flooded ecosystem.
Camacho-Erazo, Mariana, Jorge Robles, and Ángela R. Amarillo-Suárez. 2021. "Redes de Interacción Antagonística En Una Especie de Leguminos Nativa y Una Exótica En El Bosque Seco Tropical Colombiano." *Acta Zoológica Mexicana (N.S.)* 37: 1–16.	Described the factors mediating invasive species integration into the antagonistic interaction networks.
Carvalho, Thayane Ferreira, Israel Marinho Pereira, Soraya Alvarenga Botelho, Miranda Titon, and Anderson Cleiton José. 2019. "Restoration Strategies in an Area Invaded by Pteridium Aquilinum (L.) Kuhn." *Floresta e Ambiente* 26 (2). https://doi.org/10.1590/2179-8087.114617.	Assessed the performance of tree seedlings according to successional groups, planting densities and bracken fern removal, where they tested two different treatments without a control plot (not impact assessment). Also, It is not known whether Pteridium is invasive or not.
Carvalho, Thayane Ferreira, Aline Cristina Carvalho, José Cola Zanuncio, Marcio Leles Romarco de Oliveira, Evandro Luiz Mendonça Machado, Anderson Cleiton José, José Barbosa Santos, and Israel Marinho Pereira. 2022. "Does Invasion by Pteridium Aquilinum (Dennstaedtiaceae) Affect the Ecological Succession in Atlantic Forest Areas after a Fire?" *Environmental Science and Pollution Research* 29 (10): 14195–205. https://doi.org/10.1007/s11356-021-16761-7.	It is not known whether Pteridium is invasive or not.
Castellanos, Alejandro E., Hernán Celaya-Michel, Julio C. Rodríguez, and Bradford P. Wilcox. 2016. "Ecohydrological Changes in Semiarid Ecosystems Transformed from Shrubland to Buffelgrass Savanna." *Ecohydrology* 9 (8): 1663–74. https://doi.org/10.1002/eco.1756.	Desert biome (Sonoran desert). Nearctic.
Castro-Martínez, Astrid Lorena, Pablo Andrés Gil-Leguizamón, and María Eugenia Morales-Puentes. 2020. "Vegetación Asociada Con Helechales En El Parque Nacional Natural Serranía de Los Yariguíes, Colombia."	Phytosociological characterization of a single site occupied by an invasive fern.

Revista de Biología Tropical 68 (4): 1107–15. https://doi.org/10.15517/rbt.v68i4.40451.	
Ceballos, Sergio J., Yohana Jimenez, and Romina Fernandez. 2020. “Estructura de Los Bosques de Gleditsia Triacanthos En Función de La Edad (Valle de La Sala, Tucumán, Argentina).” *Ecología Austral* 30 (2): 251–59. https://doi.org/10.25260/ea.20.30.2.0.1083.	Not IAP impact assessment.
Celis, Gerardo, and Shibu Jose. 2011. “Restoring Abandoned Pasture Land with Native Tree Species in Costa Rica: Effects of Exotic Grass Competition and Light.” *Forest Ecology and Management* 261 (10): 1598–1604. https://doi.org/10.1016/j.foreco.2010.10.005.	No mention to plant invasion.
Cohen, Ian M., and James D. Ackerman. 2009. “Oeceoclades Maculata, an Alien Tropical Orchid in a Caribbean Rainforest.” *Annals of Botany* 104 (3): 557–63. https://doi.org/10.1093/aob/mcn191.	Not impact assessment. By associating its local distribution with land-use history and habitat characteristics, it was determined whether the alien plant is dependent on habitat disturbance. It was also investigated whether this exotic orchid occupies the same habitat space as two sympatric native species.
Colmanetti, Michel Anderson Almeida, Luiz Mauro Barbosa, Hilton Thadeu Zarate do Couto, José Carlos Casagrande, Regina Tomoko Shirasuna, Paulo Roberto Torres Ortiz, Renato Paiva de Lima, and Miguel Magela Diniz. 2021. “Impact of Soil Properties, Tree Layer and Grass Cover on Forest Regeneration in a Mixed Native Species Reforestation.” *Scientia Forestalis/Forest Sciences* 49 (130). https://doi.org/10.18671/SCIFOR.V49N130.23.	Savanna (Cerrado)
Costa, Rosane Oliveira, Celso Markowitsch José, Maria Tereza Grombone-Guaratini, and Dalva Maria Silva Matos. 2019. “Chemical Characterization and Phytotoxicity of the Essential Oil from the Invasive Hedychium Coronarium on Seeds of Brazilian Riparian Trees.” *Flora: Morphology, Distribution, Functional Ecology of Plants* 257 (February): 151411. https://doi.org/10.1016/j.flora.2019.05.010.	Savanna (Cerrado)
Cusack, Daniela F., and Taylor L. McCleery. 2014. “Patterns in Understory Woody Diversity and Soil Nitrogen across Native- and Non-Native-Urban Tropical Forests.” *Forest Ecology and Management* 318: 34–43. https://doi.org/10.1016/j.foreco.2013.12.036.	Not sure if all the introduced trees are really invaders. Did not compare invasive Fabaceae with native Fabaceae.
Dias, Jézili, and José Marcelo Domingues Torezan. 2020. “Factors Affecting The Abundance Of Ruderal Species And Megathyrsus Maximus, An Invasive C4 Grass In Atlantic Forest Restoration Sites.” *Floresta* 50 (4): 1931–38. https://doi.org/10.5380/rf.v50i4.67192.	Effects of planting age, canopy openness, reforestation planting features, and soil fertility on the abundance of ruderal species, M. maximus and other grasses. Invasive

	plant responses to abiotic and biotic features, not invasive impact.
Douterlungne, David, Evert Thomas, and Samuel I. Levy-Tacher. 2013. "Fast-Growing Pioneer Tree Stands as a Rapid and Effective Strategy for Bracken Elimination in the Neotropics." *Journal of Applied Ecology* 50 (5): 1257–65. https://doi.org/10.1111/1365-2664.12077.	Effect of a native fast-growing pioneer species on invasive fern. Investigated how invasive biomass were affected by native tree basal area, leaf litter production and understory light intensity. Invasive performance response to the native tree.
Ewald, Michael, Sandra Skowronek, Raf Aerts, Klara Dolos, Jonathan Lenoir, Manuel Nicolas, Jens Warrie, et al. 2018. "Analyzing Remotely Sensed Structural and Chemical Canopy Traits of a Forest Invaded by Prunus Serotina over Multiple Spatial Scales." *Biological Invasions* 20 (8): 2257–71. https://doi.org/10.1007/s10530-018-1700-9.	Study site is located in northern France.
Fabricante, Juliano Ricardo, Marina Nabuco de Araújo Oliveira, and José Alves de Siqueira Filho. 2013. "Aspectos Da Ecologia de Calotropis Procera (Apocynaceae) Em Uma Área de Caatinga Alterada Pelas Obras Do Projeto de Integração Do Rio São Francisco Em Mauriti, CE." *Rodriguésia* 64 (3): 647–54.	Tested the invader allelopathy effects on a non-native crop species (Lactuca sativa).
Falcón, Wilfredo, James D. Ackerman, and Raymond L. Tremblay. 2017. "Quantifying How Acquired Interactions with Native and Invasive Insects Influence Population Growth Rates of a Non-Indigenous Plant." *Biological Invasions* 19 (3): 895–911. https://doi.org/10.1007/s10530-016-1318-8.	How interspecific interactions affect the population demography of an invasive orchid.
Falleiros, Renan Macari, Rafael Dudeque Zenni, and Sílvia Renate Ziller. 2011. "Invasão e Manejo de Pinus Taeda Em Campos de Altitude Do Parque Estadual Do Pico Paraná, Paraná, Brasil." *Floresta* 41 (1): 123–34. https://doi.org/10.5380/rf.v41i1.21193.	Pine invasion primarily in native grassland vegetation. The forest physiognomy represented only 0.42% of the area where the invasive species was found.
Fernández, Romina D., and Roxana Aragón. 2014. "Leaf Litter Decomposition of the Most Abundant Native and Exotic Woody Species in the Piedmont of Yungas Forest, Tucumán, Argentina." *Ecologia Austral* 24 (3): 286–93.	Not impact assesment.
Fernández, Romina Daiana, Sergio Javier Ceballos, Ana Lucía González Achem, Margarita Del Valle Hidalgo, and Hugo Rafael Fernández. 2016. "Quality and Conservation of Riparian Forest in a Mountain Subtropical Basin of Argentina." *International Journal of Ecology* 2016. https://doi.org/10.1155/2016/4842165.	Recorded many exotic species and used the terms "invasive" and "exotic" interchangeably. Also, the statistical analysis did not separate the Moist Forests and Savannas/Shrubland sites.
Ferreras, A. E., M. A. Giorgis, P. A. Tecco, M. R. Cabido, and G. Funes. 2015. "Impact of Ligustrum Lucidum on the Soil Seed Bank in Invaded Subtropical Seasonally Dry Woodlands (Córdoba, Argentina)." *Biological*	Study site is on Chaco Serrano. Grasslands, savannas and shrublands biome.

Invasions 17 (12): 3547–61. https://doi.org/10.1007/s10530-015-0977-1.	
Fetter, Douglas, Doris Sippel Dörr, Jorge André Ribas Moraes, Jair Putzke, and Eduardo A. Lobo. 2020. "Methodology Proposed for Photogrammetric Monitoring of the Exotic Species Hovenia Dulcis Thunb. in the Green Belt Area Surrounding the City of Santa Cruz Do Sul, RS, Brazil." *Environmental Monitoring and Assessment* 192 (1). https://doi.org/10.1007/s10661-019-8018-7.	Photogrammetric monitoring of Hovenia dulcis canopy cover to estimate the area occupied by the species.
Fonseca da Silva, Jéssica. 2015. "Dynamics of Novel Forests of Castilla Elastica in Puerto Rico: From Species to Ecosystems." *Ecology and Evolution* 5 (16): 3299–3311. https://doi.org/10.1002/ece3.1578.	Did not mention the studied species as invasive, neither assessed its impacts. Rather, she compared the ecology of the introduced plant in two stands.
Fonseca, Daniel G., and Marcel O. Tanaka. 2015. "Influence of an Exotic Grass on Benthic Macroinvertebrate Communities in a Tropical Rural Landscape." *Hydrobiologia* 762 (1): 239–51. https://doi.org/10.1007/s10750-015-2353-7.	Savanna (Cerrado)
Fragoso, Rosimeri de Oliveira, Antonio Aparecido Carpanezzi, Katia Christina Zuffellato-Ribas, and Henrique Soares Koehler. 2017. "Restauração Florestal Em Pastagem Abandonada de Urochloa Por Meio de Diferentes Tamanhos de Galharia." *Cerne* 23 (1): 85–93. https://doi.org/10.1590/01047760201723012276.	Not impact assessment. Effects of brushwood size on natural regeneration performance in areas covered by an exotic grass.
Franklin, Kim A., Kelly Lyons, Pamela L. Nagler, Derrick Lampkin, Edward P. Glenn, Francisco Molina-Freaner, Therese Markow, and Alfredo R. Huete. 2006. "Buffelgrass (Pennisetum Ciliare) Land Conversion and Productivity in the Plains of Sonora, Mexico." *Biological Conservation* 127 (1): 62–71. https://doi.org/10.1016/j.biocon.2005.07.018.	Desert biome (Sonoran Desert). Nearctic realm. Also, addressed the effect of land cover changes on primary productivity.
Freitas, Welington Kiffer, Luís Mauro Sampaio Magalhãe, Alexander Silva de Resende, Felipe da Costa Brasil, Lise da Rocha Vivès, Marco Aurélio Soares Pinheiro, Pedro Lima Filho, and Rômulo Vinicius Luz. 2017. "INVASION IMPACT OF Artocarpus Heterophyllus LAM . (Moraceae) AT THE EDGE OF AN ATLANTIC FOREST FRAGMENT IN THE MUNICIPALITY OF RIO DE JANEIRO , BRAZIL IMPACTO DA INVASÃO DE Artocarpus Heterophyllus LAM . (Moraceae) NA BORDA DE UM FRAGMENTO DE MATA ATL." *Biosci. J. Uberlândia* 33 (2): 422–33.	Phytosociological characterization of a single site occupied by an invasive tree.
Galvão, Franklin, Cátia Regina Augustin, Gustavo Ribas Curcio, Nelson Cosmo, Carina Kozera, Bruno Polli Domanowski, and Alison Tadeu Sawczuk. 2012. "IMPACTO DE Guadua Paraguayana SOBRE REMANESCENTE DE FLORESTA OMBRÓFILA MISTA ALUVIAL – UMA ABORDAGEM BIOGEOQUÍMICA." *Floresta* 42 (2): 355. https://doi.org/10.5380/rf.v42i2.19847.	The studied species isn't an invasive alien plant. Native bamboo outbreak.
Galvão, Franklin, Cátia Regina Augustin, Gustavo Ribas Curcio, Bruno Polli	The studied species isn't an invasive

Domanowski, Carina Kozera, Alison Tadeu Sawczuk, and Annete Bonnet. 2009. "Auto-Ecology of Guadua Aff. Paraguayana (Poaceae)." *Pesquisa Florestal Brasileira* 58: 05–16. https://doi.org/10.4336/2012.pfb.58.05.	alien plant. Native bamboo outbreak.
Galvão, Franklin, Carlos Vellozo Roderjan, Mauricio Pozzobon, Cátia Regina Augustin, Gustavo Ribas Curcio, Nelson Luiz Cosmo, Bianca Ott Andrade, Rafael Rosenstock Völtz, and Tomaz Longhi-Santos. 2014. "Influence of Guadua Paraguayana Döll on the Structure and Regeneration of a Remaining Forest at the High Lands of Tibagi River, Paraná State." *Ambiência* 10 (3): 769–83. https://doi.org/10.5935/ambiencia.2014.03.09.	The studied species isn't an invasive alien plant. Native bamboo outbreak.
García, Andrea Arias, and J. Danilo Chinea. 2014. "Seed Rain under Native and Non-Native Tree Species in the Cabo Rojo National Wildlife Refuge, Puerto Rico." *Revista de Biologia Tropical* 62 (3): 1129–36. https://doi.org/10.15517/rbt.v62i3.12942.	Did not mention the studied species as invasive.
Gómez-Ruiz, Pilar Angélica, Roberto Lindig-Cisneros, and Orlando Vargas-Ríos. 2013. "Facilitation among Plants: A Strategy for the Ecological Restoration of the High-Andean Forest (Bogotá, D.C.-Colombia)." *Ecological Engineering* 57: 267–75. https://doi.org/10.1016/j.ecoleng.2013.04.049.	Effect of native nurse plants on other native species.
González-Tokman, Daniel Matías, Víctor Luis Barradas, Karina Boege, César Augusto Domínguez, Ek del-Val, Erandi Saucedo, and Cristina Martínez-Garza. 2018. "Performance of 11 Tree Species under Different Management Treatments in Restoration Plantings in a Tropical Dry Forest." *Restoration Ecology* 26 (4): 642–49. https://doi.org/10.1111/rec.12617.	Did not mention the studied species as invasive.
Griscom, Heather P., Bronson W. Griscom, and Mark S. Ashton. 2009. "Forest Regeneration from Pasture in the Dry Tropics of Panama: Effects of Cattle, Exotic Grass, and Forested Riparia." *Restoration Ecology* 17 (1): 117–26. https://doi.org/10.1111/j.1526-100X.2007.00342.x.	Did not mention the studied species as invasive.
Guido, Anaclara, and Valério D. Pillar. 2017. "Invasive Plant Removal: Assessing Community Impact and Recovery from Invasion." *Journal of Applied Ecology* 54 (4): 1230–37. https://doi.org/10.1111/1365-2664.12848.	The study site is in the Grasslands biome (Pampas).
Heringer, Gustavo, Marcelo L. Bueno, João A.A. Meira-Neto, Fábio A.R. Matos, and Andreza V. Neri. 2019. "Can Acacia Mangium and Acacia Auriculiformis Hinder Restoration Efforts in the Brazilian Atlantic Forest under Current and Future Climate Conditions?" *Biological Invasions* 21 (9): 2949–62. https://doi.org/10.1007/s10530-019-02024-7.	Invasion risk assessment. Effect of current and future climate conditions on geographic distribution of A. mangium and A. auriculiformis in Atlantic Forest restoration. Potential impact due to overlaps between suitable areas for invasion and

	potential areas for forest restoration.
Heringer, Gustavo, Jan Thiele, João Augusto Alves Meira-Neto, and Andreza Viana Neri. 2019. "Biological Invasion Threatens the Sandy-Savanna Mussununga Ecosystem in the Brazilian Atlantic Forest." *Biological Invasions* 21 (6): 2045–57. https://doi.org/10.1007/s10530-019-01955-5.	The study site is a Savanna.
Hoffmann, William A., Verusca M.P.C. Lucatelli, Franciane J. Silva, Isaac N.C. Azeuedo, Marcelo Da S. Marinho, Ana Maria S. Albuquerque, Apoena De O. Lopes, and Sirvana P. Moreira. 2004. "Impact of the Invasive Alien Grass Melinis Minutiflora at the Savanna-Forest Ecotone in the Brazilian Cerrado." *Diversity and Distributions* 10 (2): 99–103. https://doi.org/10.1111/j.1366-9516.2004.00063.x.	Savanna biome (Cerrado).
Hoyos, Laura E., Gregorio I. Gavier-Pizarro, Tobias Kuemmerle, Enrique H. Bucher, Volker C. Radeloff, and Paula A. Tecco. 2010. "Invasion of Glossy Privet (Ligustrum Lucidum) and Native Forest Loss in the Sierras Chicas of Córdoba, Argentina." *Biological Invasions* 12 (9): 3261–75. https://doi.org/10.1007/s10530-010-9720-0.	Savannas and native grasslands.
Jesus Jatoba, Luciana De, Rosa Maria Varela, José Maria Gonzalez Molinillo, Zia Ud Din, Sonia Cristina Juliano Gualtieri, Edson Rodrigues-Filho, and Francisco Antonio Macías. 2016. "Allelopathy of Bracken Fern (Pteridium Arachnoideum): New Evidence from Green Fronds, Litter, and Soil." *PLoS ONE* 11 (8): 1–16. https://doi.org/10.1371/journal.pone.0161670.	Savanna. Tested the effect of bracken allelopathy on two non-native crop species (Sesamum indicum and Triticum aestivum).
Lacerda, André Eduardo Biscaia. 2021. "Understanding the Long-Term Impact of Bamboos on Secondary Forests: A Case for Bamboo Management in Southern Brazil." *Diversity* 13 (11). https://doi.org/10.3390/d13110567.	The studied species isn't an invasive alien plant. Native bamboo outbreak.
Jung, Paulo Henrique, Flávia Gizele König Brun, Eleandro José Brun, Solon Jonas Longhi, and Aline Paula Pastorio. 2018. "Urban and Agricultural Impacts in the Structure and Diversity of Tree Vegetation in Riparian Forest." *Revista Brasileirade Ciencias Agrarias* 13 (2). https://doi.org/10.5039/agraria.v13i2a5533.	Influence of the environmental impacts of urban occupations and agricultural activities on the floristic composition and phytosociological structure of the tree layer in a riparian forest.
Lacerda, André Eduardo Biscaia. 2021. "Understanding the Long-Term Impact of Bamboos on Secondary Forests: A Case for Bamboo Management in Southern Brazil." *Diversity* 13 (11). https://doi.org/10.3390/d13110567.	The studied species isn't an invasive alien plant. Native bamboo outbreak.
Lacerda, André Eduardo Biscaia, and Betina Kellermann. 2019. "What Is the Long-Term Effect of Bamboo Dominance on Adult Trees in the Araucaria Forest? A Comparative Analysis between Two Successional Stages in Southern Brazil." *Diversity* 11 (9). https://doi.org/10.3390/d11090165.	The studied species isn't an invasive alien plant. Native bamboo outbreak.

Laurindo, Lídia Klestadt, Tancredo Augusto Feitosa de Souza, Lucas Jónatan Rodrigues da Silva, Thays Bragagnolo Casal, Karoline de Jesus Conceição Pires, Sarah Kormann, Djalma Eugênio Schmitt, and Alexandre Siminski. 2021. "Arbuscular Mycorrhizal Fungal Community Assembly in Agroforestry Systems from the Southern Brazil." *Biologia* 76 (4): 1099–1107. https://doi.org/10.1007/s11756-021-00700-5.	Comparison between disturbance levels, not the impact assessment of an IAP. Hypothesized that native tree species in an agroforestry system promote the composition of the AMG community closer to that observed in the reference system, in comparison to disturbed ecosystems without tree plantings (and with invasive pine).
Lazzarin, Luciane Cristina, Ana Carolina da Silva, Pedro Higuchi, Karine Souza, Jucelei Edson Perin, and Ealine Pereira Cruz. 2015. "Invasão Biológica Por Hovenia Dulcis Thunb. Em Fragmentos Florestais Na Região Do Alto Uruguai, Brasil." *Revista Arvore* 39 (6): 1007–17. https://doi.org/10.1590/0100-67622015000600003.	Invasiveness study.
Leite-Rossi, Luciene Aparecida, Victor Satoru Saito, Marcela Bianchessi Cunha-Santino, and Susana Trivinho-Strixino. 2016. "How Does Leaf Litter Chemistry Influence Its Decomposition and Colonization by Shredder Chironomidae (Diptera) Larvae in a Tropical Stream?" *Hydrobiologia* 771 (1): 119–30. https://doi.org/10.1007/s10750-015-2626-1.	Savanna biome.
León Cordero, Rodrigo, Fábio P. Torchelsen, Gerhard E. Overbeck, and Madhur Anand. 2016. "Invasive Gorse (Ulex Europaeus, Fabaceae) Changes Plant Community Structure in Subtropical Forest–Grassland Mosaics of Southern Brazil." *Biological Invasions* 18 (6): 1629–43. https://doi.org/10.1007/s10530-016-1106-5.	Assessed the impact of the invasive plant in areas of Atlantic Forest, in addition to the Pampas. However, the invasive did not invade forests, only its vicinity. Goarse only established within ungrazed and heavily grazed grasslands, and logged plantations, where its impacts were measured by comparing the richness and cover of natives under and beside goarse canopies. Since the invader only established in anthropogenic areas (active plantations and pastures), we did not include the study, because it is mainly a grassland invader.
Levy-Tacher, Samuel I., Ivar Vleut, Francisco Román-Dañobeytia, and James Aronson. 2015. "Natural Regeneration after Long-Term Bracken Fern Control with Balsa (Ochroma Pyramidale) in the Neotropics." *Forests* 6 (6): 2163–77. https://doi.org/10.3390/f6062163.	It is not known whether Pteridium is invasive or not.
Lisbôa, Fabrício Marinho. 2018. "Effects of Burning and Weed Control on Vegetation Cover and Soil Organic Matter Compartments in the	Effect of pasture management on vegetation cover and soil C stocks.

Brazilian Amazon." *Acta Agronomica* 67 (3): 418–23. https://doi.org/10.15446/acag.v67n3.60000.	
Londe, Vinícius, Hildeberto Caldas de Sousa, and Alessandra R. Kozovits. 2017. "Exotic and Invasive Species Compromise the Seed Bank and Seed Rain Dynamics in Forests Undergoing Restoration at Urban Regions." *Journal of Forestry Research* 28 (5): 1019–26. https://doi.org/10.1007/s11676-017-0370-2.	Just found seeds of exotic and invasive plants in seed banks of a restoration area. Not an IAP impact assessment.
López-Upton, Javier, J. René Valdez-Lazalde, Aracely Ventura-Ríos, J. Jesús Vargas-Hernández, and Vidal Guerra-de-la-Cruz. 2015. "Extinction Risk of Pseudotsuga Menziesii Populations in the Central Region of Mexico: An AHP Analysis." *Forests* 6 (5): 1598–1612. https://doi.org/10.3390/f6051598.	Modeled the risk of extinction of a native species. Did not assess the impact of invasive alien plants.
Machado, N. G., L. Sanches, L. B. Silva, J. W.Z. Novais, A. M. Aquino, M. S. Biudes, O. B. Pinto-Junior, and J. S. Nogueira. 2015. "Soil Nutrients and Vegetation Structure in a Neotropical Seasonal Wetland." *Applied Ecology and Environmental Research* 13 (2): 289–305. https://doi.org/10.15666/aeer/1302_289305.	Pantanal wetland. Flooded grasslands and savannas.
Mallerman, Julieta, Raúl Itria, Enrique Alarcón-Gutiérrez, Christian Hernández, Laura Levin, and Mario Saparrat. 2018. "Exotic Litter of the Invasive Plant Ligustrum Lucidum Alters Enzymatic Production and Lignin Degradation by Selected Saprotrophic Fungi." *Canadian Journal of Forest Research* 48 (6): 709–20. https://doi.org/10.1139/cjfr-2017-0309.	Temperate Grassland.
Mantoani, Maurício Cruz, Jézili Dias, and José Marcelo Domingues Torezan. 2016. "Mowing and Herbicide Application to Control Megathyrsus Maximus: Damage on Pre-Existing Vegetation in a 20-Year Reforestation Site." *Ciencia Florestal* 26 (3): 839–51. https://doi.org/10.5902/1980509824212.	Effect of disturbances caused by different weed control techniques.
Martínez, Oscar J.Abelleira, Mariela A. Rodríguez, Ivonne Rosario, Nataly Soto, Armando López, and Ariel E. Lugo. 2009. "Structure and Species Composition of Novel Forests Dominated by an Introduced Species in Northcentral Puerto Rico." *New Forests* 39 (1): 1–18. https://doi.org/10.1007/s11056-009-9154-7.	Did not evaluate the impact of the species itself. They hypothesized that (1) the structure and species composition of S. campanulata forests would vary as native forests on equivalent substrate types do and (2) species composition would change through tree size classes reflecting lower dominance of S. campanulata and higher species richness in juvenile compared to larger tree size classes.
Maya-Elizarrarás, Elisa, and Jorge E. Schondube. 2015. "Birds, Cattle, and Bracken Ferns: Bird Community Responses to a Neotropical Landscape Shaped by Cattle Grazing Activities." *Biotropica* 47 (2): 236–45.	Evaluated how neotropical bird communities responded to different habitats. Not the impact of the

https://doi.org/10.1111/btp.12196.	bracken fern.
Mello, J. H.F., T. P. Moulton, D. S.L. Raíces, and H. G. Bergallo. 2015. "Sobre Ratos e Jaqueiras: Modelando a Capacidade Suporte de Uma População Do Rato-de-Espinho Da Mata Atlântica Trinomys Dimidiatus (Günther,1877) – Rodentia, Echimyidae – Em Relação a Diferentes Abundâncias de Jaqueiras (Artocarpus Heterophyllus L.)." *Brazilian Journal of Biology* 75 (1): 208–15. https://doi.org/10.1590/1519-6984.11613.	Not IAP impact assessment.
Menezes, R. S.C., I. H. Salcedo, and E. T. Elliott. 2002. "Microclimate and Nutrient Dynamics in a Silvopastoral System of Semiarid Northeastern Brazil." *Agroforestry Systems* 56 (1): 27–38. https://doi.org/10.1023/A:1021172530939.	Not invasive. Effects of different tree species on soil variables in silvopastoral systems.
Montti, Lía, Mariana Villagra, Paula I. Campanello, M. Genoveva Gatti, and Guillermo Goldstein. 2014. "Functional Traits Enhance Invasiveness of Bamboos over Co-Occurring Tree Saplings in the Semideciduous Atlantic Forest." *Acta Oecologica* 54: 36–44. https://doi.org/10.1016/j.actao.2013.03.004.	Native bamboo outbreak.
Norghauer, Julian M., Adam R. Martin, Erin E. Mycroft, Arlington James, and Sean C. Thomas. 2011. "Island Invasion by a Threatened Tree Species: Evidence for Natural Enemy Release of Mahogany (Swietenia Macrophylla) on Dominica, Lesser Antilles." *PLoS ONE* 6 (4). https://doi.org/10.1371/journal.pone.0018790.	Non-native plantation stand. Not yet invasive at the studied site. Also, the Cabrits National Park is classified as Deserts and Xeric Shrubland.
Nunes, Amanda Da Silva, Pedro Higuchi, Ana Carolina da Silva, Ricardo De Vargas Kilca, Mariele Alves Ferrer da Silva, Angélica Dalla Rosa, Vanessa Fátima Soboleski, et al. 2020. "Invasão de Ligustro No Sub-Bosque de Um Remanescente de Floresta Com Araucária: Uma Abordagem Demográfica." *Ciência Florestal* 30 (3): 620–31. https://doi.org/10.5902/1980509820718.	Impact not assessed. They sought to identify which stage of the invasion process is the studied invasive plant (Ligustrum invasive fitness).
Oliveira, Guilherme de, Bruno de Souza Barreto, Daniela da Silva dos Santos, Vinícius Queiroz de Matos, and Maria Cecília Seara Santos. 2018. "Combining the Effects of Biological Invasion and Climate Change into Systematic Conservation Planning for the Atlantic Forest." *Biological Invasions* 20 (10): 2753–65. https://doi.org/10.1007/s10530-018-1727-y.	Not IAP impact assessment.
Palomeque, Ximena, Sven Günter, David Siddons, Patrick Hildebrandt, Bernd Stimm, Nikolay Aguirre, Ruth Arias, and Michael Weber. 2017. "Natural or Assisted Succession as Approach of Forest Recovery on Abandoned Lands with Different Land Use History in the Andes of Southern Ecuador." *New Forests* 48 (5): 643–62. https://doi.org/10.1007/s11056-017-9590-8.	Compared different land use histories and vegetations.
Park, Andrew, Patrick Friesen, and Aneth Aracelly Sarmiento Serrud. 2010. "Comparative Water Fluxes through Leaf Litter of Tropical Plantation	Effect of different land covers (non-native grass and mixed plantations of

Trees and the Invasive Grass Saccharum Spontaneum in the Republic of Panama." *Journal of Hydrology* 383 (3–4): 167–78. https://doi.org/10.1016/j.jhydrol.2009.12.033.	native and non-native trees) on litter hydrodynamics. Not IAP impacts.
Pizano, Camila, Kaoru Kitajima, James H. Graham, and Scott A. Mangan. 2019. "Negative Plant–Soil Feedbacks Are Stronger in Agricultural Habitats than in Forest Fragments in the Tropical Andes." *Ecology* 100 (12): 1–12. https://doi.org/10.1002/ecy.2850.	Impact was not assessed. Studied if the grass invasion success in Coffea plantations is due to positive feedbacks mediated by AMF.
Plaza Behr, Maia C., Carolina A. Pérez, Juan F. Goya, Maximiliano Azcona, and Marcelo F. Arturi. 2016. "Plantación de Celtis Ehrenbergiana Como Técnica de Recuperación de Bosques Invadidos Por Ligustrum Lucidum En Los Talares Del NE de Buenos Aires." *Ecologia Austral* 26 (2): 171–77. https://doi.org/10.25260/ea.16.26.2.0.176.	Study site is in wet fields of the Pampas biome. Analyzed the effect of the position of felling plants with respect to the clearing and the size of the clearings on their survival and growth.
Podadera, Diego S., Vera L. Engel, John A. Parrotta, Deivid L. Machado, Luciane M. Sato, and Giselda Durigan. 2015. "Influence of Removal of a Non-Native Tree Species Mimosa Caesalpiniifolia Benth. on the Regenerating Plant Communities in a Tropical Semideciduous Forest Under Restoration in Brazil." *Environmental Management* 56 (5): 1148–58. https://doi.org/10.1007/s00267-015-0560-7.	Not invasive plant. The non-native tree was planted in the restoration.
Potthast, Karin, Ute Hamer, and Franz Makeschin. 2010. "Impact of Litter Quality on Mineralization Processes in Managed and Abandoned Pasture Soils in Southern Ecuador." *Soil Biology and Biochemistry* 42 (1): 56–64. https://doi.org/10.1016/j.soilbio.2009.09.025.	Effects of litter quality on mineralization processes from different land uses. Implications for changes in vegetation cover and soil quality for active pasture management.
Ramos, Marli, Teresa Cristina Magro, Hilton Thadeu Zarate do Couto, and Tito Nunes de Castro. 2019. "Dispersão e Impacto de *Pinus Elliottii* Engelm. Var. *Elliottii* Em Área Ripária Na Floresta Nacional de Capão Bonito - SP." *Ciência Florestal* 29 (1): 75–85. https://doi.org/10.5902/1980509825789.	Pinus invasiveness and vegetation mostly covered by Savanna.
Rocha-Nicoleite, Edilane, Mari Lucia Campos, Guthieri Teixeira Colombo, Gerhard Ernst Overbeck, and Sandra Cristina Müller. 2018. "Forest Restoration after Severe Degradation by Coal Mining: Lessons from the First Years of Monitoring." *Revista Brasileira de Botanica* 41 (3): 653–64. https://doi.org/10.1007/s40415-018-0486-4.	Exotic grasses were sowed for rehabilitation purposes. Alien plant not described as invasive.
Sanabria-Silva, Ana María, and Ángela R. Amarillo-Suárez. 2017. "Same but Different: Diversity and Complexity of an Arthropod Trophic Network and Comparative Seed Viability of an Invasive and a Native Legume Species." *Journal of Arid Environments* 145: 10–17. https://doi.org/10.1016/j.jaridenv.2017.04.004.	Not IAP impact assessment. Aimed to understand how exotic species integrate into their recipient communities and the complexity of their interactions.
Saulino, Hugo H. L., and Susana Trivinho-Strixino. 2017. "Forecasting the Impact of an Invasive Macrophyte Species in the Littoral Zone through	Savanna (Cerrado)

Aquatic Insect Species Composition." *Iheringia. Série Zoologia* 107 (0): 1–8. https://doi.org/10.1590/1678-4766e2017043.	
Segura, E. M., M. A. Giorgis, and J. N. Lescano. 2021. "Native Anurans Threatened by the Alien Tree Ligustrum Lucidum in a Seasonal Subtropical Forest." *Biological Invasions* 23 (12): 3859–69. https://doi.org/10.1007/s10530-021-02617-1.	Tropical & Subtropical Grasslands, Savannas and Shrublands (Chaco Serrano).
Segura, Luciano N., Florencia D. Dosil-Hiriart, and Lucas N. González-García. 2020. "Exotic Trees Fail as a Support for Red-Crested Cardinal (Paroaria Coronata) Nests in a Native Forest of East-Central Argentina." *Hornero* 35 (1): 29–35.	Grasslands, savannas and shrublands biome.
Silva Matos, D. M., and T. A. Belinato. 2010. "Interferência de Pteridium Arachnoideum (Kaulf.) Maxon. (Dennstaedtiaceae) No Estabelecimento de Árvores Tropicais." *Brazilian Journal of Biology* 70 (2): 311–16. https://doi.org/10.1590/S1519-69842010000200012.	It is not known whether Pteridium is invasive or not.
Silva Nunes, Amanda Da, Pedro Higuchi, Ana Carolina Da Silva, Ricardo De Vargas Kilca, Mariele Alves Ferrer Da Silva, and Janaina Gabriela Larsen. 2018. "Ligustrum Lucidum as an Opportunist Invasive Species in an Araucaria Forest in South Brazil." *Rodriguesia* 69 (2): 351–62. https://doi.org/10.1590/2175-7860201869207.	Invasion mechanisms.
Smith, D M, and D M Finch. 2014. "USE OF NATIVE AND NONNATIVE NEST PLANTS BY RIPARIAN-NESTING BIRDS ALONG TWO STREAMS IN NEW MEXICO." *River Research and Applications* 30 (January): 1134–45. https://doi.org/10.1002/rra.2713.	Nearctic realm.
Sobanski, Natacha, and Marcia C.M. Marques. 2014. "Effects of Soil Characteristics and Exotic Grass Cover on the Forest Restoration of the Atlantic Forest Region." *Journal for Nature Conservation* 22 (3): 217–22. https://doi.org/10.1016/j.jnc.2014.01.001.	Did not mention the exotic plant species as invasive.
Soifer, Lydia G., and James D. Ackerman. 2019. "Extremes of Forest–Urban Gradient Offer Some Refuge for Alien Orchid Invasion." *Biological Invasions* 21 (6): 2143–57. https://doi.org/10.1007/s10530-019-01963-5.	Invasion success study.
Spiazzi, Fábio Rodrigues, Ana Carolina da Silva, Pedro Higuchi, André Luiz Guidini, Marcelo Negrini, Tiago de Souza Ferreira, Manoela Drews de Aguiar, Aline Pereira Cruz, Vanessa Fátima Soboleski, and Marcelo Negrini Amanda da Silva Nunes. 2002. "Quantificação Da Contaminação Biológica Por Espécies Arbóreas Exóticas Em Um Fragmento De Floresta Ombrófila Mista Em Lages - Sc." *Ciência Florestal*, no. 3384: 51–60.	Aimed to evaluate the stages of invasion process.
Suganuma, Marcio Seiji, José Marcelo D. Torezan, and Giselda Durigan. 2018. "Environment and Landscape Rather than Planting Design Are the Drivers of Success in Long-Term Restoration of Riparian Atlantic Forest." *Applied Vegetation Science* 21 (1): 76–84.	IAP name not provided.

https://doi.org/10.1111/avsc.12341.	
Tiberio, F. C.S., T. A. Sampaio-E-Silva, D. M.S. Matos, and A. Z. Antunes. 2016. "Os Riscos Da Introdução Da Palmeira Amazônica Euterpe Oleracea Na Floresta Atlântica." *Brazilian Journal of Biology* 76 (1): 66–72. https://doi.org/10.1590/1519-6984.12114.	They studied the invasiveness of an introduced Palm in the Atlantic Forest and after that the effects of its introduction on a native palm population. The species wasn't considered invasive when the study was performed. Nevertheless, they concluded that the hybrids might be able to interact with birds, spread and successfully establish in wild areas. But the final consequence of this invasion still needs to be addressed.
Tomazi, Aline Luiza, and Tânia Tarabini Castellani. 2016. "Artificial Perches and Solarization for Forest Restoration: Assessment of Their Value." *Tropical Conservation Science* 9 (2): 809–31. https://doi.org/10.1177/194008291600900215.	The results could not be attributed to the absence of these invasive species.
Valdez-Ramírez, Carlos, Samuel Israel Levy-Tacher, Noé Samuel León-Martínez, Darío Alejandro Navarrete-Gutiérrez, and Ángel Isauro Ortiz-Ceballos. 2020. "Cambios Químicos y Biológicos Del Suelo Provocados Por Pteridium Aquilinum (L.) Kuhn En Áreas de Influencia de La Reserva de La Biosfera de Calakmul, Campeche." *Revista Terra Latinoamericana* 38 (2): 289–300. https://doi.org/10.28940/terra.v38i2.464.	It is not known whether Pteridium is invasive or not.
Vitorino, Breno Dias, Angélica Vilas Boas da Frota, and Pietro Kiyoshi Maruyama. 2021. "Ecological Determinants of Interactions as Key When Planning Pollinator-Friendly Urban Greening: A Plant-Hummingbird Network Example." *Urban Forestry and Urban Greening* 64 (August). https://doi.org/10.1016/j.ufug.2021.127298.	Flooded Grasslands and Savannas Biome. Also, not invasive plants.
Vourlitis, George L., Francisco de Almeida Lobo, Marcelo Sacardi Biudes, Carmen Eugenia Rodríguez Ortíz, and Jose de Souza Nogueira. 2011. " Spatial Variations in Soil Chemistry and Organic Matter Content across a Vochysia Divergens Invasion Front in the Brazilian Pantanal ." *Soil Science Society of America Journal* 75 (4): 1554–61. https://doi.org/10.2136/sssaj2010.0412.	Wetland. Flooded Grasslands and Savannas.
Whitworth-Hulse, Juan I., Patricio N. Magliano, Sebastián R. Zeballos, Diego E. Gurvich, Florencia Spalazzi, and Esteban Kowaljow. 2020. "Advantages of Rainfall Partitioning by the Global Invader Ligustrum Lucidum over the Dominant Native Lithraea Molleoides in a Dry Forest." *Agricultural and Forest Meteorology* 290 (April): 108013. https://doi.org/10.1016/j.agrformet.2020.108013.	Chaco Serrano Ecoregion (Savanna).

Wolfe, Brett T., Raúl Macchiavelli, and Skip J. Van Bloem. 2019. "Seed Rain along a Gradient of Degradation in Caribbean Dry Forest: Effects of Dispersal Limitation on the Trajectory of Forest Recovery." *Applied Vegetation Science* 22 (3): 423–34. https://doi.org/10.1111/avsc.12444.	Land use comparisons.
Zamith, Luiz R., and Fábio R. Scarano. 2006. "Restoration of a Restinga Sandy Coastal Plain in Brazil: Survival and Growth of Planted Woody Species." *Restoration Ecology* 14 (1): 87–94. https://doi.org/10.1111/j.1526-100X.2006.00108.x.	Not impact, not invasion. They performed an experiment by introducing restinga shrubs and trees into a degraded sandy coastal plain to assess the feasibility of native plant reintroduction.
Zangaro, Waldemar, Luis Eduardo Azevedo Marques Lescano, Enio Massao Matsuura, Artur Berbel Lirio Rondina, and Marco Antonio Nogueira. 2016. "Differences between Root Traits of Early- and Late-Successional Trees Influence below-Ground Competition and Seedling Establishment." *Journal of Tropical Ecology* 32 (4): 300–313. https://doi.org/10.1017/S0266467416000274.	Did not mention the alien plant as invasive.
Zeballos, Sebastián R., Paula A. Tecco, Marcelo Cabido, and Diego E. Gurvich. 2014. "Composición de Especies Leñosas En Comunidades Invadidas En Montañas Del Centro de Argentina: Su Relación Con Factores Ambientales Locales." *Revista de Biología Tropical* 62 (4): 1549. https://doi.org/10.15517/rbt.v62i4.12995.	Investigated the environmental factors that underlie the replacements of native forests by exotic dominated stands. Invasibility study concluding that the woody invaders have the potential to colonize almost all the environments of the study site. Also, the study site is under the biome Grasslands, Savannas and Shrublands.
Zimmermann, Thalita G., Antonio C.S. Andrade, and David M. Richardson. 2017. "Abiotic Barriers Limit Tree Invasion but Do Not Hamper Native Shrub Recruitment in Invaded Stands." *Biological Invasions* 19 (1): 109–29. https://doi.org/10.1007/s10530-016-1267-2.	The main research questions care about the influence of abiotic factors on the recruitment of invasive and native shrubs under a non-native stand (it was planted) and a preserved restinga.
Zucaratto, Rodrigo, and Alexandra dos Santos Pires. 2014. "The Exotic Palm Roystonea Oleracea (Jacq.) O.F. Cook (Arecaceae) on an Island within the Atlantic Forest Biome: Naturalization and Influence on Seedling Recruitment." *Acta Botanica Brasilica* 28 (3): 417–21. https://doi.org/10.1590/0102-33062014abb3473.	The species wasn't invasive yet when the study was performed, as the authors stated that the species did not spread into areas away from the introduction sites. They evaluated the impact of an introduced population on native.

APPENDIX F. Definitions of invaded habitat typology by Kueffer and Dahler, 2009).

Typology of Invaded Habitat	Definition
Anthropogenic Habitat	Anthropogenic habitats include agricultural and urban land, plantation forestry, ruderal and waste sites, or roadsides. These sites are characterized by high levels of unused resources (especially light and nutrients), frequent or large disturbances, and high inputs of alien species propagules (Fig. 5.2). Species diversity is often low, and empty niche opportunities for invasive species are common.
Reference Habitat	They typically are relatively undisturbed habitats dominated by native species. Reference habitats are often characterized by high functional and species diversity and low levels of unused resources. Empty niche opportunities are relatively low and pest loads and diversity are high. Nowadays, many reference habitats are on marginal land that is characterized by harsh environmental conditions (e.g. high altitude or dry habitats). All these factors in combination may make reference habitats more resistant to invasions than disturbed habitats
Abandoned Habitat	Abandoned habitats are areas that have been heavily disturbed or intensively managed in the past, e.g. old fields or abandoned plantation forests, or they are former reference habitats that have been highly degraded due to anthropogenic influence or invasion. Abandoned habitat often contains new combinations of native and alien species, and such ecosystems have been termed novel ecosystems or emerging ecosystems. The terms abandoned habitat and novel ecosystem are similar, but abandoned habitat does not imply that ecosystem properties have to be novel.
Designed Habitat	Designed habitat is deliberately and strongly manipulated by humans to create a new habitat that suites conservation objectives. Designed habitat is characterized by its constantdependence on management. In an early management phase, designed habitat will typically be ecologically similar to anthropogenic habitat insofar as ecosystem patterns and processes are often simplified, and light availability will typically be high because of the removal of former vegetation. In contrast to anthropogenic habitat, however, soils will often be degraded and fertility low.

APPENDIX G. Empirical designs used to quantify the ecological impacts of invasive species (Kumschick et al., 2015).

Empirical designs	Definições
Invaded vs. Uninvaded	Observational approach comparing areas with the presence of the invasive species with areas where the invasive species is absent
Abundance gradient	Observational approach along a gradient of invasive species abundance
Chronosequence of invasion	Comparison between stages with different times since invasion
Before vs. After	Comparison of areas before and after the invasion
Invaded vs. Removal	Experimental approach comparing areas with the presence of the invasive species and areas with the invasive species removal treatment
Removal vs. Uninvaded reference	Experimental approach comparing the invasive species removal treatment with a reference site without the presence of the invasive species
Invasive and native removal comparisons	Experimental approach combining invasive species removal treatments with native species removal

APPENDIX H. Ecological impacts caused by invasive alien plants classified by biological scale, impact types and response variables (Vilà et al., 2011).

Biological scale	Impact type	Response variables
Plant species	Fitness	Seed set, germination rate, seedling establishment, survival, mortality
	Growth	Increase in size of whole plants or plant parts
Plant communities	Production	Biomass, Net Primary Productivity
	Abundance	Plant number, density, cover
	Diversity	Alpha diversity, richness, evenness
Animal species	Fitness	Egg production, adult emergence, survival, mortality
	Growth	Increase in size of whole animals at any life stage
Animal communities	Production	Biomass
	Abundance	Density, visits, counts
	Diversity	Alpha diversity, richness
	Behaviour	Grazing, predation, mobility, activity
Ecosystems	Soil O.M	Soil organic matter
	C pools	Soil, litter, plant Carbon
	N pools	Soil, litter, plant Nitrogen
	N available	NO_3 and/or NH_4 in soil
	N mineralization	Nitrogen mineralization rate
	N nitrification	Nitrogen nitrification rate
	P pools	Soil, litter, plant Phosphorus
	C/N	Soil, litter, plant Carbon/Nitrogen
	Microbial activity	Activity of soil bactéria, fungi or enzymes
	pH	pH
	Litter decomposition	Litter decomposition rate
	Salinity	Soil Na, electrical conductivity
	Soil moisture	Soil water content

APPENDIX I. List of included articles (n = 22) for meta-analysis on the responses of native plant species and communities to invasive plants in Neotropical forests.

Reference
Abreu, Rodolfo Cesar Real de, Francisco Ferreira de Miranda Santos, and Giselda Durigan. 2014. "Changes in Plant Community of Seasonally Semideciduous Forest after Invasion by Schizolobium Parahyba at Southeastern Brazil." *Acta Oecologica* 54: 57–64. https://doi.org/10.1016/j.actao.2013.03.013.
Amaya-Villarreal, Ángela María, and Luis Miguel Renjifo. 2010. "Effects of Gorse (Ulex Europaeus) on the Birds of a High Andean Forest Edge." *Ornitologia Colombiana* 10 (August): 11–25.
Assunção, Andressa Cristina Ribeiro, Ricardo Vieira Alexandrino, Alessandra Nasser Caiafa, and Guilherme de Oliveira. 2019. "The Invasion of Artocarpus Heterophyllus, Jackfruit, in Protected Areas under Climate Change and across Scales: From Atlantic Forest to a Natural Heritage Private Reserve." *Biological Invasions* 21 (2): 481–92. https://doi.org/10.1007/s10530-018-1840-y.
Ayup, M. M., L. Montti, R. Aragón, and H. R. Grau. 2014. "Invasion of Ligustrum Lucidum (Oleaceae) in the Southern Yungas: Changes in Habitat Properties and Decline in Bird Diversity." *Acta Oecologica* 54: 72–81. https://doi.org/10.1016/j.actao.2013.03.006.
Bellingham, Peter J., Edmund V.J. Tanner, and John R. Healey. 2005. "Hurricane Disturbance Accelerates Invasion by the Alien Tree Pittosporum Undulatum in Jamaican Montane Rain Forests." *Journal of Vegetation Science* 16 (6): 675. https://doi.org/10.1658/1100-9233(2005)016[0675:hdaibt]2.0.co;2.
Bellingham, Peter J., Edmund V.J. Tanner, Patrick H. Martin, John R. Healey, and Olivia R. Burge. 2018. "Endemic Trees in a Tropical Biodiversity Hotspot Imperilled by an Invasive Tree." *Biological Conservation* 217 (October 2017): 47–53. https://doi.org/10.1016/j.biocon.2017.10.028.
Ceballos, Sergio J., Agustina Malizia, and Natacha P. Chacoff. 2015. "Influence of the Invasion of Ligustrum Lucidum (Oleaceae) on Liana Community in Sierra de San Javier (Tucumán - Argentina)." *Ecologia Austral* 25 (1): 65–74.
Ceballos, Sergio Javier, Agustina Malizia, and Natacha Chacoff. 2020. "Alternative Pathways of Liana Communities in the Forests of Northwestern Argentina." *Biotropica* 52 (3): 533–40. https://doi.org/10.1111/btp.12765.
César, R G, R A G Viani, M C da Silva, and P H S Brancalion. 2014. "Does a Native Grass (Imperata Brasiliensis Trin.) Limit Tropical Forest Restoration like an Alien Grass (Melinis Minutiflora P. Beauv.)?" *Tropical Conservation Science* 7 (4).

Fabricante, Juliano Ricardo, Kelianne Carolina Targino de Araújo, Leonaldo Alves de Andrade, and Jéssica Viviane Amorim Ferreira. 2012. "Invasão Biológica de Artocarpus Heterophyllus Lam. (Moraceae) Em Um Fragmento de Mata Atlântica No Nordeste Do Brasil: Impactos Sobre a Fitodiversidade e Os Solos Dos Sítios Invadidos." *Acta Botanica Brasilica* 26 (2): 399–407. https://doi.org/10.1590/s0102-33062012000200015.

Ferreira, Leandro V, P I A Parolin, and Darley C L Matos. 2016. "The Effect of Exotic Grass Urochloa Decumbens (Stapf) R. D. Webster (Poaceae) in the Reduction of Species Richness and Change of Floristic Composition of Natural Regeneration in the Floresta Nacional de Carajás, Brazil." *Anais Da Academia Brasileira de Ciencias* 88 (1): 589–97.

Gomes, Milena, Eliana Cazetta, Ricardo Bovendorp, and Deborah Faria. 2021. "Jackfruit Trees as Seed Attractors and Nurses of Early Recruitment of Native Plant Species in a Secondary Forest in Brazil." *Plant Ecology* 222 (10): 1143–55. https://doi.org/10.1007/s11258-021-01167-9.

Malizia, Agustina, Oriana Osinaga-Acosta, Priscila Ana Powell, and Roxana Aragón. 2017. "Invasion of Ligustrum Lucidum (Oleaceae) in Subtropical Secondary Forests of NW Argentina: Declining Growth Rates of Abundant Native Tree Species." *Journal of Vegetation Science* 28 (6): 1240–49. https://doi.org/10.1111/jvs.12572.

Matos, F. A. R, D. P Edwards, L. F Magnago, G Heringer, A. V Neri, T. K BUTTSCHARDT, R. D ZENNI, et al. n.d. "Invasive Alien Acacias Rapidly Stock Carbon, but Threaten Biodiversity Recovery in Young Second-Growth Forests." *Philosophical Transactions of the Royal Society B: Biological Sciences* 38. https://doi.org/10.1098/rstb.2021.0072.

Mello, Thayná Jeremias, and Alexandre Adalardodeoliveira. 2016. "Making a Bad Situation Worse: An Invasive Species Altering the Balance of Interactions between Local Species." *PLoS ONE* 11 (3): 1–17. https://doi.org/10.1371/journal.pone.0152070.

Mengardo, Ana Luisa T., and Vânia R. Pivello. 2014. "The Effects of an Exotic Palm on a Native Palm during the First Demographic Stages: Contributions to Ecological Management." *Acta Botanica Brasilica* 28 (4): 552–58. https://doi.org/10.1590/0102-33062014abb3326.

Ortega-Pieck, Aline, Fabiola López-Barrera, Neptalí Ramírez-Marcial, and José G. García-Franco. 2011. "Early Seedling Establishment of Two Tropical Montane Cloud Forest Tree Species: The Role of Native and Exotic Grasses." *Forest Ecology and Management* 261 (7): 1336–43. https://doi.org/10.1016/j.foreco.2011.01.013.

Schmidt, Alexandre Deschamps, Tânia Tarabini Castellani, and Michele de Sá Dechoum. 2020. "Biotic and Abiotic Changes in Subtropical Seasonal Deciduous Forest Associated with Invasion by Hovenia Dulcis Thunb. (Rhamnaceae)." *Biological Invasions* 22 (2): 293–306. https://doi.org/10.1007/s10530-019-02089-4.

Silva, Ligia Maria Inocêncio da, Marcos Júnior da Silva, Juliana Silva Rocha, Edmilson Bianchini, José Antonio Pimenta, Renata Stolf-Moreira, and Halley Caixeta Oliveira. 2017. "Potential Allelopathic Effect of Brachiaria Decumbens Root Exudates on Neotropical Tree Seedlings." *Theoretical and Experimental Plant Physiology* 29 (4): 177–86. https://doi.org/10.1007/s40626-017-0093-y.

Souza Nascimento, Clóvis Eduardo de, Marcelo Tabarelli, Carlos Alberto Domingues da Silva, Inara Roberta Leal, Wagner de Souza Tavares, José Eduardo Serrão, and José Cola Zanuncio. 2014. "The Introduced Tree Prosopis Juliflora Is a Serious Threat to Native Species of the Brazilian Caatinga Vegetation." *Science of the Total Environment* 481 (1): 108–13. https://doi.org/10.1016/j.scitotenv.2014.02.019.

Souza, Tancredo Augusto Feitosa de, Djail Santos, Leonaldo Alves de Andrade, and Helena Freitas. 2019. "Plant-Soil Feedback of Two Legume Species in Semi-Arid Brazil." *Brazilian Journal of Microbiology* 50 (4): 1011–20. https://doi.org/10.1007/s42770-019-00125-y.

Zangaro, Waldemar, Luis Eduardo Azevedo Marques Lescano, Enio Massao Matsuura, Artur Berbel Lirio Rondina, and Marco Antonio Nogueira. 2018. "Interactions between Arbuscular Mycorrhizal Fungi and Exotic Grasses Differentially Affect the Establishment of Seedlings of Early- and Late-Successional Woody Species." *Applied Soil Ecology* 124 (December 2017): 394–406. https://doi.org/10.1016/j.apsoil.2017.12.003.

APPENDIX J. List of excluded articles for meta-analysis (n = 33) at full text screening along with reasons for exclusion.

Reference	Reasons for exclusion
Andrade, Leonaldo Alves de, Juliano Ricardo Fabricante, and Francieldo Xavier de Oliveira. 2010. "Impact of the Invasion of Prosopis Juliflora (Sw.) DC. (Fabaceae) in Areas of Caatinga in the State of Paraíba, Brazil." *Acta Scientiarum - Biological Sciences* 32 (3): 249–55. https://doi.org/10.4025/actascibiolsci.v32i3.4535.	No descriptive statistics provided.
Avalos, Gerardo, Kelly Hoell, Jocelyn Gardner, Scott Anderson, and Conor Lee. 2006. "Impact of the Invasive Plant Syzigium Jambos (Myrtaceae) on Patterns of Understory Seedling Abundance in a Tropical Premontane Forest, Costa Rica." *Revista de Biologia Tropical* 54 (2): 415–21. https://doi.org/10.15517/rbt.v54i2.13883.	No descriptive statistics provided.
Baptiste, Alberto Jean, Pedro A. Macario, Gerald A. Islebe, Benedicto Vargas-Larreta, Luciano Pool, Mirna Valdez-Hernández, and Jorge O. López-Martínez. 2019. "Secondary Succession under Invasive Species (Pteridium Aquilinum) Conditions in a Seasonal Dry Tropical Forest in Southeastern Mexico." PeerJ 2019 (5): 1–16. https://doi.org/10.7717/peerj.6974.	It is not known whether Pteridium is invasive or not.
Bello, Carolina, Ana Laura P. Cintra, Elisa Barreto, Maurício Humberto Vancine, Thadeu Sobral-Souza, Catherine H. Graham, and Mauro Galetti. 2021. "Environmental Niche and Functional Role Similarity between Invasive and Native Palms in the Atlantic Forest." *Biological Invasions* 23 (3): 741–54. https://doi.org/10.1007/s10530-020-02400-8.	Modeling outputs.
Beltrán, Luis C., Karla María Aguilar-Dorantes, and Henry F. Howe. 2020. "Effects of a Recalcitrant Understory Fern Layer in an Enclosed Tropical Restoration Experiment." *NeoBiota* 59 (July): 99–118. https://doi.org/10.3897/NEOBIOTA.59.51906.	Only inferential statistics provided.

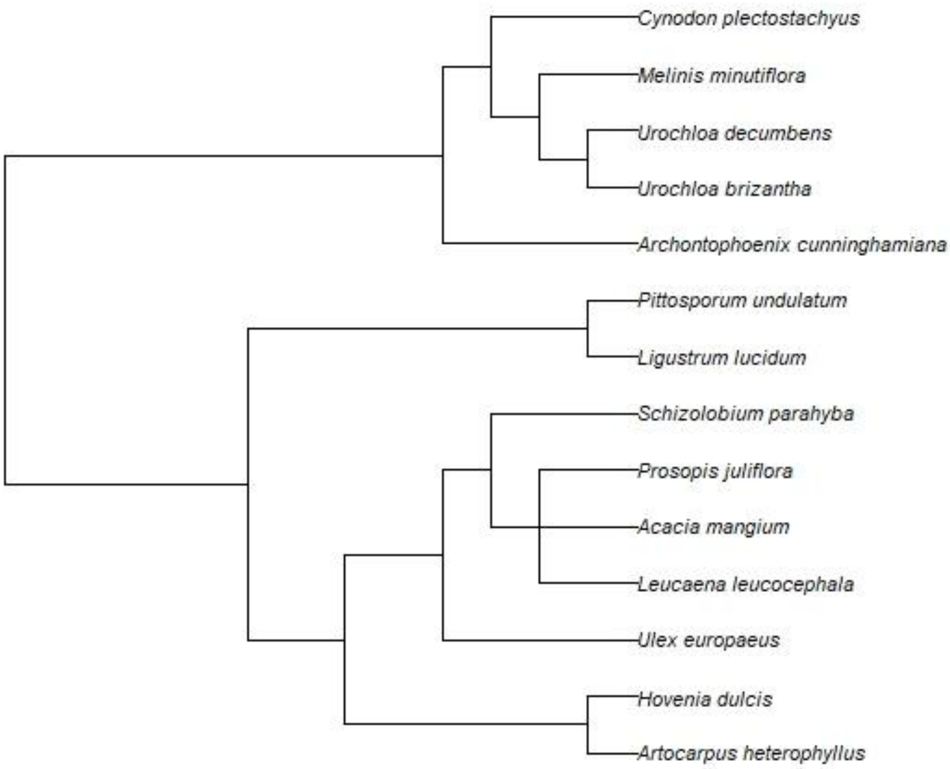
Brandão, Jeane de Fátima Cunha, Sebastião Venâncio Martins, and Isac Jonatas Brandão. 2017. "Potencial de Regeneração de Uma Área Invadida Por Pteridium Aquilinum No Parque Nacional Do Caparaó." *Floresta* 46 (4): 543–52. https://doi.org/10.5380/rf.v46i3.41387.	Compared areas with different environmental characteristics (seed rain in mono-dominant site invaded by fern and in a closed canopy forest).
Brown, Kerry A., F. N. Scatena, and Jessica Gurevitch. 2006. "Effects of an Invasive Tree on Community Structure and Diversity in a Tropical Forest in Puerto Rico." *Forest Ecology and Management* 226 (1–3): 145–52. https://doi.org/10.1016/j.foreco.2006.01.031.	According to our criteria, the analysis should compare information between the most invaded sites with the least invaded ones (abundance gradient study). However, the data wasn't provided for each site. Also, each site had other non-natives included in their analysis among the invader.
Carrera-Martínez, Roberto, Laura A. Aponte-Díaz, Jorge Ruiz-Arocho, Alexander Lorenzo-Ramos, and David A. Jenkins. 2019. "The Effects of the Invasive Harrisia Cactus Mealybug (Hypogeococcus Sp.) and Exotic Lianas (Jasminum Fluminense) on Puerto Rican Native Cacti Survival and Reproduction." Biological Invasions 21 (11): 3269–84. https://doi.org/10.1007/s10530-019-02046-1.	Effects of invasive lianas combined with the effects of an invasive mealybug infestation.
Carvalho, Thayane Ferreira, Aline Cristina Carvalho, José Cola Zanuncio, Marcio Leles Romarco de Oliveira, Evandro Luiz Mendonça Machado, Anderson Cleiton José, José Barbosa Santos, and Israel Marinho Pereira. 2022. "Does Invasion by Pteridium Aquilinum (Dennstaedtiaceae) Affect the Ecological Succession in Atlantic Forest Areas after a Fire?" Environmental Science and Pollution Research 29 (10): 14195–205. https://doi.org/10.1007/s11356-021-16761-7.	It is not known whether Pteridium is invasive or not.
Ceballos, Sergio Javier. 2020. "Vascular Epiphyte Communities in Secondary and Mature Forests of a Subtropical Montane Area." *Acta Oecologica* 105 (March): 103571. https://doi.org/10.1016/j.actao.2020.103571.	Only inferential statistics provided.
Chiba De Castro, Wagner A., Rafael O. Xavier, Federico H.L. Garrido, Jair H.C. Romero, Cleto K. Peres, and Ruberval C. Da Luz. 2019. "Fraying around the Edges: Negative Effects of the Invasive Tradescantia Zebrina Hort. Ex Bosse (Commelinaceae) on Tree Regeneration in the Atlantic Forest under Different Competitive and Environmental Conditions." *Journal of Plant Ecology* 12 (4): 713–21. https://doi.org/10.1093/jpe/rtz009.	Removal experiment, with no un-invaded area for comparison.

Condé, Tiago Monteiro, Fernando da Silva, Agostinho Lopes de Souza, Helio Garcia Leite, Eder Aparecido Garcia, Walter da Silva Costa, Antonio de Souza Chaves, and Pablo Falco Lopes. 2018. "Exotic Palms Threatens Native Palms: A Risk To Plant Biodiversity of Atlantic Forest." *Revista Árvore* 42 (2). https://doi.org/10.1590/1806-90882018000200016.	Compared primary un-invaded and invaded secondary forest. Sites differ in their environmental characteristics.
Fernandez, Romina D., Pilar Castro-Díez, Roxana Aragón, and Natalia Pérez-Harguindeguy. 2021. "Changes in Community Functional Structure and Ecosystem Properties along an Invasion Gradient of Ligustrum Lucidum." *Journal of Vegetation Science* 32 (6): 1–13. https://doi.org/10.1111/jvs.13098.	No descriptive statistics, only correlation from models (degrees of freedom, F-value, p-value, and R^2).
Fiore, Nathalia V., Carolina C. Ferreira, Maíra Dzedzej, and Klécia G. Massi. 2019. "Monitoring of a Seedling Planting Restoration in a Permanent Preservation Area of the Southeast Atlantic Forest Biome, Brazil." *Forests* 10 (9): 1–12. https://doi.org/10.3390/f10090768.	No un-invaded reference plot for comparison.
Flombaum, Pedro, Roxana Aragón, and Enrique J. Chaneton. 2017. "A Role for the Sampling Effect in Invaded Ecosystems." *Oikos* 126 (9): 1229–32. https://doi.org/10.1111/oik.04221.	They synthesized existing information using a dataset from a network of permanent monitoring plots (141 forest plots). Correlative study.
Fonseca, N.C., A.S. Albuquerque, M.J.H. Leite, and C.S. Lira. 2016. "Similaridade Florística e Colonização Biológica de Prosopis Juliflora [(Sw) DC] Ao Longo Do Rio Paraíba." *Nativa* 4 (6): 392–97. https://doi.org/10.14583/2318-7670.v04n06a08.	No un-invaded reference plot for comparison.
Hooper, Elaine, Richard Condit, and Pierre Legendre. 2002. "Responses of 20 Native Tree Species to Reforestation Strategies for Abandoned Farmland in Panama." *Ecological Applications* 12 (6): 1626–41. https://doi.org/10.1890/1051-0761(2002)012[1626:RONTST]2.0.CO;2.	Removal experiment, with no un-invaded area for comparison.
Hooper, Elaine, Pierre Legendre, and Richard Condit. 2005. "Barriers to Forest Regeneration of Deforested and Abandoned Land in Panama." *Journal of Applied Ecology* 42 (6): 1165–74. https://doi.org/10.1111/j.1365-2664.2005.01106.x.	Removal experiment, with no un-invaded area for comparison.
Hooper, Elaine R., Pierre Legendre, and Richard Condit. 2004. "Factors Affecting Community Composition of Forest Regeneration in Deforested, Abandoned Land in Panama." *Ecology* 85 (12): 3313–26. https://doi.org/10.1890/03-0655.	Removal experiment, with no un-invaded area for comparison.

Levy-Tacher, Samuel I., Ivar Vleut, Francisco Román-Dañobeytia, and James Aronson. 2015. "Natural Regeneration after Long-Term Bracken Fern Control with Balsa (Ochroma Pyramidale) in the Neotropics." *Forests* 6 (6): 2163–77. https://doi.org/10.3390/f6062163.	Removal experiment, with no un-invaded area for comparison.
Lichstein, Jeremy W, H Ricardo Grau, and Roxana Aragón. 2004. "Recruitment Limitation in Secondary Forests Dominated by an Exotic Tree." *Journal of Vegetation Science* 15: 721–28.	Only inferential statistics provided.
Machado, Marcela Xavier, Tânia Tarabini Castellani, and Michele de Sá Dechoum. 2020. "Integrating Management Techniques to Restore Subtropical Forests Invaded by Hedychium Coronarium J. Köenig (Zingiberaceae) in a Biodiversity Hotspot." *Restoration Ecology* 28 (5): 1273–82. https://doi.org/10.1111/rec.13213.	Removal experiment, with no un-invaded area for comparison.
Mantoani, Maurício Cruz, Gabriela Ribeiro de Andrade, Alba Lúcia Cavalheiro, and Jose Marcelo Domingues Torezan. 2012. "Efeitos Da Invasão Por Panicum Maximum Jacq. e Do Seu Controle Manual Sobre a Regeneração de Plantas Lenhosas No Sub-Bosque de Um Reflorestamento." *Semina: Ciências Biológicas e Da Saúde* 33 (1): 97–110. https://doi.org/10.5433/1679-0367.2012v33n1p97.	Removal experiment, with no un-invaded area for comparison.
Mantoani, Maurício Cruz, Jézili Dias, Mário Luís Orsi, and Jose Marcelo Domingues Torezan. 2013. "Efeitos Da Invasão Por Tradescantia Zebrina Heynh. Sobre Regenerantes de Plantas Arbóreas Em Um Fragmento de Floresta Estacional Semidecidual Secundária Em Londrina (PR)." *Biotemas* 26 (3). https://doi.org/10.5007/2175-7925.2013v26n3p63.	No descriptive statistics provided.
Mantoani, Maurício Cruz, and José Marcelo Domingues Torezan. 2016. "Regeneration Response of Brazilian Atlantic Forest Woody Species to Four Years of Megathyrsus Maximus Removal." *Forest Ecology and Management* 359: 141–46. https://doi.org/10.1016/j.foreco.2015.10.004.	Removal experiment, with no un-invaded area for comparison.
Mielke, Erica Costa, Raquel Rejane Bonato Negrelle, Francine Lorena Cuquel, and Walquiria Pizatto Lima. 2015. "Espécies Exóticas Invasoras Arbóreas No Parque Da Barreirinha Em Curitiba: Registro e Implicações." *Ciencia Florestal* 25 (2): 327–36. https://doi.org/10.5902/1980509818451.	No descriptive statistics provided.
Oliveira, Guilherme de, Bruno de Souza Barreto, Daniela da Silva dos Santos, Vinícius Queiroz de Matos, and Maria Cecília Seara Santos. 2018. "Combining the Effects of Biological Invasion and Climate Change into Systematic Conservation Planning for the Atlantic Forest." *Biological Invasions* 20 (10): 2753–65. https://doi.org/10.1007/s10530-018-1727-y.	Modeling outputs.
Raíces, Daniel S.L., Paula M. Ferreira, José H.F. Mello, and Helena G. Bergallo. 2017. "Smile, You Are on Camera or in a Live Trap! The Role of Mammals in Dispersion of Jackfruit and Native Seeds in Ilha Grande State Park, Brazil." *Nature Conservation Research* 2 (4): 78–89. https://doi.org/10.24189/ncr.2017.045.	Only inferential statistics provided.

Román-Dañobeytia, Francisco J., Jorge Castellanos-Albores, Samuel I. Levy-Tacher, James Aronson, Neptalí Ramírez-Marcial, and Ricardo Ribeiro Rodrigues. 2012. "Responses of Transplanted Native Tree Species to Invasive Alien Grass Removals in an Abandoned Cattle Pasture in the Lacandon Region, Mexico." *Tropical Conservation Science* 5 (2): 192–207. https://doi.org/10.1177/194008291200500208.	Removal experiment, with no un-invaded area for comparison.
Silva Matos, D. M., and T. A. Belinato. 2010. "Interferência de Pteridium Arachnoideum (Kaulf.) Maxon. (Dennstaedtiaceae) No Estabelecimento de Árvores Tropicais." Brazilian Journal of Biology 70 (2): 311–16. https://doi.org/10.1590/S1519-69842010000200012.	It is not known whether Pteridium is invasive or not.
Viana, Rafael G., Kaléo D. Pereira, Alexandre F. Castilho, Yanna K. S. Costa, Cintia H. Marega, Mailson F. Oliveira, Roberthi A. C. Teixeira, et al. 2018. "Competitive Capacity of Native Species From the Carajás National Forest, Brazil." *Journal of Agricultural Science* 10 (11): 471. https://doi.org/10.5539/jas.v10n11p471.	No descriptive statistics, only correlational data.
Williams-Linera, Guadalupe, Martha Bonilla-Moheno, and Fabiola López-Barrera. 2016. "Tropical Cloud Forest Recovery: The Role of Seed Banks in Pastures Dominated by an Exotic Grass." *New Forests* 47 (3): 481–96. https://doi.org/10.1007/s11056-016-9526-8.	Removal experiment, with no un-invaded area for comparison.
Zamora Nasca, Lucía, Lia Montti, Ricardo Grau, and Leonardo Paolini. 2014. "Efectos de La Invasión Del Ligustro, Ligustrum Lucidum, En La Dinámica Hídrica de Las Yungas Del Noroeste Argentino." *Bosque* 35 (2): 195–205. https://doi.org/10.4067/S0717-92002014000200007.	Not possible to obtain descriptive statistics from figures due to graph illegibility.

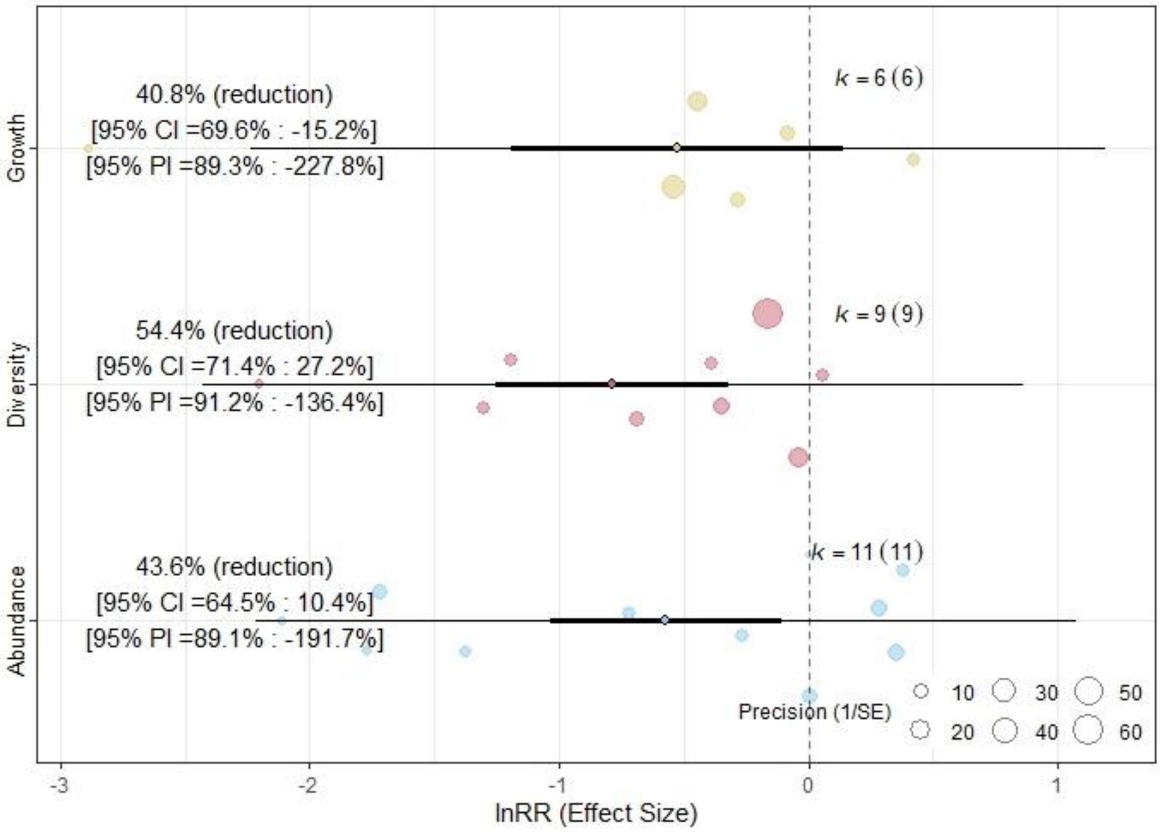
APPENDIX K. Phylogenetic tree of the invasive plant species present in the meta-analysis dataset.



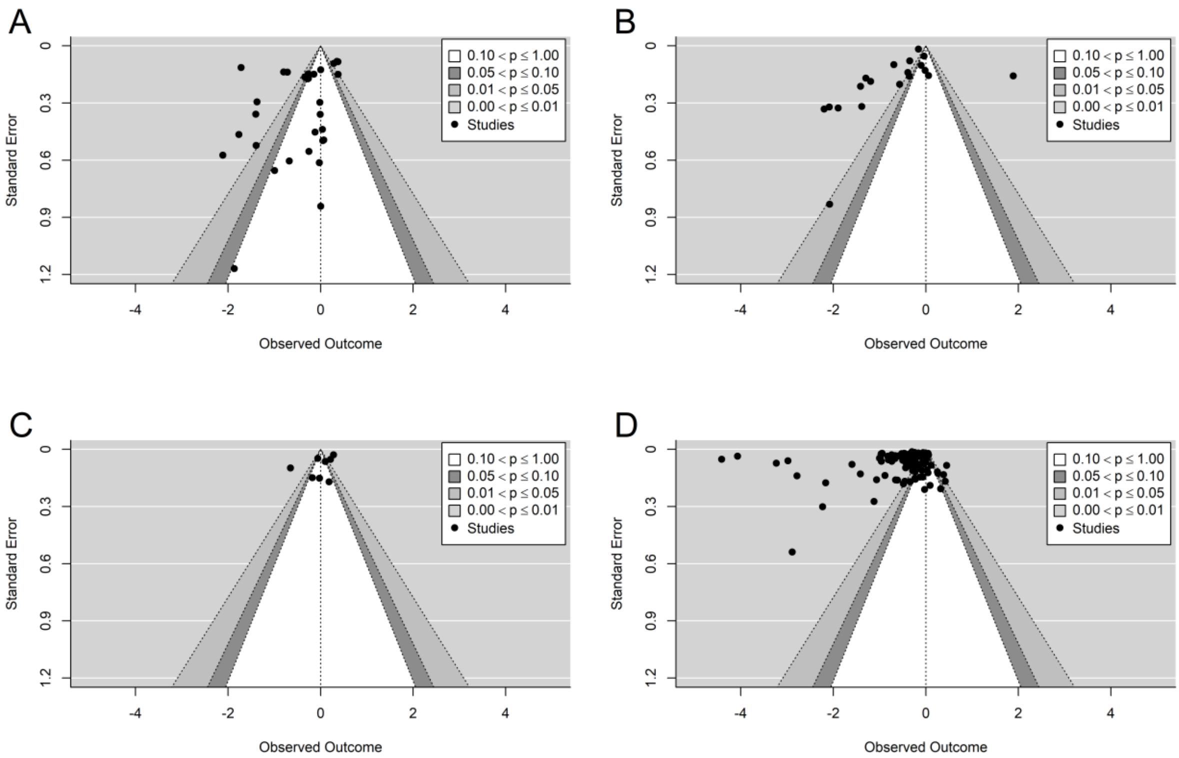
APPENDIX L. Number of factor levels (observations) per moderator for each response variable model.

Moderators	Abundance	Diversity	Fitness	Growth
Biome				
Tropical & Subtropical Moist Forest	29	16	7	55
Tropical & Subtropical Dry Forest	1	3	1	23
Invaded Habitat				
Abandoned	21	13	2	1
Designed (Active Restoration)	1	-	2	2
Forest Edge	3	-	-	-
Reference	5	6	-	-
Non-Field	-	-	4	69
Growth Form				
Herb	1	1	2	64
Shrub	3	-	-	-
Tree	26	18	6	24
Study Design				
Abundance Gradient	-	-	-	-
Chronosequence of Invasion	11	2	-	-
Invaded vs. Uninvaded	19	17	4	19
Addition	-	-	4	69

APPENDIX M. Orchard plot showing the outcomes of sensitivity analysis, where the models were fitted with only one randomly selected effect size per article for each response variable.



APPENDIX N. Funnel plots for each multi-level model, where: A) Abundance; B) Diversity; C) Fitness; D) Growth.



APPENDIX O. Funnel plot for the multi-level meta-analysis model considering all effect sizes (n = 145).