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Negative and positive impacts of alien macrofungi: a global scale database

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Abstract

Advances in ecological research during the last decades have led to an improved understanding of the impacts of alien species. Despite that, the effects of alien macrofungi have often received little attention and are still poorly understood. With the aim of reducing this knowledge gap, we compiled a database of the recorded socio-economic and environmental impacts of alien macrofungi. This database was compiled from all relevant sources we could identify, through an exhaustive literature review, considering the identity of known alien taxa and explicit indications of impacts of any kind. In total, 1440 records of both negative and positive impacts were collected for 374 distinct species in different regions of all continents, except Antarctica. The most frequently recorded impacts are related to the mutualistic interactions that these fungi can form with their host plants. In total 47.8% of all records refer to the indirect negative effect of these interactions, by facilitating the colonization of invasive plants, while 38.5% refer to their positive contribution to the growth of forestry species. Less frequently recorded negative impacts included ectomycorrhizal interactions with native plants, plant pathogenicity and human poisoning after ingestion. Additional positive impacts include the use as a food source by native species and human populations and commercial exploitation. Alien macrofungi are an increasingly prevalent component of human-dominated ecosystems, having a diverse array of negative and positive impacts on native biota and human population. Our database provided a first step towards the quantification and mapping of these impacts.

Keywords
Biogeography, biological invasions, fungi, impact assessment, non-native species

Introduction

The introduction and naturalization of alien species are recognized as important threats to native biodiversity (Simberloff et al. 2013; Bellard et al. 2016, 2021) and major causes of impacts on socio-economic activities and human welfare (Diagne et al. 2021). Current understanding of the impacts of alien species is heavily skewed towards a few species (Vilà et al. 2009; Marean 2015), taxonomic groups (Evans et al. 2018; Bartz and Kowarik 2019) and geographical regions (Kumschick et al. 2013; Heringer et al. 2021). However, the potential underestimation of impacts by frequently ignored taxa is increasingly recognized (Vilà et al. 2010).

In recent years, fungi as alien species have received some attention, through a higher availability of distribution data and information about their impacts in introduced ecosystems (Vellinga et al. 2009; Nuñez and Dickie 2014; Dickie et al. 2016; Monteiro et al. 2020, 2022). However, knowledge on impacts of alien fungi has been mainly restricted to a few pathogenic, often microscopic, taxa which have been studied because of their potential to cause severe diseases in native biota (Desprez-Loustau et al. 2007), strong damages to both agricultural and forestry production (Panzavolta et al. 2021) and, in a few cases, human health risks (Page and Westcott 2014; Ye and Liu 2018). On the contrary, macrofungi, comprising ectomycorrhizal and saprotroph fungal taxa exhibiting macroscopic spore bearing structures, are in general still widely missing from cross-taxonomic alien species impact assessments (Evans et al. 2016, 2020; Kumschick et al. 2017), despite their potential to dramatically change ecosystem functions and cause problems for human health (Dickie et al. 2016). This likely originates from a prevalent view of these taxa as having limited impacts in naturalized ranges because they mostly comprise non-pathogenic species (Vizzini et al. 2009; Desprez-Loustau et al. 2010).

Despite being comparatively less represented in invasion studies than other groups, macrofungi comprise a large number of species that have been introduced widely across the globe over recent centuries (Desprez-Loustau et al. 2010; Monteiro et al. 2022), many of which moved inadvertently in the plant trade or in deadwood or soil (Vellinga et al. 2009). The increased occurrence of some macrofungi species as well as of their effects on invaded areas has led to an increased availability of reports on their negative impacts (Desprez-Loustau et al. 2007). These impacts include toxicity to humans (French et al. 2011; Santi et al. 2012), competition with native fungi (Murat et al. 2008), facilitating the co-invasion of invasive plants (Vlk et al. 2020), and changes to ecosystem functions (Chapela et al. 2001). Interestingly, macrofungi belong to one of the groups of alien taxa for which positive impacts are commonly reported, namely by improving or enabling forestry plantations (Dickie et al. 2010), constituting a commercially valued product (Buyck 2008) or being a local food source (Dickie et al. 2016). Despite the mounting evidence of impacts, their records remain scattered across scientific and non-scientific literature, impeding an integrated examination of multiple aspects of relevance, such as the taxa involved, the regions most affected, or the type and magnitude of impacts caused. Ultimately, this knowledge is crucial to better inform invasion prevention strategies as well as in the management of existing populations of alien macrofungi.

In this context, we compiled a database of the socio-economic and environmental impacts of macrofungi reported in all relevant sources we could identify, namely scientific publications, reports, citizen science websites and databases on alien species. We reviewed sources in multiple languages and considered not only information on negative impacts but also impacts perceived as positive. We applied the precautionary principle and categorized impacts as 'negative' if they were known to have detrimental effects on native communities and human populations, or if they had no known beneficial effects (i.e., causing ecological change without any apparent gain to humans or native biota). In contrast, we categorized impacts as 'positive' if they were documented to have beneficial effects according to values associated with nature conservation or human interests (Vimercati et al. 2020). In addition, we distinguished between environmental and socio-economic impacts. Environmental impacts are those causing changes to the natural environment, whether positive or negative, resulting from effects on the air, land, water and the biota of the ecosystem. Socio-economic impacts refer to negative or positive effects on property values, agricultural productivity, public utility operations or human well-being (Simberloff et al. 2013). In total, 1440 impact records were collected for 374 different alien macrofungi species, and comprising all continents except Antarctica. Using these data, we assessed i) the taxonomic diversity of macrofungi for which impacts were recorded and ii) the typology and magnitude of recorded impacts and their geographical distribution worldwide.

Methods

We used as a starting point the recently published Global Database of Alien Macrofungi (Monteiro et al. 2020), which has allowed us to obtain a pre-identification of macrofungi taxa known to be occurring outside of their native ranges. Hence, focusing on each of these taxa, we conducted an extensive search for studies, reports and other sources that addressed impacts of any sort. Sources searched comprised broad databases on introduced taxa such as Delivering Alien Invasive Species Inventories for Europe (Hulme et al. 2019), the Global Register of Introduced and Invasive Species (Pagad et al. 2019) and the European Alien Species Information Network

(Katsanevakis et al. 2019). In addition, we used general-purpose engines (i.e., Google) and scientific search-engines (Google Scholar, ScienceDirect and JSTOR) to identify relevant information from peer-reviewed literature. The reference lists from these articles were also searched to identify further papers or book chapters which may contain useful information. We used specific keywords related to fungal impacts in multiple languages including English, French, Portuguese and Spanish. Terms used in the search were 'introduced′, 'invasive', 'established', 'alien', 'non-native' and 'exotic', combined with fungal taxonomic terms, ranging from a generic and higher denomination (e.g., 'fungi', 'macromycetes', 'basidiomycota') to a more specific designation, such as the scientific name (*Amanita muscaria* (L.) Lam., *Amanita phalloides* Secr., *Boletus edulis* Bull., *Suillus luteus* (L.) Roussel and *Pyrrhoderma noxium* (Corner) L.W.Zhou & Y.C.Dai). For each combination, we added "impact" and "effect". We also performed additional searches using specific terms related to more commonly reported impacts such as "competition", "toxicity", "plant diseases" and "ectomycorrizhal interactions". We performed an individual search for each combination of country and taxa in the Global Database of Alien Macrofungi (Monteiro et al. 2020). Finally, some records were obtained by checking macrofungi observations in citizen science websites like iNaturalist (https://www.inaturalist.org; iNaturalist 2022) and Mushroom Observer (https://mushroomobserver.org; Wilson and Hollinger 2019). Records collected from non-specialized sources were cross-checked against information available in scientific literature (e.g., species alien status) in order to assess their reliability. Only records of impacts in regions where the species are not native were included, i.e. impacts in native regions, were not considered.

To classify species impacts, we first divided them into either positive or negative. Negative impacts – referring to detrimental effects on native communities and human populations, or ecological changes without any apparent gain to humans or native communities – were divided into the following subcategories: human health problems, competition with native fungi, ectomycorrhizal interactions with native plants, plant disease agents, ectomycorrhizal interaction with alien invasive species and other ecosystem changes. Positive impacts, referring to recorded beneficial effects on nature conservation or human interests, were categorized into benefits for forestry plantations, as food source for local human populations, food source for other species, and commercial use (Table 1). Note that the previous classification is non-mutually exclusive, meaning for example that some records were simultaneously assigned to negative ectomycorrhizal interaction with alien invasive species and to positive impacts on forestry plantations. For each record, the ecofunctional type of the species (ectomycorrhizal, saprotroph or pathogenic) and a short description of the impact was also added (see online Appendices 1 and 2 regarding both negative and positive impacts of alien macrofungi for the data used in the analyses). The geographical examination of collected impacts followed the geographical scheme of GAMD (Monteiro et al. 2020), consisting of countries and the first-order administrative divisions for the six largest countries in the world (Australia, Brazil, Canada, China, Russia, USA).

Table 1. Percentage of each category of impacts on the total of records (n=1440). Environmental impacts are signaled by one asterisk (*) while socio-economic impacts are represented by two (**).

Impact categories	Description	Percentage
Negative Impacts		
Competition with native fungi species (*)	Competition between alien macrofungi and native macrofungi.	0.1
Ecosystems (*)	Changes to biochemical properties of soil without any apparent ecological or human-related benefit.	0.1
Human health (**)	Negative consequences on human health through ingestion.	0.9
Plant disease agents (*)	Negative consequences of alien macrofungi as plant disease agents.	3.6
Ectomycorrizhal interactions with native plant species (*)	Ectomycorrhizal interactions with native plants without confirmed benefits for these and potentially weakening ectomycorrhizal interactions with native fungi.	7.9
Ectomycorrizhal interactions with alien plant species (*)	Negative ecological impacts owing to promotion of alien plant invasions.	47.8
Positive Impacts		
Food source for other species (*)	Alien macrofungi used as food source for some animal groups, hence directly contributing to the sustaining of its population.	0.1
Human food source (**)	Alien macrofungi used as a human food source.	0.2
Commercial purposes (**)	Alien macrofungi used as a product in food industries.	0.8
Forestry (**)	Establishment of ectomycorrhizal interactions with important forestry trees.	38.5

Finally, in order to evaluate if the number of negative and positive impacts was directly related to the wealth of each included region, we performed for both impact categories (negative vs positive impacts) a Spearman's rank correlation (r) between the number of impacts per region and their respective per capita GDP (gross domestic product). The GDP variable represents the mean income (in US$) in 2019 (or closest year available) and can be considered a proxy of wealth of the different introduced locations. Our hypothesis is that wealthier regions will have a higher number of recorded impacts (both negative and positive) owing to more introduction opportunities (Monteiro et al. 2022). To conform with the availability of data for the per capita GDP variable, the analysis was performed at the country scale. For that reason, the numbers of alien species impacts represented at the subnational scale in the database had to be upscaled accordingly. We collected the mean income in US$ data of the year 2019 (or closest year available) from the Worldbank website (https://data.worldbank.org/; Worldbank 2019).

Results

We collected a total of 1440 records of impacts from 246 data sources. Of these, 869 were identified in the sources as negative impacts and 571 as positive. Regarding negative impacts, most were related to mutualistic interactions that alien fungi form with alien plants (47.8% of the records; Table 1), followed by negative interactions with native plants (7.7% of the records), causing plant disease (3.6% of the records), human poisoning after ingestion (1.0% of the records), competition with other fungi species (0.1% of the records) and changes in soil biochemistry and biodiversity (0.1% of the record). On the contrary, positive impacts recorded in the descending order of frequency were: beneficial interactions with non-native plants of importance for forestry (38.5% of the records; Table 1), direct commercial exploitation by the canning and other food industry (0.8% of the records) and use as direct food source for human populations (0.2% of the records). Only 0.1% of the records reported consumption by native species.

In terms of the taxonomy, a total of 374 species belonging to 2 phyla, 5 classes, 15 orders, 50 families and 85 genera respectively were reported as having impacts. The families with the highest proportion of negative impacts were Suillaceae (110 records), Amanitaceae (96 records) and Russulaceae (65 records) (Fig. 1a) meanwhile the families with most positive impacts were Sclerodermataceae (91 records), Suillaceae (80 records) and Amanitaceae (56 records) (Fig. 1b). At the species level, the ones having most records of negative impacts were *Pyrrhoderma noxium* (Corner) L.W.Zhou & Y.C.Dai (43 records), *Amanita phalloides* (Vaill. ex Fr.) Link (28 records) and *Descolea alba* (Klotzsch) Kuhar, Nouhra & M.E.Sm. (25 records) whilst *Amanita muscaria* (L.) Lam. (28 records), *Suillus granulatus* (L.) Roussel (24 records) and *Suillus luteus* (L.) Roussel (24 records) were the species most frequently recorded as having positive impacts. Furthermore, some of the species with the greatest diversity of impact types from both negative and positive categories were *Suillus luteus* (L.) Roussel (6 impact types), *Amanita pantherina* (DC.) Krombh. (4 impact types), *Amanita phalloides* (Vaill. ex Fr.) Link (4 impact types), *Amanita muscaria* (L.) Lam. (4 impact types) and *Boletus edulis* Bull. (4 impact types) (Table 2).

The global distribution of recorded impacts is uneven between regions (Fig. 2a, b), with the majority of negative ones being found in South America (225 records), Europe (190 records) and Africa (175 records) (Fig. 3a). For positive impacts, the majority of records take place in South America (191 records), Africa (154 records) and Oceania (85 records) (Fig. 3b). Regions where the impacts of alien macrofungi were least recorded are North America and Asia. Negative impacts corresponded to 75 records and 45 records in North America and Asia, respectively, and 39 records and 28 records of positive impacts for each.

Additionally, the results of the Spearman's rank correlation between the number of impacts per country and the per capita GDP were $r_s = 0.14$ for the negative impacts and $r_s = 0.04$ for the positive impacts.

Discussion

This study allowed identifying a high number and diversity of impacts of alien macrofungi in many regions of the world, including negative and positive effects on humans, native and alien plant taxa, other fungi and animal species and soil biochemistry.

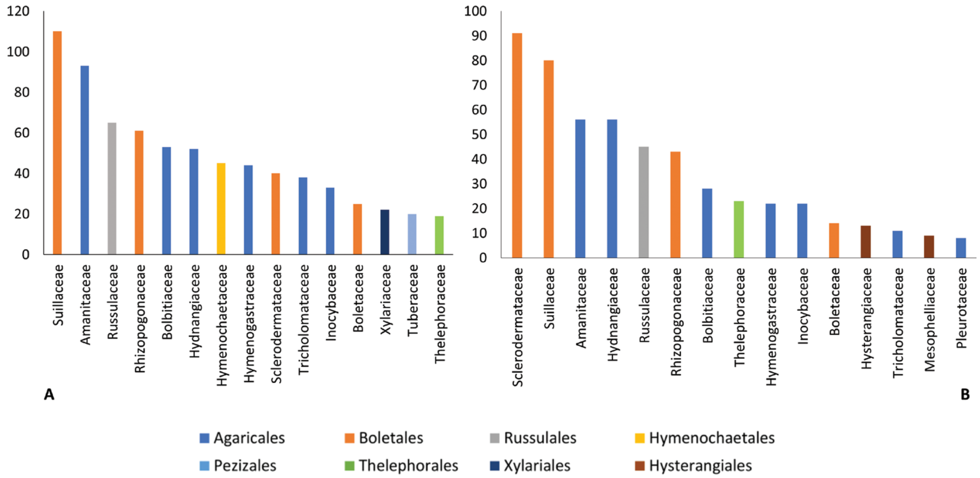

Figure 1. Number of the records per taxonomic family for negative (**A**) and positive impacts (**B**). Only the 15 families with most records are represented. Taxonomic orders are represented by distinct colors.

Notwithstanding this variety, interactions of EM macrofungi with alien plants were the most common impacts recorded. EM species are important mutualists for plants, by providing nutrients from the soil in return for photosynthetically derived carbon (Begum et al. 2019). Therefore, they can have strong indirect effects by facilitating plant invasions, including pines (Dickie et al. 2010) eucalyptus (Santolamazza-Carbone et al. 2019), Douglas fir trees (*Pseudotsuga*; Moeller et al. 2015), willows (*Salix*; McInerney and Rees et al. 2017) and alders (*Alnus*; Bogar et al. 2015). Examples of EM fungus species with a high number of plant interactions are *Suillus granulatus* (L.) Roussel and *Suillus luteus* (L.) Roussel as well as *Amanita muscaria* (L.) Lam., *Descolea alba* (Klotzsch) Kuhar, Nouhra & M.E.Sm. and *Rhizopogon roseolus* (Corda) Th.Fr. Despite these impacts, some of these species can also provide great benefits for economically important trees, by facilitating their establishment in novel environments (e.g. species from the *Suilloid* genus are always associated with invasive pines, particularly at early invasion, when invasive trees are most vulnerable; Policelli et al. 2019)). For those reasons, introduction of EM fungi does not only contribute to the thriving of their plant hosts, an impact viewed as positive for agroforestry activities, but to their spread beyond plantation areas, i.e., facilitating biological invasions. As a result, co-invasion with plants is the most geographically widespread impact of introduced EM fungi. In fact, the prevalence of this kind of impact may be related to the fact that it is easier to assume that ectomycorrhizal fungus found only on non-native trees are likely to be invasive as well in the same areas, while determining the origin of many alien pathogens or saprotrophs is harder and usually requires extensive efforts (Rizzo 2005; Tedersoo et al. 2014).

Table 2. Macrofungi species with the greatest diversity of impact types from both negative and positive categories. In the table 'X' represents the type of impacts that the species was recorded to cause in alien regions.

Species	Negative impacts				Positive impacts				Total number of different impacts
	Human health	Ecosystems	Ectomycorrhizal interactions with native species	Ectomycorrhizal interactions with non-native species	Human food source	Forestry	Food source for other species	Commercial purposes	
Suillus luteus (L.) Roussel		X	X	X	X	X		X	6
Amanita pantherina (DC.) Krombh.	X		X	X		X			4
Amanita phalloides (Vaill. ex Fr.) Link	X		X	X		X			4
Amanita muscaria (L.) Lam.			X	X		X	X		4
Boletus edulis Bull.			X	X	X	X			4
Suillus bovinus (L.) Roussel			X	X		X		X	4
Suillus granulatus (L.) Roussel			X	X		X		X	4
Amanita gemmata (Fr.) Bertill.	X			X		X			3
Chalciporus piperatus (Bull.) Bataille			X	X		X			3
Descolea alba (Klotzsch) Kuhar, Nouhra & M.E.Sm.				X		X			3
Hydnangium carneum Wallr.			X	X		X			3
Hysterangium inflatum Rodway			X	X		X			3
Laccaria fraterna (Sacc.) Pegler			X	X		X			3
Russula sardonia Fr.			X	X		X			3
Scleroderma flavidum Ellis & Everh.			X	X		X			3
Scleroderma verrucosum (Bull.) Pers.			X	X		X			3
Suillus brevipes (Peck) Kuntze			X	X		X			3
Suillus spraguei (Berk. & M.A.Curtis) Kuntze			X	X		X			3
Tricholoma saponaceum (Fr.) P.Kumm.			X	X		X			3

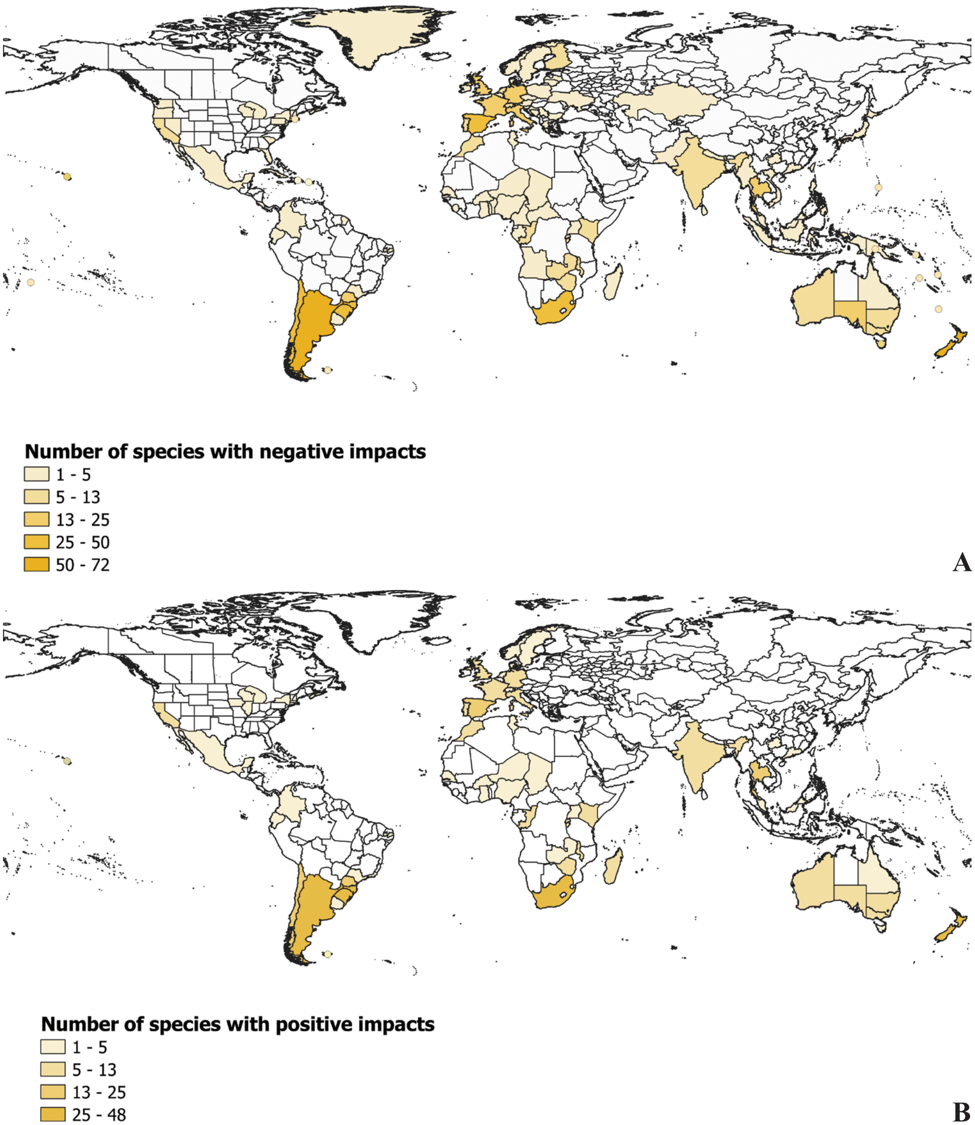

Figure 2. Global distribution of negative (**A**) and positive (**B**) impacts of alien macrofungi. The colors gradient represents the total number of number of species with recorded impacts.

The direct impacts of fungal introductions on native plant communities are also important to consider. Several studies have shown that alien EM fungi are highly persistent in their novel environments and can form novel associations with native host plants (Orlovich and Cairney 2004). For example, *Laccaria bicolor* (Maire) P.D.Orton isolates from North America were detected in Douglas fir (*Pseudotsuga menziesii*) plantations in Europe ten years after inoculation of out-planted seedlings, and were also found to colonize nearby uninoculated trees (Selosse and Le Tacon 1998). Similarly, isolates of *Amanita muscaria* (L.) Lam. have survived for > 36 years in *Pinus radiata* plantations in Australia (Sawyer et al. 2001). Besides, it is now associated with *Nothofagus* forests in Tasmania and New Zealand, presumably as a consequence of its introduction with pines (Fuhrer and Robinson 1992). Therefore, these alien EM fungi may establish on native hosts where they could start to alter ecosystem functions by being pathogenic to the native plants (Johnson et al 1997) or by changing ecosystem properties (e.g. changing a systems dominated by arbuscular mycorrhizal fungi to one dominated by EM fungi (Bai and Cotrufo 2022)). Also, these fungi can change the abundance and distribution of native EM fungi throughout time (Loo 2008).

Some species of macrofungi could also cause negative effects on native plants by causing diseases. The main pathogens in our database were root rotting fungi such as *Pyrrhoderma noxium* (Corner) L.W.Zhou & Y.C.Dai and *Heterobasidion annosum* (Fr.) Bref. The former species (*P. noxium*) is responsible for causing the brown root rot disease on more than 200 plant species (Sahashi et al. 2014) and is frequently cited for its damage to forest and hardwood plantations, as well as fruit orchards (Sahashi et al. 2012). Currently, it has a widespread non-native range among countries in Southeast Asia, Africa, Oceania, South America, Europe and the Caribbean (Ann et al. 2002). Mahogany, rubber, hoop pine, and cocoa plantings have been seriously affected by this species (Akiba et al. 2015). The second species *Heterobasidion annosum* (Fr.) Bref is responsible for causing butt and rot root in conifer trees and it is reported to be invasive in Asia and Oceania (Asiegbu et al. 2005). In native regions, such as North America, this species is a well-known problem being responsible for the loss of an estimated cost of $US 1 billion dollars annually (Smith 1990).

In terms of human health, most reported impacts were related to the consumption of some species. The most reported of these impacts is the poisoning caused by the ingestion, by mistake, of the dead cap (*Amanita phalloides* (Vaill. ex Fr.) Link) (French et al. 2011). This fungus contains the deadliest toxin of all poisonous mushrooms, with a reported mortality rate from 25% to 50% (Jander et al. 2000). It is one of the few alien macroorganisms that regularly causes human deaths and its high frequency in urban parks and similar settings increases the risk of accidental poisonings (Page and Westcott 2014). Most of the reported cases were from the United States, likely reflecting the widespread distribution of the species in some states (Wolfe et al. 2010), but also a popular interest in gathering and eating wild mushrooms and the existence of a network of support services for this kind of poisoning situations (McPartland et al. 1997; Brandenburg and Ward 2018). A good example of these services is the American Association of Poison Control Centers composed of 55 poison centers, who provide expert treatment advice and referral in case of exposure to poisonous or toxic substances (American Association of Poison Control Centers 2022). There were also reports of human poisoning from Africa, South America and Oceania. Besides, other introduced species like *Psilocybe mexicana* R.Heim and *Cortinarius orellanus* Fr. had a lower number of cases reported in Europe, probably because they are not as widespread as *Amanita phalloides* in its alien range. Finally, other species of macrofungi such as *Psilocybe mexicana* R.Heim (Johnston and Buchanan 1995) or *Amanita muscaria* (L.) Lam (Shepard 2005) were used as recreational drugs in New Zealand.

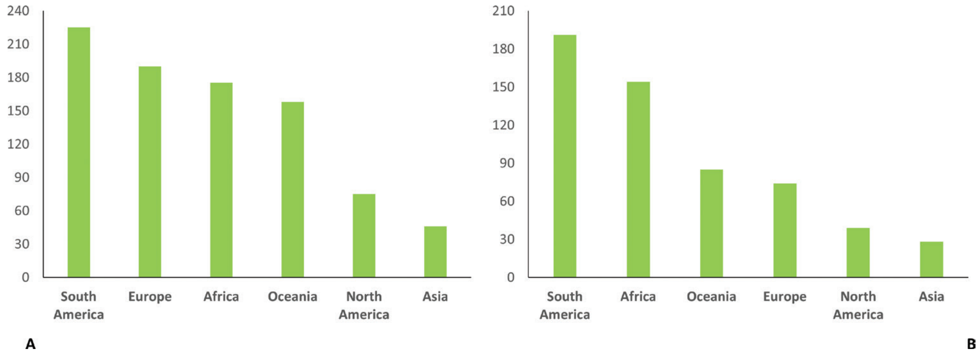

Figure 3. Total number of negative (**A**) and positive impact (**B**) records per continent.

Other less known negative impacts, with just a few records, refer to the introduction of alien radiata pines (*Pinus radiata*) and accompanying EM fungi *Amanita phalloides*, leading to observed changes in soil, including the release of recalcitrant nutrients, a loss of up to 30% of soil carbon and increased bacterial dominance (Chapela et al. 2001). Another example of impacts with low frequency includes competition, for example between the introduced Chinese truffles *Tuber indicum* Cooke and Massee and *Tuber brumale* Vitt. and the native and less aggressive Perigord truffle (*Tuber melanosporum* Vittad.) in plantations in Italy (Murat et al. 2008). On the contrary, some positive impacts that only had a few records include the case in New Zealand where mycophagous native insects like *Mycetophila fagi*, *Mycetophila filicornis*, *Zedura curtisi* use fungal tissues of *Amanita muscaria* (L.) Lam. to feed their larvae (Osawa et al. 2011). Besides, other less represented impacts include the use of the introduced *Suillus luteus* (L.) Roussel in Patagonian (Argentina) cuisine (Dickie et al 2016), the use of *Suillus granulatus* (L.) Roussel and *Suillus bovinus* (L.) Roussel in the canning industry in Madagascar (Buyck 2008) and the cultivation of *Pleurotus citrinopileatus* in some USA states as a commercial food product (Bruce 2018). Although the scope of this paper was global, some regions are clearly underrepresented, despite our efforts to search for literature in a variety of languages other than English (Nuñez and Amano 2021). This could be due to real absence of impacts by macrofungi on those areas, or more likely due to lack of research or studies accessible to our search engines (Nuñez et al. 2022). In fact, when compared with other taxa such as birds (Martin-Albarracin et al. 2015; Evans et al. 2016), mammals (Volery et al. 2021; Allmert et al. 2022) or amphians (Kumschick et al. 2017) this taxonomic group has been far less studied as a result of being complex organisms compounded by our lack of knowledge regarding their ecology, biology or even taxonomy. However, unlike in some previous studies (Martin-Albarracin et al. 2015; Allmert et al. 2022) we cannot clearly state that the number of impacts increased in wealthier regions because there was no relationship between that impact number and per capita GDP. For both negative and positive impacts, the Spearman correlation (r_s) was close to zero and for that reason any correlations were found. That is probably related to the massive plantation of exotic pines species in the Southern Hemisphere during recent centuries and consequently the introduction of associated alien macrofungi species. Therefore, despite some European countries figuring, New Zealand and Australia are in general better represented in terms of the total number of impact records in our database. In addition, some countries of South America and Africa have also very high record numbers (e.g. Brazil, Argentina, Chile and South Africa).

Despite the overall availability of impact records and some recent advances regarding the identification of alien fungi (Desprez-Loustau et al. 2007, 2010; Vellinga et al. 2009; Monteiro et al. 2020, 2022), we believe our work touches only the surface of the impacts being caused by alien macrofungi worldwide. While the impacts of fungi that form symbiotic associations with alien trees have received a relevant amount of attention, either because they facilitate the establishment of invasive species or of species of economic interest (Dickie et al. 2016), many other effects of these interactions with native taxa are likely underreported (Hui et al. 2020). For example, the EM fungus *Amanita muscaria* (L.) Lam. has been established on native Nothofagus forests in New Zealand and Australia but the consequences on plant hosts remain unknown (Osawa et al. 2011; Dunk et al. 2012). Besides, very little knowledge also appears to exist regarding other types of ecological change, including impacts on taxonomic diversity. Concerning this latter aspect, aboveground effects of plant invasions frequently include a substantial decline in local-scale diversity of plant communities (Wardle and Peltzer 2017). By analogy, we should expect that introduced macrofungi could cause a similar loss of belowground diversity of native fungi. However, evidence is currently mixed regarding how this loss actually occurs (Dickie et al. 2017). Additionally, introduced fungi can also become a food source for native animals, including a large number of insects, but there is not much evidence of how invasive fungi influence wildlife (Nuñez and Dickie 2014). Therefore, there is still a huge lack of information on this field and more survey efforts are needed to fill the presumably wide knowledge gaps about these impacts.

Finally, there are now well-defined frameworks for classifying and ranking the impacts of non-native species. For example, IUCN EICAT (IUCN 2020; Volery et al. 2020) allows assessing negative environmental impacts of alien species, SEICAT (Bacher et al. 2018) negative socioeconomic impacts, EICAT+ (Vimercati et al. 2022) positive environmental impacts, and the GISS (Nentwig et al. 2010) negative environmental and socio-economic impacts simultaneously. Certainly, the capacity to apply this sort of framework for classifying and ranking the impacts of alien macrofungi would ease the comparison of impacts with other taxonomic groups. However, to our knowledge there is no framework that considers positive socioeconomic impacts, which comprise a very substantial portion of the records of impacts in our data (39.7%). For this reason, we have developed and applied a framework appropriate to the specificities of our data, which allowed us to specify through which mechanism the impacts took place. However, this framework could not measure impact magnitude or confidence. Nevertheless, we provide the data set of impact records we have compiled together with this work, and if a more general framework becomes available in the near future, its application to this taxonomic group will become facilitated. We also expect that our findings will incentivize the construction of a comprehensive framework that encompasses more of the negative and positive impacts of biological invasions.

Conclusions

By compiling and analyzing recorded impacts of alien macrofungi, we demonstrated the highly frequent and diverse types of effects that these taxa have on recipient ecosystems, economic activities and human well-being. Besides identifying mutualistic interactions with plant species as the most frequent (either negative or positive) impact recorded, we also showed that these and other impacts have a wide taxonomic and geographical distribution, underscoring the need for transnational cooperation strategies in managing the spread of alien species beyond single-species prevention efforts (Capinha et al. 2023). Moreover, many types of impacts are likely strongly under-recorded (e.g., changes caused to local biodiversity and trophic chains) and more research is necessary to uncover their true magnitude. Related to this, although there is no relation between the existing data on impacts and their higher frequency in wealthier regions, efforts to expand the geographical scope of these assessments are still required, especially in not so well studied countries. Despite the limitation of available data, our work provides a first step towards the integrated analysis of the impacts of alien macrofungi. Our hope is that a greater focus on macrofungi in alien and invasion-related assessment will progressively help to understand the full depth of impacts caused by these taxa in non-native regions.

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Appendix 1. Negative impacts of alien macrofungi

File format: Microsoft Comma Separated Values File (.csv).

Explanation note: File containing the records of negative impacts of alien macrofungi worldwide.

Appendix 2. Positive impacts of alien macrofungi

File format: Microsoft Comma Separated Values File (.csv).

Explanation notes: File containing the records of positive impacts of alien macrofungi worldwide.

Supplementary material 1

Negative impacts of alien macrofungi

Authors: Miguel Monteiro

Data type: Ocurrences

Explanation note: File containing the records of negative impacts of alien macrofungi worldwide.

Link: https://doi.org/10.3897/neobiota.85.101770.suppl1

Supplementary material 2

Positive impacts of alien macrofungi

Authors: Miguel Monteiro

Data type: Ocurrences

Explanation note: File containing the records of positive impacts of alien macrofungi worldwide.

Link: https://doi.org/10.3897/neobiota.85.101770.suppl2