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Stranger danger: emerging biosecurity risk from fungus inoculation and cultivation

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Abstract

When non-native fungal species or non-native genotypes of a native species are introduced into a new region they can sometimes become invasive, altering the species and genetic composition, and the functioning of resident communities. There is an ever-increasing risk of escapees into the natural environment through human activity, including overlooked introduction pathways, intentional introductions as mycorrhizal inoculum or inoculation accidentally from an increase in cultivation of edible fungi in outside environments. In each case guidelines and regulation are absent or weak increasing the risk of invasion, which presents a biosecurity risk that governments need to address. There are lessons to be learned from plant and animal biology about invasive species where there has been a long history of invasion from imported exotic and cultivated plants in particular. Here we highlight some of the problems arising from the establishment of alien fungi as species and strains or genotypes in new regions, and call for urgent introduction of guidance and stronger regulation to protect native fungal biodiversity and their habitats from the harmful consequences of non-pathogenic fungal invasions. This is crucial to meet the ambition of Global Biodiversity Framework targets for reducing the impact of invasive species.

Box 1 Definitions used in the commentary

Natives: organisms that have lived/evolved in a geographic region for a long time (thousands of years)

Naturalised: organisms that are not natives but established and became fully integrated in the natural environment, hundreds of years ago, without evidence of harming native ecosystems

Aliens: non-native organisms, introduced by humans outside of their native range.

Invasives: aliens that spread rapidly, establish and harm native ecosystems in terms of community composition and/or function. This can be alien species or alien genotypes of a native species.

Fungal strain: a subtype or different genotype of a species

Introductions: when alien organisms are intentionally or unintentionally brought into new locations by humans.

1. Introduction

Humans have inadvertently moved fungi around the planet for thousands of years, sometimes with dramatic consequences for other organisms. These aliens (Box 1) sometimes rapidly spread in new areas and become invasive, causing major impacts on the resident communities and ecosystem processes. Compared to animals and plants, fungal and microbial invasions have received little attention (Kinnunen *et al*., 2016; IPBES, 2023), with the exception of some fungal pathogens of animals and plants where invasions have had major environmental and economic consequences, such as the spread of: *Batrachochytrium dendrobatidis* causing chytridiomycosis of frogs and toads, spread by trade in amphibians (Castro Monzon *et al*., 2020); *Magnaporthe oryzae* causing rice blast and *Tilletia indica* causing karnal bunt of wheat, both spreading by seed exchange; introduction of the Dutch elm disease-causing *Ophiostoma novo-ulmi* on imported timber; chestnut blight-causing *Cryphonectria parasitica* spread on imported sweet chestnut (*Castanea*) trees; and numerous introductions of ash die-back disease (Anderson *et al.*, 2004; Brasier, 2008; Orton *et al*., 2018).

The detection of invasive alien fungi is dependent on good background knowledge of a region's mycobiota but, unfortunately, this is often lacking. Thus, the scale of fungal invasions and the drivers that facilitate invasion are poorly understood (IPBES, 2023). What is evident, however, is that it is all too easy to introduce invasive taxa or genotypes, and extremely hard to manage them once they have established (Dickie *et al*., 2016). Plant pathogens aside, the global alien fungi database listed 648 species and 31 varieties of alien macrofungi (Monteiro *et al*., 2020), 374 of which have been recorded, with varying degrees of evidence, as having some form of negative impact in colonised areas (Monteiro *et al*., 2023).

At the same time, fungi are increasingly promoted as a natural solution to some of the global issues we are facing, including use of mycorrhizal fungi in sustainable agriculture (Elnahal *et al*., 2022) and forestry (Govindu *et al.*, 2020), food and fungal-derived products (Chang, 2006; Ramos *et al*., 2019), biomaterials (Aiduang *et al*., 2022), habitat creation and restoration (Wainhouse & Boddy, 2022), and bio-control agents against pests (Chaudhary *et al*., 2024) and pathogens (Thambugala *et al*., 2020). An inevitable consequence of this is that some fungi - both native and alien species and genotypes/strains - are being released into the wild – intentionally and unintentionally, often as a small number of strains or genotypes. Strains used for commercial applications may also be further developed through traditional breeding methods, chemical mutagenesis or gene editing (Sonnenberg *et al*., 2017; Dong *et al.* 2022) to select for advantageous traits which could increase

their invasive potential in a natural setting, such as temperature or substrate tolerance, growth rate, fruit body production or nutrient acquisition.

This commentary focusses on invasive fungi that, unlike fungal pathogens and biocontrol agents (Goettel *et al.,* 2001; FAO, 2017), are not yet adequately scrutinised through risk assessment, regulation, and registration which, where they do exist, are focussed on product quality and human, plant or animal health, rather than wider ecological impact or invasion risk (Ghorui *et al.*, 2024; Santos *et al* 2024). Specifically, we focus on two functional groups of fungi: (1) mycorrhizas and (2) saprotrophs. Fungi in these niches have large-scale and likely increasing commercial value through the production of (1) mycorrhizal inoculum, a $1.4 billion industry and growing due to use in sustainable agriculture and forestry (Mordor Intelligence, 2026), and (2) edible/medicinal saprotrophic mushroom cultivation $50-90 billion global market (More *et al.*, 2025).

We highlight the potential problems stemming from the mass movement of alien species and strains used for these purposes into new regions. While there is compelling evidence of the invasion risk in both groups, the potential negative impacts are rarely considered (Schwartz *et al.*, 2006; Ricciardi *et al*., 2017; Basiru & Hijri, 2022; Jayaraman *et al*., 2024).

We (1) give examples of invasive mycorrhizal and saprotrophic fungi and their large-scale introduction pathways into the environment; (2) draw lessons from plant and animal introductions that have caused damage to native ecosystems, genetic diversity and species populations; and (3) consider future problems and preventative measures for these two types of commercial fungi. We emphasise not only potential problems of alien fungal species invasions, but also of alien genotypes of species that are native.

2.Examples of invasive mycorrhizal and saprotrophic fungi and large-scale introduction pathways into the environment

2.1 Mycorrhizal fungal invasions

Long-distance movement of live plant material via global trade leads not only to the movement of invasive fungal pathogens but also the root-associating mycorrhizal fungi. Over 300 ectomycorrhizal fungal species have been moved to new geographic regions, but most have occurred in Europe, Brazil, New Zealand and South Africa (Vellinga *et al.*, 2009; Monteiro *et al.*, 2020), affecting a range of host plant families. *Amanita phalloides* (death cap) is one of the most studied invasive ectomycorrhizal fungi. Native to Europe and introduced throughout the southern hemisphere, it is invasive in the San Francisco Bay Area of California, where it is spreading following introduction in the early 1960s, though naturalised and non-invasive on the east coast (Wolfe *et al.* 2010). By 2008,

it had become a dominant species, displacing native mycorrhizal fungi to occupy 17.5% of root tips sampled in California (Wolfe *et al*., 2010). Now, *A. phalloides* in its invasive range produces sexual fruit bodies without mating with a different individual (i.e. it is clonal). This enables the successful genotype to spread rapidly (Wang *et al*., 2023), and is a reproductive advantage shared with some invasive plants (Pyšek & Richardson, 2007).

Not only can mycorrhizal fungi disrupt the native fungal communities but they can sometimes aid their plant partners in being invasives, e.g. suilloid fungi with pines in the southern hemisphere (Desprez-Loustau *et al*., 2007; Vellinga *et al.*, 2009; Policelli *et al*., 2019; Hoeksema *et al*., 2020; Monteiro *et al*., 2023), and *Pisolithus* spp. and *Laccaria fraterna* (amongst others) with *Eucalyptus* around the world (Dell *et al*., 2002; Díez, 2005). Indeed, in a recent review of the impact of alien fungi, nearly 50% of all recorded negative impacts were through facilitation of non-native plants (Monteiro *et al.*, 2023). Compared to the plant trade, commercial mixtures of ectomycorrhizal and of arbuscular mycorrhizal fungi (AMF) are relatively modern, and their increasing use has serious potential to harm native mycobiota (Schwartz *et al.*, 2006; Hart, 2017; Basiru & Hijri, 2022; Monteiro *et al.*, 2023; Ricciardi *et al*., 2017), and not helped by frequent lack of availability of inoculum of native origin and lack of inclusion of information on origin. Though negative impacts of inoculum are rarely investigated beyond the host plant, there is evidence that AMF added to soil as inoculants can interfere with native AMF, including suppression, exclusion and stimulation (Koch *et al.*, 2010; Basiru & Hijri, 2022).

2.2 Saprotrophic fungi invasions

There are fewer documented examples of saprotrophic fungi becoming invasive or having negative consequences on other species, communities or ecosystems in their invaded range (Monteiro *et al.*, 2023). However, the potential of major ecosystem disruption by saprotrophs is illustrated by the golden oyster mushroom *Pleurotus citrinopileatus*. This commercially grown fungus is native to Asia, but is spreading rapidly in parts of the USA, linked to two commercial strains, with severe ecological changes detected in the invaded communities (Bruce, 2018; Veerabahu *et al*., 2025). It has also now escaped from cultivation in Europe, and established in Denmark, Hungary, Italy, France, Germany, Spain, Austria, Belgium and UK (GBIF Secretariat, 2023; Wainhouse *et al.*, 2025).

Other species, such as *Favolaschia claudopus* which is believed to originate from Madagascar (Zhang & Dai, 2021), are extending their global range, particularly in Europe, through human mediated movement of soil and wood products and can be considered potentially invasive species. Several such species have appeared in Europe and USA in recent years fruiting on horticultural mulch (such as *Agrocybe putaminum, Agrocybe rivulosa*, *Leratiomyces ceres*, *Psilocybe cyanescens* and others),

thought to have been introduced on imported wood products (Nauta, 2003; Shaw *et al*., 2004; Halama, 2016). While *Leratiomyces ceres* fruiting is apparently restricted to woodchip, the mycelium has been detected more widely in undisturbed soils too (Bridge & Prior, 2010), with unknown consequences for native soil fungi. Some saprotrophic fungi introduced by humans appear to have naturalised without harming native fungal communities, like *Clathrus archeri* in USA and Europe, while its native populations in Australia and New Zealand are contracting (Pietras *et al*., 2021).

2.3 Large-scale introduction pathways into the environment

As with plants and animals, large-scale introduction pathways for fungi occur by various dispersal mechanisms, from deliberate application of fungi for a purpose, or unintentional release as a byproduct of another process, such as tree imports (Table 1). Recognising these introduction pathways will be critical for controlling future invasions, however, more work is needed to predict their relative risk.

Table 1. Potential source of invasion from deliberate and unintentional introduction of alien saprotrophic and mycorrhizal fungal species/strains/genotypes from inoculation and cultivation

	Intentional introduction of alien genotype/species	Accidental introduction of alien genotypes/species
Saprotrophic fungi	Establishment of edible/medicinal fungi from mycelium [1]Establishment of fungi for conservation/habitat creation	[2,3]Spore release from growth rooms, outdoor growth, transportation and point of sale of edible/medicinal fungi [4-6]Establishment of fungi from imported wood products or soil
Mycorrhizal fungi	[7-9]Mycorrhizal inoculum for plant growth in forestry, horticulture and agriculture Mycorrhizal inoculum for farming edible fungi, e.g.	[10-13]Mycorrhizal fungi in imported soil and on rootstock of imported/nursery plants

	truffles, and translocation conservation	

References: [1]Wainhouse & Boddy (2022), [2]Bruce (2018); [3]Veerabahu *et al*. (2025), [4]Nauta (2003); [5]Shaw *et al*. (2004); [6]Halama (2016),[7]Schwartz *et al*. (2006), [8]Govindu *et al*. (2020), [9]Basiru & Hijri (2022), [10]Chapela *et al*. (2001), [11] Díez (2005), [12]Vellinga *et al.* (2009), [13]Monteiro *et al.* (2020).

3 Lessons from plant and animal introductions

There is a long history of transporting, trading and introducing non-native plants and animals in many countries (van Kleunen *et al*., 2018), and lessons can be learned from invasions of these.

3.1 Traits that facilitate invasion

The traits valued for plant cultivation, such as rapid growth, long-lived growth form and abundant flowering/fruiting, promote the naturalisation of cultivated plants (Kinlock *et al*., 2022; Booy, 2019; Datta *et al*., 2020). Trait selection in plant cultivars is analogous to strain selection in fungi where similar advantageous traits are selected for in mycorrhizal fungal inoculum (Thomsen, 2018) and saprotrophic edible fungi (Van Griensven, 2008). Analysis of 17,396 alien plants introduced to the UK showed the use of plants within horticulture and availability within nurseries best explained plant naturalisations and invasiveness (Kinlock *et al*., 2022), and indicated that human cultivation affected the distribution of traits of naturalised plants.

Parallels with mushroom cultivation are immediately obvious, and the recent spread of two cultivated strains of *Pleurotus citrinopileatus* in North America (Bruce, 2018; Veerabahu *et al*., 2025) may be a harbinger of a wider problem. While the proportion of plant species that spread beyond their cultivated range is small compared to the number of plant species in cultivation, any that do become invasive have negative consequences for entire ecosystems (Pyšek *et al*., 2020; Vilà *et al.*, 2011). Again, this will apply to fungi (Monteiro *et al*., 2023).

3.2 Adverse genetic change resulting from strain/genotype invasions

Many plants and animals living in the wild are continually exploited on a large scale, e.g. by fishing, hunting and logging, and maintaining these activities frequently depends on augmentation of populations by replacing those removed with large numbers of individuals from elsewhere (Laikre *et al.*, 2010). This can include: (1) non-locally sourced populations; (2) genetically modified organisms (GMOs); (3) locally sourced populations that have been captively bred/grown and then returned; and (4) alien species not naturally present at the release site. Such releases of genetically exotic

plant and animal species or exotic genotypes of native species can lead to four types of adverse genetic change: (1) loss of genetic variation, (2) loss of adaptations, (3) change of genetic composition, and (4) change of population structure (Laikre *et al*., 2010). The analogous large-scale releases of fungal strains carry the same concerns as for plants and animals.

While these issues are also relevant to fungi and their different strains, direct evidence is thus far scarce. The risk of changes to community composition and functioning, and of novel genotypes outcompeting native genotypes, from mycorrhizal inoculum was first pointed out 20 years ago (Schwartz *et al.*, 2006). There is now some evidence that mycorrhizal inoculation sometimes, but not always, alters soil biodiversity (Cornell *et al*., 2021) but the full impact and scale of adverse genetic change within populations is not known.

3.3 Risk of native species loss by hybridisation

Genetic and demographic swamping that occurs through hybridization of alien and indigenous species and genotypes can lead to loss of indigenous genetic diversity or, at worst, extinction of rare taxa (Todesco *et al.,* 2016). English bluebells (*Hyacinthoides non-scripta*) were feared to be threatened by 'extinction-by-hybridisation' following the escape of the 'Spanish' bluebell (*H. hispanica*) and the proliferation of their hybrids (*Hyacinthoides* × *massartiana*) (Ruhsam *et al*., 2023). Similarly in animals, the Ethiopian wolf (*Canis simensis*) and Scottish wildcat (*Felis silvestris silvestris*) are threatened by hybridisation with domesticated dog and cat respectively (Marino & Sillero-Zubiri, 2011; Gerngross *et al*., 2023). Examples of genotype hybridization within a species include black poplar (*Populus nigra*) which is threatened by hybridisation with the ornamental cultivar 'Lombardy' poplar (*Populus nigra italica*) (van Broeck *et al*., 2005). Commercial forestry planting of silver fir (*Abies alba*) also threatens the locally distinctive genotype of a relict population of the species in Bialowieza, Poland (Mejnartowicz, 1996).

The risk of such hybridisation between wild native and exotic or domesticated genotypes extends to fungi, though currently there is little evidence of this, but then few studies have been performed. Examples include: (i) hybridisation and genetic swamping between cultivated strains of European edible saprotroph *Agaricus bisporus* (cultivated mushroom) and the indigenous genotype in California (Kerrigan, 1998). More than 50% of the population was identified as having European ancestry, suggesting that the native genotype was being outcompeted. (ii) *Pleurotus* species (oyster mushrooms) often hybridise with other members of the genus resulting in hybrid vigour with characteristics of offspring outperforming those of the parents (Abdulgani *et al.*, 2017; Barh *et al.*, 2024). (iii) *Hericium erinaceus* (though globally red-listed as of Least Concern, but with numerous distinct clades and cryptic species (Hallenberg *et al*., 2013; Cesaroni *et al*., 2019; Koga *et al*., 2025), is

already in need of protection in much of Europe to prevent extinction due to habitat loss, and a likely candidates for being severely impacted by hybridisation with cultivated non-native species and strains. *H. erinaceus'* popularity among mushroom farms and home-growers is rapidly rising (de Mattos-Shipley *et al*., 2016; Chutimanukul *et al*., 2023), so it is difficult to predict extent of hybridisation without the baseline information on genetic structure of native populations.

3.4 Negative outcomes for native ecosystems and communities

Plant invasions also directly contribute to loss of species by competition and indirectly by loss of habitat. A meta-analysis of plant invasions showed large negative effects on plant community fitness, diversity and abundance plus smaller effects on nutrient cycling within ecosystems (Vilà *et al*., 2011). For example, dense growth and shallow root systems of invasive Himalayan balsam (*Impatiens glandulifera*) alter community structure and increase erosion (Coakley & Petti, 2021). In British woodlands, the invasion of *Rhododendron ponticum* casts dense shade and secretes allelopathic chemicals through its roots to suppress competing plants (Manzoor *et al*., 2020). Added to the harm caused to the natural environment (Dehnen-Schmutz *et al*., 2022), managing the invasion of *R. ponticum* is hugely costly and time consuming (Dehnen-Schmutz & Williamson, 2006).

Similarly, invasive saprotrophic and mycorrhizal fungi can have effects at the ecosystem scale. The invasive *P. citrinopileataus* strains are associated with a nearly 50% drop in fungal biodiversity in the woody resources it occupies (Veerabahu et al 2025). Within 20 years, following introduction of exotic *Pinus radiata* (Monterey pine) tree plantations to Ecuador grasslands, there was a loss of up to 30% stored soil carbon (Chapela *et al.* 2001). This was attributed largely to *Suillus luteus* which was ectomycorrhizal with the pine and used stored carbon to produce 3-fold more fruit body biomass than the total produced by all mycorrhizal fungi in native pine forest. For saprotrophic edible fungi like *P. citrinopileatus* which have been bred to produce large continuous crops of mushrooms, decomposition rates and C turnover might be expected to be relatively faster as a result (Lustenhouwer *et al*., 2020).

4 Potential future problems and preventative measures

Issues arising from the unintentional spread of macrofungal species in non-native habitats are increasingly documented (Monteiro *et al.* 2023). However, little is known of the consequences from accidental release of non-native strains or the deliberate releases of putatively native species or strains. If there is a single major lesson from the plant world, it is that action needs taking before problems arise (Dehnen-Schmutz & Conroy, 2018). Mycologists are in a stronger position than

botanists were several hundred years ago when the spread of alien plant species began in that we know that alien species/genotypes can invade and wreak havoc with our native communities.

We need to act now to: (1) determine what are the most likely traits and pathways that might result in escape or release of invasive non-pathogenic fungal species/genotypes into the natural environment; (2) instigate measures to prevent escape or release of invasive species/strains; and (3) start tracking invasions and produce mitigation plans where invasions have already begun.

4.1 Measures to prevent release of invasive fungal species/genotypes

Knowledge is power, so resolving knowledge gaps is crucial but so also is raising awareness of the issue among stakeholders, creating guidelines and advice on appropriate species and strain use, evaluation of ethics, and legislation regulating sale and use of non-native fungal species and genotypes.

Currently, non-pathogenic fungi sit within a regulatory gap where it is often not clear who is responsible for them. In the UK for example, the recent biosecurity strategy does not recognise non-pathogenic fungi as a biosecurity risk (Defra, 2025). Regulation of other fungi, specifically bio-control agents offer a useful model for regulation of mycorrhizal inoculum and edible/medicinal saprotrophs. In the EU (and largely retained in the UK), for example, fungal bio-control agents are controlled under Plant Protection Product Regulations (e.g. *Regulation (EC) No 1107/2009, Regulation (EU) 2022/1438*) where strict regulatory procedures require detailed strain-specific risk assessment, including assessment of potential to cause environmental harm, before they can undergo wild release. While the EU also has regulation for mycorrhizal inoculum (Microbial Biostimulant (PFC 6(A), CMC-7)) only basic safety assessments are needed at the species level. This is understandable since the introduction of biocontrol agents is to cause harm to a specific target organism, and the purpose of risk assessment is to minimise the harm beyond its target. For edible saprotrophic, and mycorrhizal fungi, the perception of use is largely positive (though we have clearly shown above that there is potential for considerable harm), which may be one of the reasons for weak or absent guidelines, risk assessment or regulation to manage their incidental and intentional release.

Principles for conservation translocations of threatened wood-inhabiting fungi (Nordén *et al.* 2020; Box 2) and for inoculations into standing trees for habitat creation (Wainhouse & Boddy, 2022; Box 2) have already been suggested and can be adapted for commercial or non-conservation applications. The IUCN guidelines for conservation translocation, which include ecological replacement (introduction of an alien organism to replace the function of another) are also relevant

for mycorrhizal inoculation and offer some insight to risk assessment and evaluating unintended consequences of introducing alien organisms or genotypes which include invasion risk, ecological harm and gene escape (IUCN Species Survival Commission, 2013). For plants, Green Lists have been developed to encourage use of species with low invasion risk in large-scale planting schemes (Dehnen-Schmutz, 2011). For fungi, rules could ideally be stronger.

We recommend that non-native species/strains of edible/medicinal mushrooms should only be grown in contained indoor facilities. Standard protocols need to be developed for management of spent substrates to safely denature non-native fungal growth. Only confirmed native/local strains that have been responsibly and legally sourced should be used in outdoor applications. This could be aided by production of a centralised database with full metadata and DNA (especially for species of conservation concern), plus a standardised method for tracking cultures, and collections of native/local strains from different bioregions that are guaranteed not to have already been subject to hybridisation or genetic dilution. For large-scale mycorrhizal inoculations, for example in forestry, horticulture or agriculture, a variety of regional native strains should be used to prevent monocultures and gene dilution. With regard to mycorrhizal inoculation, some general recommendations have been made by Schwartz et al. (2006; Box 3).

The guidance for all inoculation scenarios will need refinement and updating with increase in collective knowledge and understanding of invasion biology and the effect of introducing alien species/genotypes on fungal community composition and ecosystem functioning.

Box 3: Recommendations for minimising ecological harm from mycorrhizal inoculations adapted from Schwartz et al. (2006):

(1) determine whether inoculation is actually necessary;

(2) adopt approaches that maintain indigenous fungi present in soil, inoculating with local strains if fungal propagules are absent or density is low; and

(3) if local species/strains are unavailable, isolates with traits that minimize the risk that the introduced fungi become problem invasives should be used (cf. Datta et al. 2020).

The following traits are important: high specificity and benefit to the target plant partner, along with ability to colonise it rapidly; low dispersal ability; poor long-term competitive ability with native soil fungi; and, for ectomycorrhizal species, a poor ability to use carbon sources other than from the host plant.

(4) avoid relying on mixtures of species as a means of increasing the probability of establishing successful mycorrhizal partnerships as mixtures also raise the risk of introducing species/genotypes that become invasive, and strongly competing inocula may lead to invasion by low quality mutualists (Martignoni *et al*, 2020).

4.2 Tracking and mitigating invasions

Early detection and subsequent monitoring of non-native fungi is crucial for determining whether a fungus is likely to become invasive, understanding how it spreads, and eradicating it, e.g. by targeted removal, or potentially managing them before they become too widespread. Monitoring and management must be a combined effort between mycologists/conservationists, regulators, land managers, myco-industry – including both mycorrhizal inoculum and food production, and community scientists. With plants, community science approaches to monitor the latest species that are showing invasive potential (Dehnen-Schmutz & Conroy, 2018) are being adopted in a growing number of countries (Dehnen-Schmutz, pers. comms), and this seems an obvious approach with fungi where there is a rich tradition of amateur mycologists recording fungi in many countries (Andrew *et al*., 2017). A community science initiative has begun in Europe to do this (Mielke *et al.*, 2025; FunDive, Eyes on Alien Mushrooms).

Horizon scanning for potential invasives is generally done for plants, animals and pathogenic fungi. The same systematic process is needed for saprotrophic and mycorrhizal fungi, particularly for those cultivated for food/medicinal purposes or commercial strains of putatively beneficial species. Some

291 countries, such as Sweden (SLU Artdatabanken, 2025), and Norway (NBIC, 2023) are already leading
292 the way by carrying out horizon scanning of non-pathogenic macrofungi including cultivated species.

293 Dickie *et al.* (2016) have reviewed some management options for invasive ectomycorrhizal fungi.
294 Control of invasive species is very difficult; prevention is clearly better than cure, but if prevention
295 has failed then early detection and rapid response is likely to yield the best chance of successful
296 eradication/control.

297 **5 Concluding remarks**

298 Target 6 of the Global Biodiversity Framework is clear about the risks of invasive non-native species.
299 Meeting the ambition of this target demands that we address fungal invasions alongside plants and
300 animals (Fungal Conservation Network, 2024). Numerous introduced plants have escaped cultivation
301 into the wild (Dehnen-Schmutz, 2022), though the lag time between introduction and becoming
302 naturalised varies widely. In the UK, for example, which has a long history of collecting and importing
303 plants from around the world, this has ranged from 4 to over 350 years (Hill *et al.*, 2005), so it is the
304 plants being cultivated now that are most likely to be identified as the next invasives (Dehnen-
305 Schmutz, 2011), and the impacts of new species being introduced now may not be seen until several
306 human generations in the future. This immediately highlights the need for careful consideration of
307 what problems current fungus growing and inoculation practices might unleash in the future. We
308 expect the threat will increase as new strains are developed for these purposes.

309 Invasive mycorrhizal fungi, imported accidentally in trees for creating forest plantations outside of
310 their range provide a salutary lesson about the harm that non-native fungi can do in natural
311 ecosystems (Section 2.1). Yet production and use of mycorrhizal inoculants is increasing. The market
312 for mycorrhiza inoculum is already valued at 1.3 billon globally and set to rise to over 2 billion by
313 2030 (Mordor Intelligence, 2026). and so their use while already widespread, is increasing, and
314 products containing species/strains that are not native to a locality or of limited genetic diversity
315 could potentially pose major negative consequences for native populations, communities and
316 ecosystem function.

317 Large-scale outdoor cultivation of non-native edible mushrooms, including, for example, *Pleurotus*
318 *citrinopileatus*, native to Asia, is already widespread in North America and appearing in Europe
319 (Section 2.2). Non-native genotypes of native species are of equal concern because hybridisation,
320 whether intra- or inter-specific, threatens genetic diversity and at worst could lead to extinction of
321 genotypes or species through genetic swamping and dilution. Even small, localised releases may be a
322 problem for protected taxa, such as *Hericium* species in Europe, as *H. erinaceus* from non-locally

sourced inoculum is being increasingly cultivated. Inoculation with non-native species/strains for conservation and habitat creation pose the same risks, though if the guidelines that have already been formulated are followed then the risk should be very low (Nordén et al. 2020).

We strongly recommend: (1) halting deliberate introduction of exotic or commercially modified genotypes/species; (2) regulation of the use of non-pathogenic macrofungi being released either deliberately or accidentally for human benefit, with a requirement to undertake risk assessment and specify species names and country of origin on all fungal inoculum products; (3) control of invasive fungi through inclusion in existing invasive species regulation, similarly to animals and plants by governmental institutions; (4) a joint effort of institutional culture collections and the cultivation community to cocreate a decentralised national culture collection of suitable genotypes, accessible to researchers, cultivators and industry at minimal cost, that are formally registered and from long continuity sites etc., (5) alongside engagement activities that explain the necessity for these measures and the consequences of using cultures of unknown origin with unknown risks

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