scientific reports

OPEN

Intercontinental movement of exotic fungi on decorative wood used in aquatic and terrestrial aquariums

Robert A. Blanchette✉, Nickolas N. Rajtar, Amelia G. Lochridge & Benjamin W. Held

The intercontinental movement of fungi or fungus-like organisms brings nonnative species into areas where they may become invasive pathogens of trees and other plants. In the past century, many examples such as Dutch elm disease, sudden oak death, laurel wilt, and others have resulted in large economic losses and ecological disasters. Although various safeguards to prevent the transport of potential pathogens have been in effect, new avenues of introduction have occurred causing new disease outbreaks. This study examined fungi in wood shipped from Asia that is used for decorative purposes in aquatic and terrestrial aquariums. From 44 imported wood samples, 202 cultures representing 123 different fungal taxa were obtained and identified using molecular methods. These included 31 species not previously reported in the United States, 21 potential plant pathogens, 37 species of wood decay fungi and 24 taxa with a 97% sequence match or less to known isolates suggesting these are unknown species. The results demonstrate that wood used for decorative purposes in aquariums harbor large numbers of diverse fungi that remain viable during shipping and storage. These fungi are currently being imported into areas where they are not native, and they may pose serious biosecurity threats to the United States and other countries around the world.

Keywords Ascomycota, Basidiomycota, Invasive microorganisms, Plant pathogens, Microbial ecology, Spiderwood

The introduction of microorganisms and insects into new areas where they are not native has resulted in devastating losses from many invasive pathogens and pests. This intercontinental movement has been responsible for the loss of billions of trees in the United States alone[1]. Diseases such as Dutch elm disease, white pine bister rust, chestnut blight, sudden oak death, laurel wilt, and many others were caused by introductions that have not only killed massive numbers of woody plants in the urban and forest landscapes but also resulted in extreme ecological damage[1–5]. These past introductions occurred from the transport of soil, timber, wood products, living trees, or other plant material. Although some of the most damaging invasive pathogens were introduced into the United States over 100 years ago and efforts to prevent these introductions from occurring were put into effect, these efforts have not always been successful[6,7]. New avenues for exotic fungi to be introduced continue to be realized[8]. This is a problem not only for the United States but for many countries worldwide as new plant diseases continue to be introduced[4,9,10]. Recently nonendemic fungal pathogens of plants and people were found on imported wooden handicrafts[8]. These authors suggest that fungal pathogens are of particular concern and pose a very high risk due to their rapid emergence, low resistance in host populations, and limited surveillance infrastructure for detection.

Importation of materials and microorganisms from Asia has been responsible for many introductions in the past. New studies have shown that many of the introduced *Phytophthora* species have likely originated in Asia[11,12]. In addition to these highly virulent known pathogens, many undescribed species have been found in that region. It has been suggested that these little-known species could also become destructive diseases if given the opportunity to move into areas where they are not native[13]. Many have a wide host range and could undergo jumps to new hosts after importation. Eco-evolutionary dynamics of fungi suggest that trees or other plants that have not evolved with the pathogen would have little to no resistance to these fungi or fungal-like organisms[10].

Recently, an unusual fungus was found colonizing wood used for decoration in aquatic aquariums[14]. *Xylaria apoda*, a fungus not previously reported in the United States and native to Asia, was found growing underwater on wood in aquariums located in Minnesota and Colorado. The wood had been imported from Asia and was

Department of Plant Pathology, University of Minnesota, 55108 St. Paul, MN, USA. ✉email: robertb@umn.edu

purchased from pet stores. Although the various woods had been dried, shipped and stored for a long period of time, the fungus remained viable and grew throughout the submerged wood producing fruiting bodies. Finding the same exotic fungus in wood from aquariums located in two different states within the United States raises serious concerns that this wood, widely used throughout the world for decorative purposes in aquariums, could be harboring other exotic microorganisms including potential plant pathogens. Several different types of wood, such as wood classified as spiderwood and driftwood, are sold by vendors from Asia online and also in pet stores. Spiderwood has unusual shapes with multiple branches and galls and driftwood consists often of degraded tropical woods from coastal areas or from the forest floor that contain interesting patterns with holes and crevices that are attractive decorations in fish tanks (Figs. 1 and 2). This study was done to determine what fungi and Oomycota are being transported alive in imported decorative aquarium woods and to identify pure cultures of fungi obtained after arrival in the United States by DNA sequencing. The introduced fungi were also evaluated to determine if any of them have potential to be pathogenic or cause detrimental effects when introduced into new ecosystems.

Results

Forty-four samples of decorative wood used for aquariums that originated from Asia were found to visually appear to have varying amounts of discolored and decayed zones. Some samples had pseudosclerotial plates produced by fungi while others had various stages of white rot, white-pocket rot or other evidence of degradation (Fig. 1). Samples sold as driftwood were extensively degraded and many had large holes present throughout the wood. This wood appeared to be extractive rich tropical hardwoods that had been degraded on the forest floor. When samples were split open for isolation, evidence of mud and sand were present within the voids in some samples (Fig. 2).

Isolations made from the wood yielded 204 cultures of viable fungi representing 123 taxa (Table 1). Representative taxa in the Ascomycota, Basidiomycota and Mucoromycota were found but no fungal-like organisms in the Oomycota were obtained. A large number of fungi appeared to be from Asia and not previously documented in the United States. This included many fungi that are potential plant pathogens and also fungi that cause wood decay (Table 1 Fig. 3). In addition, 24 taxa have a low ITS sequence match (97% or less) and

Fig. 1. Wood samples sold for aquarium decorative purposes and used for culturing fungi showing evidence of fungal colonization and decay. Dark colored areas of dead wood were present along with lighter colored sapwood (**a** and **b**). The older dead wood was the location where many fungi were isolated. White rot was present in many samples (**c**–**f**) and fungi produced incipient decay leaving a bleached white appearance (**c** and **d**) or zones of advanced decay (**e** and **f**). A white pocket rot was evident inside several of the samples that were split open for isolation and culturing (**e** and **f**).

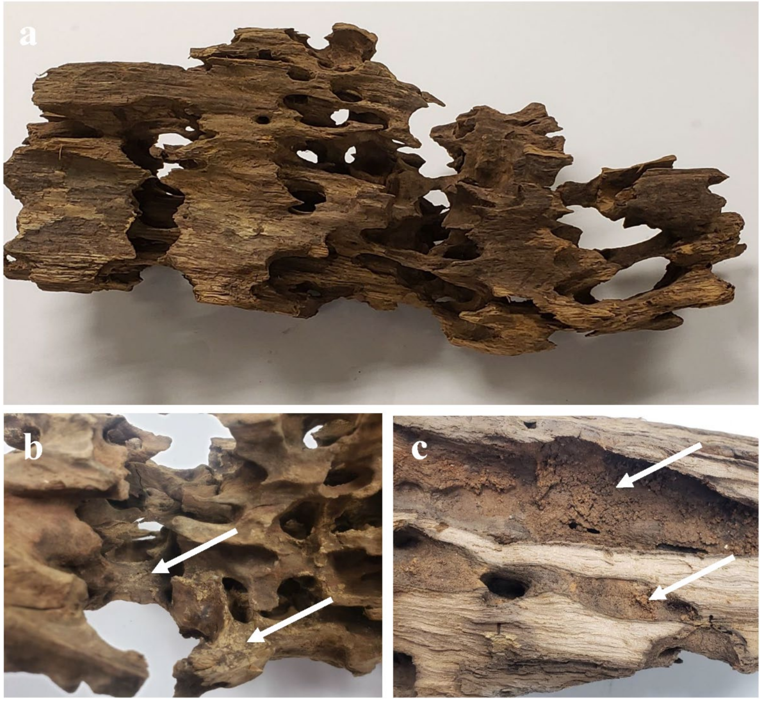

Fig. 2. Samples sold as driftwood were pieces of tropical woods that had substantial degradation resulting in holes throughout the wood. The holes make the wood attractive for use in aquariums (**a**). The inner zones of this decayed wood often had residual mud and soil present (**b** and **c**).

may represent new species and or genera. Taxa such as *Apiosporella hesperidica*, *Campylocarpon fasciculare*, *Diatrypella japonica*, *Epicoccum sorghinum*, *Fusarium verticilloides*, *Phaeoacremonium scolyti*, *Paecilomyces maximus*, *Talaromyces funiculosus*, and others are known pathogens of agricultural crops and trees. Other fungi may have potential to be plant pathogens such as *Hawksworthiomyces* sp. and *Moristroma germanicum* and possible human pathogens *Apiospora intestine*, *Coniochaete hoffmannii* and *Melbranchea ostraviensis*. Fungi causing post-harvest problems of fruits and vegetables were also found. These included several Penicillium species. Two entomopathogens, *Cordyceps farinose* and *Purpureocillium lilacinum* were found. A large number of Basidiomycota known to cause brown and white rot in wood were found including the bioluminescent *Neonothopanis nambi* which was isolated several times. A large representation of Xylariales in the Ascomycota were also found. These fungi cause a soft rot attack of wood. In addition, many other saprophytic taxa were identified such as *Aspergillus* sp., *Cladosporium* sp., *Penicillium* sp., and *Trichoderma* sp.

Discussion

The introduction of non-native fungal species is a biosecurity threat to our natural resources and can have devastating effects for agriculture, forestry and the environment[10]. In addition to attacking specific types of trees or other plants causing their death, invasive pathogens can devastate ecosystems[1,2,4]. This study demonstrates that decorative wood used for aquariums contains large numbers of fungi representing many different taxa including nonnative species, potential plant pathogens, and other fungi that could be detrimental to the environment and economy. In a relatively small sample size of 44 different pieces of imported wood for use in aquariums, 204 cultures of fungi were obtained representing 123 different taxa. From this group of fungi, 30 were not previously reported in the United States. Information on vendor sites selling these woods for aquariums boasts that many hundreds have been sold. Although it is not known how many fungi are viable in all these imported woods, the results reported in this study show that with just 44 different samples, there are very large numbers of diverse viable fungi routinely being imported from Asia to other countries in this wood. Many of these are known plant pathogens. The list of imported fungi found in our study alone (Table 1) is a reason for serious concern about potentially dangerous biosecurity risks, however, this represents a small fraction of these types of wood samples being imported that could be introducing a plethora of foreign fungi.

Some of our most serious introduced diseases to the United States are thought to originate from Asia. This includes chestnut blight, Dutch elm disease, sudden oak death, Port Orford cedar root disease, laurel wilt and others[6,12,15–18]. Researchers also indicate that there are many unknown species of fungi and Oomycota in Asia that have the potential to be pathogens[13,19]. Although we did not isolate any Oomycota species from our samples, the presence of mud and soil inside the holes and crevices of the degraded wood being imported indicates that this could be an avenue for various exotic *Phytophthora* to enter since they reside in aquatic and wet soil environments. Recommendations to people that purchase wood for aquariums are to repeatedly soak and rinse wood in water before putting the wood into an aquarium. This helps eliminate some of the heartwood extractives

Genus and species	Query Coverage	Max identity	Number of times isolated	Sample IDs	GenBank Number
Aleurodiscus formosanus	99%	99%	6	Spiderwood-142	PQ600598
Alternaria alternata	100%	100%	9	Spiderwood-71	PQ600599
Amyloporia xantha	100%	99%	2	Spiderwood-52	PQ600600
Annellophorella ellisii	100%	97%	1	Spiderwood-140	PQ600601
Annulohypoxylon stygium	100%	99%	1	Spiderwood-222	PQ600602
Apiospora intestini	100%	99%	2	Spiderwood-103	PQ600603
Aplosporella hesperidica	100%	100%	1	Spiderwood-193	PQ600604
Aspergillus fumigatus	100%	100%	1	Spiderwood-80	PQ600605
Aspergillus pachycaulis	100%	99%	3	Spiderwood-137	PQ600606
Aspergillus pseudoglaucus	100%	100%	2	Spiderwood-119	PQ600607
Aspergillus sclerotiorum	100%	99%	1	Spiderwood-169	PQ600608
Aspergillus versicolor	100%	100%	1	Spiderwood-191	PQ600609
Aureobasidium pullulans	100%	100%	1	Spiderwood-176	PQ600610
Campylocarpon fasciculare	100%	99%	3	Spiderwood-60	PQ600611
Chaetomella pseudocircinoseta	100%	99%	1	Spiderwood-63	PQ600612
Cladosporium cladosporioides	100%	100%	2	Spiderwood-69	PQ600613
Cladosporium pseudocladosporioides	100%	100%	1	Spiderwood-93	PQ600614
Cladosporium sphaerospermum	100%	100%	1	Spiderwood-30	PQ600615
Cladosporium tenuissimum	100%	100%	2	Spiderwood-62	PQ600616
Clonostachys rosea	100%	99%	1	Spiderwood-41	PQ600617
Coniochaeta luteorubra	100%	99%	3	Spiderwood-129	PQ600618
Coniophora hanoiensis	91%	94%	2	Spiderwood-207	PQ600619
Coniophora merulioides	100%	99%	2	Spiderwood-185	PQ600620
Coniothyrium palmicola	99%	98%	1	Spiderwood-148	PQ600621
Cordyceps farinosa	100%	99%	1	Spiderwood-183	PQ600622
Crepatura ellipsospora	100%	98%	1	Spiderwood-221	PQ600623
Cylindrocarpon olidum	100%	96%	1	Spiderwood-223	PQ600624
Cylindroconidiis aquaticus	72%	88%	1	Spiderwood-107	PQ600625
Daldinia eschscholtzii	100%	99%	1	Spiderwood-158	PQ600626
Diatrypella japonica	99%	98%	1	Spiderwood-61a	PQ600627
Distoseptispora longnanensis	68%	87%	1	Spiderwood-190	PQ600628
Ectophoma insulana	100%	100%	1	Spiderwood-144	PQ600629
Epicoccum nigrum	100%	100%	1	Spiderwood-131	PQ600630
Epicoccum sorghinum	100%	99%	2	Spiderwood-81	PQ600631
Epicoccum thailandicum	100%	99%	1	Spiderwood-101	PQ600632
Exophiala sideris	100%	99%	1	Spiderwood-99	PQ600633
Fomitopsis monomitica	99%	100%	1	Spiderwood-217	PQ600634
Fomitopsis hengduanebsis	100%	99%	1	Spiderwood-83b	PQ600635
Fusarium verticillioides	100%	100%	1	Spiderwood-42	PQ600636

Table 1. Top Blastn results for ITS rDNA region, percent similarity to sequences in the GenBank database and GenBank accession numbers for fungi isolated from Asian wood purchased in the United States and sold for use in aquariums. Ascomycota represented in yellow, Basidiomycota in blue, Mucoromycota in purple.

from the tropical woods and reduces water discoloration in aquariums and possible toxicity to fish and plants. Disposal of the water from this wood into the environment could easily release *Phytophthora* and also the fungal species that may be in the wood. Additional sampling and investigation using more selective methods of isolating *Phytophthora* species with baits and selective culture media is needed to determine if this could be a successful avenue for importing species of plant pathogenic Oomycota species.

The forests in Asia where this wood is being collected appears to be an area that has received little mycological study and is rich in undescribed taxa. Of the 123 different taxa identified in this study, 24 have ITS sequence matches of 97% or less to known fungi. This includes many wood decay fungi. An isolate most closely related to *Hawkworthiomyces* in the Ophiostomatales, is from a group that has been suggested to all have the capacity to decay wood and likely have an association with sapwood infecting insects[20]. Since many of the Ophiostomatales

Gelatinofungus brunneus	100%	98%	2	Spiderwood-126	PQ600637
Gymnopilus dilepis	100%	100%	1	Spiderwood-88	PQ600638
Gymnopilus igniculus	100%	99%	1	Spiderwood-98	PQ600639
Hawksworthiomyces crousii	92%	90%	1	Spiderwood-115	PQ600640
Heterophaeomoniella pinifoliorum	100%	84%	2	Spiderwood-162	PQ600641
Humicola homopilata	100%	99%	1	Spiderwood-159	PQ600642
Hymenochaete rubiginosa	100%	98%	3	Spiderwood-86	PQ600643
Hypoxylon commutatum	100%	100%	1	Spiderwood-181	PQ600644
Hypoxylon trugodes	100%	99%	1	Spiderwood-177	PQ600645
Hysterobrevium walvisbayicola	69%	89%	1	Spiderwood-154	PQ600646
Kirschsteiniothelia tectonae	98%	93%	1	Spiderwood-168	PQ600647
Knufia tsunedae	97%	99%	1	Spiderwood-9	PQ600648
Malbranchea ostraviensis	100%	98%	1	Spiderwood-117	PQ600649
Meyerozyma guilliermondii	100%	100%	1	Spiderwood-72	PQ600650
Microascus croci	100%	99%	1	Spiderwood-182	PQ600651
Moristroma germanicum	100%	91%	1	Spiderwood-20	PQ600652
Mucor janssenii	100%	100%	1	Spiderwood-195	PQ600653
Neoleptodontidium aciculare	97%	94%	1	Spiderwood-32	PQ600654
Neoleptodontidium aquaticum	96%	96%	4	Spiderwood-54a	PQ600655
Neonectria candida	100%	100%	1	Spiderwood-227	PQ600656
Neonothopanus nambi	100%	100%	6	Spiderwood-4	PQ600657
Paecilomyces dactylethromorphus	100%	100%	1	Spiderwood-197	PQ600658
Paecilomyces maximus	99%	100%	2	Spiderwood-43	PQ600659
Paecilomyces parvisporus	100%	100%	1	Spiderwood-147	PQ600660
Paecilomyces variotii	100%	100%	3	Spiderwood-74	PQ600661
Paraconiothyrium archidendri	100%	99%	1	Spiderwood-153	PQ600662
Paraconiothyrium hawaiiense	100%	100%	2	Spiderwood-83a	PQ600663
Paradictyoarthrinium hydei	100%	99%	1	Spiderwood-95	PQ600664
Penicillium amphipolaria	98%	100%	1	Spiderwood-114	PQ600665
Penicillium brefeldianum	100%	100%	1	Spiderwood-205	PQ600666
Penicillium cremeogriseum	100%	100%	1	Spiderwood-209	PQ600667
Penicillium expansum	100%	100%	1	Spiderwood-228	PQ600668
Penicillium glabrum	100%	100%	1	Spiderwood-175	PQ600669
Penicillium glaucoroseum	99%	100%	1	Spiderwood-151	PQ600670
Penicillium jensenii	100%	100%	1	Spiderwood-66	PQ600671
Penicillium mallochii	100%	100%	1	Spiderwood-40	PQ600672
Penicillium mexicanum	100%	100%	1	Spiderwood-77	PQ600673
Penicillium ochrochloron	100%	100%	1	Spiderwood-8	PQ600674
Penicillium ortum	100%	100%	1	Spiderwood-203	PQ600675
Peniophora albobadia	98%	98%	2	Spiderwood-38	PQ600676
Perenniporia meridionalis	100%	98%	2	Spiderwood-89	PQ600677

Figure 1. (continued)

are known tree pathogens, this exotic species introduced into the United States should remain suspect until proven otherwise. There also are what appear to be new species of *Coniophora* and *Pycnoporellus* which cause brown rot, several new species of *Phanerochaete* that cause white rot and possibly 2 new species of *Scytalidium*, a genus that is known to have species that cause soft rot in wood. The best blast match for one of the *Phanerochaete* species was *P. sordida*, which can be found in many countries including the United States, but the ITS sequence match to this species was only 94%. With such a low match it was considered a species not previously reported in the United States (Table 1; Fig. 1). This was also the case for *Terana caerulea* with only a 93% match to most known sequences for this fungus. This *Terana* is likely a new species and was listed as not present in the United States. The introduction of non-native species of wood decay fungi could impact the wood decay community, biomass degradation, and native wood inhabiting insects with potential to cause adverse effects on ecosystem functioning as demonstrated by the recently introduced fungus, *Flavodon ambrosius*[21,22]. Another example of an invasive decay fungus is the brown-rotter, *Serpula lacrymans*, with a natural range in Asia but it has been

Perenniporia tephropora	99%	100%	1	Spiderwood-91	PQ600678
Perenniporia truncatospora	100%	99%	2	Spiderwood-156	PQ600679
Phaeoacremonium scolyti	100%	99%	5	Spiderwood-18	PQ600680
Phanerochaete sordida	100%	94%	4	Spiderwood-69a	PQ600681
Phanerochaete sp.	100%	100%	1	Spiderwood-136	PQ600682
Phanerochaete stereoides	99%	95%	1	Spiderwood-70	PQ600683
Phanerodontia chrysosporium	100%	97%	3	Spiderwood-67	PQ600684
Phanerochaete concrescens	100%	99%	1	Spiderwood-208	PQ600685
Phlebia subserialis	100%	98%	1	Spiderwood-36	PQ600686
Phlebia tremellosa	100%	97%	1	Spiderwood-112	PQ600687
Phoma insulana	100%	100%	1	Spiderwood-170	PQ600688
Porostereum spadiceum	100%	99%	1	Spiderwood-184	PQ600689
Pseudoantrodia monomitica	99%	100%	3	Spiderwood-120	PQ600690
Pseudochaetosphaeronema martinelli	97%	94%	1	Spiderwood-39	PQ600691
Purpureocillium lilacinum	100%	99%	1	Spiderwood-145	PQ600692
Pycnoporellus fulgens	93%	86%	2	Spiderwood-215	PQ600693
Pygmaeomyces thomasii	93%	88%	1	Spiderwood-82a	PQ600694
Rasamsonia emersonii	97%	91%	1	Spiderwood-118	PQ600695
Roseograndinia minispora	100%	98%	2	Spiderwood-163	PQ600696
Scytalidium circinatum	100%	95%	1	Spiderwood-44	PQ600697
Scytalidium lignicola	100%	96%	2	Spiderwood-210	PQ600698
Stachybotrys chartarum	100%	100%	1	Spiderwood-178	PQ600699
Stagonosporopsis cucurbitacearum	100%	100%	5	Spiderwood-75a	PQ600700
Talaromyces aculeatus	100%	100%	3	Spiderwood-102	PQ600701
Talaromyces amestolkiae	100%	99%	2	Spiderwood-23	PQ600702
Talaromyces funiculosus	100%	100%	1	Spiderwood-174	PQ600703
Talaromyces muroii	100%	100%	1	Spiderwood-172	PQ600704
Talamycetes rotundus	98%	99%	1	Spiderwood-171	PQ600705
Talaromyces stollii	100%	100%	2	Spiderwood-3	PQ600706
Talaromyces striatoconidius	100%	99%	1	Spiderwood-113	PQ600707
Terana caerulea	100%	93%	6	Spiderwood-14	PQ600708
Thysanorea nonramosa	98%	98%	1	Spiderwood-164	PQ600709
Trichoderma asperellum	100%	100%	1	Spiderwood-202	PQ600710
Trichoderma hamatum	100%	99%	3	Spiderwood-25	PQ600711
Trichoderma harzianum	99%	97%	1	Spiderwood-192	PQ600712
Trichoderma koningiopsis	100%	100%	1	Spiderwood-198	PQ600713
Trichoderma longibrachiatum	100%	100%	1	Spiderwood-149	PQ600714
Umbelopsis isabellina	100%	99%	2	Spiderwood-111	PQ600715
Umbelopsis nana	100%	100%	4	Spiderwood-2	PQ600716
Xylaria adscendens	100%	98%	1	Spiderwood-186	PQ600717
Xylaria arbuscula	100%	99%	1	Spiderwood-94	PQ600718
Xylaria hypoxylon	98%	99%	1	Spiderwood-81a	PQ600719
Zalaria obscura	100%	99%	1	Spiderwood-180	PQ600720

Figure 1. (continued)

moved to other regions of the world where it has found a new niche causing timber decay in houses resulting in enormous economic losses[23,24]. A recent report has documented the introduction of *Xylaria apoda* in Minnesota and Colorado and its ability to grow in submerged aquarium wood[14]. Our study found several different species of *Xylaria* as well as several other fungi in the Xylariales. All these fungi have the capacity to cause wood decay and produce a soft rot type of degradation. Many of these fungi can survive adverse conditions, grow in woods that have decay resistance, and some soft rot fungi can colonize preservative treated wood[25]. This group of fungi also contains tree pathogens such as *Kretzschmaria deusta* that causes a serious root and butt rot of hardwoods and *Entoleuca mammata* that causes a canker disease of poplar[26]. These are all reasons we should be concerned about the importation of new species in this group.

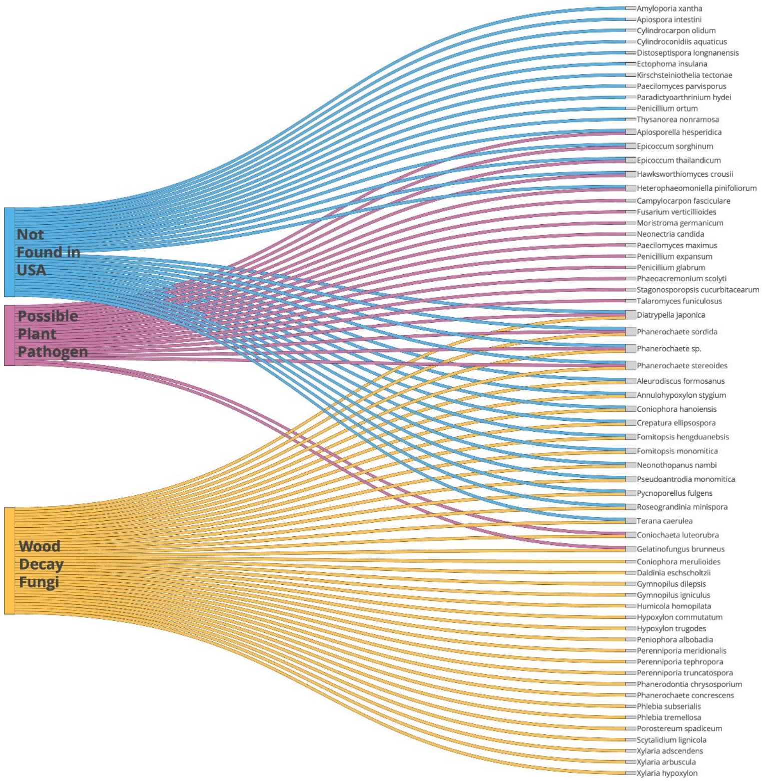

Fig. 3. Selected fungal taxa from isolates that were cultured from wood originating from Asia and sold for decoration in aquariums that are possible plant pathogens, wood decay fungi or have not been documented in the United States. Several taxa are represented in more than one category.

The results presented here indicate that current regulations to prevent the importation of non-native fungi on decorative woods used in aquariums are ineffective. In this investigation alone, over 100 different live taxa were cultured and the risk of new exotic invasive species that could become naturalized is significant. New strategies for fumigation and sterilization treatment are needed that will be effective on high density, extractive rich tropical woods to close this pathway of fungal and fungal-like organism introductions. Better phytosanitary regulations on imported wood have been repeatedly suggested[8,27] and the results presented here reinforce the need for improved regulations that would prevent new introductions that could have catastrophic effects on our natural resources and ecosystem functioning. A global strategy to combat the introduction of exotic fungi with the potential to become devastating plant and animal diseases has been suggested many times[4,10,28]. An important way to deal with this problem is to improve biosurveillance on a global scale. The biosurveillance study presented here has revealed a previously unknown avenue where many fungi are being moved between continents. Taking action to stop the importation of these fungi and fungal-like organisms before they become serious problems in their new environment is essential.

Materials and methods

Decorative wood labelled as 'spiderwood' and 'driftwood' was purchased from online vendors Amazon.com and Temu.com. All the wood received appeared dry and wrapped in plastic. Although the exact location where the wood was collected is not known, the vendors address suggested China, Vietnam, Thailand, and possible other Asian countries. Once received, wood segments were cut from the samples and placed in different types of media including i) Malt extract agar (MEA) with antibiotics (15 g malt extract 15 g agar in 1000 ml distilled water amended with 0.1 g/L streptomycin sulphate added after autoclaving ii) a semi selective media for Basidiomycota (15 g of malt extract, 15 g of agar, 2 g of yeast extract, 0.06 g of Benlomyl with 0.1 g of streptomycin sulfate, and 2 ml of lactic acid added after autoclaving) and iii) PARPH, a *Phytophthora* selective culture media [950 ml deionized water, 50 ml clarified V8 juice and 15 g of Difco Agar and autoclaved for 30 min and allowed to cool to 50 °C. Then 5 ml of PCNB (pentachloronitrobenzene), 1 ml rifampicin (dissolved in methanol) and 50 mg of hymexazol were added.] These types of culture media were used because of previous success in investigations to obtain diverse fungal taxa from wood[29–32]. Plates were incubated at 22 °C and once growth appeared, pure cultures were transferred to additional MEA plates. Isolates of pure cultures were then used for DNA extraction and sequencing. Cultures are stored in the University of Minnesota Forest Pathology culture collection in the Department of Plant Pathology.

Identification of fungal cultures was done by extracting DNA from pure cultures grown on petri plates using a PrepMan™ Ultra sample preparation reagent according to manufactures' protocol. The internal transcribed spacer gene region (ITS) was amplified using primers ITS1F and ITS4[33]. PCR was carried out in 25 µl reactions which contained ~ 12ng of DNA template, 0.25 µM forward primer, 0.25 µM reverse primer, 2.5 µg/µL BSA, 1X GoTaq® green mastermix and 9 µl nuclease free sterile water. Thermocycler program parameters for amplification were: 95 °C for 3 min, followed by 35 cycles of 95 °C for 1 min, 62 °C 45 s (-1 °C /cycle for 10 cycles, and then 52 °C for remaining 25 cycles), and 72 °C for 45 s and a final extension at 72 °C for 5 min. Amplicons were verified by electrophoresis on a 1% agarose gel with SYBR green 1 pre-stain and imaged with a Dark Reader DR45 (Clare Chemical Research–Denver, CO). Sanger sequencing was done with PCR primers on an ABI 3730xl DNA sequencer (Applied Biosystems–Foster City, CA). Consensus sequences were assembled using Geneious 9.0[34] and were used with the BLASTn program[35] using the megablast option in GenBank. Identification of cultures was based on the highest BLAST match score of a genus-species accession from a taxonomic study. Sequences representative of each taxon obtained were deposited in GenBank and are listed in Table 1. For each of the taxa, the biogeography was assessed using multiple sources, including both Index Fungorum and Mycobank, as well as the U.S. National Fungus Collections Nomenclature Database (https://nt.ars-grin.gov), the National Center for Biotechnology Information life-map tree database (http://lifemap-ncbi.univ-lyon1.fr/), and the Global Biodiversity Information Facility (GBIF; https://www.gbif.org).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 27 November 2024; Accepted: 14 March 2025
Published online: 17 March 2025

References

1. Bonello, P. et al. Invasive tree pests devastate ecosystems—A proposed new response framework. *Front. Glob. Change* **3**, 2 (2020).
2. Boyd, I. L., Freer-Smith, P. H., Gilligan, C. A. & Godfray, H. C. J. The consequence of tree pests and diseases for ecosystem services. *Science* **342**, 1235773 (2013).
3. Ghelardini, L. et al. Ecology of invasive forest pathogens. *Biol. Invasions* **19**, 3183–3200 (2017).
4. Lovett, G. M. et al. Nonnative forest insects and pathogens in the United States: Impacts and policy options. *Ecol. Appl.* **26**, 1437–1455 (2016).
5. Williams, G. M. et al. The global forest health crisis: A public-good social dilemma in need of international collective action. *Annu. Rev. Phytopathol.* **61**, 377–401 (2023).
6. Anagnostakis, S. L., Chestnut & Blight The classical problem of an introduced pathogen. *Mycologia* **79**, 23–37 (1987).
7. Fisher, M. C. et al. Threats posed by the fungal kingdom to humans, wildlife, and agriculture. *mBio* 11, e00449 (2020).
8. Smith, J. A., Quesada, T., Alake, G. & Anger, N. Transcontinental dispersal of nonendemic fungal pathogens through wooden handicraft imports. *mBio* **13**, e01075 (2022).
9. Brasier, C. M. The biosecurity threat to the UK and global environment from international trade in plants. *Plant Pathol.* **57**, 792–808 (2008).
10. Wingfield, M. J., Brockerhoff, E. G., Wingfield, B. D. & Slippers, B. Planted forest health: The need for a global strategy. *Science* **349**, 832–836 (2015).
11. Brasier, C. M., Vettraino, A. M., Chang, T. T. & Vannini, A. *Phytophthora lateralis* discovered in an old growth *Chamaecyparis* forest in Taiwan. *Plant. Pathol.* **59**, 595–603 (2010).
12. Jung, T. et al. The destructive tree pathogen *Phytophthora ramorum* originates from the Laurosilva forests of East Asia. *J. Fungi* **7**, 226 (2021).
13. Jung, T. et al. A survey in natural forest ecosystems of Vietnam reveals high diversity of both new and described *Phytophthora* taxa including *P. ramorum*. *Forests* **11**, 93 (2020).
14. Blanchette, R. A., Rajtar, N. N., Yandrasits, H., Cassidy Stephens, K. & Held, B. W. Aquatic *Xylaria*: An exotic fungus introduced into the United States on aquarium decorative wood. *Mycologia* **117**, 213-221 (2025).
15. Brasier, C. M. China and the origins of Dutch elm disease: An appraisal. *Plant. Pathol.* **39**, 5–16 (1990).
16. Harrington, T. C. et al. Isolations from the Redbay ambrosia beetle, *Xyleborus glabratus*, confirm that the Laurel wilt pathogen, *Raffaelea lauricola*, originated in Asia. *Mycologia* **103**, 1028–1036 (2011).
17. Hummer, K. E. History of the origin and dispersal of white pine blister rust. *Horttech* **10**, 515–517 (2000).
18. May, C. Outbreaks of the Dutch elm disease in the United States. Circular No. 322 from the U.S. Dept. of Agriculture (1934).
19. Jung, T. et al. Worldwide forest surveys reveal forty-three new species in *Phytophthora* major clade 2 with fundamental implications for the evolution and biogeography of the genus and global plant biosecurity. *Stud. Mycol.* **107**, 251-388 (2024).
20. De Beer, Z. W. et al. *Hawksworthiomyces* gen. nov. (*Ophiostomatales*), illustrates the urgency for a decision on how to name novel taxa known only from environmental nucleic acid sequences (ENAS). *Fungal Biol.* **120**, 1323–1340 (2016).
21. Hulcr, J. et al. Invasion of an inconspicuous ambrosia beetle and fungus may affect wood decay in southeastern North America. *Biol. Invasions* **23**, 1339–1347 (2021).
22. Skelton, J. et al. Fungal symbionts of bark and ambrosia beetles can suppress decomposition of pine sapwood by competing with wood-decay fungi. *Fungal Ecol.* **45**, 100926 (2020).
23. Hess, J. et al. Niche differentiation and evolution of the wood decay machinery in the invasive fungus *Serpula lacrymans*. *ISME J.* **15**, 592–604 (2021).
24. Kauserud, H. et al. Asian origin and rapid global spread of the destructive dry rot fungus *Serpula lacrymans*. *Mol. Ecol.* **16**, 3350–3360 (2007).
25. Rajtar, N. N. et al. Diverse *Xylaria* in the Ecuadorian Amazon and their mode of wood degradation. *Bot. Stud.* **64**, 30 (2023).
26. Sinclair, W. A. & Lyon, H. H. *Diseases of Trees and Shrubs* (Comstock Pub. Associates, 2005).
27. Roy, B. A. et al. Increasing forest loss worldwide from invasive pests requires new trade regulations. *Front. Ecol. Environ.* **12**, 457–465 (2014).
28. Hantula, J., Müller, M. M. & Uusivuori, J. International plant trade associated risks: Laissez-faire or novel solutions. *Environ. Sci.* **37**, 158–160 (2014).
29. Blanchette, R. A., Held, B. W., Hellmann, L., Millman, L. & Büntgen, U. Arctic driftwood reveals unexpectedly rich fungal diversity. *Fungal Ecol.* **23**, 58–65 (2016).
30. Blanchette, R. A., Held, B. W., Jurgens, J., Stear, A. & Dupont, C. Fungi attacking historic wood of Fort Conger and the Peary Huts in the High Arctic. *PLoS ONE* **16**, e0246049 (2021).
31. Held, B. W., Salomon, C. E. & Blanchette, R. A. Diverse subterranean fungi of an underground iron ore mine. *PLoS ONE* **15**, e0234208 (2020).

32. Otto, E. C., Held, B. W., Gould, T. J. & Blanchette, R. A. Fungal diversity in multiple post-harvest aged red pine stumps and their potential influence on heterobasidion root rot in managed stands across Minnesota. *Front. Fungal Biol.* **2**, 782181 (2021).
33. Gardes, M. & Bruns, T. D. ITS primers with enhanced specificity for basidiomycetes–application to the identification of mycorrhizae and rusts. *Mol. Ecol.* **2**, 113–118 (1993).
34. Kearse, M. et al. Geneious basic: An integrated and extendable desktop software platform for the organization and analysis of sequence data. *Bioinformatics* **28**, 1647–1649 (2012).
35. Zhang, Z., Schwartz, S., Wagner, L. & Miller, W. A greedy algorithm for aligning DNA sequences. *J. Comput. Biol.* **7**, 203–214 (2000).

Acknowledgements
The authors thank Henry Yandrasits for alerting us about the unusual fungi growing on wood in his aquarium andTy Flanagan for assistance in the laboratory. Funding was provided in part by the Environment and Natural Resources Trust Fund, Minnesota Invasive Terrestrial Plants and Pests Center for project: Biosurveillance of invasive pathogens of woody plants in Minnesota, and USDA Hatch Project MIN22-089.

Author contributions
R.A.B. planned the research and sampling. R.A.B., N.N.R., A.L. and B.W.H. performed laboratory work and analyzed the data. RAB led the manuscript drafting with contributions from all authors. R.A.B., N.N.R. and B.W.H. prepared the figures and tables. All authors reviewed the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to R.A.B.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.