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FEAR OF FUNGI

Emerging pathogens threaten natural ecosystems and food security **PAGE 186**



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PAGE 155



FICTION

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Michael Frayn on science, farce and uncertainty

PAGE 163

INNOVATION

SCIENCE MEANS BUSINESS

Getting to grips with technology transfer

PAGE 2XX

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Emerging fungal threats to animal, plant and ecosystem health

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The past two decades have seen an increasing number of virulent infectious diseases in natural populations and managed landscapes. In both animals and plants, an unprecedented number of fungal and fungal-like diseases have recently caused some of the most severe die-offs and extinctions ever witnessed in wild species, and are jeopardizing food security. Human activity is intensifying fungal disease dispersal by modifying natural environments and thus creating new opportunities for evolution. We argue that nascent fungal infections will cause increasing attrition of biodiversity, with wider implications for human and ecosystem health, unless steps are taken to tighten biosecurity worldwide.

Emerging infectious diseases (EIDs) caused by fungi are increasingly recognized as presenting a worldwide threat to food security^{1,2} (Table 1 and Supplementary Table 1). This is not a new problem and fungi have long been known to constitute a widespread threat to plant species. Plant disease epidemics caused by fungi and the fungal-like oomycetes have altered the course of human history. In the nineteenth century, late blight led to starvation, economic ruin and the downfall of the English government during the Irish potato famine and, in the twentieth century, Dutch elm blight and chestnut blight laid bare urban and forest landscapes. The threat of plant disease has not abated, in fact it is heightened by resource-rich farming practices and exaggerated in the landscape by microbial adaptation to new ecosystems, brought about by trade and transportation³, and by climate fluctuations^{4,5}.

However, pathogenic fungi (also known as mycoses) have not been widely recognized as posing major threats to animal health. This perception is changing rapidly owing to the recent occurrence of several high-profile declines in wildlife caused by the emergence of previously unknown fungi^{6,7}. For example, during March 2007, a routine census of bats hibernating in New York State revealed mass mortalities⁸. Within a group of closely clustered caves, four species of bats were marked by a striking fungus growing on their muzzles and wing membranes, and the name 'white nose syndrome' (WNS) was coined. After the initial outbreak, the ascomycete fungus *Geomyces destructans* was shown to fulfil Koch's postulates and was described as the cause of WNS in American bat species^{9,10}. Mortalities exhibiting WNS have subsequently been found in an increasing number of bat overwintering sites and, by 2010, the infection was confirmed to have emerged in at least 115 roosts across the United States and Canada, spanning over 1,200 km (ref. 11). Bat numbers across affected sites have declined by over 70% and analyses have shown that at least one affected species, the little brown bat *Myotis lucifugus*, has a greater than 99% chance of becoming locally extinct within the next 16 years (ref. 11). Other species of bats across this region are declining as a consequence of this infection, and the prognosis for their survival and their role in supporting healthy ecosystems, is poor¹².

Cases of this sort are no longer perceived to be atypical. The probability of extinction is increasing for some species of North American bats, but another fungal infection has caused the greatest disease-driven loss of biodiversity ever documented. The skin-infecting amphibian fungus

Batrachochytrium dendrobatidis was discovered in 1997 (ref. 13) and named in 1999 (ref. 14). *B. dendrobatidis* has been shown to infect over 500 species of amphibians in 54 countries, on all continents where amphibians are found^{15,16}, and is highly pathogenic across a wide diversity of species. Studies using preserved amphibian specimens showed that the first appearance of *B. dendrobatidis* in the Americas coincided with a wave of population declines that began in southern Mexico in the 1970s and proceeded through Central America to reach the Panamanian isthmus in 2007 (ref. 17). As a consequence of the infection, some areas of central America have lost over 40% of their amphibian species¹⁸, a loss that has resulted in measurable ecosystem-level changes¹⁹. This spatiotemporal pattern has been broadly mirrored in other continents¹⁵, and ongoing reductions in amphibian diversity owing to chytridiomycosis have contributed to nearly half of all amphibian species being in decline worldwide²⁰.




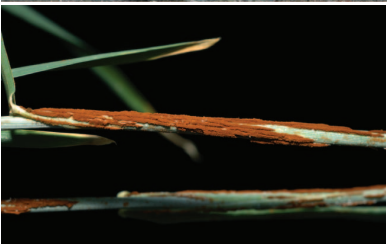
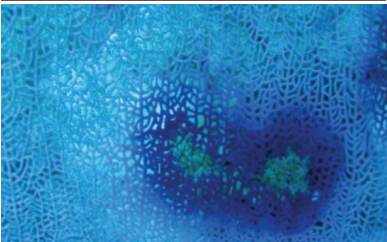


Fungal infections causing widespread population declines are not limited to crops, bats and frogs; studies show that they are emerging as pathogens across diverse taxa (Table 1), including soft corals (for example, sea-fan aspergillosis caused by *Aspergillus sydowii*)²¹, bees (the microsporidian fungus *Nosema* sp. associated with colony collapse disorder)²², and as human and wildlife pathogens in previously non-endemic regions (for example, the emergent virulent VGII lineage of *Cryptococcus gattii* in the northwest America²³ and *Cryptococcus neoformans* across southeast Asia²⁴). The oomycetes have life histories similar to those of fungi and are also emerging as aggressive pathogens of animals, causing declines in freshwater brown crayfish (for example, the crayfish plague caused by *Aphanomyces astaci*)²⁵, Tilapia fish (for example, epizootic ulcerative syndrome caused by *A. invadans*)²⁶ and many species of plants^{27,28}. Although the direct causal relationship is uncertain in some of these diverse host-pathogen relationships, it seems that pathogenic fungi are having a pronounced effect on the global biota¹.

Increasing risk of biodiversity loss by Fungi

For infectious disease systems, theory predicts that pathogens will co-evolve with, rather than extirpate, their hosts^{29,30}. Such evolutionary dynamics mirror population-level processes in which density dependence leads to the loss of pathogens before their hosts are driven extinct³¹. For these reasons, infection has not been widely acknowledged as an

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Table 1 | Major fungal organisms posing threats to animal and plant species.

	Host	Pathogen (Phylum)	Disease dynamics leading to mass mortality in animal and plant hosts
	Amphibian species (for example, the common midwife toad, <i>Alytes obstetricans</i>)	<i>Batrachochytrium dendrobatidis</i> (Chytridiomycota)	Worldwide dispersal of a hypervirulent lineage by trade ⁶⁴ . Ultra-generalist pathogen manifesting spillover between tolerant/susceptible species. Extent of chytridiomycosis is dependent on biotic and abiotic context ^{15,82} .
	Rice (<i>Oryza sativa</i>); <i>Magnaporthe grisea</i> species complex on 50 grass and sedge species, including wheat and barley	<i>Magnaporthe oryzae</i> (Ascomycota)	Rice blast disease in 85 countries, causing 10–35% loss of harvest. Global blast population structure determined by deployment of seeds with inbred race-specific disease resistance (RSR). Invasions occur by 'host hops' and altered pathogen demographics.
	Bat spp. (little brown bats, <i>Myotis lucifugus</i>)	<i>Geomyces destructans</i> (Ascomycota)	New invasion of North American bat roosts occurred in approximately 2006, and disease is spreading rapidly ⁸ . Pathogen reservoir may exist in cave soil. Disease is more aggressive compared to similar infections in European bats, possibly owing to differences in roosts and host life histories ⁶⁵ .
	Wheat (<i>Triticum aestivum</i>); 28 <i>Puccinia graminis</i> f. <i>tritici</i> species, but <i>P. graminis</i> is found on 365 cereal or grass species	<i>Puccinia graminis</i> (Basidiomycota)	Wheat stem rust is present on six continents. Population structure is determined by deployment of RSR cultivars and long-distance spread of aeciospores. Strain Ug99 poses a notable threat to resistant wheat varieties, causing up to 100% crop loss.
	Coral species (for example, the sea fan, <i>Gorgonia ventalina</i>)	<i>Aspergillus sydowii</i> (Ascomycota)	Sea-fan aspergillosis caused by a common terrestrial soil fungus ^{21,86} . Epizootics are associated with warm-temperature anomalies. Coral immunosuppression is probably a factor causing decline.
	Bee species (for example, the hive of the domestic honeybee (<i>Apis mellifera</i>) suffering colony collapse disorder)	<i>Nosema</i> species (Microsporidia)	Microsporidian fungal infections are associated with colony collapse disorder and declining populations. Pathogen prevalence is probably a part of a multifactorial phenomenon that includes environmental stressors and polyparasitism ^{87,88} .
	Sea turtle species (the loggerhead turtle, <i>Caretta caretta</i>)	<i>Fusarium solani</i> (Ascomycota)	Soil-dwelling saprotroph and phytopathogenic fungus. Infection causes hatch failure in loggerhead turtle nests and suboptimal juveniles ⁴⁴ . The disease dynamics fulfil Koch's postulates. Environmental forcing is suspected but not proven.

Images in Table 1, with permission: *A. obstetricans* chytridiomycosis mortalities, M.C.F.; *M. oryzae*, N. Talbot; WNS-affected little brown bats, A. Hicks; *P. graminis*, R. Mago; *G. ventalina* infected with *A. sydowii*, D. Harvell; *A. mellifera* hive suffering from colony collapse disorder, J. Evans; sea turtle eggs infected with *F. solani*, J. Diéguez-Urbeondo and A. Marco.

extinction mechanism owing to such intrinsic theoretical biotic limitations³². Inspection of species conservation databases would seem to confirm this idea. The International Union for Conservation of Nature (IUCN) red list database details threats to species worldwide, and analysis of the database has shown that of the 833 recorded species extinctions, less than 4% (31 species) were ascribed to infectious disease⁷. Ecological studies on host–pathogen relationships support this finding by showing that lower parasite richness occurs in threatened host species, suggesting that parasite decline and ‘fade out’ occurs when hosts become rare³³. Therefore, given that macroevolutionary and ecological processes should promote diversity and prevent infectious diseases from driving their host species to extinction, we posed the question of whether we are witnessing increasing disease and extinction events driven by fungi on an increasingly large scale, or, alternatively, if there is evidence that a reporting bias has skewed our opinion of the current level of threat.

EIDs are those pathogens that are increasing in their incidence, geographic or host range, and virulence^{34,35}. Current attempts to detect EID events centre on capturing changes in the patterns of disease alerts recorded by disease monitoring programmes. ProMED (the Program for Monitoring Emerging Diseases; <http://www.promedmail.org>) and HealthMap (<http://healthmap.org>) have two approaches for detecting and monitoring outbreaks worldwide in plant and animal hosts: first, by active reporting of disease outbreaks, and second, by capturing diverse online data sources. To ascertain whether there are changing patterns of fungal disease, we reviewed all disease alerts in ProMED (1994–2010) and HealthMap (2006–10) for combinations of search terms to catalogue fungal alerts. We then classified these according to their relative proportion against the total number of disease alerts, and discriminated between plant- or animal-associated fungal pathogens (Supplementary Table 2). We also searched the primary research literature for reports in which EIDs have caused host extinction events, either at the regional scale (extirpations) or globally (Supplementary Table 3). These analyses show a number of positive trends associated with infectious fungi. Overall, fungal alerts comprise 3.5% of the ~38,000 ProMED records screened. However, over the period from 1995 to 2010, the relative proportion of fungal alerts increased in the ProMED database from 1% to 7% of the database total (Fig. 1a and Supplementary Table 2). This trend is observed for both plant-infecting (0.4% to 5.4%) and animal-infecting (0.5% to 1.4%) fungi. HealthMap shows a recent (2007–11) positive trend in the proportion of records of fungi infecting animals (0.1% to 0.3%) and plants (0.1 to 0.2%), and fungal disease alerts

were shown to occur worldwide (Fig. 1b). Web of Science literature searches and compilation of previous meta-analyses of infection-related species extinction and regional extirpation events show that fungi comprise the highest threat for both animal-host (72%) and plant-host (64%) species (Fig. 1c and Supplementary Tables 3 and 4). This effect is more pronounced for animal hosts (39 animal species affected versus 4 plant species); moreover, there is a notable increase in host loss during the second half of the twentieth century, driven mainly by the emergence of *B. dendrobatidis* (Fig. 1d). This effect is moderated after correcting for mass-species loss in regions of high epizootic loss (such as the mass extirpations of amphibians in Central America). However, fungi remain the major cause (65%) of pathogen-driven host loss after this correction. Our estimates are probably conservative owing to the cryptic nature of most disease-driven species impacts. For example, the lack of disease-related IUCN red list records is due to a lack of baseline data on the incidence of pathogens in natural systems compounded by inadequate disease diagnostics, reporting protocols and a lack of centralized recording mechanisms. Hence, the true numbers of extinctions and extirpations caused by fungi and oomycetes are likely to be greater as we have not been able to categorize the probably high levels of species loss in major plant (such as the *Phytophthora* dieback in Australia caused by *Phytophthora cinnamomi*; Supplementary Table 3) or animal outbreaks (for example, the effects of *B. dendrobatidis* emergence in the American wet tropics). We cannot discount the idea that sampling bias owing to increasing awareness of pathogenic fungi as EIDs may contribute to the patterns that we document. However, because of our observation that increases in the amount of disease caused by fungi are seen across many sources of data, including disease alerts, the peer-reviewed literature and previously noted patterns in human fungal EIDs³⁵, we believe that these trends are real. Therefore, the answer to our question seems to be that the data do indeed support the idea that fungi pose a greater threat to plant and animal biodiversity relative to other taxonomic classes of pathogen and hosts, and that this threat is increasing.

Fungal–disease dynamics leading to host extinction

Here we illustrate several key biological features of fungi that contribute to the epidemiological dynamics underlying contemporary increases in disease emergence and host extinction (Box 1).

High virulence

Fungi, like some bacterial and viral infections, can be highly lethal to naive hosts with rates of mortality approaching 100% (for example,

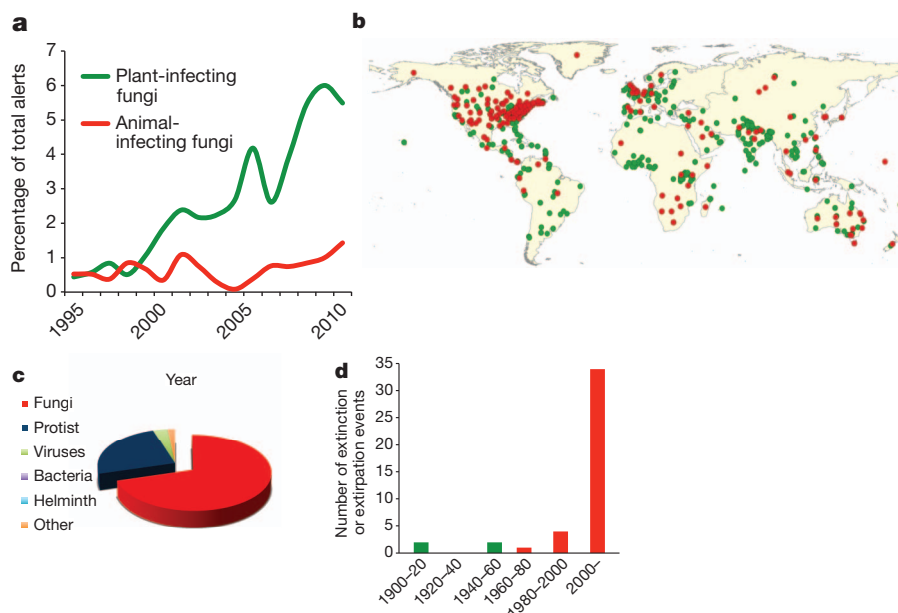


Figure 1 | Worldwide reporting trends in fungal EIDs. **a, b**, Disease alerts in the ProMED database for pathogenic fungi of animals and plants (**a**), and the spatial location of the associated reports (**b**). **c, d**, Relative proportions of species extinction and/or extirpation events for major classes of infectious disease agents (**c**) and their temporal trends for fungal pathogens (**d**). Primary data sources are given in the Supplementary Information.

BOX 1

Modelling host extinctions caused by pathogenic fungi

A simple susceptible–infected model shows that the presence of a threshold host population size for disease persistence does not prevent host extinction during a disease outbreak, especially in cases in which a lethal pathogen invades a large host population. In a large host population transmission is rapid and all hosts can become infected before the host population is suppressed below the threshold. The model follows the dynamics of susceptible (S) and infected (I) hosts during the short time duration of an epidemic (deaths that are not due to disease, and births, are ignored): $dS/dt = -\beta SI$; $dI/dt = \beta SI - \alpha I$, where β is the pathogen transmission rate, and α is the disease-induced death rate. For the parameters shown in Fig. 2a, the threshold population size below which the pathogen has a negative growth rate is $N_T = 20$ individuals. Figure 2a shows that large host populations are rapidly driven extinct, but only a fraction of individuals are killed in small host populations.

Pathogens with a long-lived infectious stage have an increased potential to cause host extinction. In this model, the disease is transmitted through contact between susceptible hosts and free-living infectious spores (Z), resulting in infected hosts, I : $dS/dt = -\beta SZ$; $dI/dt = \beta SZ - \alpha I$; $dZ/dt = \phi I - \mu Z - \beta NZ$, where β is the transmission rate, α is the pathogen-induced death rate and ϕ is the rate of release of spores from infected hosts. Figure 2b shows that fraction of hosts killed in a disease outbreak increases with the duration of the free-living infectious spore stage ($1/\mu$, where μ is the spore mortality rate).

Saprophytic growth by a pathogen can lead to extinction of the host, and even allow the pathogen to persist in the absence of its host. In this model, free-living infectious spores are released from infected hosts (with rate ϕ), and can increase in abundance through saprophytic growth, with rate σ . To illustrate the effects of saprophytic pathogen growth on host and pathogen equilibria (Fig. 2c), density-independent host reproduction (with rate b), density-dependent host mortality (with rate $d_0 + d_1 N$, where $N = S + I$), and density-dependent spore mortalities (at rate $\mu_0 + \mu_1 Z$) were included: $dS/dt = bN - (d_0 + d_1 N)S - \beta SZ$; $dI/dt = \beta SZ - \alpha I - (d_0 + d_1 N)I$; $dZ/dt = \phi I + \sigma Z - (\mu_0 + \mu_1 Z)Z - \beta NZ$.

The presence of a tolerant host species can lead to the extinction of a susceptible host species. In this model, species A is the tolerant host species, which can become infected and shed infectious spores but does not die as a result of the disease, whereas the susceptible host species (species B) has a disease-induced per-capita mortality rate of α_B . Figure 2d shows that species B is driven extinct at high densities of species A. $dS_A/dt = b_A N_A - (d_{A0} + d_{A1} N_A)S_A - \beta_A S_A Z$; $dI_A/dt = \beta_A S_A Z - (d_{A0} + d_{A1} N_A)I_A$; $dS_B/dt = b_B N_A - (d_{B0} + d_{B1} N_B)S_B - \beta_B S_B Z$; $dI_B/dt = \beta_B S_B Z - (d_{B0} + d_{B1} N_B)I_B - \alpha_B I_B$; $dZ/dt = \phi_A I_A + \phi_B I_B - \mu Z - \beta_A N_A Z - \beta_B N_B Z$, where all parameters are as previously defined, but with the subscripts A or B referring to host species A or B, respectively.

B. dendrobatidis in amphibians, *G. destructans* in bats and *Ophiostoma ulmi* in elm trees). Virulence is a measure of the relative capacity of a microbe to cause damage to a host³⁶, and high virulence is associated with rapid intra-host growth rates, ultimately leading to rapid inter-host transmission^{37,38}. Fungi have a high reproductive potential and in a large host population this effect can result in all individuals becoming infected before the population is driven to the low densities at which the pathogen can no longer spread (Fig. 2a). Thus, host extirpation can occur before density dependence limits the rate of transmission, a feature that has contributed to the mass extirpations seen in frog populations across the US Sierra Nevada mountains³⁹. Similarly, even if the pathogen does not drive the host to complete extinction, it may severely reduce the

population size to the point at which the species is vulnerable owing to catastrophic collapses as a result of stochastic³² or Allee effects⁴⁰.

Long-lived environmental stages

Fungi have remarkably resilient dispersal stages (a feature that they share with some spore-forming bacteria, such as *Bacillus anthracis*). The ability to survive independently outside of their host, as a free-living saprophyte or as durable spores in the environment, is probably the most important feature in driving the emergence of pathogenic fungi, owing to an increased risk of transporting the inocula to naive hosts (Fig. 2b)⁴¹. Furthermore, pathogenic fungi with a saprophytic stage (called sapronoses; Fig. 2c) can lead to host extirpation because their growth rate is decoupled from host densities and many fungal diseases threatening natural populations are caused by opportunistic fungi with long-lived environmental stages. Many fungi in the phylum Ascomycota are common soil organisms and are tolerant of salinity with the consequence that, when they enter the marine system through freshwater drainage, they are able to infect susceptible hosts such as corals (*A. sydowii*⁴²), sea otters (*Coccidioides immitis*⁴³) and the nests of loggerhead turtles (*Fusarium solani*⁴⁴). In terrestrial environments, potentially lethal fungi are ubiquitous, such as the causative agent of aspergillosis, *Aspergillus fumigatus*, and soil surveys have shown that *Geomyces* spp. are common soil organisms. Viable *G. destructans* has been recovered from the soil of infected bat caves⁴⁵, showing that the pathogen is able to survive and persist in infected roosts when the bats are absent. Likewise, long-term persistence of fungal inoculum in the agricultural landscape is achieved by quiescent survival on plant debris, such as the spores of wheat stem rust (*Puccinia graminis*), which overwinter on straw stubble before infecting a secondary host.

Generalist pathogens and opportunistic pathogens

Although many fungi demonstrate extreme host specialization, exemplified by the gene-for-gene interactions between biotrophic fungi and their plant hosts, broad host ranges twinned with high virulence can be a lethal combination. Fungi exhibit the broadest spectrum of host ranges for any group of pathogens, and *B. dendrobatidis* and the oomycete *Phytophthora ramorum* (the cause of sudden oak death and ramorum blight) are known to infect 508 (ref. 16) and 109 (ref. 3) host species, respectively. Different host species vary in their susceptibility to infection and these differences create the potential for parasite-mediated competition when the pathogens concerned are generalists⁴⁶. Host species that can tolerate high infection loads while serving as a source of infectious stages (known as pathogen spill-over) act as community ‘super spreaders’ by maintaining persistent infectious stages in the system (Fig. 2d). Invasive North American signal crayfish, which tolerate infection by the oomycete *A. astaci*, force the infection into more susceptible European species that then decline²⁵, and similarly, although *P. ramorum* is deadly to *Notholithocarpus densiflorus* (tanoak) and several *Quercus* species⁴⁷, many of its other hosts survive infection but generate inoculum themselves for new infections. Furthermore, disease-tolerant life-history stages of otherwise susceptible species can maintain high pathogen levels leading to extinction dynamics. In chytridiomycosis, the long-lived multi-year tadpole stages of amphibians such as the mountain yellow-legged frog *Rana muscosa* and the midwife toad *Alytes obstetricans* are not killed by chytrid infections, but they can build up high loads of *B. dendrobatidis* that can infect and overwhelm juvenile metamorphs of the same species, leading to rapid population loss³⁹. Ultimately, when host-generalist pathogens manifest long-lived environmental stages, conditions may occur that lead to long-distance dispersal and infection of naive hosts and environments⁵.

Trade and transport promotes globalization of fungi

Fungi comprise most of the viable biomass in the air, with an average human breath containing between one and ten fungal spores⁴⁸. This ability of fungi to disperse results in some species with cosmopolitan distributions^{5,49,50}. However, these species are in the minority and it is noticeable that few fungi exhibit truly globally distributions; instead they

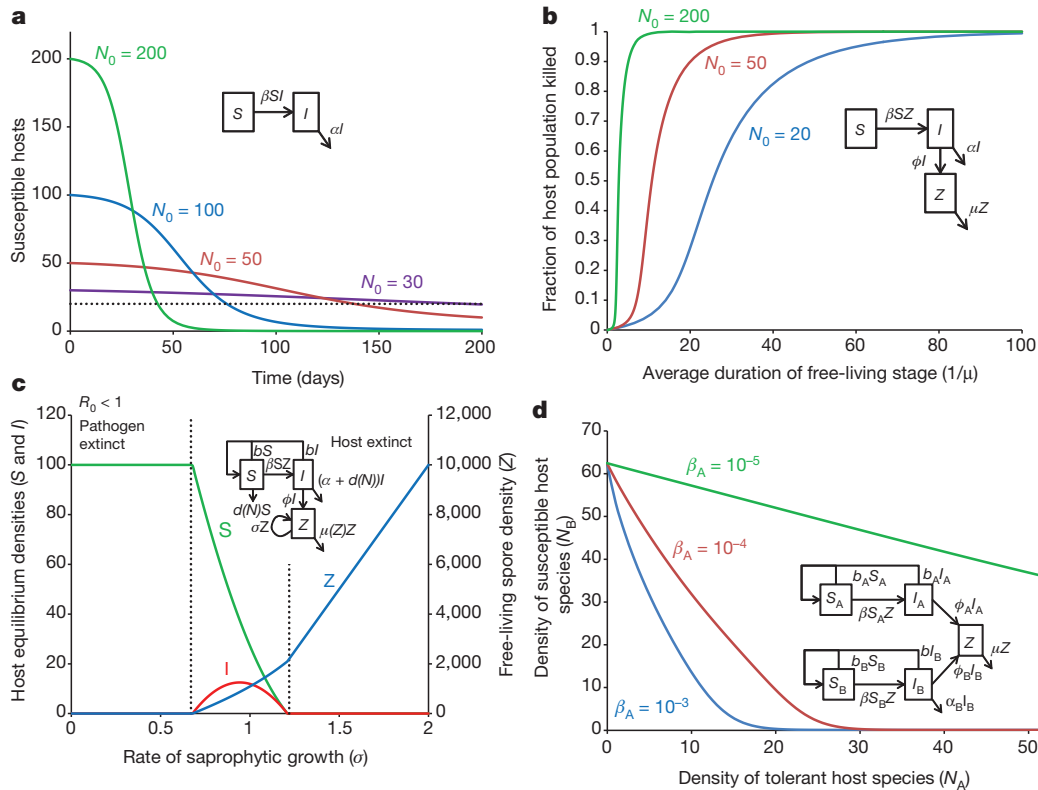


Figure 2 | Fungal disease dynamics leading to host extinction. **a**, The presence of a threshold host population size for disease persistence does not prevent host extinction during a disease outbreak, especially in cases in which a lethal pathogen invades a large host population. In a large host population transmission is rapid and all hosts can become infected before the host population is spread below the threshold (pathogen transmission rate, $\beta = 0.001$ per individual per day; disease induced-death rate, $\alpha = 0.02$ per day; simulations start with one infected individual and N_0 susceptible individuals). **b**, Long-lived infectious stages can increase the potential for host extinction. The fraction of hosts killed in a disease outbreak is shown as a function of the duration of the free-living infectious spore stage (pathogen transmission rate, $\beta = 5 \times 10^{-6}$; disease-induced death rate, $\alpha = 0.02$; rate of release of spores from infected hosts, $\phi = 10$; outbreaks initiated with one infected host in a population of N_0 susceptible individuals). **c**, Saprophytic growth: equilibrium densities of susceptible and infected hosts and free-living spores as a function of the rate of saprophytic growth, σ . With no (or low levels of) saprophytic growth, the basic reproductive rate of the pathogen (R_0) is less than 1, the pathogen cannot invade the system and the host persists at its disease-free equilibrium density. Intermediate levels of saprophytic growth allow the pathogen to invade

exhibit spatially restricted endemic ranges⁵¹. In many cases, local adaptation and host specificity are thought to underlie fungal endemicity^{51,52}. Nevertheless, when local climatic and vegetative constraints are projected globally it becomes clear that potential ranges of pathogenic fungi may be much larger than their realized range⁵³. If fungi are contained spatially by the combination of physical limits on dispersal, abiotic conditions, host distributions and genetic limits on adaptation, then how are pathogenic fungi able to overcome these barriers? Although fungi have shown the ability to undergo range expansions in response to environmental shifts⁵⁴, human-mediated intercontinental dispersal of unrecognized fungal pathogens is the major component in initiating new chains of transmission.

Pathogenic fungi have dispersed alongside early human migrations, and several thousand years ago two of these fungi, *Coccidioides immitis* and *C. neoformans* lineage VNI, seem to have invaded South America and southeast Asia, respectively, vectored by humans and their domesticated animals^{24,55}. Similar ancient patterns of human-associated disease spread are detected by studies of the genome diversity of many plant fungal pathogens⁵⁶. However, more recent increases in fungal disease are

attributable to the many-fold increase in fungal-infected trade products and food⁵⁷. The consequences of recent introductions of pathogens in association with trade are well known; examples include the Irish Famine⁴ (a consequence of *Phytophthora infestans* late blight introduction from South America), the destruction of the North American chestnuts⁵⁸ (caused by the importation of *Cryphonectria parasitica*-infected Asian chestnut trees to the east coast of the United States in the early twentieth century) and the Second World War introduction of *Heterobasidion annosum* into Italy from the USA (vectored by untreated wooden transport crates)⁵⁹. Human-mediated intercontinental trade has also been linked clearly to the spread of animal-pathogenic fungi through the transportation of infected vector species. *B. dendrobatidis* has been introduced repeatedly to naive populations worldwide as a consequence of the trade in the infected, yet disease-tolerant species such as North American bullfrogs (*Rana catesbeiana*)⁶⁰⁻⁶² and African clawed frogs (*Xenopus laevis*)^{63,64}. Whether the emergence of bat WNS constitutes an introduction of *G. destructans* into North America from Europe or elsewhere remains to be shown. However, the widespread but apparently non-pathogenic nature of the infection in European bats tentatively

suggests that the disease may have been vectored from this region in contaminated soil⁶⁵.

Accelerated evolution of virulence in pathogenic fungi

Human activities are not only associated with the dispersal of pathogenic fungi, they also interact with key fungal characteristics, such as habitat flexibility, environmental persistence and multiple reproductive modes, to cause the emergence of disease. Importantly, many fungi are flexible in their ability to undergo genetic recombination, hybridization or horizontal gene transfer⁶⁶, causing the clonal emergence of pathogenic lineages but also allowing the formation of novel genetic diversity leading to the genesis of new pathogens^{56, 67}. Reproductive barriers in fungi are known to evolve more rapidly between sympatric lineages that are in the nascent stages of divergence than between geographically separated allopatric lineages, in a process known as reinforcement^{68, 69}. As a consequence, anthropogenic mixing of previously allopatric fungal lineages that still retain the potential for genetic exchange can drive rapid macroevolutionary change. Although many hybrids are inviable owing to genome incompatibilities, large phenotypic leaps can be achieved by the resulting 'hopeful monsters', leading to host jumps and increased virulence⁷⁰. Such mechanisms are thought to drive the formation of new pathotypes in plant pathogens⁵², and oomycetes as well as fungi exhibit the genesis of new interspecific hybrids as lineages come into contact^{71, 72}. Evidence of the effect of multiple fungal co-dispersal events and recombination can also be seen in the recent *C. gattii* outbreaks in northwestern North America. In this case, strains that do not normally recombine have increased their virulence by undergoing recombination and adaptation to overcome mammalian immune responses^{23, 67}. Recent studies based on the resequencing of *B. dendrobatidis* genomes have shown that, although several lineages exist, only a single lineage (known as the *B. dendrobatidis* global panzootic lineage) has emerged in at least five continents during the twentieth century to cause epizootic amphibian declines⁶⁴. Notably, the genome of the *B. dendrobatidis* global panzootic lineage shows the hallmarks of a single hybrid origin and, when compared against other newly discovered lineages of *B. dendrobatidis*, is more pathogenic, suggesting that transmission and onward spread of the lineage has been facilitated by an increase in its virulence. Given that the rate of intra- and inter-lineage recombination among fungi will be proportional to the contact rates between previously geographically separate populations and species, these data from across plant and animal fungal pathosystems suggest that the further evolution of new races is inevitable given current rates of homogenization of previously allopatric, geographically separated, fungal lineages.

Environmental change as a driver of fungal EIDs

Climate fluctuation can be a potent cofactor in forcing changing patterns of fungal phenology⁷³ and are known to govern plant fungal EIDs. Models of climate change for the coming decades predict increases in global temperature, atmospheric CO₂, ozone and changes in humidity, rainfall and severe weather⁷⁴. For this reason, many interactions must be taken into consideration when attempting to predict the future effects of climate change on plant diseases⁷⁵. First, the physiological and spatial changes that plants may undergo in response to the various different components of climate change and the resulting effects on the pathogen⁷⁶, and second, the effects on the pathogen's physiology and dispersal external to their plant hosts⁷⁵. Frequently, however, experimental models have only taken into account one element of climate change, a common example being the free-air CO₂ enrichment (FACE) studies that model the effects of elevated atmospheric CO₂ (ref. 77). A notable result here has been rice blast severity being higher at higher CO₂ levels⁷⁸. However, although there has been a general trend for increased disease severity under simulated climate-change conditions⁷⁹, and although some species are thought to be changing their distribution in response to these changes (for example, *P. graminis*⁸⁰), other elements of climate change, such as

increased ozone, have been shown to have the opposite effect (for example, in *Puccinia recondita*⁷⁷).

Evidence for the idea that climate change has an impact on the dynamics and distribution of animal-infecting fungi is less clear-cut than that in relation to plant-infecting fungi and, although arguments have been made that warming trends may have contributed to the emergence of *B. dendrobatidis* in Central America and Europe^{81, 82}, there is active debate about these conclusions^{83, 84}. Regardless, it is clear that the disease state, chytridiomycosis, is linked to environmental factors; regional climate warming can increase the local range of the pathogen⁵⁴ and disease risk is inversely related to rates of deforestation⁸⁵. Correlations between ecosystem change and a rise in infection by opportunistic pathogens has been proposed to account for the occurrence of coral reef declines worldwide. For example, disease caused by a variety of microbes threatens hard corals to the extent that two of the most abundant Caribbean reef-builders (staghorn and elkhorn corals) are now listed under the US Endangered Species Act. Across varied reef systems, the occurrence of warm-temperature anomalies leading to bleaching events is associated with increases in disease caused by opportunistic pathogens such as *A. sydowii*⁸⁶. In an allied colonial system, colony collapse disorder has resulted in steep declines of the European honeybee *Apis mellifera* in Europe and North America⁸⁷. These losses seem to be influenced by a mixture of aetiological agents that are fungal (for example, microsporidian (*Nosema ceranae*)), viral (for example, Kashmir bee virus and Israeli acute paralysis virus) and ectoparasitic (for example, *Varroa destructor*) in origin. So far, no single environmental cause has been identified that can account for the apparent reduction in the ability of honeybee colonies to resist these infections, and agricultural chemicals, malnutrition and modern beekeeping practices have all been suggested as potential cofactors for colony-collapse disorder⁸⁸. The increasing use of azole-based agricultural chemicals has been implicated as a factor underpinning the increase in the frequency of multiple-triazole-resistant (MTR) isolates of *A. fumigatus* infecting humans⁸⁹. The widespread agricultural use of azoles as a means of combating crop pathogens is speculated to have led to selection for MTR alleles, an idea that is supported by the recent discovery that resistance clusters onto a single lineage in Dutch populations of the fungus⁹⁰. Efforts must now be turned to integrating epidemiological studies with those on environmental change so that the many possible interactions and outcomes can be assessed, as making blanket predictions for fungal diseases is currently impossible⁹¹. The highly coordinated response to the recent outbreak of wheat stem rust (*P. graminis*, strain Ug99) is a positive step towards this goal^{77, 92}.

Fungal EIDs impact food security and ecosystem services

Impacts of fungal diseases are clearly manifested in crops and there are direct measurable economic consequences associated with die-off in forest and urban environments. Losses that are due to persistent and epidemic outbreaks of fungal and oomycete infection in rice (rice blast caused by *Magnaporthe oryzae*), wheat (rust caused by *P. graminis*), maize (smut caused by *Ustilago maydis*), potatoes (late blight caused by *P. infestans*) and soybean (rust caused by *Phakospora pachyrizi*) vary regionally but pose a current and growing threat to food security². Our estimates of loss of food are based on the 2009–10 world harvest statistics of five of our most important crops and make certain basic assumptions of calorific value and worldwide average production (Supplementary Table 1). Our calculations show that even low-level persistent disease leads to losses that, if mitigated, would be sufficient to feed 8.5% of the 7 billion humans alive in 2011. If severe epidemics in all five crops were to occur simultaneously, this would leave food sufficient for only 39% of the world's population, but the probability of such an event occurring is very low indeed.

Invasive tree diseases have caused the loss of approximately 100 million elm trees in the United Kingdom and the United States^{52, 93}, and 3.5 billion chestnut trees have succumbed to chestnut blight in the United States (Supplementary Table 5). Losses of western Canadian pine trees to the mountain pine beetle–blue-stain fungus association will result in the

release of 270 megatonnes of CO₂ over the period from 2000 to 2020, with a clearly ascribed economic cost both for the wood itself and the carbon released⁹⁴. These, and other diseases such as ‘sudden oak death’ in California and ‘foliar and twig blight’ and ‘dieback’ on ornamental trees, woody shrubs and forestry plants in the European Union, affect ecological diversity, are costly to manage and account for huge losses of fixed CO₂. Indeed, we calculate regional losses of absorbed CO₂ to total 230–580 megatonnes for just a handful of diseases (Supplementary Table 5) with the higher figure equating to 0.069% of the global atmospheric CO₂. We have included both emerging (Jarrah dieback, sudden oak death and pine beetle–blue-stain fungus) and emergent diseases (Dutch elm blight and chestnut blight), as these represent the few examples for which informed estimates are possible. We are unable to quantify any of the many other recent emerging diseases, such as red band needle blight of pines, *Phytophthora alni* on alders or pitch pine canker on Monterey pines, owing to a lack of data and economic interest, both of which are trends that must be reversed. Assessing the economic burden of fungal mycoses in animals is a challenging task. Although the impact of fungal EIDs is manifested in domestic animal settings, particularly the amphibian trade⁹⁵ and in regions where virulent lineages have established⁹⁶, reporting mechanisms for outbreaks do not widely exist. In natural settings, valuations have recently estimated the losses to US agriculture that are the result of declines in bat populations at more than US\$3.7 billion per year (ref. 12). However, although broad ecosystem-level impacts of other fungal EIDs of wildlife are suspected, economic valuations of the ecosystem services that these species support are wholly lacking.

Mitigating fungal EIDs in animals and plants

The high socioeconomic value of crops means that detection and control of fungal diseases in agriculture far outpaces that in natural habitats. Epidemiological models have been developed to predict the risk of seasonally specific crop pathogens, allowing targeted control, and specific threats are assessed through consortia of research, governmental and global non-governmental organizations, led by the United Nations Food and Agricultural Organization (FAO), and related organizations. Scientifically led development of disease-resistant crop varieties has been mainly successful, although monocultures have in some instances vastly increased the susceptibility of harvests to highly virulent pathogens, a pertinent example being *P. graminis* Ug99. Conversely, although there have been some attempts to mitigate the fungal disease burden in wildlife *in situ*—most notably efforts to eliminate *B. dendrobatidis* in infected populations with the antifungal itraconazole⁹⁷ and the use of probiotic bacteria⁹⁸—communicable wildlife EIDs are essentially unstoppable once they have emerged. International biosecurity against the spread of plant fungal pathogens, although not perfect, is more advanced than protocols to protect against the introduction of animal-associated fungi. Fundamentally, this is the result of a financial dynamic: wildlife is not correctly valued economically, whereas crops are.

The World Organisation for Animal Health (also known as the OIE) and the FAO may be the best-placed authorities to coordinate tighter biosecurity controls for trade-associated fungal pathogens of animals. The OIE has listed *B. dendrobatidis* and the crayfish pathogen *A. astaci* in the Aquatic Animal Health Code as internationally notifiable infections, and the FAO compiles outbreak data on transboundary animal diseases using the emergency prevention information system (EMPRES-i). Similarly, the IUCN Wildlife Health Specialist Group determines policy that is specific to combating emerging wildlife disease internationally. On national scales there are a number of initiatives being deployed and in the United States the National Wildlife Health Centre has developed the national federal plan⁹⁹ to mitigate WNS in bats. Intensive monitoring and surveillance will be increasingly important in the coming years because predictive modelling and small-scale experiments can never fully predict future disease spread and severity. An increased political and public profile for the effects of fungal diseases in natural habitats is needed to highlight the importance of fungal disease control outside of the managed agricultural environment to

policy makers. If this occurs, then there will be more sympathy for attempts to improve the regulatory frameworks that are associated with biosecurity in international trade, as this is the most important tool to tackle both plant and animal fungal EIDs now and in the future. The monitoring of fungal inocula in wild populations should be the utmost priority and tighter control of international trade in biological material must be imposed, and with considerable haste. Inadequate biosecurity will mean that new fungal EIDs and virulent races will emerge at an increasingly destructive rate. In addition to better global monitoring and control, attention must also be turned to increasing our understanding of the interactions between hosts, pathogens and the environment, across regional and global scales. Integrated approaches encompassing theoretical and practical epidemiology, climate forecasting, genomic surveillance and monitoring molecular evolution are needed. These should be facilitated by scientists from currently disparate research fields entering into regular global discussions to develop clear and urgent strategies for working towards the elusive magic bullet for emerging fungal diseases: effective prevention and timely control.

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Crop <i>Host species</i>	2009/2010 harvest (million tonnes)	Calories per 100g flour (un- cooked)	Disease/Pathogen and variation in % losses	Loss of food* for x million over 1 year, given diet of 2,000 calories per day
Rice <i>Oryza sativa</i>	701 harvest but 476* milled for food	325	Rice Blast <i>Magnaporthe oryzae</i> 10-35%	212 to 742
Wheat <i>Triticum aestivum</i>	679 harvest but 432* for food	341	Stem Rust <i>Puccinia graminis</i> 10-70%	202 to 1,413
Maize <i>Zea mays</i>	820 harvest but 271* for food	355	Corn Smut <i>Ustilago maydis</i> 2-20%	26 to 262
Potato <i>Solanum tuberosum</i>	333* harvest but for food	357	Late Blight <i>Phytophthora infestans</i> 5-78%	81 to 1,270
Soybean <i>Glycine max</i>	232 harvest but 148* for food	372	Soybean Rust <i>Phakospora pachyrhizi</i> 10-80%	75 to 600
				TOTAL: Could feed 596 – 4,287 million mouths per annum**

Table S1: Food security and crop losses due to fungal/oomycete diseases: Five major crops that feed the world's population are challenged by the fungal/oomycete diseases shown. All global harvests are from 2009/2010 (www.fao.org or FAOSTAT1). *Figures are estimates and are based on 100% of milled rice and 100% of potato harvest being used for human consumption. However, 34% of the global wheat harvest is produced in developing countries, of which 100% is assumed to be used for human food, but only 45% of the total wheat harvest produced from developed countries is used for human food (the rest is used as animal feed and biofuel). Of the global maize harvest, 32% is produced in developing countries and 100% is assumed to be used for food and in the US 2.5% of their total harvest of 333m tonnes of maize (41% of global harvest) is used directly as food. Of the global soybean harvest, 36% is from US and Canada (10% of this is used as food, the rest goes into processed food and animal feed) and 64% is produced in developing nations, where 100% is assumed to be used as food. These figures do not take into account post-harvest storage losses.

**This is 8.5% - 61.2% of the world's population, based on the 2011 population estimate of 7 billion people.

Database	Year	Animal fungal alerts	Plant fungal alerts	Total fungal alerts	Total EID alerts
HealthMap	2007	9	9	18	9369
HealthMap	2008	13	20	33	5659
HealthMap	2009	8	15	23	11284
HealthMap	2010	23	29	52	8672
HealthMap	2011	28	18	46	8674
Total		81	91	172	43658
ProMED	1995	6	5	11	1153
ProMED	1996	10	11	21	1923
ProMED	1997	9	20	29	2384
ProMED	1998	20	12	32	2357
ProMED	1999	14	22	36	2079
ProMED	2000	7	37	44	2002
ProMED	2001	21	46	67	1930
ProMED	2002	14	41	55	1894
ProMED	2003	6	47	53	2092
ProMED	2004	2	64	66	2382
ProMED	2005	10	108	118	2582
ProMED	2006	18	62	80	2374
ProMED	2007	21	111	132	2829
ProMED	2008	19	123	142	2251
ProMED	2009	24	144	167	2399
ProMED	2010	37	142	179	2586
ProMED	2011	40	66	106	2307
Total		278	1061	1338	37524

Table S2. Summary of HealthMap (2006-2011) and ProMed (1994-2011) alerts for mycoses with the first year of data collection excluded. For our analyses we downloaded the complete ProMED and HealthMap databases from the start of data collection through to the last year of complete data collection (2010). We then used Boolean searches of the database using generic fungal search terms (fung*, mycosis) and refined this with the following specific search terms (rust, blast, blight, wilt, sigatoka, bunt, smut, light leaf spot, jarrah, oak death, blue stain, aspergillosis, blastomycosis, cryptococcosis, foot fungus, histoplasmosis, mucormycosis, paracoccidioidomycosis, sporotrichosis, thrush, valley fever, white nose syndrome, fusarium keratitis, dermatophytosis, zygomycosis, basidiobolomycosis, chromoblastomycosis, lobomycosis, mycetoma). Records were subsequently curated to remove false positives.

Table S3

Published infectious disease-driven extinction and regional extirpation events across animal and plant taxa. Data was acquired from the following review sources [1-9] and from *Web of Science* literature searches.

Host species [§]	Pathogen species	Kingdom (Phylum)	Factors driving emergence	Year of occurrence	Reference
Tropical central American amphibian spp. (30 species and 4 families) EXTINCTION/EXTIRPATION	<i>Batrachochytrium dendrobatidis</i>	Fungi (Chytridiomycota)	Pathogen invasion/endemic host populations	late 1980's - present	[7, 10]
Australian amphibian spp. (<i>n</i> ~ 4; 2 families) EXTINCTION	<i>B. dendrobatidis</i>	Fungi (Chytridiomycota)	Pathogen invasion/endemic host population	early 1980's	[11, 12]
<i>Alytes obstetricans</i> (Common midwife toad) EXTIRPATION	<i>B. dendrobatidis</i>	Fungi (Chytridiomycota)	Pathogen invasion/endemic host population	1997	[13]
<i>Nextophrynooides asperginis</i> (Kihansi spray toad) EXTINCTION	<i>B. dendrobatidis</i>	Fungi (Chytridiomycota)	Pathogen / habitat modification	2003	[14]
<i>Leptodactylus fallax</i> (Dominica and Montserrat Mountain Chicken Frog) EXTIRPATION	<i>B. dendrobatidis</i>	Fungi (Chytridiomycota)	Pathogen invasion/endemic host population	2000 (Dominica) 2009 (Montserrat)	[15, 16]
<i>Myotis lucifugus</i> (little brown bat) EXTIRPATION*	<i>Geomyces destructans</i>	Fungi (Ascomycota)	Pathogen invasion?	~2006	[17, 18]
<i>Partula turgida</i> (Hawaiian tree snail) EXTINCTION	<i>Steinhausia</i> sp.	Fungi (Microsporidia)	Pathogen invasion/endemic host population	1996	[19]
Native European Crayfish (eg. white clawed crayfish <i>Austropotamobius pallipes</i>) EXTIRPATION*	<i>Aphanomyces astaci</i>	Protoctista (Oomycota)	Pathogen invasion/spill-over	~1970's	[20, 21]
<i>Lottia alveus</i> (Eelgrass limpet) EXTINCTION	<i>Labyrinthula zosterae</i>	Protoctista (Slime molds; Heterokontophyta)	Knock-on effect of pathogen-driven food loss	~1930	[22]

Hawaiian native Land Birds ~ 9 (Table 7, van Riper <i>et al.</i> 1986) EXTINCTION	Avian malaria?	Protoctista (<i>Apicomplexa</i> – <i>Plasmodium</i> sp.)	Pathogen invasion and habitat loss	~1830 - 2002	[23]
<i>Sarcophilus harrisii</i> (Tasmanian Devil) EXTIRPATION*	Tasmanian devil facial tumour disease	Mammalian infectious cancer	Frequency- dependent contact; low host genetic diversity(?)	1996	[24]
<i>Mustela nigripes</i> (Black footed ferret) EXTIRPATION	Canine distemper virus (CDV)	ssRNA Virus (genus Morbillivirus)	Pathogen spill- over from unknown vector	1985	[25]
<i>Lycaon pictus</i> (African Wild Dog) EXTIRPATION	Canine distemper virus (CDV)	ssRNA Virus (genus Morbillivirus)	Pathogen spill- over from domesticated dogs	~1960 - present	[26, 27]
<i>Rattus macleari</i> (Christmas Island rat) EXTINCTION(?)	<i>Trypanosoma</i> <i>lewisii</i> ?	Protoctista (Euglenozoa)	Pathogen spill- over following introduction of <i>R.</i> <i>rattus</i> ?	~1905	[28]
<i>Castanea dentata</i> (Chestnut trees) EXTIRPATION	<i>Cryphonectria</i> <i>parasitica</i>	Fungi (Ascomycota)	Pathogen invasion	~1900 - ~1930	[29]
<i>Ulmus</i> spp. (Elm trees) EXTIRPATION	<i>Ophiostoma ulmi</i>	Fungi (Ascomycota)	Pathogen invasion, recombination	~1910	[30]
Jarrah dieback (multiple species of <i>Eucalyptus</i> and Proteaceae) EXTIRPATION/ EXTINCTION(?)	<i>Phytophthora</i> <i>cinnamomi</i>	Protoctista (Oomycota)	Pathogen invasion	1935	[31]
<i>Pinus radiata</i> (Monterey pine) EXTIRPATION(?)	<i>Fusarium</i> <i>circinatum</i>	Fungi (Ascomycota)	Pathogen invasion	1946	[32]
Sudden oak death syndrome (multiple species) EXTIRPATION(?)	<i>Phytophthora</i> <i>ramorum</i>	Protoctista (Oomycota)	Pathogen invasion	~1995	[33]

<i>Torreya taxifolia</i> (Florida torreyi) EXTINCTION* (~99% decline)	<i>Pestalotiopsis microspora</i> ?	Fungi (Ascomycota)	Unknown.	~1950	[34]
<i>Zostera marina</i> and <i>Zostera caulescens</i> (Eelgrass) EXTIRPATION	<i>Labyrinthula zosterae</i>	Protoctista (Slime mold; Heterokontophyta)	Unknown	~1930	[35]

Note: We only include species where there is published evidence of extinction/extirpation, or published evidence of declines with a high likelihood of future loss. Many EIDs did not meet these strict criteria despite causing high levels of population decline (e. g. bird West Nile Virus, Red squirrel parapox virus, Prairie dog plague). * indicates species where extirpation or extinction is predicted based on projections of future population viability. (?) indicates that data is persuasive but deficient

Table S4.1

Data for Fig. 1. Summary of major taxonomic groups of pathogens that cause animal species extinctions/extirpations from Table S1

Taxonomic groups of pathogens	Disease-driven extinction/ extirpation events (% of total)	Corrected for community-level extinctions (% of total)
Fungi	39 (72.0)	11 (64.7)
Protist	12 (22.0)	3 (17.6)
Viruses	2 (3.7)	2 (11.7)
Bacteria	0 (0)	0 (0)
Helminths	0 (0)	0 (0)
others*	1 (1.9)	1 (5.88)

*Note: 'Others' includes mammalian carcinogenic cell lines and prions

Table S4.2

Data for Fig. 1. Summary of major taxonomic groups of pathogens that cause plant species extinctions/extirpations from Table S1

Taxonomic groups of pathogens	Disease-driven extinction/ extirpation events	Corrected for community-level extinctions
Fungi	4 (57.1)	4 (57.1)
Protist	3 (42.8)	3 (42.8)
Viruses	0 (0)	0 (0)
Bacteria	0 (0)	0 (0)
Helminths	0 (0)	0 (0)
others*	n/a	n/a

Disease	Pathogen	Host range	Regional losses ¹	Regional losses of absorbed CO ₂ (megatonnes) ^{2,3}
Dutch Elm	<i>Ophiostoma ulmi</i>	Elm	25 million elms (UK, 1990's) 77 million elms (USA, by 2001)	0.395 ² to 1 ³
Chestnut blight	<i>Cryphonectria parasitica</i>	Chestnut	3.5 billion US chestnuts (USA, by 1940's)	13.8 to 35
Sudden oak death / ramorum blight	<i>Phytophthora ramorum</i>	Oak, larch etc.	1.4 million oaks in California Pre-emptive cull of 4 million larches (UK 2011)	0.012 to 0.05
'Jarrah' dieback	<i>Phytophthora cinnamomi</i>	2,000 of 9,000 native spp. in Western Australia	1 million hectares of western Australia (by 2009)	9 to 23
Pine beetle / blue stain	<i>Grossmania clavigera</i>	Lodge pole pine	16.3 million hectares of western Canada (by 2011)	207 - 520
				TOTAL: ~ 230 to 580 megatonnes

Table S5. Tree carbon sequestration losses caused by fungal/oomycete diseases

Regional losses¹ are given as trees felled/succumb to disease and resulting losses in CO₂ absorption for 5 different fungal/oomycete pathogens. Such regional losses determined for total number of lost trees estimated over period stated, with minimum² and maximum³ estimates based on either ² carbon sequestration data-base at Office of Sustainability, Tufts University US (with 25 -120 year old trees is 2.52 lbs to 5.58 lbs CO₂ per year per tree: 25 – 120 year old pines is 15 – 11.7 lbs CO₂ per year: crude mean of values is 3.95 Kg CO₂ per tree per year) or on the assumption³ that one broad-leaved tree will absorb around 0.01 tonne of CO₂ per annum [36]. Estimates for losses due to *Phytophthora cinnamomi* are based on a eucalyptus planting density of 2300 trees per hectare [37]. Pine beetle/blue stain losses are based on a pine planting density of 1400 trees per hectare. We note that we have not evaluated losses owing to timber decay as a result of tree death. Atmospheric CO₂ levels (December 2011, <http://co2now.org/>) were recorded at 391.80 ppm or 834.5 Gigatonnes; maximum regional losses recorded herein equate with 0.069% global CO₂

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