Averting a North American biodiversity crisis

A newly described pathogen poses a major threat to salamanders via trade

By Tiffany A. Yap1,2,3, Michelle S. Koo4, Richard F. Ambrose1,4, David B. Wake2,3, Vance T. Vredenburg4,5

In the midst of an ongoing sixth mass extinction (1), more than 40% of all amphibians are threatened (2). Chytridiosis, an emerging infectious disease (EID) caused by the fungal pathogen Batrachochytrium dendrobatidis (Bd), has been more devastating than any infectious wildlife disease recorded, with >200 amphibian species collapsing to or near extinction (3). Recently, a new infectious chytrid fungal pathogen from Asia and specific to salamanders (4), Batrachochytrium salamandricorans (Bsal), has been described (5). With no effective means to control spread of Bsal once it is established in wild host populations, Bsal invasion of North America could lead to rapid epizootic (wildlife epidemic) declines and extinctions in the world’s richest and most diverse salamander fauna. We demonstrate the likelihood of Bsal introduction to North America via international trade, the likelihood of species being exposed to Bsal, and the potential impact of species exposure to Bsal. This presents a unique opportunity for wildlife management officials and the international amphibian trade community to prevent the spread of this deadly pathogen and to develop and implement rapid risk assessments and international responses to EIDs in wildlife.

This highly virulent Bsal pathogen was discovered in the Netherlands during a mass die-off in European fire salamanders (4, 5). Martel et al. (4) proposed that Bsal originated in Asia and spread to wild European salamanders via the international salamander pet trade. They warned that Bsal represents a substantial threat to salamanders in other regions (e.g., North America) that may also be naïve to the pathogen. Furthermore, they identified three actively traded Asian salamander species as reservoirs for Bsal: Cynops cyanurus, Cynops pyrrhogaster, and Paramesotriton deloustali.

Bsal has already spread from the Netherlands to Belgium (4), and there is evidence of its spread in international trade (6). The introduction of Bsal to naïve areas could lead to major salamander declines, which would have severe ecosystem impacts. In woodland communities, salamanders represent a substantial portion of vertebrate biomass and play key roles in trophic dynamics and the carbon cycle (7).

NORTH AMERICAN THREAT. North America is the world’s salamander biodiversity hotspot with 48% of 676 recognized salamander species representing 9 of the 10 known families within the order Caudata (190 species in the United States, 137 in Mexico, and 21 in Canada) (8). Bsal has not been reported in North America, although few studies have been published in the short time since Bsal was described (9, 10).

We combined projections from a Bsal habitat suitability model (HSM) (see the map, top left) (Fig. 1A) with a host species-richness map (see the map, top right) (Fig. 1B) to create a predictive model of host vulnerability (see the map, bottom) (Fig. 1C). We assumed host risk to be higher in areas of greater salamander species richness. Because the true niche of Bsal is unknown, we estimated occur-

4Institute of the Environment and Sustainability, University of California, Los Angeles, CA, USA. 2*Museum of Vertebrate Zoology, University of California, Berkeley, CA, USA. 3*Department of Biology, San Francisco State University, San Francisco, CA, USA. 4*Department of Environmental Health Sciences, University of California, Los Angeles, CA, USA. 5*Department of Integrative Biology, University of California, Berkeley, CA, USA. *E-mail: vanev@sfsu.edu

Mapping the threat of Bsal to North American salamanders. (A) Bsal habitat suitability model based on 133 carrier occurrences and six bioclimatic variables. (B) Salamander species-richness map. (C) Salamander Bsal vulnerability model. Major ports (black squares) for salamander imports follow the table (22). Port 6 represents Mexico City.
The U.S. vulnerability zones contain numerous species from the two most Bsal-susceptible families, Plethodontidae and Salamandridae (4). North American newts (Family Salamandridae), which exhibited high levels of infection and 100% mortality (5), have large, vagile populations important in both terrestrial and freshwater ecosystems, and they may act as superspreaders of infectious disease by greatly increasing Bsal transmission in these regions (11). The Mexican vulnerability zone, located in an area of high beta diversity and endemicism, has already been experiencing severe salamander declines (12, 13).

### RISK IN TRADE

Risk of Bsal invasion is compounded by the magnitude of international salamander trade. We examined the most recent 5 years (2010–2014) of live salamander trade entering the United States and identified the most active ports of entry using total gross imports (779,002 salamanders). About 99% originated from Asia, and 98% were species native to Asia (see the table). The major sources were Hong Kong, mainland China, Singapore, and Japan. Alarmingly, species in the genera Cynops and Paramesotriton, which included all three putative Bsal reservoirs (4), made up 91% of all salamander imports.

The five most-active U.S. ports were located within or near the predicted salamander vulnerability zones (see the map, bottom) and accounted for more than 98% of all U.S. salamander imports. Trade data from Canada and Mexico were not analyzed; however, Mexico City is a likely port of entry and is located within a predicted salamander high-vulnerability area.

**Bsal** is highly transmissible by direct contact (4); therefore, shipments containing co-housed animals and shared water increase the potential for pathogen spread. Given the magnitude of international salamander trade originating from Asia and containing potential Bsal reservoirs, the risk of Bsal introduction to North America is high.

### MITIGATION AND RESPONSE

Species declines and extinctions due to wildlife EIDs and the lack of rapid responses (14, 15) warrant immediate action to mitigate the spread of Bsal. Preventive action is far more cost-effective than emergency responses to disease outbreaks due to pathogen spread (16), and potentially irreversible environmental consequences could be avoided (17). The U.S. Fish and Wildlife Service can play a pivotal role in mitigating the threat of Bsal spread by placing an immediate ban on live salamander imports until effective EID prevention and management protocols are in place.

Immediate action in the United States, although critically important, is not sufficient. Because of globalization and human-mediated movements, an international infrastructure that facilitates rapid responses—similar to that of the World Health Organization (WHO) for human disease—is required to mitigate the spread of EIDs in wildlife (14).

Although the World Organization for Animal Health (OIE) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) provide guidelines for animal disease and the trade of endangered species, respectively, membership is voluntary, systematic record-keeping is limited, and wildlife EIDs are not prioritized. These institutions should work with government agencies and experts in disease ecology and animal trade to implement an international effort for surveillance, research, and management actions in an adaptive management framework for effective wildfire EID intervention (16). To enhance global biosecurity and to help prevent the spread of Bsal and other wildlife EIDs, a mandatory international system that will track all traded species, identify potential wildlife EID threats, and develop and facilitate emergency protocols is needed (18).

Immediate efforts are required to monitor zones of salamander Bsal high vulnerability (see the map, bottom). New studies on the basic biology of Bsal and on host-pathogen dynamics should also be a priority. Future studies should incorporate new data on transmission, susceptibility, and other potentially influential variables (e.g., species life-history traits, host microbiome, or co-occurring pathogens) to better understand the complex disease system. In the interim, the trade industry should take preventive measures from protocols that have been developed for the detection of Bsal (19) and the treatment of infected individuals (20, 21).

### REFERENCES AND NOTES
20. Materials and methods are available as supplementary materials on Science Online.

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### SUPPLEMENTARY MATERIALS
www.sciencemag.org/content/349/6247/481/suppl/DC1