BIODIVERSITY

Averting a North American biodiversity crisis

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

By **Tiffany A. Yap[1,2,3], Michelle S. Koo[2], Richard F. Ambrose[1,4], David B. Wake[2,5], Vance T. Vredenburg[2,3]***

In the midst of an ongoing sixth mass extinction (*1*), more than 40% of all amphibians are threatened (*2*). Chytridiomycosis, 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 salamandrivorans* (*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.

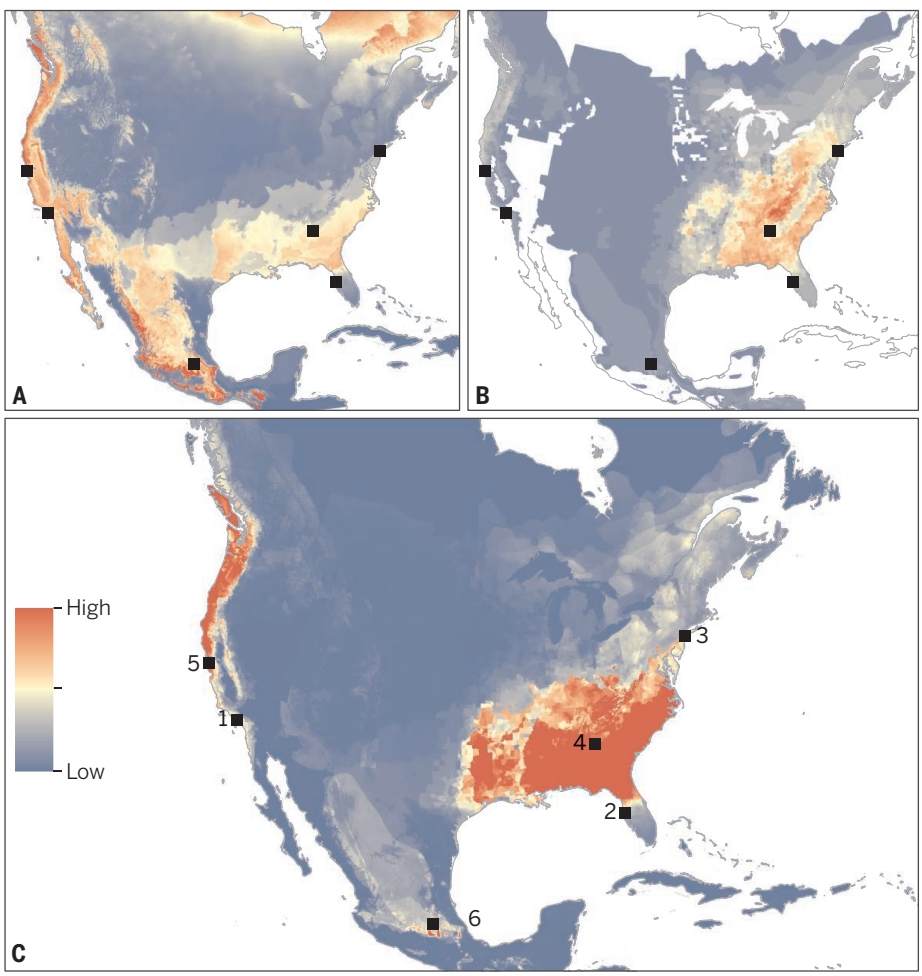
POLICY

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-



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.

[1]Institute 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: vancev@sfsu.edu

rences on the basis of native ranges of the three putative *Bsal* reservoir species in Asia (fig. S1). We identified three zones of high risk in North America (see the map, bottom): southeastern United States (the southern extent of the Appalachian Mountains and neighboring southeast region), western United States (the Pacific Northwest and the Sierra Nevada), and the highlands of central Mexico (portions of the Sierra Madre Oriental and the Trans-Mexican volcanic belt).

Major U.S. ports for salamander imports

PORT	*Bsal* THREAT	NON-*Bsal* THREAT	ALL SHIPMENTS
1 Los Angeles, CA	418,692	1,198	419,890
2 Tampa, FL	272,338	1,140	273,478
3 New York, NY	55,441	70	55,511
4 Atlanta, GA	13,272	40	13,312
5 San Francisco, CA	3,164	6,459	9,623
Total (top 5 U.S. ports)	762,907	8,907	771,814
All U.S. ports combined	768,572	10,430	779,002

Imported salamanders were considered a *Bsal* threat if they have native ranges in Asia or were in shipments that passed through Asian ports before entering the United States. Those not considered a *Bsal* threat are not native to Asia and never passed through an Asian port before entering the United States. All values are number of salamanders (*22*).

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 endemism, 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 cohoused 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 wildlife 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

1. D. B. Wake, V. T. Vredenburg, *Proc. Natl. Acad. Sci. U.S.A.* **105** (suppl. 1), 11466 (2008).
2. S. N. Stuart *et al.*, *Science* **306**, 1783 (2004).
3. L. F. Skerratt *et al.*, *EcoHealth* **4**, 125 (2007).
4. A. Martel *et al.*, *Science* **346**, 630 (2014).
5. A. Martel *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 15325 (2013).
6. A. A. Cunningham *et al.*, *Vet. Rec.* **176**, 468 (2015).
7. M. L. Best, H. H. Welsh Jr., *Ecosphere* **5**, art16 (2014).
8. AmphibiaWeb, Information on amphibian biology and conservation (2015); http://amphibiaweb.org/.
9. C. Muletz, N. M. Caruso, R. C. Fleischer, R. W. McDiarmid, K. R. Lips, *PLOS ONE* **9**, e103728 (2014).
10. E. K. Bales *et al.*, *PLOS ONE* **10**, e0116405 (2015).
11. J. O. Lloyd-Smith, S. J. Schreiber, P. E. Kopp, W. M. Getz, *Nature* **438**, 355 (2005).
12. K. R. Lips *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 3165 (2006).
13. T. L. Cheng, S. M. Rovito, D. B. Wake, V. T. Vredenburg, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 9502 (2011).
14. J. Voyles *et al.*, *EcoHealth* **11**, 2008 (2014).
15. D. M. Tompkins, S. Carver, M. E. Jones, M. Krkošek, L. F. Skerratt, *Trends Parasitol.* **31**, 149 (2015).
16. K. E. Langwig *et al.*, *Front. Ecol. Environ* **13**, 195 (2015).
17. K. A. Oye *et al.*, *Science* **345**, 6 (2014).
18. H.-K. Chan, H. Zhang, F. Yang, G. Fischer, *Science* **348**, 291 (2015).
19. M. Blooi *et al.*, *J. Clin. Microbiol.* **51**, 4173 (2013).
20. M. Blooi *et al.*, *Sci. Rep* **5**, 1 (2015).
21. M. Blooi *et al.*, *Sci. Rep.* **5**, 11788 (2015).
22. Materials and methods are available as supplementary materials on *Science* Online.

ACKNOWLEDGMENTS

This work was supported by UCLA–Charles F. Scott Fellowship (T.A.Y.) and NSF IOS-1258133 (V.T.V.). We thank S. M. Rovito for Mexican species occurrence data and the Museum of Vertebrate Zoology at University of California, Berkeley, for technical support. Original data are archived at AmphibiaWeb, VertNet, the International Union for Conservation of Nature, WorldClim, and the U.S. Fish and Wildlife Service, and we thank these organizations and collections for sharing their data. We also thank the anonymous reviewers.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/349/6247/481/suppl/DC1

10.1126/science.aab1052