Received: 23 August 2019 | Revised: 6 December 2019 | Accepted: 14 January 2020
DOI: 10.1111/conl.12707

Conservation Letters
A journal of the Society for Conservation Biology
Open Access
WILEY

POLICY PERSPECTIVE

Integral chain management of wildlife diseases

An Martel[1] | **Mireia Vila-Escale**[2] | **Daniel Fernández-Giberteau**[3] | **Albert Martinez-Silvestre**[4] | **Stefano Canessa**[1] | **Sarah Van Praet**[1] | **Pep Pannon**[2] | **Koen Chiers**[1] | **Albert Ferran**[2] | **Moira Kelly**[1] | **Mariona Picart**[2] | **Dolors Piulats**[5] | **Zhimin Li**[1] | **Viviana Pagone**[5] | **Laia Pérez-Sorribes**[3] | **Carolina Molina**[3] | **Aïda Tarragó-Guarro**[6] | **Roser Velarde-Nieto**[7] | **Francesc Carbonell**[8] | **Elena Obon**[8] | **Diego Martínez-Martínez**[9] | **Daniel Guinart**[2] | **Ricard Casanovas**[6] | **Salvador Carranza**[5] | **Frank Pasmans**[1]

[1]Wildlife Health Ghent, Department of Pathology, Bacteriology and Avian Diseases, Faculty of Veterinary Medicine, Ghent University, Merelbeke, Belgium
[2]Oficina Tècnica de Parcs Naturals. Diputació de Barcelona, Barcelona, Spain
[3]Grup de Recerca de l'Escola de la Natura de Parets del Vallès – Ajuntament de Parets del Vallès, Parets del Vallès, Spain
[4]Catalonian Reptile and Amphibian Rescue Center (CRARC), Masquefa, Spain
[5]Institute of Evolutionary Biology (CSIC-UPF), Barcelona, Spain
[6]Departament de Territori i Sostenibilitat, Generalitat de Catalunya, Barcelona, Spain
[7]Departament de Medicina i Cirurgia Animals, Facultat de Veterinària, Universitat Autònoma de Barcelona, Bellaterra, Spain
[8]Àrea de Gestió Ambiental Servei de Fauna i Flora (Centre de Fauna de Torreferrussa), Santa Perpètua de Mogoda, Spain
[9]Forestal Catalana, Barcelona, Spain

Correspondence
An Martel, Wildlife Health Ghent, Department of Pathology, Bacteriology and Avian Diseases, Faculty of Veterinary Medicine, Ghent University, B-9820 Merelbeke, Belgium.
Email: an.martel@ugent.be

Funding information
Ministerio de Ciencia, Innovación y Universidades, Grant/Award Numbers: CGL2015-70390-P, PGC2018-098290-B-I00; Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya, Grant/Award Number: 2017-SGR-00991; Laboklin

Abstract
The chytrid fungus *Batrachochytrium dendrobatidis* has caused the most prominent loss of vertebrate diversity ever recorded, which peaked in the 1980s. Recent incursion by its sister species *B. salamandrivorans* in Europe raised the alarm for a new wave of declines and extinctions in western Palearctic urodeles. The European Commission has responded by restricting amphibian trade. However, private amphibian collections, the main end consumers, were exempted from the European legislation. Here, we report how invasion by a released, exotic newt coincided with *B. salamandrivorans* invasion at over 1000 km from the nearest natural outbreak site, causing mass mortality in indigenous marbled newts (*Triturus marmoratus*), and posing an acute threat to the survival of nearby populations of the most critically endangered European newt species (Montseny brook newt, *Calotriton arnoldi*). Disease management was initiated shortly after detection in a close collaboration between policy and science and included drastic on site measures and intensive disease surveillance. Despite these efforts, the disease is considered temporarily contained but not eradicated and continued efforts will be necessary to minimize the probability of further pathogen dispersal. This precedent demonstrates the importance of tackling wildlife diseases

at an early stage using an integrated approach, involving all stakeholders and closing loopholes in existing regulations.

KEYWORDS
amphibian, *Batrachochytrium salamandrivorans*, biodiversity, conservation, policy, wildlife diseases

1 | INTRODUCTION

Counteracting drivers of biodiversity loss is a major challenge for global change science and policy (IPBES, 2019). Globalization has precipitated multiple introductions of devastating wildlife and plant fungal diseases such as Dutch elm blight, sudden oak death, American chestnut blight, white nose syndrome in bats and chytridiomycosis in amphibians (Fisher et al., 2012). Of all known pathogens, *Batrachochytrium dendrobatidis* has caused the most prominent loss of vertebrate diversity ever recorded, with extinctions or declines in 500 amphibian species in Australia and the Americas (Scheele et al., 2019). The recent emergence of its sister species *B. salamandrivorans* (Martel et al., 2013) raised the alarm for a possible new wave of declines and extinctions similar to that caused by *B. dendrobatidis* (Martel et al., 2014; Yap, Koo, Ambrose, Wake, & Vredenburg, 2015). The European Commission took action to restrict amphibian trade (EU2018/320), included *B. salamandrivorans* in EU-wide regulations on transmissible animal diseases (EU2018/1882), and deployed a European wide early warning system with disease emergency teams and a network of diagnostic centers (ENV.B.3/SER/2016/0028). Trade in live amphibians is a prominent source of invasive alien species and pathogen pollution, serving as the most probable vehicle for *B. salamandrivorans* introductions (Fitzpatrick, Pasmans, Martel, & Cunningham, 2018). The temporary trade restriction law (EU2018/320) lists health protection measures for commercial animal movements between EU member states and for introduction of salamanders from a third country. Unfortunately, the main end consumers of this trade, private amphibian collections, are exempted from existing European legal frameworks. Noncommercial animal movements among private collectors are not governed by legislation that can be used as a basis for controlling pathogen outbreaks.

We report how *B. salamandrivorans* invaded and caused mortalities in a Spanish amphibian community, likely through spillover from introduced alien pet amphibians, in a region home to the most critically endangered European newt species. The combination of early detection, intensive management, and close collaboration between policy and science succeeded in temporary disease containment but not eradication. This precedent demonstrates the importance of tackling wildlife diseases at an early stage using an integrated approach, involving all stakeholders and closing loopholes in existing regulations.

2 | DRASTIC RESPONSE TO DISEASE OUTBREAK

In March 2018, *B. salamandrivorans* was detected in a small reservoir in the Montnegre i el Corredor Natural Park in Catalonia (NE Spain), approximately 1,000 km from its nearest known occurrence in northern Europe (Figure 1). Infection was discovered during a campaign to eradicate invasive exotic newts (*Triturus anatolicus* (Anatolian crested newt) and *Ichthyosaura alpestris* (alpine newt)). Initial detection of *B. salamandrivorans* in two healthy Anatolian crested newts during an opportunistic disease screening was followed by a mortality event in native marbled newts (*T. marmoratus*) in May 2018 (Figure 1). The inclusion of *B. salamandrivorans* in regulatory frameworks, awareness of its threat to biodiversity, and close proximity to the range of the critically endangered Montseny brook newt (*Calotriton arnoldi*) (Carranza & Martinez-Solano, 2009) stimulated decision making by local and regional authorities and their response to the detected outbreak, in close collaboration with scientists. Such a combination of policy, science, and action on the ground is common against epidemics of livestock diseases, but rarely applied to wildlife diseases (OIE, 2018). Absence of efficient protocols to curb chytridiomycosis-driven loss of biodiversity (Garner et al., 2016) prompted authorities to implement broad-spectrum precautionary actions. Disease control included implementation of biosecurity, habitat management and disinfection, host removal and disease surveillance throughout the park (Figure 1, Supporting Information Materials and Methods and Table S1) and was based on a combination of a successful mitigation action of *B. dendrobatitidis* in Mallorcan midwife toads (Bosch et al., 2015) and by epidemiological models, suggesting that removal of the host community is currently the only possible response to eliminate a *B. salamandrivorans* outbreak (Canessa et al., 2018; Canessa, Bozzuto, Pasmans, & Martel, 2019; Thomas et al., 2019).

In total, 690 urodeles and 184 anurans were tested for *B. salamandrivorans* infection during the period March 2018 to May 2019 (Table S1). Streamlined decision processes, including permit issuing and contracting, allowed deployment of

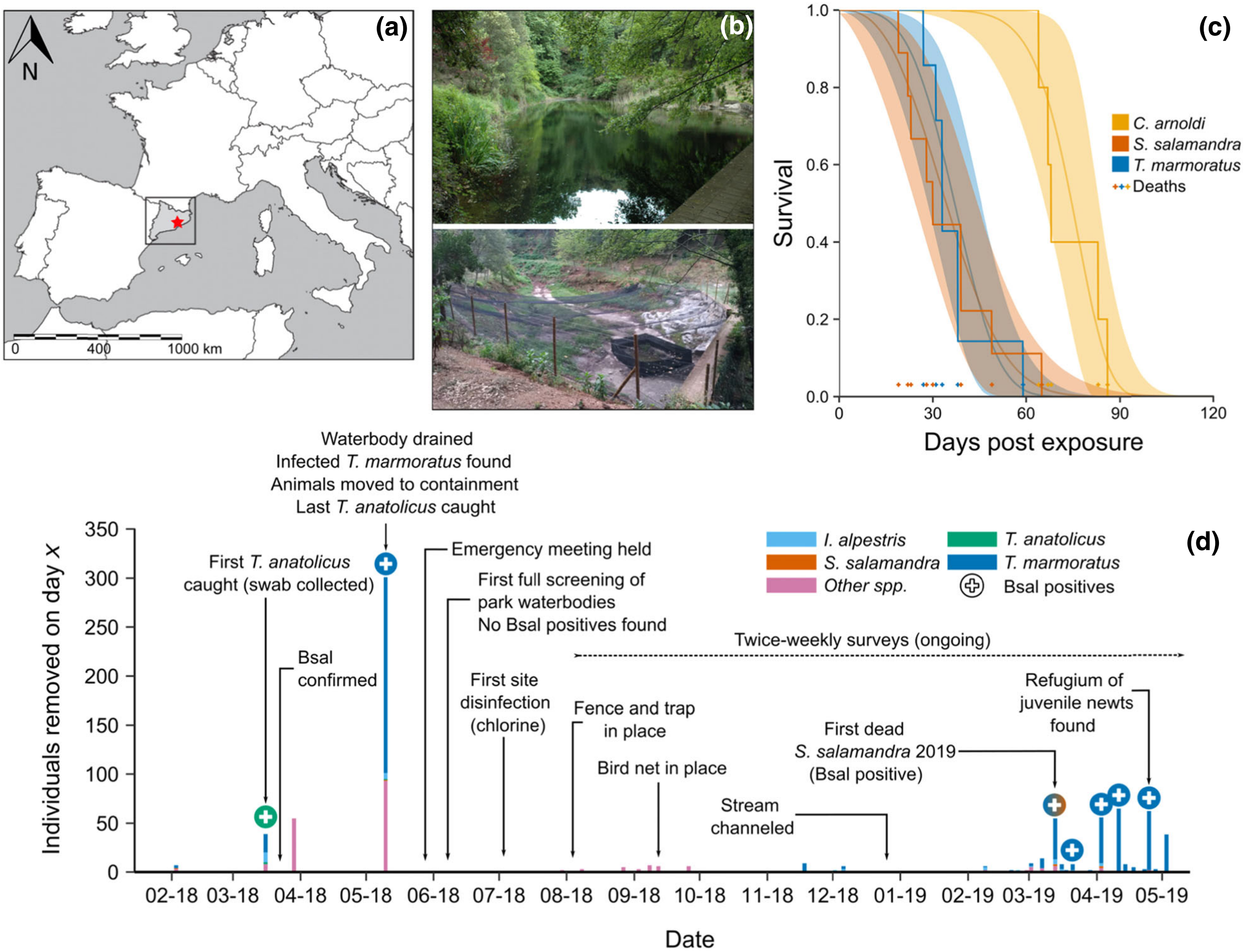

FIGURE 1 Overview of *B. salamandrivorans* detection and subsequent actions. (a) Location of the Montnegre i el Corredor Natural Park in Catalonia, Spain and Europe; (b) the outbreak site before and after mitigation interventions; (c) survival of *T. marmoratus*, *S. salamandra* and the critically endangered Montseny brook newt *C. arnoldi* after experimental infection with *B. salamandrivorans*; (d) timeline of management actions and removal of amphibian hosts at the outbreak site

resources from six weeks after first detection of *B. salamandrivorans* (Figure 1).

One year after detection, analysis of the removal data suggests a large proportion of the indigenous *T. marmoratus* population has been removed (mean estimate: 0.82, 95% CI 0.75–0.89; Table S1; Methods in Supplementary Material). Estimates for the invasive Anatolian newts are highly uncertain, but the species has not been resighted since May 2019 (Figure 1, Table S1). Several screening surveys of all waterbodies in the park did not return any positive result beyond the outbreak site; therefore, we currently consider *B. salamandrivorans* to be at least temporarily contained, albeit not eradicated at the outbreak site (Table S1).

Our experience with *B. salamandrivorans* field management—to our knowledge, the first such attempt ever made—highlights several useful lessons for future analogous efforts. The analysis of the results indicates that the largely passive trapping strategy achieved very low removal rates (e.g., a mean rate of 3% for indigenous newts), whereas epidemiological studies suggest eliminating *B. salamandrivorans* requires an intensive effort, with >90% removal within a very short time frame (Canessa et al., 2018, 2019). Moreover, juvenile stages without reproductive activity might escape traps located near waterbodies. In our case, large numbers of infected juveniles were found outside the fenced perimeter a year after detection (Figure 1). We recommend actively targeting those terrestrial life stages; soil sanitation might also be considered. In general, in a future attempt we would seek greater integration of quantitative data collection and analysis (e.g., epidemiological and removal modeling) into management planning from the beginning and during the outbreak, and not simply for post-hoc analysis. Such an "outbreak science" framework is increasingly recommended for mitigation of human and livestock diseases (Polonsky et al., 2019). Increasing likelihood of pathogen eradication could be effectuated by increasing the probability of early disease detection and minimizing response time. An efficient early warning system combined with the availability of specific, evidence-based emergency action plans would facilitate an immediate response. Such plans should provide a strong decision support framework for potentially controversial measures, such as the removal of protected species.

3 | TRACING THREATS TO ENDANGERED WILDLIFE

In parallel with the emergency precautionary responses, laboratory experiments (see infection trial section Supplementary Materials) were carried out to assess the risk for the indigenous urodele species and the suitability of the invasive newts as pathogen vectors. Experimental exposure of the endangered Montseny brook newts and indigenous fire salamanders (*Salamandra salamandra*) and marbled newts to the local *B. salamandrivorans* isolate (Figure 1) resulted in lethal infections. In contrast, the invasive Anatolian crested newts developed chronic, non-lethal infections, with latency periods of undetectable infection and subsequent flare-ups that allowed spillover of infection to marbled newts (Figure S1). These experimental findings are highly consistent with the disease dynamics observed in the field, confirm the threat to native wildlife, and corroborate the likelihood of the invasive newts as disease vectors and reservoirs. The experimental evidence, however, is circumstantial, and does not pinpoint the source of invasive newts and pathogen. We presume exotic newts have been released to the site by a private collector since at least 2016. This assumption is reinforced by the remarkable local diversity of alien invasive newts, known past introductions by the suspected collector in the region (e.g., introduction of Turkish *Ommatotriton ophryticus*; Fontelles, Guixé, Martínez-Silvestre, Soler, & Villero, 2011), and experimental evidence that the invasive Anatolian newts can be long-term carriers and disease reservoirs. Moreover, the distance to the nearest known outbreaks (over 1000 km), poor dispersal ability (Spitzen-van der Sluijs et al., 2018) and the known sensitivity of *B. salamandrivorans* to environmental factors (Blooi et al., 2015; Stegen et al., 2017) reduce the likelihood of passive transport. However, existing regulations do not allow access to private collections. Private amphibian keepers are not subject to sanitary regulations, hampering epidemiological tracing, and disease eradication, which leaves the invasion hazard undetermined and unmitigated. Although we here link *B. salamandrivorans* invasion to pet release, alternative routes of pathogen introduction on passive vectors such as fomites should be considered. As a precautionary principle, the application of biosecurity measures during activities in amphibian habitats is likely to minimize opportunities for human-mediated pathogen introductions and further dispersal.

4 | INTEGRAL CHAIN MANAGEMENT OF WILDLIFE DISEASES

Prevention of wildlife diseases among all invasion pathway is a priority that cannot be further delayed. Pathogen invasions in wildlife are most commonly addressed when threatening livestock and/or public health. However, attempts to mitigate the impact of infectious threats should be considered integral components of biodiversity protection legislation, in this case the EU's Habitats Directive. Decision making for disease management should identify responses based on clearly defined objectives and risk assessment. Here, the emergence of an acute, invasive, and human-mediated threat to the survival of a critically endangered species prompted decision-makers to act rapidly and drastically in order to contain and eradicate disease. The inability to eradicate disease in our case, even following detection and coordinated response using best practice, demonstrates the necessity of intercepting wildlife diseases at an early stage, before the invasion of natural systems. Failure to do so has resulted in the emergence of a World Organization for Animal Health (OIE) listed wildlife disease (Aquatic OIE, 2017) 1000 km from the nearest outbreak, directly threatening Europe's most endangered newt and requiring ongoing intensive mitigation efforts. To avoid similar scenarios, we propose an integral chain management of trade-associated wildlife diseases, aimed at minimizing the probability of disease introduction using principles such as Hazard Analysis of Critical Control Points (Codex Alimentarius, 1997), as is commonplace in disease mitigation in humans and livestock. We envisage three links to this chain: the animal trade, the domestic host population, and hosts/susceptible species in the wild. Regulation of the wildlife trade is slowly improving; response to disease outbreaks in the wild, although challenging, can be made easier by early warning systems, science support and streamlined decision processes as evidenced by the Catalan case.

Current evidence points to the role of the captive *B. salamandrivorans* reservoir combined with amphibian movements (in a broad sense, including traffic of animals between hobbyists) as a likely vehicle for further *B. salamandrivorans* introductions in naïve regions (Fitzpatrick et al., 2018; this report). Elimination of this reservoir requires extensive screening and treatments. While current legislation regulates commercial trade, hobbyists (pet keepers) are exempted from European legislation, yet allegedly play a key role in *B. salamandrivorans* epidemiology (Fitzpatrick et al., 2018; this report). In the absence of legislation, disease control in amphibians is largely based on stakeholders' voluntary participation, stressing the need for increased awareness and voluntary compliance of the private sector with the clean trade principle. Since the domestic host population presents the weak link, initiatives to reduce the probability of pathogen pollution by supporting amphibian pathogen-free collections of pet keepers would be a valuable addition to the existing pan European policy initiatives (EU2018/1882, ENV.B.3/SER/2016/0028) and OIE (OIE, 2017).

The current voluntary participation of hobbyists in *B. salamandrivorans* disease control may be encouraged by the distinct advantage of improved health of a pathogen-free collection. Hobbyist societies should raise awareness and encourage their members to subscribe to the clean trade principle. Absence of *B. salamandrivorans* (and other amphibian pathogens) from the commercial trade would benefit from a code of conduct subscribed by professional organizations. The European Commission is advised to implement the temporary directive (EU2018/1882, ENV.B.3/SER/2016/0028) in the upcoming Animal Health Law and to extend this legislation to include the private sector. The principle to eradicate the *B. salamandrivorans* disease reservoir from the live amphibian trade chain could be expanded to include other trade related and OIE listed amphibian pathogens (ranaviruses, *B. dendrobatidis*) and amphibians (anurans, caecilians). Finally, the EU and EU member states should be encouraged to adopt and maintain early warning systems and emergency action plans that can be deployed immediately upon pathogen detection. Wide implementation of biosecurity protocols for activities in amphibian habitats is encouraged.

ACKNOWLEDGEMENTS

A.M. and F.P. are supported by ENV.B.3/SER/2016/0028. S. Canessa was supported by grant FWO16/PDO/019. M. Kelly was supported by grant 1111119N. S. Carranza was supported by the Ministerio de Ciencia, Innovación y Universidades grant numbers CGL2015-70390-P and PGC2018-098290-B-I00 (Co-funded by FEDER) and Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya under Grant number 2017-SGR-00991. CRARC pcr analyses were performed by Laboklin (Germany). The captive breeding program of *Calotriton arnoldi* is supported by LIFE15 NAT/ES/000757.

ORCID

An Martel https://orcid.org/0000-0001-7609-5649
Stefano Canessa https://orcid.org/0000-0002-0932-826X

REFERENCES

Blooi, M., Martel, A., Haesebrouck, F., Vercammen, F., Bonte, D., & Pasmans, F. (2015). Treatment of urodelans based on temperature dependent infection dynamics of *Batrachochytrium salamandrivorans*. *Scientific Reports*, *5*, 8037.

Bosch, J., Sanchez-Tomé, E., Fernandez-Loras, A., Oliver, J. A., Fisher, M. C., & Garnter, T. W. J. (2015). Successful elimination of a lethal wildlife infectious disease in nature. *Biology Letters*, *11*, 20150874.

Canessa, S., Bozzuto, C., Grant, E. H. C., Cruickshank, S. S., Fisher, M. C., Koella, J. C., … Schmidt, B. R. (2018). Decision-making for mitigating wildlife diseases: From theory to practice for an emerging fungal pathogen of amphibians. *Journal of Applied Ecology*, *55*, 1987–1996.

Canessa, S., Bozzuto, C., Pasmans, F., & Martel, A. (2019). Quantifying the burden of managing wildlife diseases in multiple host species. *Conservation Biology*, *33*(5), 1131–1140.

Carranza, S., & Martínez-Solano, I. (2009). *Calotriton arnoldi*. In: IUCN 2013. 2013 IUCN Red List of Threatened Species Version 2013.1. www.iucnredlist.org.

Codex Alimentarius Commission. Codex Alimentarius (1997). Annex to CAC/RCP 1-1969, Rev. 3.EU 2018/320. Commission Implementing Decision (EU) 2018/320 of February 2018 on certain animal health protection measures for intra-Union trade in salamanders and the introduction into the Union of such animals in relation to the fungus *Batrachochytrium salamandrivorans. Official Journal of the European Union L 62*, 5.3.2018, pp.18–33.

EU 2018/1882. Commission Implementing Regulation (EU) 2018/1882 on the 'Animal Health Law' and Commission Delegated Regulation (EU) 2018/1629. *Official Journal of the European Union*, *L308/21*.

ENV.B.3/SER/2016/0028. European Commission Tender. Mitigating a new infectious disease in salamanders to counteract the loss of European biodiversity.

Fisher, M. C., Henk, D. A., Briggs, C.J., Brownstein, J. S., Madoff, L. C., McCraw, S. L., & Gurr, S. J. (2012). Emerging fungal threats to animal, plant and ecosystem health. *Nature*, *484*, 186–194.

Fitzpatrick, L. D., Pasmans, F., Martel, A., & Cunningham, A. A. (2018). Epidemiological tracing of *Batrachochytrium salamandrivorans* identifies widespread infection and associated mortalities in private amphibian collections. *Scientific Reports*, *8*, 13845.

Fontelles, F., Guixé, D., Martínez-Silvestre, A., Soler, J., & Villero, D. (2011). Hallada población introducida de *Ommatotriton ophryticus* en el Prepirineo catalán. *Boletín de la Asociación Herpetológica Española*, *22*, 153–156.

Garner, T. W. J., Schmidt, B. R., Martel, A., Pasmans, F., Muths, E., Cunningham, A. A., … Bosch, J. (2016). Mitigating amphibian chytridiomycoses in nature. *Philosophical Transactions of the Royal Society B*, *371*, 20160207.

IPBES Global Assessment Report on Biodiversity and Ecosystem Services (2019).

Martel, A., Blooi, M., Adriaensen, C., Van Rooij, P., Beukema, W., Fisher, M. C., … Pasmans, F. (2014). Recent introduction of a chytrid fungus endangers Western Palearctic salamanders. *Science*, *346*, 630–631.

Martel, A., Spitzen-van der Sluijs, A., Blooi, M., Bert, W., Ducatelle, R., Fisher, M. C., … Pasmans, F. (2013). *Batrachochytrium salamandrivorans* sp. nov. causes lethal chytridiomycosis in amphibians. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 15325–15329.

OIE World Organisation for Animal Health (2017). *Aquatic Animal Health Code*. Retrieved from http://www.oie.int/en/international-standard-setting/aquatic-code/access-online/

OIE World Organisation for Animal Health (2018). *Terrestrial Animal Health Code*. Retrieved from https://www.oie.int/fileadmin/Home/eng/Health_standards/tahc/2018/en_sommaire.htm

Polonsky, J. A., Baidjoe, A., Kamvar, Z. N., Cori, A., Durski, K., Edmunds, W. J., … Jombart, T. (2019). Outbreak analytics: A developing data science for informing the response to emerging pathogens.

Philosophical Transactions of the Royal Society B, *374*(1776), 20180276.

Scheele, B., Pasmans, F., Skerratt, L., Berger, L., Martel, A., Beukema, W., … Canessa, S. (2019). Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. *Science*, *363*, 1459–1463.

Spitzen-van der Sluijs, A., Stegen, G., Bogaerts, S., Canessa, S., Steinfartz, S., Janssen, N., … Martel, A. (2018). Post-epizootic salamander persistence in a disease-free refugium suggests poor dispersal ability of *Batrachochytrium salamandrivorans*. *Scientific Reports*, *8*, 3800.

Stegen, G., Pasmans, F., Schmidt, B., Rouffaer, L. O., Van Praet, S., Schaub, M., & Martel, A. (2017). Drivers of salamander extirpation mediated by *Batrachochytrium salamandrivorans*. *Nature*, *544*, 353–356.

Thomas, V., Wang, Y., Van Rooij, P., Verbrugghe, E., Balaz, V., Bosch, J., … Pasmans, F. (2019). Mitigating *Batrachochytrium salamandrivorans* in Europe. *Amphibia-Reptilia*, *40*, 265–290.

Yap, T. A., Koo, M. S., Ambrose, R. F., Wake, D. B., & Vredenburg, V. T. (2015). Averting a North American biodiversity crisis. *Science*, *349*, 481–482.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: MartelA, Vila-EscaleM, Fernández-GiberteauD, et al. Integral chain management of wildlife diseases. *Conservation Letters*. 2020;e12707. https://doi.org/10.1111/conl.12707