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Chapter *in* Revue Scientifique et Technique de l OIE · December 2019

DOI: 10.20506/rst.38.2.2998

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Rev. Sci. Tech. Off. Int. Epiz., 2019, **38** (2), 459-475

Impacts of epizootic ulcerative syndrome on subsistence fisheries and wildlife

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Summary

Epizootic ulcerative syndrome (EUS), caused by the water mould (Oomycota) *Aphanomyces invadans*, has spread throughout the world's major continents over the last 50 years, with the apparent exception of South and Central America. With over 160 susceptible fish species representing 54 families and 16 orders recorded to date, EUS is of international concern and infection with *A. invadans* is a World Organisation for Animal Health (OIE) listed disease. This paper examines what little has been reported on the impacts of EUS on subsistence fisheries and wildlife, or what can be deduced about those impacts, and concludes that there is a need for systematic data collection on the size and socio-economic importance of subsistence fisheries. Such fisheries are often relied upon by the poorest communities, thus food and nutrition security impacts can be significant. Similarly, impacts on wildlife are poorly documented, emphasising the lack of, and the need for, research on and modelling of the ecosystem-level impacts of EUS and other aquatic animal diseases. The history of EUS and several other aquatic animal diseases also brings into question the effectiveness of current measures for controlling the international spread of aquatic animal diseases and calls for a re-think on how best to meet this ongoing challenge.

Keywords

Aphanomyces invadans – Environmental degradation – Epizootic ulcerative syndrome (EUS) – Fish disease – Food security – Poverty – Translocation.

Introduction

Epizootic ulcerative syndrome (EUS) is a seasonal epizootic disease that affects a vast range of freshwater and estuarine fish; with over 160 teleost species known to be susceptible to the disease. It is the first known non-salmonid disease affecting estuarine and freshwater fish that has spread internationally with major impacts, especially in the developing world. It is also referred to as red spot disease, mycotic granulomatosis and ulcerative mycosis. Baldock *et al.* proposed renaming the disease 'epizootic granulomatous aphanomycosis', but EUS remains the most commonly used term (1). Despite its long history, going back to the first report of the disease in farmed ayu (*Plecoglossus altivelis*) in Japan (2), EUS continues to be at the forefront of scientific study, with two recent major reviews by Kamilya and Baruah (3) and, most recently, Kar's book entitled, *Epizootic Ulcerative Fish Disease Syndrome* (4).

Listed as an 'infection with *Aphanomyces invadans*' by the World Organisation for Animal Health (OIE) (5), EUS has a complex infectious aetiology. It is clinically characterised by the presence of *Aphanomyces invadans* (syn. *A. piscicida*) and necrotising ulcerative lesions that usually lead to a pathognomonic granulomatous response. The lesions, often on the lateral surface, can be on any part of the fish and may manifest as follows:
– pinpoint haemorrhagic spots
– localised swellings
– localised raised areas on the body surface
– scale protrusion or loss
– skin erosion
– reddened areas of the skin under the scales
– exposure of underlying musculature
– ulceration (6).

The OIE's *Manual of Diagnostic Tests for Aquatic Animals* provides a comprehensive description of the disease (7).

Aphanomyces invadans is a water mould (Oomycetes), a fungus-like eukaryotic microorganism that includes other important fish pathogens, such as species of *Saprolegnia* and *Achlya*. Oomycetes belong to the Straminopiles kingdom,

doi: 10.20506/rst.38.2.2998

being more closely related to diatoms, brown algae and golden brown algae than true fungi (8). Unlike fungi, Oomycetes do not have chitin-based cell walls; instead their cell walls are composed of cellulosic compounds and glycan, and the nuclei within the filaments are diploid, rather than haploid as is the case in fungi (9). Previous names for *A. invadans* include *A. piscicida* (10) and *A. invaderis* (11).

This disease agent is transmitted via water-borne free-swimming secondary zoospores that germinate upon attaching themselves to fish skin that has been damaged by flushing of low pH water (from disturbed acid sulphate soils) or by parasites. Moreover, EUS and associated mortalities are seasonal. Infection occurs mostly at water temperatures of 18–22°C and after periods of heavy rainfall (12), conditions that favour sporulation (13) whilst delaying the immune response of the host fish (14, 15). Natural EUS spread within a catchment area can occur upstream or downstream, and by flooding (7). The global spread of EUS across natural boundaries has probably occurred through the translocation of live fish (16). Huchzermeyer *et al.* (17) raised the possible role of live and frozen fish imports from Asia as a means of EUS spread to Africa, either through carrier fish (noting that Nile tilapia are considered resistant to infection) or through the transport of water harbouring zoospores. They also speculated on the possibility of EUS being spread through sun-dried and smoked fish, or the action of birds. An investigation by the Food and Agriculture Organization of the United Nations (FAO) of an EUS outbreak in the Democratic Republic of the Congo identified that fish of the Clariidae, Channidae and Protopteridae families were of greatest concern due to their importance as food species and the fact that they are air breathing and can be readily transported live to market (18). EUS appears to readily cross land barriers as evidenced in its reported spread, likely to be human or bird assisted, to seasonal water bodies in India and Bangladesh (19, 20, 21).

Kamilya and Baruah (3) and, more recently, Kar (4), have reviewed the long history of EUS since its first reported occurrence in Japan in 1971 and subsequent reports in Australia in 1972, across Asia in the 1980s and 1990s, in the United States of America (USA) in 1980, Africa in the mid-to-late 2000s, and most recently in Canada in 2010. However, to date, EUS has not been reported in Central or South America. The first EUS-related epizootics were especially alarming because many species were clinically affected, leading to speculation at the time on possible pollutants in the water and associated public health concerns. The complexity of the disease, difficulty in isolating the pathogen, and, to an extent, the reluctance of the scientific community at the time to accept that a species of fungus or a fungus-like organism could be the primary causative agent of such a fish disease, meant that a firm establishment of the role of *A. invadans* in the aetiology of EUS was not reached until the Fifth Symposium on Diseases in Asian Aquaculture in 2002 (1). The majority of the experts who participated at the meeting concluded EUS to be an 'aphanomycosis', with *A. invadans* being the sole necessary infectious cause. Thus, despite *Aphanomyces* being associated with EUS as early as 1992 (22), and transmitted experimentally to produce ulcers in 1995 (15), it was another ten years before consensus was reached on the disease's aetiology, which was 20 years after the first major Asian epizootics had taken place.

This paper describes the known and likely impacts of EUS on subsistence fisheries and wildlife, and attempts to extrapolate what are, in the view of the authors, the key lessons to be learned.

Impacts of epizootic ulcerative syndrome on subsistence fisheries

Subsistence fishing is defined, for the purposes of this paper, as fishing that is carried out using artisanal (i.e. traditional, non-mechanised) fishing techniques in very poor communities, primarily to feed the family and relatives of the fisher (23, 24, 25). It is acknowledged, however, that pure subsistence fisheries are rare, because part of the catch is often sold or exchanged for other goods or services (26). Globally, subsistence fishing can occur in fresh (rivers, reservoirs, floodplains, community tanks), brackish (estuaries and backwaters) and coastal marine waters. EUS does not occur in marine waters and hence the syndrome's impacts are confined to fresh and brackish water (inland) subsistence fisheries.

Subsistence fishery stock losses

Production losses due to outbreaks of EUS are difficult to quantify simply because the impacts of aquatic animal diseases, be they on aquaculture, subsistence fisheries, capture fisheries or the environment, are seldom quantified with precision. Subsistence fisheries are especially difficult to measure in terms of volume or value (23), mainly because of their dispersed, usually unregulated nature which makes data collection a relatively resource-intensive exercise. As a result, monitoring of this sector by fishery management agencies in developing countries is typically their lowest priority, so subsistence fisheries are not well, if at all, reflected in catch statistics (27). The difficulty in measuring the size of subsistence fisheries can be further exacerbated by illegal subsistence fishing in some jurisdictions (25) or subsistence-fishing activities that create cross-jurisdictional issues between government agencies. An example of this is indigenous peoples' fishing activities that may come under the purview of both fisheries agencies and social service-type government entities, and as a result may not be monitored or reported by either. Moreover, there may be little incentive for already under-resourced fishery management agencies to invest in a fishery that does not contribute directly to the market economy. These challenges and the associated uncertainties in the available data should be acknowledged when considering the estimations included in the scientific literature of the disease's impacts on capture fisheries.

Perhaps the most notable epidemiological characteristic of EUS, and of *A. invadans* as its primary causative agent, is its vast host range and the relatively small number of species reported to be resistant to clinical signs of the disease during EUS epizootics. For the purposes of this paper, an up-to-date list of species known to be susceptible to EUS has been compiled, which comprises over 160 species of bony fish representing 54 families and 16 orders (Table I). This wide host range means that many more species are likely to be susceptible to clinical disease that are yet to

Table I
Fish species reported to be susceptible to the clinical disease associated with epizootic ulcerative syndrome

Scientific name	Common name
*Acanthocobitis botia**	Mottled loach
Acanthopagrus australis	Yellowfin sea bream
Acanthopagrus berda	Black bream
*Ailia coila**	Gangetic ailia
*Ailia punctata**	Jamuna ailia
Alosa sapidissima	American shad
Ambassis agassizii	Chanda perch
*Amblypharyngodon mola**	Mola carplet
Ameiurus melas	Black bullhead
Ameiurus nebulosus	Brown bullhead
Amniataba percoides	Striped grunter
Anabas testudineus	Climbing perch
Archosargus probatocephalus	Sheepshead
Arius spp.	Fork-tailed catfish
*Badis badis**	Badis
Bairdiella chrysoura	Drums or croakers
Bidyanus bidyanus	Silver perch
*Botia dario**	Bengal loach
*Branchygobius nunus**	–
Brevoortia tyrannus	Atlantic menhaden
Brycinus lateralis	Striped robber
*Canthophrys gongota**	Gongota loach
Carassius auratus auratus	Goldfish
Catla catla	Catla
*Chaca chaca**	Squarehead catfish
*Chanda nama**	Elongate glass-perchlet
*Chandramara chandramara**	–
Channa marulius	Great snakehead fish
*Channa punctata**	Spotted snakehead
Channa striatus	Striped snakehead
*Chela cachius**	–
*Cirrhinus ariza**	Reba
*Cirrhinus cirrhosus**	Mrigal carp
Cirrhinus mrigala	Mrigal
Clarias batrachus	Walking catfish
Clarias gariepinus	Sharptooth African catfish
Clarias ngamensis	Blunt-toothed African catfish
*Clarias theodorae**	Snake catfish
Colisa lalia	Dwarf gourami
Coptodon rendalli	Redbreast tilapia
*Corica soborna**	Ganges river sprat
*Ctenopoma multispine**, **	Many-spined ctenopoma
*Danio devario**	Sind danio
Enteromius paludinosus	Straightfin barb
Enteromius poechii	Dashtail barb
Enteromius thamalakanensis	Thamalakane barb
*Enteromius trimaculatus**, **	Threespot barb
Enteromius unitaeniatus	Longbeard barb
*Esomus danrica**	Flying barb
Esomus sp.	Flying barb
*Gagata cenia**	Indian gagata
*Gangra viridescens**	–
Glossamia aprion	Mouth almighty
Glossogobius giuris	Bar-eyed goby
Glossogobius sp.	Goby
*Gudusia chapra**	Indian river shad

Scientific name	Common name
Helostoma temmincki	Kissing gourami
Hepsetus odoe	African pike
*Heteropneustes fossilis**	Stinging catfish
Hydrocynus vittatus	Tigerfish
*Hypophthalmichthys nobilis**	Bighead carp
*Hyporhampus quoyi**	Quoy's garfish
*Ichthyocampus carce**	–
Ictalurus punctatus	Channel catfish
*Johnius coitor**	–
Kurtus gulliveri	Nursery fish
*Labeo bata**	Bata
*Labeo boga**	–
Labeo cylindricus	Red-eye labeo
Labeo lunatus	Upper Zambezi labeo
Labeo rohita	Rohu
Lates calcarifer	Barramundi or sea bass
*Leiodon cutcutia**	Ocellated pufferfish
Leiopotherapon unicolor	Spangled perch
*Lepidocephalichthys guntea**	Guntea loach
Lepomis macrochirus	Bluegill
Liza spp.	Mullets
Lutjanus argentimaculatus	Mangrove jack
Maccullochella ikei	Freshwater cod
Maccullochella peelii	Murray cod
Macquaria ambigua	Golden perch
Macquaria novemaculeata	Australian bass
*Macrognathus aculeatus**	Lesser spiny eel
*Macrognathus pancalus**	Barred spiny eel
Marcusenius macrolepidotus	Bulldog
*Mastacembelus armatus**	Zig-zag eel
Melanotaenia splendida	Rainbow fish
Micralestes acutidens	Silver robber
Micropterus salmoides	Largemouth black bass
Monopterus alba	Swamp eel
Mugil cephalus	Grey mullet or striped mullet
Mugil curema	White mullet
Mugil spp.	Mullets

Scientific name	Common name
*Mystus bleekeri**	Day's mystus
*Mystus cavasius**	Gangetic mystus
*Mystus tengara**	Tengara catfish
*Mystus vitatus**	Striped dwarf catfish
Myxus petardi	Pinkeye mullet
*Nandus nandus**	Gangetic leaffish
Nematalosa erebi	Bony bream
*Neoeucirrhichthys maydelli**	Goalpara loach
*Notopterus notopterus**	Bronze featherback
*Ompok pabda**	Pabdah catfish
Oncorhynchus mykiss	Rainbow trout
Oreochromis andersonii	Three-spotted tilapia
Oreochromis machrochir	Greenhead tilapia
Osphronemus goramy	Giant gourami
*Osteobrama cotio**	–
Oxyeleotris lineolatus	Sleepy cod
Oxyeleotris marmoratus	Marble goby
*Pachypterus atherinoides**	Indian potasi
*Parambassis baculis**	Himalayan glassy perchlet
*Parambassis ranga**	Indian glassy fish
*Pellona ditchela**	Indian pellona
*Pethia conchonius**	Rosy barb
*Pethia gelius**	Golden barb
*Pethia phutunio**	Spottedsail barb
*Pethia ticto**	Ticto barb
Petrocephalus catostoma	Churchill
*Pharyngochromis acuticeps**	Zambezi bream
Platycephalus fuscus	Dusky flathead
Plecoglossus altivelis	Ayu
Pogonias cromis	Black drum
Pollimyrus isidori, **	Elephant fish
Psettodes sp.	Spiny turbot
*Pseudapocryptes elongatus**	–
*Puntius chola**	Swamp barb
Puntius gonionotus	Silver barb
Puntius sophore	Pool barb
*Puntius terio**	Onespot barb

Scientific name	Common name
*Rasbora daniconius**	Slender rasbora
*Rhinomugil corsula**	Corsula
Rohtee sp.	Keti-Bangladeshi
*Salmostoma bacaila**	Large razorbelly minnow
*Salmostoma phulo**	Finescale razorbelly minnow
Sargochromis carlottae	Rainbow bream
Sargochromis codringtonii	Green bream
Sargochromis giardi	Pink bream
Scatophagus argus	Spotted scat
Schilbe intermedius	Silver catfish
Schilbe mystus	African butter catfish
Scleropages jardini	Saratoga
Scortum barcoo	Barcoo grunter
Selenotoca multifasciata	Striped scat
Serranochromis angusticeps	Thinface largemouth
Serranochromis robustus	Nembwe
*Sicamugil cascasia**	Yellowtail mullet
Sillago ciliata	Sand sillago
Siluridae (genus)	Wels catfish
*Sperata seenghala**	Giant river-catfish
Strongylura krefftii	Long tom
Synclidopus macleayanus	Narrow banded sole
*Systomus sarana**	Olive barb
Therapon sp.	Therapon, grunters
Tilapia sparrmanii	Banded tilapia
Toxotes chatareus	Common archer fish
Toxotes lorentzi	Primitive archer fish
*Trichogaster chuna**	Honey gourami
*Trichogaster fasciatus**	Banded gourami
*Trichogaster labiosa**	Thick-lipped gourami
*Trichogaster lalius**	Dwarf gourami
Trichogaster pectoralis	Snakeskin gourami
Trichogaster trichopterus	Three-spot gourami
Tridentiger obscurus obscurus	Dusky tripletooth goby
*Wallago attu**	Wallago
*Xenentodon cancila**	Freshwater garfish

* Species not listed in the current OIE *Manual of Diagnostic Tests for Aquatic Animals* as being susceptible to *Aphanomyces invadans* infection (7)
** Presumptive diagnosis based on clinical signs only (17) – all other species are confirmed as being susceptible to *A. invadans* based on histological diagnosis (28, 29, 30, 31, 32)
Note: All species nomenclature has been made consistent with FishBase (33)

be reported, and most inland fisheries in tropical and sub-tropical regions, including subsistence fisheries, would likely be affected by an EUS outbreak. However, Lilley *et al.* noted that some commercially important species, such as common carp (*Cyprinus carpio*), Nile tilapia (*Oreochromis niloticus*) and milkfish (*Chanos chanos*), are considered naturally resistant to infection (34).

The wide host range of EUS has special relevance for subsistence fisheries because the subsistence fishery catch (compared to commercial capture fisheries) is typically not species specific, in that each harvest could include a range of fish species, sizes and year classes. Indeed, examination of the fish diseases listed by the OIE reveals that *A. invadans* has the highest number of documented host aquatic animal species susceptible to clinical disease, especially in the tropics and sub-tropics where subsistence fishing is most common. A review of the literature to support this paper indicates that the number of host species reported to date is close to 170.

Of those susceptible species, estimates of infection prevalence vary from 20 to 90%, although mortality patterns are seasonal (28). In fact, Das (29) estimated declines ranging from 28 to 97% in landings of those fish species susceptible to EUS from the Indian controlled portion of the Brahmaputra River system during the EUS outbreaks of 1988–1991 (Table II).

Reports indicate that seasonal fish grow-out in temporary water-bodies is widely practised in South Asia and these locations could be classed in many cases as subsistence fisheries (19, 20, 21). Fish are either introduced or make their way into these water bodies and are harvested primarily when the water-bodies dry out towards the end of the dry season. These reports, however, tend to focus on the financial impact caused by the decrease in fish sales of extra fish caught. Currently, measures of direct losses to subsistence fisheries attributable to EUS are unavailable.

Epizootic ulcerative syndrome may affect the production of susceptible species in countries where rice-fish culture is practised, either incidentally to rice farming or as part of planned rice-fish-integrated farming. Since many cyprinids, the dominant human food species in Asia, including South Asia, are susceptible to EUS, some impact on the

Table II
Decline in landings of some highly susceptible species in the Indian-controlled portion of the Brahmaputra River System during the epizootic ulcerative syndrome outbreaks of 1988–1991, prevalence of lesions in these species and estimated severity on wild fish in Bangladesh

Species	Decline in landings (%) [a]	Percentage affected	Severity index [b]
Amblypharyngodon mola	37–71	3.7	XXX
Channa punctata [c]	85–94	30.7	XXX
Channa striatus [c]	82–88	65.1	XXXX
Cirrhinus cirrhosus	28–66		
Labeo bata	54–87		
Labeo rohita	49–63		
Nandus nandus [c]	82–97	40.9	XXXX
Puntius spp.[c]	64–90		

a) Data sourced from (29)
b) A subjective measure with 'XXXX' representing the highest severity (28)
c) Species caught by subsistence fishers (32)

Table III
Inland fishery production in Asia and Africa (35)

Country	Inland capture production (million tonnes)
Asia	
People's Republic of China	2.32
India	1.50
Bangladesh	1.05
Myanmar	0.89
Cambodia	0.51
Indonesia	0.43
Thailand	0.19
Philippines	0.16
Africa	
Uganda	0.39
Nigeria	0.38
Tanzania	0.31
Egypt	0.23
Democratic Republic of the Congo	0.23

communities practising rice-fish culture is expected. This impact can be reduced by farming cyprinid species that are EUS resistant.

Importance of inland capture fisheries

Given the paucity of published information on subsistence fishing in areas affected by EUS, it is worth reflecting on the importance of inland fisheries as a food source more broadly (i.e. including commercial inland fisheries). In 2016, capture fishery production worldwide was 90.9 million tonnes, of which inland fisheries provided 11.6 million tonnes (12.8%) (35). Of the 16 major inland fishery production countries (which make up almost 80% of the global total), eight are in Asia and five in Africa (Table III). Furthermore, the production figures presented in Table III are likely to be gross underestimates, due the fact that inland fishery production is often under-reported (36). The relative importance of inland fisheries in these countries as a source of food security is therefore likely to be greater than that reflected in the data presented. Indeed, 15 of the 21 countries with the highest per capita inland fish production are low-income food-deficit countries (LIFDCs) (35). These countries have been classified as such by FAO on the basis of having low per capita gross national income (GNI, the gross domestic product plus incomes earned by foreign residents, minus income earned in the domestic economy by non-residents) and being net importers of food (noting that countries can opt not to be classified as LIFDCs). LIFDCs provide 43% of global inland capture fishery production. Inland fisheries are an important food source for several countries in Africa, which accounts for 25% of global inland catches (35).

Based on the general importance of inland-capture fisheries as a food source in developing countries in Asia and Africa, the role of subsistence fisheries in these same countries is expected to be significant, and perhaps crucial in those that are LIFDCs. Importantly, two groups of inland fishery species common to Asia and Africa – carps, barbels and other cyprinids, and tilapias and other cichlids, respectively – are heavily represented in those fish species known to be susceptible to EUS (Table I), further heightening the seriousness of EUS impacts in these countries.

Food and nutrition security

An estimated 90% of global inland fishery production is directed at human consumption (35) as, by definition, is 100% of subsistence fishery take. Diminished subsistence fishery resources due to EUS-related stock losses will therefore affect the food and nutrition security of subsistence-fishing-dependent communities, but longer-term flow-on consequences to community health and livelihoods and even deeper societal impacts might also be expected.

There is a long tradition in Africa and Asia of supplementing a basic diet of corn ('mealie meal') or rice with locally sourced protein, such as chicken or fish (37). Subsistence fisheries in developing countries can play a crucial role in the nutritional security of communities near water, of which Thilsted *et al.* (38) provide an excellent review. They highlight the high concentrations of bio-available vitamins and minerals (such as vitamin B_{12}, calcium, iron and zinc), essential fatty acids and animal protein that small fish can provide for infants and young children, particularly for child development via the nutrition of pregnant and lactating women. Small indigenous fish species, often caught by subsistence fishers, are typically eaten whole and can make a significant contribution to the micronutrient intake of fisher families. Fish consumption can also enhance the uptake of micronutrients from plant-sourced foods (38, 39, 40). Huchzermeyer *et al.* (17) pointed to the serious risk of EUS spreading in the Congo River catchment and the potential impact of this on what is a diverse, sensitive and poorly studied rainforest ecosystem, on which a large part of the Congolese population depends for its protein. The authors also cited several sources documenting the largest artisanal fisheries in Zambia as those of the Bangweulu floodplain and swamp, with over 5,000 artisanal fishers, in which EUS has now also been reported.

These food security impacts would be mitigated in some circumstances where there is ready access to alternative, EUS-resistant species. Das (29) noted that landings of Indian river shad (*Gudusia chapra*), a species not known to be susceptible to the clinical disease associated with EUS, increased almost nine-fold during a period of massive declines in the landing of wild fish from the Brahmaputra River (1988–1991). This also included a decline in *Channa* species by 85–88%, indicating a possible shift by fishers to a species not previously targeted.

Freshwater fish are a rich source of protein for human health, particularly for the poorest and most vulnerable (36, 41). The importance of subsistence fisheries for the rural poor in developing countries where such fisheries are a key protein and nutrient source is much greater than might be indicated purely by the volume of the catch lost to disease. The FAO (42) estimated that the effect of EUS on the fish stocks of the Zambezi River catchment affected the food security of 32 million people. Local communities in Africa have historically relied less on subsistence fisheries for nutrition security than their counterparts in Asia. This is largely because, in Africa, inland fisheries are mainly confined to rivers and reservoirs, without the large-scale irrigation systems seen in Asia. Despite this, in areas where other sources of protein have become limited, the importance of fish, albeit in small quantities, is likely to be significant.

Aside from the direct stock losses caused by EUS, policy interventions in the form of fishing bans during outbreaks can add to the food security impact on subsistent-fishery-dependent communities. In the authors' experience, the immediate response of policy-makers in many countries in Asia and Africa has been to take the precaution of banning fishing in public waters to allay public food-safety concerns. Despite the paucity of hard data in most countries, there are some examples that show the importance of subsistence fisheries to traditional societies. For example, notwithstanding the tropical/sub-tropical climatic range of EUS and its confinement to fresh and brackish waters, studies in Samoa, Canada and Alaska provide some insight into the potentially significant role of subsistence fisheries as a food source. Miller (43) estimated the annual fish consumption from Great Bear Lake in Canada to be about three tonnes per family per year. An analysis of a much bigger data set by Berkes (24) revealed that subsistence fisheries in Canada provide 60 kg of fish per person per year, equating to 42 kg of edible protein, a level of fish consumption similar to Alaskan natives who in the 1980s were harvesting 104 kg of dressed fish per person per year. In Samoa, subsistence fishing has been estimated to be 4,600 tonnes per year, almost twice the commercial catch (44).

Cultural changes

The impact of aquatic animal diseases, such as EUS, on poor rural communities can be exacerbated by the replacement of locally harvested food with cheap and readily available, but nutritionally inadequate, commercially processed foods. The reliance on low-cost processed foods, coupled with an erosion of artisanal fishing skills over periods when subsistence fishery stocks are meagre, could pose a longer-term risk to nutrition security in many rural communities. Despite nutritional deficiencies, sales of instant noodles, for example, have increased rapidly over recent decades due to convenience (including long shelf life) and affordability, especially in Asia and Africa (45, 46). Periods when locally harvested foods are not as readily available, as would be the case during the years it would take for EUS-impacted fisheries to recover, present an opening for more readily available, nutritionally poor products to gain a foothold in affected local communities and be culturally accepted as part of the staple diet.

Beyond the direct nutrition security concern, diseases that affect subsistence fisheries can also undermine family relationships and, thereby, community stability. In South Africa, for example, women and children comprise >20% and 15% of subsistence fishers, respectively (47). Subsistence fishing therefore provides a level of independence and financial emancipation that might be undermined by EUS.

Concomitant adverse environmental conditions

The impacts of EUS can also be further complicated by adverse environmental conditions, such as the toxicity of iron and aluminium in acidic waters, and flood events that are usually associated with EUS outbreaks (17, 48, 49, 50, 51). The FAO (18) noted that the EUS outbreaks in the Democratic Republic of the Congo were associated with seasonal flooding cycles and low-pH water, and that local weather patterns had been disrupted as a consequence of global warming. These types of environmental conditions are likely to compound the impact of EUS on subsistence fishers, who not only have less and poorer-quality fish (typically ulcerated), but who are also affected by the changes in water flow and quality preceding EUS outbreaks.

The role of poverty

The food and nutrition impacts of subsistence fishery losses are likely to be more significant in poorer countries and communities. In this context, an examination of poverty levels alongside the importance of inland fisheries and fish consumption can provide insight into the likely significance and extent of EUS impacts at a subsistence fisher level.

Table IV and Figure 1 present two indices of poverty, the GNI and the Multidimensional Poverty Index (MPI), of EUS-positive countries. Information on inland fishery production (as a relative proxy for sustainable fishery take) and per capita fish consumption are also provided. The global distribution of EUS is weighted towards tropical and sub-tropical countries, which typically have lower GNIs and higher MPIs (i.e. developing countries). Of the 28 states (27 countries and Hong Kong, Special Administrative Region of the People's Republic of China) known to be EUS-positive, eight have GNIs of US$ 10,000–30,000 and 14 have GNIs below US$ 10,000. In addition, of the 11 countries with the lowest GNI, five are LIFDCs as defined by FAO. Moreover, two of these LIFDCs, India and Bangladesh, have the largest inland capture fisheries in the world. Of the five African countries declared EUS-positive to date, Zimbabwe, Zambia and Namibia have a GNI below US$ 10,000, and Botswana and South Africa have GNIs below US$ 15,000.

All eight Asian countries which have important inland fisheries (India, Bangladesh, Myanmar, Cambodia, Indonesia, Thailand and the Philippines) have reported EUS, but, to date, no official record exists of the disease from the five leading African countries in inland capture fish production (Uganda, Nigeria, Tanzania, Egypt and the Democratic Republic of the Congo). Because many cichlids are known to be susceptible to EUS, the risk of the disease spreading to new countries in Africa that have inland capture fisheries significant to livelihoods and food security is high. The FAO in its annual *The State of World Fisheries* report categorises per capita kilogram inland fishery catch values into five groups: 0.1–1, 1–2, 2–5, 5–10 and 10–35 kg of catch per capita of country population. Of the known EUS-positive countries, five (Cambodia, Myanmar, Bangladesh, Laos and Zambia) have per capita inland fishery catches above 10 kg. The importance of inland fisheries to food and nutrition security (primarily in terms of protein supply) is expected to be especially significant in these countries.

Epizootic ulcerative syndrome has yet to be reported in South or Central America, although there is speculation that the disease agent might have originated from tropical or sub-tropical South America (4). A cautious approach would be to assume that these regions too are at high risk given the wide host range of EUS and the steady spread of EUS globally over the last 50 or so years.

Given the apparent importance of subsistence fisheries to the well-being of low socio-economic communities, there is an urgent need to collect data both on the catch from these fisheries and its importance as a food source, against which the impacts of a disease, such as EUS, can be assessed.

Wildlife impacts

Wildlife is defined variously in the literature to include solely undomesticated animals, undomesticated animals and plants or all undomesticated life forms. The authors have adopted a definition of wildlife consistent with that used by the OIE; that is, feral animals, captive wild animals and wild animals (5). It is worth noting at the outset that there is a lack of published scientific information on the wildlife impacts of EUS, or indeed other aquatic animal diseases, beyond that which might be extrapolated from impacts on capture fisheries. There is a clear need therefore for increased research and modelling of the broad ecological impacts of EUS and other aquatic animal diseases.

The discussion in this paper on the impacts on wildlife of EUS relies largely on information available on EUS impacts on inland fisheries, characterised by serious seasonal stock losses of a wide range of fish species in fresh and estuarine waters, resulting not only in the immediate loss of stock but also subsequent recruitment. In wild fish, EUS has been relatively well studied in Australia since at least 1976, where it has infected a wide range of species in the east of the country. Outbreaks of the disease in Australia are, as elsewhere, seasonal, typically occurring after rainfall events and associated water-quality changes (52). Some affected species are important components of ecosystems (e.g. bony herring, which are a primary food source for a number of piscivorous fish and birds), although the presence in some systems of large numbers of EUS-resistant feral fish (e.g. common carp and Nile tilapia) may reduce the overall impact of the temporary reduction in the numbers of prey fish. Outbreaks of EUS over a 200-km section of the Murray–Darling River system in 2008 and 2010 resulted in high rates of infection and pathology in bony herring (*Nematalosa erebi*), spangled perch (*Leiopotherapon unicolor*), Murray cod (*Macchullochella peelii*) and golden perch (*Macquaria ambigua*) (53). Other native species and feral fish species, such as common carp, did not appear to be clinically infected. The outbreaks occurred after high-flow

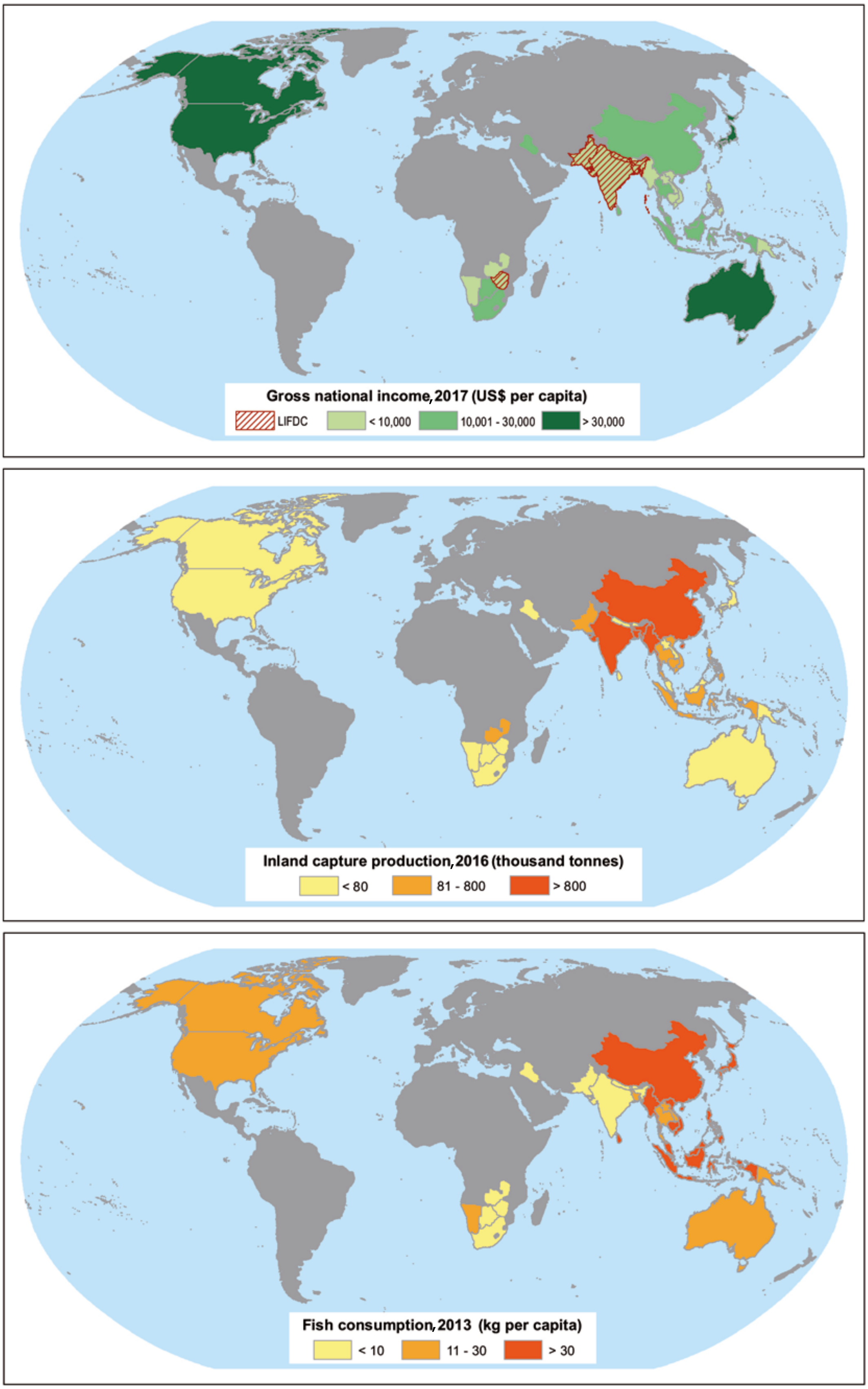
Table IV
Comparison of poverty indices, inland fishery production and fish consumption of epizootic ulcerative syndrome-positive states

Country	Gross national income per capita, 2017 (US$)	Multidimensional poverty index	Inland capture production, 2016 (thousand tonnes)	Per capita fish consumption, 2013 (kilograms per annum)
Zimbabwe	1,588 (LIFDC)	0.128	15.71	3.2
Nepal	2,337 (LIFDC)	0.116	21.50	2.30
Papua New Guinea	2,712	NA	13.5	17.5
Cambodia	3,095	0.150	509.35	41.4
Bangladesh	3,341 (LIFDC)	0.188	1,048.24	21.2
Zambia	3,464	0.264	83.92	10.0
Myanmar	4,943	NA	886.78	60.70
Pakistan	5,031 (LIFDC)	0.237	136.89	1.9
Laos	5,049	0.186	70.92	21.7
Vietnam	5,335	0.016	107.53	34.80
India	5,663 (LIFDC)	0.282	1,462.06	6.1
Bhutan	7,081	0.128	0.01	6.3
Philippines	8,395	0.033	159.62	30.20
Namibia	9,770	0.205	2.80	12.1
Indonesia	10,053	0.024	432.48	31.80
Sri Lanka	10,789	NA	73.93	30.1
Iraq	11,608	0.052	23.50	3.3
South Africa	12,087	NA	0.90	6.3
People's Republic of China	13,345	0.023	2,318.05	37.9
Thailand	14,519	0.004	187.30	27.0
Botswana	14,663	NA	0.04	4.1
Malaysia	24,620	NA	5.85	59.2
Japan	37,268	NA	27.95	48.9
Canada	42,582	NA	30.38	22.60
Australia	42,822	NA	1.0	26.30
United States of America	53,245	NA	22.42	21.5
Hong Kong (Special Administrative Region of the People's Republic of China)	54,265	NA	–	65.5
Singapore	78,162	NA	–	49.30

LIFDC: low-income food-deficit country
NA: not available

events in winter and, although EUS had been previously detected in 2008 in bony herring, the 2010 outbreak had the characteristics of a new outbreak of disease in a naïve population. The majority of the fish classes affected were of larger size, with severe ulceration and infection rates of over 20% in some areas, suggesting high sensitivity to the pathogen. In another native fish, silver perch (*Bidyanus bidyanus*), clinical infection rates reached 90% with over 50% mortality under culture conditions, although mortality in the wild has not yet been measured. In Australia, EUS has also been found in other species of native fish in the Gulf of Carpentaria river drainages and far-northern Queensland, although these events do not appear, in the authors' experience, to have been epizootics but rather limited to a few individuals at times of very low water levels, and sometimes in the early wet season when inflows into depleted water bodies first occur.

In Bangladesh, a comprehensive review by Lilley *et al.* (28) reported that large-scale surveys of fish populations (sample size >34,000 fish) found that approximately 26% of sampled fish had lesions (Table II). While not all fish may have had clinical EUS, the presence of lesions in winter and in EUS-susceptible fish indicate that the lesions



LIFDC: low-income food-deficit country

Fig. 1
Inland capture fishery production, fish consumption and gross national income of epizootic ulcerative syndrome-positive countries

were predominantly EUS lesions. The surveys sampled 69 species of which 15 had no samples with lesions, although, for some of these species, sample numbers were low (<50). The highest prevalence of lesions was noted in Gangetic ailia (*Ailia coila)* (66.7%), and a total of 24 species had infection rates of 20% or higher. Subasinghe and Hossain (54) found infection rates of 2–37% (1993–1994) and 0–11% (1994–1995) in wild fish in three floodplains in Bangladesh, with lower rates of infection in stocked hatchery-reared fish. In the 1990s, there was a decrease in the occurrence of clinical EUS in wild fish in Bangladesh. Species which previously experienced extreme mortality subsequently had lower rates of infection and evidence of healed lesions.

In the Bangweulu floodplains and swamps of the Upper Congo River Basin (in Zambia), annual outbreaks of EUS have been recorded since the initial severe outbreak in 2014 (17). Affected fish in this environment appeared to be the last to leave drying floodplains and attracted many piscivorous bird species.

In the Brahmaputra River, landings of the apparently EUS-resistant clupeid, the Indian river shad, rose significantly during a period of massive decline in landings of other fish due to EUS outbreaks, including a significant decline in *Channa* species (29). This shift in landings may indicate an increase in the shad population due to a decrease in the numbers of predatory species.

It is not possible with the current data to estimate what the long-term population level effects of EUS are or would be in the future. However, a consideration of how other diseases have impacted aquatic wildlife may give some insight into the possible longer-term effects of EUS. Sindermann (55) reviewed the impacts of a fungal disease (*Ichthyophonus hoferi*) in fish in the western North Atlantic. In addition to the direct mortality effects, there was also a flow-on effect of increased availability of food for those species resistant to *I. hoferi* infection, which manifested in an increase in the individual weight of cod landed. In this case, a cornerstone species (herring) was the main species affected, with other species affected to a lesser extent. Sindermann considered that the more probable long-term effect of mass mortality 'is a gradual return to the former population size and only temporary disturbances of many parts of the ecosystem in which the species is enmeshed' (56).

Other fungi and fungus-like species, such as *Aphanomyces astaci* and *Batrachochytrium dendrobatidis,* have caused massive loss of wildlife biodiversity; freshwater crayfish and frogs, respectively. Although there can be large declines in the abundance of highly susceptible wildlife species, EUS outbreaks are transient and seasonal in nature, with apparent potential for at least some susceptible fish species to develop a degree of tolerance to infection. Pradhan *et al.* (30), for example, observed that epizootics of EUS appeared to be less severe in years subsequent to the initial outbreak. Lilley *et al.* (28) noted that there may nonetheless be long-term losses to EUS after the initial epizootic, although this may be almost impossible to quantify. Over time, it is likely that EUS will infect new species as was the case in EUS-endemic areas of Uttar Pradesh, India, where Pradhan *et al.* (30) found the disease in species not previously reported to be susceptible to EUS, including some species that were previously considered resistant. Overall, EUS may have limited although locally important long-term effects on wild fish populations. Similarly, flow-on ecosystem impacts from these direct mortalities may also be expected to be transient in nature.

The effect of major disease epizootics limiting the availability of food to piscivorous wildlife is poorly documented. One aquatic animal disease where the effects on wildlife were relatively well documented was the series of epizootics resulting from pilchard herpesvirus (PHV) in southern Australia in 1995 and 1998 (31). While there are significant differences between EUS and the PHV outbreaks, similar general impacts on piscivorous wildlife observed with changes in fish population structure caused by PHV could also occur as a result of EUS. These changes could include the removal of a piscivorous species from a locality, reduced breeding success, or dietary changes that can have flow-on nutritional impacts on piscivorous species (57). Many piscivorous bird species changed prey after the pilchard epizootics, as sea bird prey selection is largely based on the size of prey rather than the species (31). Some fish size classes are demonstrably more susceptible to EUS-associated clinical disease than others. This could translate to impacts on the breeding success of piscivorous birds that favour the affected size classes (53, 57).

In the case of EUS, there would have been flow-on effects, such as an increase in the numbers of resistant prey fish species when large predatory fish numbers were substantially reduced. The change in prey species abundance may result in changes in the diets of wildlife, although the long-term impacts would be difficult to measure in isolation from other factors. Pilchard herpesvirus affected a single cornerstone species in Australia. Given its wide host range, EUS may impact a wider range of piscivorous animals on a seasonal basis; although in the initial outbreaks of EUS in the Upper Congo River Basin, impacts were mostly restricted to a few families of fish (especially Clariidae and some Cyprinidae) with some of the more abundant species not being impacted (17).

Wildlife impacts, in particular, have to be considered in light of the role each species plays in the ecosystem that it inhabits. The relationship between species is complex and can often be more than a purely predator–prey association as mentioned previously, although this alone is important and may include, for example, piscivorous fish, birds and reptiles. Other mechanisms for indirect or flow-on impacts may be, for example, to affect the balance of species with symbiotic associations, or impact on endangered or threatened species, thus leading to more profound ecosystem impacts. A full examination of these complexities is, however, beyond the scope of this paper, which aims to highlight the absence of, and the need for, studying and modelling of the ecosystem-level impacts of EUS and other aquatic animal diseases.

Conclusions and recommendations

Epizootic ulcerative syndrome, like many other aquatic animal diseases, has likely had direct and indirect impacts on subsistence fisheries and wildlife far greater than those indicated in the relatively few studies that have been undertaken to date. This is because, as an area of study, subsistence fisheries and wildlife lie at the fringes of commercial fish-stock-monitoring activity and largely 'take a back seat' in the event of disease epizootics. The impacts on subsistence fisheries, in particular, are expected to be at least as significant as those on commercial inland fisheries, perhaps greater, given the critical food and nutritional security role that subsistence fishing can play in many poor rural communities. The role of small fish in maternal health and child health and development is especially important. Similarly, many of the short- and longer-term impacts of aquatic animal disease on wildlife probably go undetected, both because of the challenges and costs of working in aquatic environments and the low priority that has been given to this area as a research need. Clearly, these are areas for which resources are much needed, both in terms of research and greater efforts to monitor and model fish stock and ecosystem changes, as is routinely undertaken for commercial fisheries.

The historical reluctance to give sufficient credence to the theory that *A. invadans* is the primary causative agent in EUS is, in retrospect, surprising since it was known at the time that another water mould, *A. astaci*, was responsible for massive freshwater crayfish mortalities in Europe from the late 1800s and continues to spread to new areas to this day. *Aphanomyces astaci* caused local extinctions of naïve populations of crayfish wherever it emerged, often in conjunction with the spread of North American crayfish, which carry the disease and replace native species. *Batrachochytrium dendrobatidis*, the amphibian chytrid fungus, has caused mass extinctions of frog species, and infection with the fungus was listed by the OIE in 2018, reflecting its potential threat to amphibian populations. Fungi and fungus-like species need to be given fuller consideration in investigations of new diseases, rather than being overlooked as secondary pathogens.

The detection of EUS in at least five countries in Africa represents a difficult but critically important challenge to the regional authorities responsible for managing aquatic animal disease risks. The syndrome has yet to be reported in Central and South America and, left unchecked, its spread to or discovery in these regions is inevitable. Given the disease's wide host range, the potential impacts on fisheries, aquaculture and ecosystems in Africa and the Americas is extreme.

As with several other aquatic animal disease agents, the history of the global spread of EUS highlights the shortcomings of international biosecurity practices for mitigating the risks of aquatic animal disease spread, both within countries and internationally. In the case of EUS, by the time that the disease's aetiology was broadly accepted and it was formally listed as a notifiable disease (so that countries could more readily take action to mitigate the risk of spread through trade in aquatic animals or their products), the pathogen had already spread to much of Asia. There is an opportunity to learn from what eventuated with EUS (as well as several other diseases with similar histories, such as white spot disease in shrimp, infectious salmon anaemia and tilapia lake virus). Researchers can re-examine current national and international standards for aquatic animal disease management with a view to developing new, perhaps more precautionary, approaches to the way risks of aquatic animal disease spread are managed. A change from the current largely pathogen-specific approach to one of greater emphasis on preventing the spread of diseases more generally is worth consideration. Such a change is especially important given the growing importance of aquaculture and the increasing emergence of previously unknown aquatic animal diseases, as well as the potential for an increase in disease events that can be expected as a result of climate-change-related environmental stressors.

Acknowledgements

C.V. Mohan was supported by the CGIAR Research Program on Fish Agri-Food Systems led by WorldFish. Technical inputs provided by P. Pradhan, Principal Scientist, National Bureau of Fish Genetic Resources, Indian Council of Agricultural Research, Ministry of Agriculture and Farmers Welfare, India, and S.J. Teoh, Geographic Information System Specialist, WorldFish, are gratefully acknowledged.

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L'impact du syndrome ulcératif épizootique sur la pêche de subsistance et sur la faune sauvage

B. Herbert, J.B. Jones, C.V. Mohan & R.P. Perera

Résumé

En l'espace d'un demi-siècle, le syndrome ulcératif épizootique dû à l'oomycète *Aphanomyces invadans* s'est propagé dans toutes les régions du monde, à l'exception, semble-t-il, de l'Amérique du Sud et Centrale. Avec plus de 160 espèces de poissons répertoriées comme sensibles, réparties en 54 familles et 16 ordres, le syndrome ulcératif épizootique est une maladie préoccupante à l'échelle internationale et figure parmi les maladies listées par l'Organisation mondiale de la santé animale (OIE) sous le nom d'infection à *A. invadans*. Les auteurs font état des très rares signalements concernant l'impact du syndrome ulcératif épizootique sur la pêche de subsistance et sur la faune sauvage et tentent d'en tirer quelques conclusions, en insistant sur la nécessité de procéder à une collecte systématique de données afin de déterminer l'envergure et l'importance socioéconomique de la pêche de subsistance. Les communautés les plus pauvres étant souvent celles qui dépendent le plus de cette activité, la maladie a sans doute un impact majeur sur la sécurité alimentaire et nutritionnelle de ces populations. De même, l'impact sur la faune sauvage n'a pas vraiment été étudié jusqu'à présent, d'où la nécessité de conduire des travaux de recherche et de modélisation sur l'impact du syndrome ulcératif épizootique (et d'autres maladies des animaux aquatiques) à l'échelle des écosystèmes. L'histoire du syndrome ulcératif épizootique et d'autres maladies des animaux aquatiques pose également la question de l'efficacité des mesures appliquées actuellement pour maîtriser la propagation internationale de ces maladies et invite à repenser la réponse à apporter à ce défi toujours présent.

Mots-clés

Aphanomyces invadans – Dégradation de l'environnement – Maladie des poissons – Pauvreté – Sécurité alimentaire – Syndrome ulcératif épizootique – Transfert d'espèces.

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Efectos del síndrome ulcerante epizoótico sobre la pesca de subsistencia y los animales silvestres

B. Herbert, J.B. Jones, C.V. Mohan & R.P. Perera

Resumen

En los últimos 50 años, el síndrome ulcerante epizoótico, causado por el hongo acuático (oomiceto) *Aphanomyces invadans*, se ha diseminado por casi todos los continentes del planeta, con la aparente salvedad de Sudamérica y Centroamérica. Se trata de una enfermedad de importancia internacional que, hasta donde consta a día de hoy, afecta a más de 160 especies piscícolas de 54 familias y 16 órdenes. De ahí que la infección por *A. invadans* sea una patología inscrita en la lista de la Organización Mundial de Sanidad Animal (OIE). Los autores, tras exponer lo poco que hasta ahora se ha descrito de los efectos de la enfermedad sobre la pesca de subsistencia y la fauna silvestre o lo que es posible inferir acerca de esos efectos, llegan a la conclusión de que se requiere una labor sistemática de obtención de datos sobre la magnitud e importancia socioeconómica de la actividad pesquera de subsistencia, de la que dependen a menudo las comunidades más pobres, por lo que las consecuencias para la seguridad nutricional y alimentaria pueden ser de calado. Tampoco están bien descritas las repercusiones de la enfermedad en los animales silvestres, lo que pone de relieve la ausencia, y por ende la necesidad, de investigaciones y de modelos sobre los efectos ecosistémicos del síndrome ulcerante epizoótico y otras varias enfermedades de los animales acuáticos. La historia de estas patologías también arroja dudas sobre la eficacia de las medidas aplicadas actualmente para controlar la propagación internacional de las enfermedades de los animales acuáticos y exige replantearse cuál es la respuesta idónea a este problema que no cesa.

Palabras clave

Aphanomyces invadans – Degradación ambiental – Enfermedad de los peces – Pobreza – Seguridad alimentaria – Síndrome ulcerante epizoótico – Traslado.

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