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Threats to UK freshwaters under climate change: Commonly traded aquatic ornamental species and their potential pathogens and parasites

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Abstract

The aquatic ornamental industry, whilst providing socio-economic benefits, is a known introduction pathway for non-native species, which if invasive, can cause direct impacts to native species and ecosystems and also drive disease emergence by extending the geographic range of associated parasites and pathogens and by facilitating host-switching, spillover and spill-back. Although current UK temperatures are typically below those necessary for the survival and establishment of commonly-traded tropical, and some sub-tropical, non-native ornamental species, the higher water temperatures predicted under climate-change scenarios are likely to increase the probability of survival and establishment. Our study aimed primarily to identify which of the commonly-traded non-native ornamental aquatic species (fish and invertebrates), and their pathogens and parasites, are likely to benefit in terms of survival and establishment in UK waters under predicted future climate conditions. Out of 233 ornamental species identified as traded in the UK, 24 were screened, via literature search, for potential parasites and pathogens (PPPs) due to their increased risk of survival and establishment under climate change. We found a total of 155 PPPs, the majority of which were platyhelminths, viruses and bacteria. While many of the identified PPPs were already known to occur in UK waters, PPPs currently absent from UK waters and with zoonotic potential were also identified. Results are discussed in the context of understanding potential impact, in addition to provision of evidence to inform risk assessment and mitigation approaches.

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Keywords
Alien species, disease emergence, horizon scanning, invasive non-native species, risk screening

Introduction

The global trade in aquatic ornamental species is extensive, involving over 140 countries (Evers et al. 2019; Hood et al. 2019). Its value is estimated to be in the region of 15–30 billion US dollars annually, with a trade of 1.3 billion ornamental fishes reported (Evers et al. 2019; King 2019). The total value of live ornamental fishes imported into the UK in 2020 was £16.2 million (OATA 2020). The industry includes trade of both freshwater and marine ornamentals, however 76% of the 1244 metric tonnes of live fishes imported into the UK in 2020 were tropical freshwater fishes (OATA 2020). Though generally less well studied, invertebrates (including Mollusca and Crustacea) also represent an important group of traded aquatic ornamentals (Keller and Lodge 2007; Ng et al. 2016).

While the ornamental industry clearly provides economic and social benefits, it is a known pathway for the introduction of non-native species (NNS), pathogens and parasites, which pose a potential threat to aquatic biodiversity if they become invasive (Padilla and Williams 2004; Copp et al. 2005a; Peeler et al. 2011; Hood et al. 2019). Ornamental species are typically kept in closed systems, isolated from open waterways; but deliberate introduction into the wild, often the result of animals overbreeding or getting too large to house, or accidental introduction following escape, is known to occur (e.g. Courtenay 1999; Crossman and Cudmore 1999; Padilla and Williams 2004; Copp et al. 2005b; Duggan et al. 2006; Wood et al. 2022). Introductions of NNS can drive disease emergence by extending the geographic range of associated parasites and pathogens, and by facilitating host-switching or via spillover and spill-back (Peeler et al. 2011). Outbreaks of Koi Herpes Virus (KHV) and Spring Viraemia of Carp (SVC) in UK fisheries, which resulted in substantial mortalities in common carp *Cyprinus carpio carpio* L. 1758 and economic losses, have been linked to the introduction of koi carp *C. carpio koi*, an ornamental variety of common carp (Taylor et al. 2010, 2011, 2013).

In recognition of the threat posed by live non-native fishes, legislation that restricts the keeping of live fishes is in place in the UK. Key legislation includes 'The Prohibition of Keeping or Release of Live Fish (Specified Species) (England) Order 2014' (and its predecessors in 1998 and 2003) implemented under the 'Import of Live Fish (England and Wales) Act 1980', and 'The Keeping and Introduction of Fish (England and River Esk Catchment Area) Regulations 2015'. These legislative instruments apply primarily (if not exclusively) to freshwater fishes, prohibiting their keeping in England without a licence, with similar powers applying in Wales, Scotland and Northern Ireland. The original 1998 Order listed only species considered to be of concern at that time, with the 2003 Order extending the list to include some additional species. These orders were perhaps the most advanced of their kind in Europe and North America (Copp et al. 2005a). The 2014 Order took a much wider approach, with the schedule listing all taxonomic Orders that contained freshwater fish species and stating that all non-native freshwater fishes required a licence to be kept with the exception of those (primarily native species) listed in the 2014 Order's annexes. However, two general licences have been issued permitting the keeping of fishes in garden ponds and/or indoor aquaria. The first, defined here as the 'garden pond fish list' (UK Government 2021a) details standard ornamental pond fishes, namely koi carp, goldfish *Carassius auratus* L. 1758, orfe *Leuciscus idus* L. 1758, grass carp *Ctenopharyngodon idella* Cuvier & Valenciennes, 1844 and sturgeon (*Acipenser* spp.), permitted to be kept in aquaria or secure outdoor garden ponds. The second, defined as the 'ornamental fish list' (UK Government 2019), comprises mainly tropical and subtropical genera (and in some cases species), which are considered to pose a low risk of becoming established or invasive in UK waters, and permitted to be kept in indoor aquaria only. Parallel legislation exists in relation to crayfish in the form of the 'Prohibition of Keeping of Live Fish (Crayfish) Order 1996', which only permits the keeping of red-clawed crayfish *Cherax quadricarinatus* Von Martens, 1868 for ornamental purposes under a general licence and for the use of all non-native fishes in fisheries in the form of 'The Keeping and Introduction of Fish (England and River Esk Catchment Area) Regulations 2015'. Legislation also exists to prevent the introduction of NNS in to the wild (e.g. Wildlife and Countryside Act 1981), and to limit activities associated with specific NNS (e.g. Invasive Alien Species (Enforcement and Permitting) Order 2019). Further, in relation to aquatic animal disease risk specifically, under 'The Aquatic Animal Health (England and Wales) Regulations 2009', live aquatic animal imports require certification.

Currently, UK temperatures are typically below those necessary for the survival and establishment of the commonly-traded tropical, and some sub-tropical, ornamental fishes (species on the ornamental fish list). However, elevated water temperatures (a 2 °C increase) forecasted by future climate change scenarios are predicted to increase the probability of survival and establishment for some existing fish species (Britton et al. 2010). Hence there may be an increased risk of pathogen and parasite introductions, transmissions and disease emergence events (Marcos-López et al. 2010). Climate modelling under four different Representative Concentration Pathway (RCP) scenarios, *sensu* Moss et al. (2010), indicates that global mean surface temperature may increase by between 0.4 and 2.6 °C by the mid-21st century (Moss et al. 2010; Van Vuuren et al. 2011; Nazarenko et al. 2015). An understanding of the trade in ornamental species, and potential disease threats associated with commonly-traded species that may have an increased risk of establishment in the wild under future climate conditions, is essential to mitigate threats and protect aquatic biodiversity, and ensure the sustainability of an important industry.

The aim of our study was to identify commonly-traded non-native (NN) ornamental fishes, crustacea and molluscs at increased risk of survival and establishment in UK waters under elevated temperatures predicted by climate change forecasting. Further, applying the workflow proposed by Foster et al. (2021), organisms known, or with potential to be, pathogenic or parasitic that have been observed associating with these NN ornamental species at any point in the ornamental fish trade pathway were identified. Applications of the outcomes to inform risk assessment and mitigation measures to protect and sustain the ornamental industry in the long term are discussed.

Methods

Records of commonly imported species, such as packing lists that document details of ornamental species imported via the Heathrow Border Control Post (BCP), were not available for use during this study. Therefore, to identify the NN freshwater ornamental species most commonly-imported into UK, a proxy measure was adopted that combined outputs from three different, but complementary methodologies: expert elicitation, eBay retailer search and Google search.

Expert elicitation involved use of the list, provided by the Ornamental Aquatic Trade Association (OATA; https://ornamentalfish.org/), of ornamental species/genera considered by OATA to be the most commonly traded in the UK (by volume). Further, a short list of those NN ornamental species most likely to establish in UK, i.e. species from warm temperate or sub-tropical climatic zones, was provided by the Fish Health Inspectorate (FHI) for England and Wales.

A list of ornamental live-fish retailers was constructed from an eBay search carried out on 8 October 2020 using the term ‘live fish’. Search results were filtered for NN fishes that fell under the water type categories of ‘fresh’, ‘pond’, ‘all water types’ and ‘not specified’. Species were recorded from all listings between 9 September and 8 October 2020, inclusive. The total number of listings for each NN fish species was used as a proxy measure of trade volume. A separate eBay search using the term ‘live invertebrates’ was carried out on 13 October 2020. Search results were filtered for NN invertebrates that fell under the water type categories of ‘fresh’, ‘pond’, ‘all water types’ and ‘not specified’. Initial results indicated that significantly fewer invertebrate species were listed compared to fish species. Therefore, all NN invertebrate species listings returned by the search, with no restrictions on the date, were recorded. The number of listings per NN invertebrate species was not recorded and species listed multiple times were recorded only once.

A Google search was carried out on 20 October 2020 using the term ‘fish species for cold or unheated aquaria”, and this provided information on popular ornamental fish species likely to be traded in the UK. Although returning primarily temperate species, it also included tropical fish species with wide temperature tolerances, which therefore do not require heated aquaria, e.g. Endler’s livebearer *Poecilia wingei* Poeser, Kempkes & Isbrücker, 2005, and zebra danio *Danio rerio* Hamilton, 1822 (López-Olmeda and Sánchez-Vázquez 2011). In the search for cold or unheated aquaria species, the most popular NN fish species listed in the first 20 websites or blogs (See Suppl. material 1: List S1) were used to represent commonly-traded species. All species mentioned were recorded only once.

A master list of species' common and scientific names was developed. If the species scientific name was absent in the eBay listing or on the website/blog, then it was searched for (using the common name) on FishBase (www.fishbase.se/search.php) for all fish species or via a google search for the invertebrate species. Where fishes and invertebrates were not identified to species level, the entry was removed from the master list. Species recorded via any of the methodologies were collated into the single master list (See Suppl. material 1: Table S1).

The master list was refined by removal of species, based on the following criteria: i) the NN species is present on the 'garden pond fish list' or is not present on the 'ornamental fish' list under The Prohibition of Keeping or Release of Live Fish (Specified Species) (England) Order 2014; and ii) the NN species is recorded as present within UK waters on the Global Biodiversity Information Facility (GBIF; www.gbif.org). Although climate change may increase the risk of some of these NNS, either increasing their current range or establishing new populations as a result of further introductions, the associated pathogen risk was considered to exist already because the species is already present.

Data analysis and modelling

To aid the selection of species for potential pathogen and parasite (PPP) screening, a high-level estimation of climate suitability for each NNS on the master list was undertaken using a species distribution modelling (SDM) approach. Note that the term potential 'pathogen or parasite' is used as a catch-all term, given that evidence for pathogenic or parasitic association was not extensively reviewed in the present study and in fact is often unavailable, in particular for novel environments or hosts. The development of SDMs involved selection of temperature variables under the current climate (2020) and, under future climate, represented by an intermediate climate change scenario, the RCP 4.5 scenario, which predicts stabilisation of radiative forcing (Van Vuuren et al. 2011) and an increase in global annual mean surface air temperature of between 1 and 2 °C (Nazarenko et al. 2015).

The global distribution for each species on the master list was obtained from the GBIF. The climatic zone classification sub-tropical or temperate and the native continent(s) were determined using FishBase. No equivalent database to FishBase exists for invertebrates, so the native range of each invertebrate species was determined via a Google search, and the climatic zone of each range was then climate classified by matching the invertebrate species with fish species from a similar range. Species classified as subtropical or temperate, or with an occurrence record on the GBIF that was outwith the tropical bands (i.e. between the tropics of Capricorn and Cancer), were selected for further analysis (See Suppl. material 1: Table S2). The total number of geo-referenced occurrences for the selected species was recorded. To reduce bias of repeated sampling or multiple reports of a species within the same location, only one record per coordinate was included in the analysis. Species with <100 geo-referenced records were excluded from further analysis (See Suppl. material 1: Table S1). A threshold of 100 geo-referenced records balanced the accuracy of suitability model outputs and number of species for which models could be run. For each species, occurrence data were cleaned using the CoordinateCleaner package in R (Zizka et al. 2019); this package includes a wrapper function that identifies and removes potential errors in the data based on: country and coordinate mismatches, coordinates at sea, zero coordinates, coordinates assigned to country centroids and significant outliers.

Global climate variables at a spatial resolution of ten arc-minutes were downloaded for the present day from the WorldClim dataset (http://worldclim.org) – these are observed data that have been interpolated from current climatic conditions recorded by weather stations (Hijmans et al. 2005). Six temperature variables were then selected for the species distribution models: 1) Annual mean temperature; 2) Mean diurnal range (Mean of monthly: max temp – min temp); 3) Max temperature of warmest month; 4) Min temperature of coldest month; 5) Mean temperature of warmest quarter; and 6) Mean temperature of coldest quarter. Future climate projections were downloaded from the WorldClim dataset. These are derived from five bias-corrected CMIP5 Global Climate Models (GDFL-CM3, HadGEM2-CC, MIROC5, INM-CM4.0, and CSSM4) which specifically related to the 2050 projection (mean for 2041–2060) of the RCP 4.5 climate change scenario.

Species distribution models (SDMs) were employed for NNS on the refined master list to predict the potential suitability of the UK climate for the NNS with respect to the selected temperature variables, both under current (2020) and future climate conditions (in 2050), as represented by climate change scenario RCP 4.5 (Moss et al. 2010). The SDMs were run in R using the SDM package (Naimi and Araújo 2016). Occurrences used in the SDMs were limited to a maximum of 1000 per species. Pseudo-absences were then assigned to each species. The number of pseudo-absences was not fixed across species, rather the number of pseudo-absences was equal to the number of occurrence records for that species as suggested for classification techniques by Barbet-Massin et al. (2012). No pseudo-absence was assigned to a coordinate representing a presence occurrence. Both presences and pseudo-absences input into the SDMs were restricted to the continent within which the native range of the species occurs. For species with distributions that extend across more than one continent, presences and pseudo-absences from all relevant continents were input into the SDMs.

Ensemble models were built for current climate conditions by using two different machine learning methods (boosted-regression trees and random forests). These models estimated the effects of the selected temperature variables, for the present day, on the distribution of each species within the continent of their native range. As no data were available to evaluate the model predictions independently, data were split at random into training (70%) and test data (30%). This random split of the data was repeated five times. To account for the influence of pseudo-absences on model outputs, five random and independent pseudo-absence sets were generated. In total, 50 model replicates were run (two modelling techniques × five pseudo absences × five split samplings) for each species. A geographical representation of the UK was created by cropping a rectangular area using the drawExtent function, which was split into 3828 ten arc-min grid cells (≈ 340 km^2). A suitability score for each species, was predicted for each grid cell using the un-weighted ensemble models, with scores ranging from 0 to 1. A suitability score of 1 indicates that the model predicts the presence of the species in a given location and a score of 0 indicates that the model predicts the absence of the species in that location, based solely on temperature predictors. An overall UK suitability score for each species, for both the present day and under the 2050 scenario, was then calculated by taking the mean of all grid cell suitability scores. Species with a mean suitability score of ≥0.15 in 2050 were selected for parasite/symbiont screening.

Consistent with the framework outlined by Foster et al. (2021), PPP screening consisted of (Table 1): i) organisms associated with each species, i.e. those classified as pathogens, parasites or symbionts, were searched for on PubMed; ii) the associated organisms revealed in the first two pages of a Google search result (using the following terms and format: "*species name*" AND pathogen OR parasite OR commensal OR symbiont OR protist OR bacteria OR virus) were screened for information supplementary to that provided through the PubMed search; and iii) search results were categorised into two groups – PPPs reported to be associated with (or infect) species at any point within the ornamental trade pathway, including wild sourcing (i.e. natural host-PPP interactions), and PPPs known to infect the species through laboratory challenge studies only. Where possible, whether the host-PPP interaction was associated with sub-clinical or asymptomatic infection, clinical signs of disease and/or mortality were noted. Additionally, the country of observation and the point in the ornamental fish trade pathway (e.g. wild, farm, retailer, hobbyist etc.) were recorded.

Table 1. The process undertaken to find information on pathogens, parasites and symbionts associated with each species, with a suitability score of ≥0.15, on PubMed. Only steps one to three were carried out in the present study (adapted from Foster et al. 2021).

Step 1	Search full species name in [All Fields]. If 0, then go to 2, if ≥1, then go to 3
Step 2	Search genus name in [All Fields]. If 0, then decide whether continuing at a higher taxonomic level, is appropriate. If ≥1, go to 4.
Step 3	Conduct search using the criteria: (*Species name* [All Fields]) AND (microbiome[Title/Abstract] OR symbio*[Title/Abstract] OR pathogen*[Title/Abstract] OR parasit*[Title/Abstract] OR protist[Title/Abstract] OR protozoa[Title/Abstract] OR bacteria*[Title/Abstract] OR virus[Title/Abstract] OR host[Title/Abstract] OR reservoir[Title/Abstract] OR vector[Title/Abstract] OR infection [Title/Abstract])
	Scan papers for pathogen/symbiont reports and IDs and record
Step 4	Conduct search using criteira: (G*enus name* [All Fields]) AND (microbiome[Title/Abstract] OR symbio*[Title/Abstract] OR pathogen*[Title/Abstract] OR parasit*[Title/Abstract] OR protist[Title/Abstract] OR protozoa[Title/Abstract] OR bacteria*[Title/Abstract] OR virus[Title/Abstract] OR host[Title/Abstract] OR reservoir[Title/Abstract] OR vector[Title/Abstract] OR infection [Title/Abstract])
	Scan papers for pathogen/symbiont reports and IDs and record
Step 5	Engage with taxon group specialists, as appropriate, to sense check & compile additional information.

Results

Commonly-traded species

The master list of species commonly imported to the UK contained 193 species of ornamental fish, and 40 species of ornamental invertebrate, (total 233, See Suppl. material 1: Table S1). A total of 160 fish species were removed from the master list, and not subject to suitability scoring, because they met at least one of the following criteria: i) present on the list of 'garden pond' fishes, ii) absent from the list of 'ornamental fish' species or recorded as present in the UK on the GBIF, iii) low number (<100) of GBIF records, or iv) distribution was restricted to within the tropical bands (See Suppl. material 1: Table S1).

A total of 32 invertebrate species were removed from the master list because they met at least one of the following criteria: i) species list or recorded as present in the UK on GBIF, ii) low number (<100) of GBIF records, iii) distribution was restricted to within the tropical bands. One further invertebrate species, *Pomacea maculata* Perry, 1810 (synon. *P. insularum*), was removed from the master list because all *Pomacea* spp. were banned from import into the UK (OATA 2021; UK Government 2021b) at the time of our study (See Suppl. material 1: Table S1). Therefore, the refined master list subjected to suitability analysis comprised 33 fish and seven invertebrate species (Table 2).

The majority of fish species (30.3%; *n* = 10) on the refined master list belong to the Order Cypriniformes, which includes the loaches, carps, barbs and minnows; taxa that are common in the aquarium trade. A notable proportion of the fish species on the refined master list (21%; *n* = 7) are the smaller ray-finned fishes of the Order Cyprinodontiformes, such as killifishes and livebearers (e.g. mollies, guppies), which are popular aquarium fishes. Also common on the refined master list are species of the taxonomic orders Siluriformes (18.1%; *n* = 6), representing the catfishes, and Cichliformes (15.1%; *n* = 5), representing the cichlids and angelfishes. Invertebrate species on the refined master list comprise snails, crabs, shrimps and a crayfish. Three were of the taxonomic Order Decapoda (Table 2). Species within orders Notostraca and Cycloneritida are also present on the list.

Species estimates of UK temperature suitability

Mean UK suitability scores for the fish species ranged from 0.08 to 0.59 under current climate conditions and 0.08 to 0.62 under future (2050) climate conditions (Table 2). The highest suitability score in 2050 was seen for the dojo loach *Misgurnus anguillicaudatus* Cantor, 1842, and the Japanese rice fish *Oryzias latipes* Temminck & Schlegel, 1846 (Table 2, also see Suppl. material 1: Fig. S1). Although there was no difference in suitability between current day and 2050 for 15 fish species, suitability increased (mean increase in suitability of 0.05) for 15 fish species. The greatest increase

Table 2. Outputs of species distribution models (SDMs), using UK temperatures under current and future climate conditions (i.e. 2050, under Representative Concentration Pathway, RCP 4.5, scenario), for ornamental freshwater fish and invertebrate species identified via eBay and Google searches in addition to expert elicitation as commonly traded in the UK (ordered by decreasing mean RCP 4.5 suitability score, then by mean current day suitability score and then by native continent. Also given is the number of records (*n*) from the Global Biodiversity Information Facility (GBIF; www.GBIF.org) used to carry out the SDMs (after selection of 1000 random points, removal of duplicates and cleaning). Species in bold had a mean suitability score of ≥ 0.15 under RCP4.5 2050 and were therefore subject to pathogen and parasite screening.

Taxon group/Scientific name	Common name	Native Continent	n	Current	RCP 4.5
FISHES					
Misgurnus anguillicaudatus	dojo loach	Asia	781	0.59	0.62
Oryzias latipes	Japanese rice fish	Asia	247	0.53	0.58
Aphanius mento	pearl-spotted killifish	Asia	135	0.35	0.38
Rhodeus ocellatus	rosy bitterling	Asia	311	0.23	0.32
Pimephales promelas	fathead minnow	North America	859	0.19	0.31
Enneacanthus chaetodon	black banded sunfish	North America	177	0.23	0.29
Misgurnus mizolepis	Chinese muddy loach	Asia	244	0.26	0.28
Garra rufa	red garra	Asia and Europe	234	0.25	0.28
Notropis chrosomus	rainbow shiner	North America	376	0.26	0.27
Amatitlania nigrofasciata	convict cichlid	North America	487	0.21	0.26
Xiphophorus variatus	variable platy	North America	276	0.15	0.20
Pethia conchonius	rosy barb	Asia	128	0.17	0.19
Xiphophorus hellerii	swordtail	North America	943	0.13	0.17
Paracheirodon axelrodi	cardinal tetra	South America	129	0.17	0.17
Corydoras paleatus	pepper corydoras	South America	126	0.15	0.16
Barbodes semifasciolatus	gold barb	Asia	141	0.16	0.15
Astronotus ocellatus	oscar	South America	241	0.16	0.15
Osteoglossum bicirrhosum	arawana	South America	126	0.15	0.15
Phractocephalus hemioliopterus	redtail catfish	South America	120	0.14	0.14
Pethia ticto	ticto barb	Asia	113	0.13	0.13
Hypostomus plecostomus	suckermouth catfish	South America	277	0.13	0.13
Hypseleotris compressa	empire gudgeon	Australasia	855	0.11	0.12
Pygocentrus nattereri	red bellied piranha	South America	532	0.12	0.12
Poecilia reticulata	guppy	North & South America	936	0.11	0.11
Corydoras aeneus	bronze corydoras	South America	278	0.12	0.11
Melanotaenia nigrans	black-banded rainbowfish	Australasia	212	0.10	0.10
Amphilophus citrinellus	midas cichlid	North America	193	0.10	0.10
Cyprinella lutrensis	red shiner	North America	902	0.10	0.10
Rocio octofasciata	Jack Dempsey	North America	595	0.10	0.10
Pterophyllum scalare	angelfish	South America	152	0.10	0.10
Poecilia velifera	sail-fin molly	North America	175	0.09	0.09
Vieja melanura	redhead cichlid	North America	706	0.09	0.09
Poecilia sphenops	common molly	North & South America	519	0.08	0.08
INVERTEBRATES					
Palaemonetes paludosus	ghost shrimp	North America	249	0.31	0.35
Tarebia granifera	quilted melania	Asia & Australasia	160	0.26	0.28
Cherax quadricarinatus	redclaw crayfish (blue lobster)	Australasia	108	0.22	0.22
Triops australiensis	tadpole shrimp	Australasia	145	0.21	0.21
Neritina pulligera	dusky nerite	Africa, Asia & Australasia	111	0.18	0.19
Marisa cornuarietis	Colombian ramshorn apple snail	North & South America	195	0.15	0.17
Metasesarma aubryi	red apple crab	Asia	312	0.13	0.13

in suitability score was seen for the fathead minnow *Pimephales promelas* Rafinesque, 1820, whose score increased by nearly 63% from 0.19 to 0.31. For three fish species, suitability scores reduced between the current day and 2050, though by only a small amount (Table 2): gold barb *Barbodes semifasciolatus* Günther, 1886, bronze corydoras *Corydoras aeneus* Gill, 1858 and the oscar, *Astronotus ocellatus* Agassiz, 1831.

Mean suitability scores for the invertebrate species ranged from 0.15 to 0.33 and from 0.17 to 0.44 under current day and 2050, respectively (Table 2). The highest suitability score in 2050 was seen for the ghost shrimp *Palaemonetes paludosus* Gibbes, 1850. In total, four invertebrate species showed a small increase in suitability score between the present day and 2050. No difference in suitability score between current day and 2050 was seen for three species: red-clawed crayfish, tadpole shrimp *Triops australiensis* Spencer & Hall, 1895, and red apple crab *Metasesarma aubryi* A. Milne-Edwards, 1869. In contrast to fishes, a reduction in suitability in 2050 was not seen for any of the listed invertebrate species.

Potential pathogen and parasite screen

In total, 18 fish and six invertebrate host species were screened for potential pathogens and parasites based on their suitability score of ≥0.15 under RCP 45 2050. A total of 504 records were returned from the literature (PubMed and Google) search. The number of records against each screened host species ranged between 0 and 144, with four species (tadpole shrimp; black banded sunfish *Enneacanthus chaetodon* Baird, 1855; rainbow shiner *Notropis chrosomus* Jordan, 1877; dusky nerite *Neritina pulligera* L., 1767) returning no records. A total of 243 records were deemed unsuitable for the PPP screen following review of the abstract to assess whether or not the publication included both the host species and/or a PPP. In total, 163 records documented natural interactions between hosts and PPPs (Table 3) and 98 records reported host species susceptibility to PPP infection under laboratory conditions (See Suppl. material 1: Table S2).

In total, 155 PPPs across four biological kingdoms (Animalia, Fungi, Prokaryotes and Protists) and two domains (Bacteria and Viruses) were identified as associated with the screened host species. The majority belonged to phyla within the Animalia kingdom (66%; *n* = 100), specifically Acanthocephala (2%, *n* = 3), Annelida (1%, *n* = 2), Arthropoda (6%, *n* = 10), Cnidaria (1%, *n* = 2), Nematoda (10%, *n* = 16), and Platyhelminthes (43%, *n* = 67) (Table 3).

Viruses represented 12% of the total PPPs identified as associated with screened host species, and they belonged to a number of RNA virus families, including *Rhabdoviridae, Birnaviridae*, as well as the DNA virus family, the iridioviruses (Table 3). Evidence suggests that a large proportion of the viruses identified can cause clinical disease (72%) and/or mortality (56%) in potential hosts screened. Sub-clinical infection by some viruses was also reported to be present in some of the screened potential hosts. Bacterial PPPs represented 11% of PPPs associated with screened hosts and belonged to a number of groups including Aeromonads, *Mycobacterium*, *Vibrio* and *Streptococcus*, and these were largely opportunistic bacteria, which are commonly associated with disease (88%) and mortality (84%) across a wide range of species (Table 3).

The greatest number of PPPs were reported for fathead minnow, with 27 in total (Table 3). Screening also highlighted 25 PPPs associated with dojo loach, 17 PPPs associated with red-claw crayfish and 12 PPPs associated with red garra *Garra rufa* Heckel, 1845.

Many of the PPPs found to be associated with the screened host species are known to already occur in UK waters. In particular, species of bacteria associated with screened hosts have a wide global distribution and are likely already associated with disease in aquatic organisms in the UK. Also known to cause disease in the UK is the protist *Ichthyophthirius multifiliis* Fouquet, 1876, commonly known as 'Ich' – the causative agent of white-spot disease. This protozoan was identified in several screened ornamental fishes including: swordtail *Xiphophorus helleri* Heckel, 1848, oscar, arawana *Osteoglossum bicirrhosum* Cuvier, 1829 and cardinal tetra *Paracheirodon axelrodi* Schultz, 1956. In addition, *Trichodina* Ehrenberg, 1838, another widespread protozoan genus already found in the UK, was identified as associated with several of the screened ornamental species. *Aphanomyces astaci* Schikora, 1906, which is widely distributed throughout Europe and the causative agent of the crayfish plague, was associated with the redclaw crayfish. Arthropoda PPPs, common in the UK, associated with listed species included *Argulus japonicus* Thiele, 1900 and *Argulus foliaceus* L., 1758.

However, PPPs not known to occur in UK waters were identified. For example, infection of fathead minnow by viral haemorrhagic septicaemia virus (VHSv), the aetiological agent of OIE-listed Viral Haemorrhagic Septicaemia, and of the oscar by infectious spleen and necrosis virus (ISKNv) were reported. In addition, the protist *Aphanomyces invadans* David & Kirk, 1997, the aetiological agent of OIE listed Epizootic Elcerative Syndrome, was reported as associated with the rosy barb *Pethia conchonius* Hamilton, 1822. Further, the fungi *Pseudoloma neurophilia* was reported to cause mortality in the fathead minnow. Finally, the Cnidarian, *Myxobolus axelrodi*, was associated with the cardinal tetra and was also reported to cause mortalities.

Also identified were PPPs with zoonotic potential, including two trematodes, *Isthmiophora hortensis* Asata, 1926 and *Clinostomum complanatum* Rudolphi, 1814 were reported as associated with the dojo loach and rosy bitterling *Rhodeus ocellatus* Kner, 1868, respectively. One cestode, *Schyzocotyle acheilognathi* Yamaguti, 1934, also with known zoonotic potential, was reported as associated with swordtail. Bacterial PPPs known to infect both fishes and humans were also identified as associated with screened fishes, including: *Acinetobacter pittii* Nemec et al., 2011, *Aeromonas veronii* Hickman-Brenner et al., 1987, *A. hydrophila* Chester, 1901, *Vibrio cholerae* Pacini, 1854, *Shewanella putrefaciens* MacDonell & Colwell, 1986, *Mycobacterium marinum* Aronson, 1926 and *Mycobacterium goodii* Brown et al., 1999. Antimicrobial resistance was reported for some bacterial strains identified in screened species, including a strain of *Aeromonas sobria* Popoff & Vron, 1981 (in swordtail and dojo loach).

Table 3. List of potential pathogens and parasites reported as natural infections of ornamental fish and invertebrate species traded into the UK , whereby literature evidence was found (Y = Yes) for: Disease = clinical signs or disease in the animal caused by the associated pathogen or parasite; Mort. = mortalities in the animal as a result of the associated pathogen or parasite; Sub. = sub-clinical or asymptomatic infection in the animal. Location types: 'Aquarium' includes reports on specimens held in aquaria by hobbyists, public aquaria, vets or laboratories; 'Retail (Pet shop)' (Retail P) includes ornamental fish shops, both stand-alone and within ornamental markets; 'Border' refers to Import/Border Border Control Inspection Posts; 'Retail B' = Retail bait shop; 'Retail S' = Retail Spa.

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
Viruses							
Aquatic birnavirus	*Garra rufa*		Y		Ireland	Retail S	(Ruane et al. 2013)
Athtabvirus	*Cherax quadricarinatus*	Y	Y		Australia	Farm	(Sakuna et al. 2018)
Chequa iflavirus	*Cherax quadricarinatus*	Y	Y	Y	Australia	Farm	(Sakuna, et al. 2017)
Cherax quadricarinatus iridovirus	*Cherax quadricarinatus*	Y	Y		China	Farm	(Xu et al. 2016)
Decapod ambidensovirus[1]	*Cherax quadricarinatus*	Y	Y		Australia	Farm	(Bochow et al. 2015)
Fathead minnow calicivirus	*Pimephales promelas*	Y		Y	USA	Retail B	(Mor et al. 2017)
Fathead minnow nidovirus	*Pimephales promelas*	Y		Y	USA	Retail B	(Batts et al. 2012)
Fathead minnow picornavirus	*Pimephales promelas*	Y			USA	Retail B	(Phelps et al. 2014)
Fathead minnow rhabdovirus	*Pimephales promelas*	Y	Y		USA	Farm	(Iwanowicz and Goodwin 2002)
Golden shiner reovirus	*Pimephales promelas*	Y		Y	USA	Retail B	(Boonthai et al. 2018)
Hepatopancreatic reovirus	*Cherax quadricarinatus*	Y	Y	Y	Australia	Farm	(Edgerton et al. 2000)
ISK necrosis virus	*Astronotus ocellatus*				Australia	Retail P	(Go et al. 2016)
ISK necrosis virus	*Astronotus ocellatus*			Y	India	Retail P	(Girisha et al. 2021)
Loach birnavirus	*Misgurnus anguillicaudatus*	Y			Taiwan	Farm	(Chou et al. 1993)
Parvo-like virus	*Cherax quadricarinatus*	Y	Y		Australia	Farm	(Bowater et al. 2002)
South American cichlid iridovirus	*Astronotus ocellatus*	Y	Y		USA	Retail P	(Koda et al. 2018)
Spawner-isolated mortality virus	*Cherax quadricarinatus*		Y	Y	Australia	Farm	(Owens and McElnea 2000)
Turbot reddish body iridovirus	*Astronotus ocellatus*				USA	Retail P	(Go et al. 2016)
Viral Haemorraghic Septicaemia[2]	*Pimephales promelas*			Y	USA	Wild	(Cornwell et al. 2013)
Bacteria							
Acinetobacter pittii	*Misgurnus anguillicaudatus*	Y	Y		China	Farm	(Wang et al. 2019)
Aeromonas hydrophila	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Aeromonas hydrophila	*Misgurnus anguillicaudatus*	Y	Y		South Korea	Farm	(Jun et al. 2010)
Aeromonas sobria	*Corydoras paleatus*			Y	Italy	Wholesaler	(Sicuro et al. 2020)
Aeromonas sobria	*Garra rufa*	Y	Y		Slovakia	Farm	(Majtán et al. 2012)
Aeromonas sobria	*Misgurnus anguillicaudatus*			Y	Italy	Wholesaler	(Sicuro et al. 2020)
Aeromonas sobria	*Misgurnus mizolepis*	Y	Y		South Korea	Farm	(Yu et al. 2015)
Aeromonas sobria	*Xiphophorus hellerii*			Y	Italy	Wholesaler	(Sicuro et al. 2020)
Aeromonas veronii	*Astronotus ocellatus*	Y	Y		India	Farm	(Sreedharan et al. 2011)
Aeromonas veronii	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
Bacteria							
Chryseobacterium cucumeris	*Misgurnus anguillicaudatus*	Y	Y		South Korea	Farm	(Kim et al. 2020)
Citrobacter freundii	*Garra rufa*	Y	Y		South Korea	Farm	(Baeck et al. 2009)
Edwardsiella ictaluri	*Pethia conchonius*	Y	Y	Y	Australia	Border	(Humphrey et al. 1986)
Listonella anguillarum	*Misgurnus anguillicaudatus*	Y	Y		China	Farm	(Qin et al. 2014)
Mycobacterium abscessus	*Xiphophorus variatus*	Y	Y		Italy	Border	(Zanoni et al. 2008)
Mycobacterium fortuitum	*Xiphophorus variatus*	Y	Y		Italy	Aquarium	(Zanoni et al. 2008)
Mycobacterium goodii	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Mycobacterium gordonae	*Cherax quadricarinatus*	Y	Y		Israel	Farm	(Davidovich et al. 2019)
Mycobacterium marinum	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Rickettsia-like organism	*Cherax quadricarinatus*	Y	Y		Ecuador	Farm	(Romero et al. 2000)
Shewanella putrefaciens	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Shewanella putrefaciens	*Misgurnus anguillicaudatus*	Y	Y		China	Farm	(Qin et al. 2014)
Streptococcus agalactiae	*Garra rufa*	Y	Y		Ireland	Retail S	(Ruane et al. 2013)
Streptococcus iniae	*Astronotus ocellatus*	Y			Iran	Aquarium	(Tukmechi et al. 2009)
Vibrio cholerae	*Garra rufa*	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Protists							
Achlya sp.	*Astronotus ocellatus*	Y			Iran	Aquarium	(Peyghan et al. 2019)
Aphanomyces astaci	*Cherax quadricarinatus*	Y	Y		Taiwan	Farm	(Hsieh et al. 2016)
Aphanomyces invadans	*Pethia conchonius*	Y	Y		India	Wild	(Pradhan et al. 2014)
Dermocystidium salmonis	*Paracheirodon axelrodi*	Y	Y		Germany	Aquarium	(Langenmayer et al. 2015)
Ichthyobodo necator	*Xiphophorus hellerii*				USA		(Callahan et al. 2005)
Ichthyophthirius multifiliis	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
Ichthyophthirius multifiliis	*Osteoglossum bicirrhosum*				Brazil	Wild	(Rodrigues et al. 2014)
Ichthyophthirius multifiliis	*Paracheirodon axelrodi*				Brazil	Retail P	(Hoshino et al. 2018)
Ichthyophthirius multifiliis	*Xiphophorus hellerii*				Australia	Wild	(Dove and Ernst 1998)
Piscinoodinium pillulare	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
Piscinoodinium pillulare	*Osteoglossum bicirrhosum*				Brazil	Wild	(Rodrigues et al. 2014)
Tokophrya huangmeiensis	*Cherax quadricarinatus*				China	Farm	(Tahir et al. 2017)
Trichodina acuta	*Misgurnus anguillicaudatus*				China	Farm	(Wang et al. 2017)
Trichodina acuta	*Xiphophorus hellerii*				Brazil	Farm	(Piazza et al. 2006; Garcia et al. 2009)
Trichodina heterodentata	*Xiphophorus hellerii*				Australia	Wild	(Dove 2000)
Trichodina lechriodentata	*Misgurnus anguillicaudatus*				China		(Zhao and Tang 2007)
Trichodina modesta	*Misgurnus anguillicaudatus*				China		(Zhao and Tang 2007)
Trichodina sp.	*Paracheirodon axelrodi*				Brazil	Wild	(Tavares-Dias et al. 2010)
Trichodina sp.	*Pimephales promelas*				USA	Wild	(Weichman and Janovy 2000)
Trichodina sp.	*Xiphophorus hellerii*				Sri Lanka	Farm	(Thilakaratne et al.
Fungi							
Apotaspora heleios	*Palaemonetes paludosus*	Y			USA	Wild	(Sokolova and Overstreet 2018)
Exophiala pisciphila	*Paracheirodon axelrodi*	Y			Czechia	Aquarium	(Rehulka et al. 2017)
Glugea pimephales	*Pimephales promelas*	Y			Canada	Wild	(Forest, et al. 2009)
Pleistophora hyphessobryconis	*Paracheirodon axelrodi*				Czechia	Aquarium	(Novotný and Dvořák 2001)
Pleistophora sp.	*Pimephales promelas*			Y	USA	Farm	(Ruehl-Fehlert et al. 2005)

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Fungi							
Pseudoloma neurophilia	*Pimephales promelas*	Y	Y		UK	Aquarium	(Sanders et al. 2016)
Animal Kingdom							
Acanthocephala							
Acanthochepalan polymorphus sp.	*Astronotus ocellatus*				Brazil	Wild	(Azevedo et al. 2007)
Neoechinorhynchus panucensis	*Amatitlania nigrofasciata*				Mexico	Wild	(Salgado-Maldonado 2013)
Triaspiron aphanii	*Aphanius mento*				Turkey	Wild	(Smales et al. 2012)
Annelida							
Chaetogaster limnaei	*Tarebia granifera*				Jamaica	Wild	(McKoy et al. 2011)
sp.	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)
Glossiphonidae gen. sp.	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)
Arthropoda							
Argulus foliaceus	*Astronotus ocellatus*				Turkey		(Toksen 2006)
Argulus japonicus	*Rhodeus occellatus*				Japan	Wild	(Yamauchi and Shimizu 2013)
Argulus multicolor	*Astronotus ocellatus*				Brazil	Wild	(Tavares-Dias and Neves 2017)
Dolops nana	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)
Ergasilus ceylonensis	*Xiphophorus hellerii*				Sri Lanka	Farm	(Thilakaratne et al. 2003)
Lamproglena monodi	*Astronotus ocellatus*				Brazil	Wild	(Azevedo et al. 2012)
Lernaea cyprinacea	*Corydoras paleatus*				Argentina	Wild	(Plaul et al. 2010)
Lernaea cyprinacea	*Pimephales promelas*				USA	Wild	(Marcogliese 1991)
Lernaea cyprinacea	*Rhodeus ocellatus*				Japan	Wild	(Nagasawa and Torii 2014)
Lernaea cyprinacea	*Xiphophorus hellerii*				Iran	Farm	(Mirzaei 2015)
Neoergasilus japonicus	*Pimephales promelas*				USA	Wild	(Hudson and Bowen 2002)
Probopyrus pandalicola	*Palaemonetes paludosus*				USA	Wild	(Beck 1980)
Sebekia mississippiensis	*Xiphophorus helleri*				USA	Retail P	(Boyce et al. 1987)
Cnidaria							
Myxobolus axelrodi	*Paracheirodon axelrodi*		Y				(Camus et al. 2017)
Thelohanellus misgurni	*Misgurnus mizolepis*						(Kwon and Kim 2011)
Nematoda							
Anguillicoloides crassus	*Amatitlania nigrofasciata*				Germany	Wild	(Emde et al. 2016)
Camallanus acaudatus	*Osteoglossum bicirrhosum*				Brazil	Wild	(Rodrigues et al. 2014)
Camallanus cotti	*Amatitlania nigrofasciata*				Germany	Wild	(Emde et al. 2016)
Camallanus cotti	*Misgurnus anguillicaudatus*				Canada	Aquarium	(Moravec and Justine 2006)
Camallanus cotti	*Xiphophorus hellerii*				USA	Wild	(Vincent and Font 2003)
Camallanus sp.	*Paracheirodon axelrodi*				Brazil	Retail P	(Hoshino et al. 2018)
Contracaecum bancrofti	*Misgurnus anguillicaudatus*				Australia	Wild	(Shamsi et al. 2019)
Contracaecum sp.	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
Contracaecum sp.	*Osteoglossum bicirrhosum*				Brazil	Wild	(Oliveira et al. 2019)
Contracaecum sp.	*Pimephales promelas*				USA	Wild	(Martins et al. 2017)
Eustrongylides excisus	*Aphanius mento*				Turkey	Wild	(Aydo_du et al. 2011)
Eustrongylides sp.	*Osteoglossum bicirrhosum*				Brazil	Wild	(Oliveira et al. 2019)
Gnathostoma nipponicum	*Misgurnus anguillicaudatus*				South Korea	Retail P	(Sohn et al. 1993)
Mexiconema cichlasomae	*Xiphophorus hellerii*				Mexico	Wild	(Moravec et al. 1998)
Procamallanus inopinatus	*Astronotus ocellatus*				Brazil	Wild	(Tavares-Dias, Sousa and Neves 2014)
Procamallanus pintoi	*Corydoras paleatus*				Argentina	Wild	(Ailán-Choke et al. 2018)
Procamallanus sp.	*Paracheirodon axelrodi*				Brazil	Wild	(Tavares-Dias et al. 2010)

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
Nematoda							
Procamallanus spiculastriatus	*Astronotus ocellatus*				Brazil	Wild	(Pinheiro et al.2019)
Pseudocapillaria margolisi	*Pethia conchonius*				India	Wild	(De and Maity 1996)
Pseudoproleptus sp.	*Astronotus ocellatus*				Brazil	Wild	(Pinheiro et al. 2019)
Platyhelminthes							
Acanthatrium hitaense	*Tarebia granifera*				Thailand	Wild	(Dechruska and Krailas 2007)
Acanthostomum sp.	*Paracheirodon axelrodi*				Brazil	Retail P	(Hoshino et al. 2018)
Caballerotrema aruanense	*Osteoglossum bicirrhosum*				Brazil	Wild	(Oliveira et al. 2019)
Centrocestus formosanus	*Barbodes semifasciolatus*				Vietnam	Wild	(Chai et al.2012)
Centrocestus formosanus	*Melanoides tuberculata*				USA	Wild	(Tolley-Jordan and Chadwick 2018)
Centrocestus formosanus	*Osteoglossum bicirrhosum*				Iran	Wild	(Mood et al. 2010)
Centrocestus formosanus	*Tarebia granifera*				USA	Wild	(Tolley-Jordan and Chadwick 2018)
Centrocestus formosanus	*Tarebia granifera*				Thailand	Wild	(Dechruska and Krailas 2007)
Clinostomum complanatum	*Misgurnus anguillicaudatus*				Taiwan	Farm	(Wang et al. 2017)
Clinostomum complanatum	*Rhodeus ocellatus*				Japan	Wild	(Aohagi et al. 1992)
Clinostomum marginatum	*Astronotus ocellatus*				Brazil	Wild	(Tavares-Dias and Neves 2017)
Clonorchis sinensis	*Misgurnus anguillicaudatus*				China	Wild	(Zhang et al. 2014)
Clonorchis sinensis	*Misgurnus anguillicaudatus*				South Korea	Wild	(Shin 1964)
Clonorchis sinensis	*Rhodeus ocellatus*				South Korea	Wild	(Rhee et al. 1983)
Craspedella pedum	*Cherax quadricarinatus*				South Africa	Wild	(Tavakol et al. 2016)
Crassiphiala bulboglossa	*Pimephales promelas*				USA	Wild	(Wisenden et al. 2012)
Dactylogyrus olfactorius	*Pimephales promelas*				USA	Wild	(Lari et al. 2016)
Dactylogyrus simplex	*Pimephales promelas*				USA	Wild	(Knipes and Janovy 2009)
Dactylogyrus bychowskyi	*Pimephales promelas*				USA	Wild	(Knipes and Janovy 2009)
Dactylogyrus pectenatus	*Pimephales promelas*				USA	Wild	(Knipes and Janovy 2009)
Dactylogyrus ostraviensis	*Pethia conchonius*			Y	Australia	Border	(Trujillo-Gonz‡lez et al. 2019)
Dactylogyrus sp.	*Garra rufa*				Iraq	Wild	(Abdullah 2017)
Dactylogyrus sp.	*Xiphophorus hellerii*				Sri Lanka	Farm	(Thilakaratne et al. 2003)
Diceratocephala boschmai	*Cherax quadricarinatus*				Thailand	Wild	(Ngamniyom et al. 2019)
Diceratocephala boschmai	*Cherax quadricarinatus*				South Africa	Wild	(Tavakol et al. 2016)
Didymorchis sp.	*Cherax quadricarinatus*				South Africa	Wild	(Tavakol et al. 2016)
Diplostomidae sp.	*Paracheirodon axelrodi*				Brazil	Retail P	(Hoshino et al. 2018)
Echinostoma cinetorchis	*Misgurnus anguillicaudatus*				South Korea	Retail P	(Seo et al. 1984)
Echinostoma sp.	*Melanoides tuberculata*				Philippines	Wild	(Paller et al. 2019)
Gonocleithrum aruanae	*Osteoglossum bicirrhosum*				Brazil	Wild	(Tavares-Dias et al. 2014)
Gonocleithrum coenoideum	*Osteoglossum bicirrhosum*				Brazil	Wild	(Rodrigues et al. 2014)
Gonocleithrum cursitans	*Osteoglossum bicirrhosum*				Iran	Retail P	(Mehdizadeh et al. 2016)
Gonocleithrum planacrus	*Osteoglossum bicirrhosum*				Brazil	Wild	(Rodrigues et al. 2014)
Gussevia asota	*Astronotus ocellatus*				Peru	Wild	(Mendoza-Franco et al. 2010)
Gussevia asota	*Astronotus ocellatus*				Panama	Wild	(Mendoza-Franco et al. 2007)
Gussevia asota	*Astronotus ocellatus*				South Korea	Farm	(Kim et al. 2002)
Gussevia astronii	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
Nematoda							
Gussevia rogersi	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)
Gyrodactylus anisopharynx	*Corydoras paleatus*				Argentina	Wild	(Rauque et al. 2018)
Gyrodactylus anisopharynx	*Corydoras paleatus*				Brazil	Wild	(Boeger et al. 2005)[3]
Gytrodactylus bullatarudis	*Xiphophorus hellerii*				Australia	Wild	(Dove and Ernst 1998)
Gyrodactylus cichlidarum	*Astronotus ocellatus*				Iran	Retail P	(Mousavi et al. 2013)
Gyrodactylus corydori	*Corydoras paleatus*				Brazil	Wild	(Bueno-silva et al. and Boeger 2009)
Gyrodactylus macracanthus	*Misgurnus anguillicaudatus*				Australia	Wild	(Dove and Ernst 1998)
Gyrodactylus medaka	*Oryzias latipes*				Japan	Wild	(Nitta and Nagasawa 2018)
Gyrodactylus samirae	*Corydoras paleatus*				Brazil	Wild	(Popazoglo and Boeger 2016)
Gyrodactylus sp.	*Misgurnus anguillicaudatus*				USA	Wild	(Reyda et al. 2020)
Gyrodactylus sp.	*Paracheirodon axelrodi*				Brazil	Wild	(Tavares-Dias et al. 2010)
Gyrodactylus sp.	*Xiphophorus hellerii*				Sri Lanka	Farm	(Thilakaratne et al. 2003)
Gyrodactylus superbus	*Corydoras paleatus*				Argentina	Wild	(Rauque et al. 2018)
Haematoloechus similis	*Tarebia granifera*				Thailand	Wild	(Dechruska and Krailas 2007)
Haplorchis pumilio	*Barbodes semifasciolatus*				Vietnam	Wild	(Chai et al. 2012)
Haplorchis pumilio	*Melanoides tuberculata*				USA	Wild	(Tolley-Jordan and Chadwick 2018)
Haplorchis pumilio	*Melanoides tuberculata*				Thailand	Wild	(Dechruska and Krailas 2007)
Haplorchis pumilio	*Tarebia granifera*				USA	Wild	(Tolley-Jordan and Chadwick 2018)
Haplorchis sp.	*Tarebia granifera*				Laos	Wild	(Ditrich et al. 1990)
Haplorchis taichui	*Melanoides tuberculata*				Thailand	Wild	(Chontananarth and Wongsawad 2010)
Haplorchis taichui	*Melanoides tuberculata*				Laos	Wild	(Nawa et al. 2001)
Haplorchis taichui	*Tarebia granifera*				Thailand	Wild	(Chontananarth and Wongsawad 2010)
Haplorchis taichui	*Tarebia granifera*				Laos	Wild	(Nawa et al. 2001)
Herpetodiplostomum sp.	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)
Isthmiophora hortensis[4]	*Misgurnus anguillicaudatus*				China	Wild	(Qiu et al. 2017)
Isthmiophora hortensis[4]	*Misgurnus anguillicaudatus*				South Korea	Wild	(Ryang 1990)
Isthmiophora hortensis[4]	*Misgurnus anguillicaudatus*				South Korea	Retail P	(Jong-Yil Chai et al. 1985)
Loxogenoides bicolor	*Melanoides tuberculata*				Thailand	Wild	(Ukong et al. 2007)
Loxogenoides bicolor	*Tarebia granifera*				Thailand	Wild	(Ukong et al. 2007)
Massaliatrema misgurni	*Misgurnus anguillicaudatus*				Japan	Retail P	(Ohyama et al. 2001)
Megulurous sp.	*Melanoides tuberculata*				Philippines	Wild	(Paller et al. 2019)
Metorchis orientalis	*Rhodeus ocellatus*				China	Wild	(Qiu et al. 2017)
Notocotylid sp.	*Tarebia granifera*				Jamaica	Wild	(McKoy et al. 2011)
Ornithodiplostomum ptychocheilus	*Pimephales promelas*				USA	Wild	(Wisenden et al. 2012)
Ornithodiplostomum ptychocheilus	*Pimephales promelas*				Canada	Wild	(Sandland and Goater 2001; Sandland et al. 2001)[5]
Paracaryophyllaeus gotoi	*Misgurnus anguillicaudatus*				Japan	Wild	(Scholz et al. 2001)
Parapleurophocercous sp.	*Melanoides tuberculata*				Philippines	Wild	(Paller et al. 2019)
Parapleurophocercous sp.	*Tarebia granifera*				Philippines	Wild	(Paller et al. 2019)
Philophthalmus gralli	*Melanoides tuberculata*				USA	Wild	(Tolley-Jordan and Chadwick 2018)

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
Nematoda							
Philophthalmus gralli	*Tarebia granifera*				USA	Wild	(Tolley-Jordan and Chadwick 2018)
Philophthalmus sp.	*Tarebia granifera*				Jamaica	Wild	(McKoy et al. 2011)
Posthodiplostomum minimum	*Pimephales promelas*				Canada	Wild	(Schleppe and Goater 2004)
Posthodiplostomum minimum	*Pimephales promelas*				USA	Farm	(Mitchell et al. 1982)
Posthodiplostomum sp.	*Astronotus ocellatus*				Brazil	Wild	(Neves et al. 2013)[6]
Pimephales promelas	*Posthodiplostomum* sp.				USA	Wild	(Weichman and Janovy 2000)
Proteocephalus gibsoni	*Astronotus ocellatus*				Brazil	Wild	(Tavares-Dias and Neves 2017)
Proteocephalus misgurni	*Misgurnus anguillicaudatus*				Russia	Wild	(Scholz et al. 2014)
Prototransversotrema steeri	*Xiphophorus hellerii*				Sri Lanka	Farm	(Dove 2000)
Pseudolevinseniella anenteron	*Cherax quadricarinatus*				Thailand	Wild	(Ngamniyom et al. 2019)
Paradiplozoon bingolensis	*Garra rufa*				Turkey	Wild	(Civanova et al. 2013)
Schyzocotyle acheilognathi	*Pimephales promelas*				USA	Retail B	(Boonthai et al. 2017)
Schyzocotyle acheilognathi	*Xiphophorus hellerii*				USA	Wild	(Vincent and Font 2003)
Stellantchasmus falcatus	*Tarebia granifera*				Thailand	Wild	(Chontananarth et al. 2018)
Temnosewellia sp.	*Cherax quadricarinatus*				Thailand	Wild	(Ngamniyom et al. 2019)
Tetracotyle wayanadensis	*Pethia conchonius*				India	Wild	(Jithila and Prasadan 2018)
Thometrema sp.	*Astronotus ocellatus*				Brazil	Wild	(Tavares-Dias and Neves 2017)
Uvulifer ambloplitis	*Pimephales promelas*				USA	Wild	(Weichman and Janovy 2000)
Telethecium nasalis	*Osteoglossum bicirrhosum*				Brazil	Wild	(Kritsky et al. 1996)

[1] variant *Cherax quadricarinatus densovirus*; [2] Rhabdovirus; [3] Also Pie and Boeger (2006) and Bueno-silva and Boeger (2009); [4] Also Reported under synonym *Echinostoma hortense* ; [5] Aso Schleppe and Goater (2004); [6] Also Tavares-Dias and Neves (2017) and Pinheiro et al. (2019).

Discussion

Trade in live aquatic ornamental species is vast, benefitting from globalisation and improved transport in recent decades. Over 140 countries are involved in the international trade of more than 1500 fish and 300 aquatic invertebrate species (Weir et al. 2012; Hood et al. 2019). Our study provides an assessment of freshwater ornamental trade in the UK in which commonly traded species and their likelihood of establishment in UK waters under current and future climate conditions, with their potential pathogens and parasites also identified..

These data on commonly traded species are a snapshot in time, which potentially limits accuracy and prevents the assessment of seasonal and annual variations. That said, the six species identified were listed amongst the 30 species reported to predominate the global trade in ornamental freshwater organisms in a relatively recent review: Endler's livebearer, goldfish, zebra danio, neon tetra *Paracheirodon innesi* Myers, 1936, angel fish *Pterophyllum scalare* Schultze, 1823, and discus *Symphysodon aequifasciatus* Pellegrin, 1904 (Dey 2016).

Access to robust ornamental trade data, in particular with respect to species traded and import origin, is fundamental to fill knowledge gaps and inform risk screenings and the risk analysis process (Copp et al. 2016; Chan et al. 2019). A comprehensive understanding of spatial and temporal trade patterns to species level will increase capacity to identify high risk links, facilitating targeted and cost-effective surveillance. Species-level information will also support analyses from a conservation point of view, particularly for marine species that are wild sourced, and ensure there is increased transparency in the source, quantity and sustainability of trade for each species (Andersson et al. 2021). In the UK, aquatic species imports from third party countries are electronically recorded on the 'Import of Animals Food and Feed System' (IPAFFS). Historically, non-susceptible aquatic species imported from the EU for ornamental use were not recorded on any system. As of January 2021, all aquatic imports must be recorded on IPAFFS, but records on this database are categorised by international commodity codes (www.uktradeinfo.com/find-commodity-data/help-with-classifying-goods/). However, the purpose of these codes is to enable the application of appropriate tariffs to imported goods and they do not provide sufficient resolution to identify consignments to species level, so cannot be used to inform disease susceptibility or invasive potential. Import data at the species-level for the UK currently exist in paper format only (on the invoices that accompany all other relevant import certification), though there are periods for which species-level electronic data have been available for freshwater fishes, including ornamental varieties, imported to England between 2000 and 2004 inclusive (see Copp et al. 2007). Limitations with respect to access to detailed live ornamental import data are not unique to the UK (Rhyne et al. 2012, 2017; Leal et al. 2016; Pinnegar and Murray 2019; Biondo and Burki 2020). Creation of an import data App, or extension of an existing, established App, is an opportunity to capture detailed import data, integrating species trade information with other crucial information such as invasiveness potential, associated disease threats and conservation status. Such a system would enhance capacity for real-time monitoring and analysis, at the point of exporter application for import, allowing trade in high risk species to be tracked and incidences of illicit trade, such as the import of prohibited species, to be detected in a timely manner (Rhyne et al. 2017).

Legislative instruments restrict the keeping of many temperate species but do allow the keeping of numerous commonly traded tropical and sub-tropical species. The application of SDMs indicated that, while establishment of commonly traded species if released into the wild is unlikely in the UK under current conditions, predicted temperature increases associated with climate change may increase risks of survival and establishment. The mean increase in temperature suitability of 2.4% and 1.8% for fish and invertebrates, respectively, by 2050 under RCP 4.5 demonstrated in our study may seem a small increase in 'risk', but RCP 4.5 represents a moderate climate-change scenario, and temperature increases may be greater than this scenario predicts. Although a broad scale indication of the change in suitability under climate change is provided, careful interpretation of SDM outputs may be required. For instance, the red shiner *Cyprinella lutrensis* Baird & Girard, 1853, is widespread across the USA and has been identified, using the Fish Invasiveness Screening Kit, as posing a medium risk of being invasive in England and Wales (Copp et al. 2009). However, the red shiner had a relatively low suitability score (0.10) under current day conditions in our study (Table 2). The Chinese muddy loach *Misgurnus mizolepis* Guenther, 1888 had a suitability score of 0.26 under current day conditions, yet there has been only one record of a reproducing population in the UK (in southern England), which was subsequently eradicated (Zięba et al. 2010).

Although outside the scope of our study, there will be value in assessing species suitability at a finer spatial resolution, for example accounting for differences in conditions across the entirety of the UK (Thrush and Peeler 2013), for example, the notably warmer conditions in the South compared to the North UK, affecting the risks of survival and establishment of sub-tropical and tropical species (see Suppl. material 1: Figs S1, S2). Further, extension of the SDMs to incorporate environmental factors such as rainfall, habitat type or elevation (Logez et al. 2012), species' life-history traits such as size or fecundity (Copp and Fox 2007; Liu and Olden 2017), and consideration of the likelihood of release of each species (i.e. potential propagule pressure) will be of value. For example, inclusion of elevation will account for species with native distributions at higher altitudes within the tropical zone that may be more adapted to temperature conditions more similar to the temperate zone species due to Rapoport's latitudinal rule to altitude (Stevens 1992).

In total, 155 PPPs were found to be associated with the screened ornamental fishes and invertebrates. Despite following a standardised approach for each host species, the number of PPPs identified in the literature may be skewed by the research effort applied to a species and affected by the use of different accepted names or synonyms. One of the key drivers of impacts associated with NN aquatic species (Peeler et al. 2011) are PPPs, with disease emergence events resulting from NNS introductions being well documented (Taraschewski 2006; Peeler et al. 2011; Lymbery et al. 2014). Disease emergence can be driven solely by a switch in geographical range, because a new environment may favour increased PPP virulence, or by host switching and pathogen/parasite spillover (Peeler et al. 2011; Foster et al. 2021). Thermal tolerances of a PPP may also determine the likelihood and impact of disease emergence resulting from co-transportation, particularly for PPPs that can survive outside a host or have free-living stages (Barber et al. 2016).

Even if the long-term survival of an ornamental species is not supported by future UK temperatures, the host species may persist long enough to transmit a PPP to a native susceptible host or introduce a free-living stage which can survive. Temperature may also determine the likelihood of PPPs causing disease and morbidity in infected hosts. For example, KHV is thought to only cause clinical signs and mortality between 16 °C and 25 °C (OIE 2019), whereas outbreaks of VHS rarely occur above 15 °C (Baillon et al. 2020). While beyond the scope of this study there will be value in building on the present study by examining the environmental tolerances of the PPPs and the likely impact of climate change. Indeed, PPPs introduced via the ornamental pathway may cause wider impact, for example causing mortality and yield loss in aquaculture systems and affecting human health, although strong biosecurity and health and safety precautions can mitigate against such risks.

The PPPs that cause mortalities or clinical expression of disease in the traded host species are more likely to be detected via visual inspection or quarantine at border control posts or other stages in the ornamental trade pathway (Table 3). However, PPPs that live symbiotically with a host, or those PPPs that have sub-clinical or latent infection stages, provide a greater challenge to detection (Gomez et al. 2006; Becker et al. 2014). Traditionally, the testing of host species for PPP presence often requires destructive sampling, which limits the number of specimens and ultimately reduces the probability of PPP detection. However, new methodologies that incorporate molecular techniques at border control posts, such as environmental DNA, may present a good non-lethal option (Trujillo-González et al. 2019b; Brunner 2020) for improved PPP detection. Measures such as heat ramping (gradually increasing the water temperature over a minimum period) can be used during quarantine to detect latent infections (Eide et al. 2011); however, this may not appropriate for all PPPs, when surveillance aims to target multiple PPPs and where there is a need to adhere to animal welfare laws and guidance.

Though the remit of our study was to undertake a high-level screening to identify all PPPs associated with commonly traded ornamental species, rather than novel threats *per se*, we note that while some of the identified PPPs are known in the UK, others are not. Some PPPs are already known within the ornamental fish trade industry, and do not cause widespread impact or can be successfully treated to minimise impact. However, the abundance and diversity of PPPs increases potential for future disease outbreaks under changing environmental conditions. Even where a PPP has not yet been implicated in any mortality events, the changing climate and alterations to host communities (e.g. due to species introductions) may provide the perfect storm for disease emergence into the future. Next steps should aim to assess the risk associated with each PPP, focussing on the interplay between the PPP, all potential hosts and changing environmental conditions.

In conclusion, the ornamental fish trade is largely free from serious and untreatable diseases. However, through screening of a small subset of ornamental freshwater species, our study highlights the abundance and diversity of PPPs present in ornamental species commonly traded in the UK. An understanding of hazards associated with PPPs, in particular under changing ecological and environmental conditions, is crucial to determine and communicate risks and enhance risk awareness amongst stakeholders and the general public, thereby enabling mitigation through management actions (Britton et al. 2011) to ensure a safe and sustainable ornamental aquatics industry into the future (Copp et al. 2016).

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Supplementary material 1

Threats to UK freshwaters under climate change: Commonly traded aquatic ornamental species and their potential pathogens and parasites

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Data type: Lists, Tables and Maps

Explanation note: This supplementary file provides a list of all websites used in the Google search, a table of all fish and invertebrate species observed as being sold in the UK and criteria for further analysis and a table of results for the pathogen and parasite screen based on laboratory studies (and the reference list for this table).

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Link: https://doi.org/10.3897/neobiota.76.80215.suppl1