Economic costs of protistan and metazoan parasites to global mariculture

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SUMMARY

Parasites have a major impact on global finfish and shellfish aquaculture, having significant effects on farm production, sustainability and economic viability. Parasite infections and impacts can, according to pathogen and context, be considered to be either unpredictable/sporadic or predictable/regular. Although both types of infection may result in the loss of stock and incur costs associated with the control and management of infection, predictable infections can also lead to costs associated with prophylaxis and related activities. The estimation of the economic cost of a parasite event is frequently complicated by the complex interplay of numerous factors associated with a specific incident, which may range from direct production losses to downstream socio-economic impacts on livelihoods and satellite industries associated with the primary producer. In this study, we examine the world's major marine and brackish water aquaculture production industries and provide estimates of the potential economic costs attributable to a range of key parasite pathogens using 498 specific events for the purposes of illustration and estimation of costs. This study provides a baseline resource for risk assessment and the development of more robust biosecurity practices, which can in turn help mitigate against and/or minimise the potential impacts of parasite-mediated disease in aquaculture.

Keywords: Aquaculture, production, mortality, finfish, Crustacea, Mollusca, ornamentals, economic cost, review.

INTRODUCTION

Pre-harvest mortalities in marine aquaculture result from the complex interplay of a broad range of factors that include stock source/genotype, developmental defects, predation and cannibalism, impaired nutrition, physical damage, sub-optimal/hostile environmental conditions and disease. Economic losses accrue not only from mortalities but also from impacts on growth and food conversion, post-harvest downgrading or rejection of carcasses and derived products, fish escapes, management decisions that impact on profitability, e.g. protracted decisions to treat, grade or harvest, and the costs and effects of particular husbandry and management practices, e.g. fallowing, grading, vaccination, treatment and stock handling.

Parasitic diseases attributable to obligate or opportunistic eukaryotic pathogens continue to have a major impact on global finfish and shellfish aquaculture, and in many regions they represent a key constraint to production, sustainability and economic viability. Although robust data can often be generated concerning the general patterns of stock loss within a typical production cycle, obtaining accurate figures for the impacts of disease can be more problematic due to a number of considerations, which include production scale, available resources, difficulties in making rapid or accurate parasite identifications at the farm level and poor record keeping. The frequent association of disease with other pre-disposing factors, such as poor water quality and the broad variety of precipitating events that may act to stress the farm population, also means that untangling the impacts of disease from those attributable to other causes may be difficult or impossible. Thus, in many cases, the economic impact of parasitic diseases can only be estimated.

Parasite-induced impacts in marine aquaculture can be divided into two broad categories: unpredictable/sporadic and predictable/regular. For both, there may be costs in treating and managing infections once established, but for predictable infections there will also be costs associated with prophylactic treatment/management. For example, the management costs associated with controlling infections of caligid copepods, e.g. *Lepeophtheirus salmonis* and *Caligus* spp. in farmed Atlantic salmon (*Salmo salar*) can largely be predicted within a production cycle as

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these parasites pose a perennial threat to captive reared stocks. The infection dynamics of these species are well understood, and they can be controlled through the employment of an integrated pest management strategy (IPMS) involving the use of a broad range of management tools in addition to direct treatment intervention. The global Atlantic salmon production industry is well established (> 40 years) and can draw upon the long-term, shared experiences of parasite control and management that have led to the development of effective strategies to minimise mortalities, damage and loss of profit (see Frenzl *et al*. 2013, 2014). For many other new or less-established industries, however, particularly those restricted to a small number of production sites, the parasite threats may be largely unknown and emerging, and new infections can have a devastating impact. The impact of *Paramoeba perurans* (syn. *Neoparamoeba perurans*), the causative pathogen of amoebic gill disease (AGD), on the early Tasmanian production of rainbow trout, *Oncorynchus mykiss*, serves as an appropriate example (Munday *et al*. 1990).

Many parasite infection events are complicated by the complex interplay of numerous factors making it difficult to calculate the precise costs attributable to the parasite. The Chilean crash in national salmon production from 385 086 tonnes (t) in 2006 to 230 678 t in 2010 (FAO FishStatJ, 2013), for example, appears to have been multifactorial with the key pathogens involved being ISAv (infectious salmon anaemia virus) and the caligid copepod *Caligus rogercresseyi*. Major contributing factors included a large number of marine farms in production, the high stocking densities employed, a concentration of farms within a small area (~ 40% of the salmon production around Chiloé Island), a lack of biosecurity measures, weak disease surveillance, poor sanitary control and a failure to employ zone management (Ibieta *et al*. 2011). Many farm sites were subject to infection from other disease agents, such as salmonid rickettsial septicaemia (SRS) caused by *Piscirickettsia salmonis* (see Olivares and Marshall, 2010), infectious pancreatic necrosis (IPN) caused by the pancreatic necrosis virus (IPNV) (Ibieta *et al*. 2011), *P. perurans* (see Bustos *et al*. 2011; Rozas, 2011) and rising *C. rogercresseyi* infections (Rozas and Asencio, 2007), which were suggested to predispose salmon stocks to the ISAv infection. By the end of 2008, 105 Chilean sites were confirmed as ISAv positive with a further 44 suspect sites; a quarter of the positive sites were owned by a single company who declared losses of US$ 81·2 billion for the second half of 2007 (Marine Harvest, 2007). As can be seen from the above, the calculation of the proportion of this loss that could be deemed to be attributable to *C. rogercresseyi* is not possible.

Although immediate losses to production can often be estimated, it is usually difficult to calculate the full magnitude of the downstream socio-economic effects of major disease events on the livelihoods and associated industries centred around primary producers. While insurance claims may provide some guidance as to losses, these may be overinflated, based on 'best price' or on an estimated loss of trade/income. In addition, the costs of remedial action (e.g. treatment, disposal and monitoring) and/or changes to management practices and infrastructure also need to be considered. The resilience of the Chilean salmonid aquaculture industry, which rapidly implemented improved infectious disease control measures and was able to fall back on well-established coho salmon, *Oncorynchus kisutch*, and rainbow trout industries (24 and 38% of national salmonid production in 2011, respectively), arguably minimised the full potential economic impact of the 2007 crisis (Alvial *et al*. 2012*a*, *b*). Although there are a number of studies that have attempted to estimate the full economic consequences of parasite infections, both through the documentation of a specific disease event (Roberts *et al*. 1994; Torgerson and MacPherson, 2011; Charlier *et al*. 2012) and through the estimation of the potential impact of disease introduction (Paisley *et al*. 1999; Riddington *et al*. 2006; Voort van der *et al*. 2013), the data and resources required to undertake such studies generally preclude the accurate estimation of the cost of parasite-associated impacts. For example, teasing out the role and the precise economic impact attributable to parasitic agents, e.g. *P. perurans* and *C. rogercresseyi*, from that due to the other contributing factors leading to the Chilean 2007 crisis, is a near-impossible task, and therefore, the costs can only be speculated upon. For this reason, the economic impact of these parasites in the Chilean 2007 crisis, is not included in this summary.

In this review, we provide an overview of the world's major marine and brackish aquaculture production industries and assess the impacts of the major parasite species that affect production or otherwise impose an economic cost. As discussed above, it is not possible to provide a comprehensive review of all parasite-related losses in aquaculture, but we provide estimates for some of the more serious loss-related events and provide brief details relating to each. For each event resulting in a notable loss, i.e. either mortality or deviation from projected revenue, we cite either figures given in the original publication or have applied a simple formula to determine the likely loss to the stock only at the point in the production cycle when the disease event occurred. In the absence of details within the original report, many of the costs provided here are assumption-based and so a degree of caution should be exercised. It is anticipated that this study will prove informative for risk assessment by new aquaculture-based enterprises and will aid an appreciation of the sporadic nature and impact of some parasite-induced

Table 1. Aquaculture production in brackish and marine environments in 2011 presented in tonnes (t) for each broad class of aquatic species. Figures are calculated from the FAO FishStatJ databases (2011)

	Brackish		Marine		Combined	
	Tonnage	%	Tonnage (t)	%	Tonnage (t)	%
Algae	635 654	11·55	20 265 356	51·66	20 901 010	46·722
Aq. inverts. (unspec.)			74 664	0·19	74 664	0·167
Ascidiacea			12 369	0·03	12 369	0·028
Cnidaria			69 749	0·18	69 749	0·156
Crustacea	2 829 894	51·41	705 530	1·80	3 535 424	7·903
Echinoidea			6791	0·02	6791	0·015
Holothuroidea			138 186	0·35	138 186	0·309
Mollusca	99 341	1·80	14 069 022	35·86	14 168 363	31·672
Pisces	1 939 393	35·24	3 888 446	9·91	5 827 844	13·028
Total	5 504 282		39 230 113		44 734 400	

Table 2. The top 30 marine and brackish finfish aquaculture industries ranked by the value of production. Figures are predominantly derived from the FAO Fisheries and Aquaculture FishStatJ databases (2011)

Common name	Latin name	Tonnage (t)	Value (US$ × 1000)	Largest producer
Atlantic salmon	*Salmo salar*	1 711 455	9 628 336	Norway (1 059 958 t; 61·93%)
Rainbow trout	*Oncorhynchus mykiss*	298 186	2 118 922	Chile (208 482 t; 69·92%)
Milkfish	*Chanos chanos*	823 781	1 427 587	Indonesia (467 044 t; 56·70%)
Japanese amberjack[a]	*Seriola quinqueradiata*	146 274	1 375 841	Japan (146 240 t; 99·98%)
Gilthead sea bream	*Sparus aurata*	154 771	928 666	Greece (70 600 t; 45·62%)
Coho salmon	*Oncorhynchus kisutch*	159 694	916 647	Chile (144 120 t; 90·25%)
European seabass	*Dicentrarchus labrax*	144 315	860 939	Turkey (47 013 t; 32·58%)
Turbot	*Scophthalmus maximus*	75 413	600 332	China (64 000 t; 84·87%)
Silver sea bream	*Pagrus auratus*	64 684	572 754	Japan (61 186 t; 94·59%)
Groupers	*Epinephelus* spp.	95 153	550 585	China (59 534 t; 62·57%)
Bastard halibuts	*Paralichthys olivaceus*	44 280	484 846	Rep. Korea (40 805 t; 92·15%)
Pompano	*Trachinotus* spp.	115 133	461 032	China (115 000 t; 99·88%)
Flathead grey mullet	*Mugil cephalus*	125 678	441 875	Egypt (84 001 t; 66·84%)
Barramundi	*Lates calcarifer*	55 685	258 645	Malaysia (17 607 t; 31·62%)
Cyprinids[b]	*Cyprinus carpio, Hypophthal michthys molitrix, Ctenopharyngodon idellus*[c]	100 000	235 992	Egypt (100%)
Red seabream	*Pagrus major*	124 799	166 241	China (122 964 t; 98·53%)
Korean rockfish	*Sebastes schlegelii*	17 338	137 136	Rep. Korea (100%)
Chinook salmon	*Oncorhynchus tshawytscha*	15 131	103 140	New Zealand (13 362 t; 88·31%)
Large yellow croaker	*Larimichthys crocea*	80 212	95 452	China (100%)
Red drum	*Sciaenops ocellatus*	67 339	91 878	China (64 838 t; 96·29%)
Tiger pufferfish	*Takifugu rubripes*	14 906	85 986	China (11 632 t; 78·04%)
Porgies, sea breams		58 029	86 732	China (56 313 t; 97·04%)
Atlantic bluefin tuna	*Thunnus thynnus*	3410	72 832	Croatia (1610 t; 47·21%)
Cobia	*Rachycentron canadum*	40 863	66 258	China (37 210 t; 91·06%)
Meagre	*Argyrosomus regius*	13 742	55 428	Egypt (12 092 t; 87·99%)
Atlantic cod	*Gadus morhua*	16 126	50 508	Norway (15 249 t; 94·56%)
Lefteye flounders[d]	*Psettina breviríctis*	47 589	47 589	China (100%)
Southern bluefin tuna	*Thunnus maccoyii*	1987	44 261	Australia (100%)
Tilapia[b]	*Oreochromis niloticus/ O. mossambicus*	617 533	42 033	Egypt (580 617 t; 94·02%)
Mangrove red snapper	*Lutjanus argentimaculatus*	5259	32 113	Malaysia (5237 t; 99·58%)
Total		5 238 765	22 040 586	

[a] Australian production figures are missing from FAO FishStatJ databases.
[b] As this table includes all species cultured in brackish and marine waters, species cultured in inland brackish waters are included for completeness.
[c] See Sadek (2011).
[d] In the absence of a Latin name it is not known whether this generic term refers the culture of *Psettina breviríctis* or *Paralichthys olivaceus*, which is known as the bastard halibut, olive or Japanese flounder, given this uncertainty it is listed separately in the table.

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Table 3. The top 25 farmed marine molluscan species ranked by the value of their respective industry. Data are extracted from the FAO FishStatJ database of production figures for 2011 and are based on the identifiable stocks. Although a number of additional high value, general classes of mollusc that are listed by country also appear within the database, the species composition of some of these cannot be determined and so are not included in the listing below

Common name	Latin name	Tonnage (t)	Value (US$×1000)	Largest producer
Pacific cupped oyster	*Crassostrea gigas*	4 533 804	3 620 764	China (3 756 310 t; 82·85%)
Japanese carpet shell	*Ruditapes philippinarum*	3 681 436	3 438 190	China (3 546 502 t; 98·15%)
Yesso scallop	*Patinopecten yessoensis*	1 426 179	2 072 999	China (1 306 124 t; 91·58%)
Chilean mussel	*Mytilus chilensis*	288 583	1 148 561	Chile (100%)
Abalone species	*Haliotis* spp.[a]	86 445	676 004	China (76 786 t; 88·83%)
Constricted tagelus	*Sinonovacula constricta*	744 794	670 315	China (100%)
Peruvian calico scallop	*Argopecten purpuratus*	63 231	623 870	Peru (52 213 t; 82·58%)
Blood cockle	*Anadara granosa*	443 686	468 045	China (293 200 t; 66·08%)
Mediterranean mussel	*Mytilus galloprovincialis*	1 019 420	447 630	China (707 401 t; 69·39%)
Blue mussel	*Mytilus edulis*	176 445	348 965	France (61 800 t; 35·03%)
Green mussel	*Perna canalicula*	222 633	219 689	New Zealand (101 311 t; 45·51%)
Pearl oyster shells	*Pinctada* spp.[b]	55	216 255	Japan (20 t; 36·36%)
Japanese hard clam	*Meretrix* spp.[c]	119 771	165 460	Vietnam (∼ 60 000 t; ∼ 50·1%)
Sea snails	*Babylonia/Hemifusus* spp.[d]	203 266	123 992	China (100%)
Asian clam	*Corbicula fluminea*	36 983	65 756	China (22 327 t; 60·37%)
Northern quahog	*Mercenaria mercenaria*	28 841	62 873	USA (100%)
American cupped oyster	*Crassostrea virginica*	71 355	58 219	USA (67 975 t; 95·26%)
Grooved carpet shell	*Ruditapes decussatus*	4138	52 834	Portugal (2315 t; 55·94%)
Sydney cupped oyster	*Saccostrea commercialis*	5700	41 638	Australia (100%)
Korean mussel	*Mytilus coruscus*	70 416	29 247	Rep. Korea (100%)
Penguin wing oyster	*Pteria penguin*	48 449	27 471	Indonesia (100%)
Pacific geoduck	*Panopea generosa*	607	21 415	USA (100%)
Inflated ark	*Scapharca broughtonii*	2110	20 248	Rep. Korea (100%)
Pen shells	*Atrina* spp.	30 126	19 281	China (100%)
S. Amer. rock mussel	*Perna perna*	15 970	12 776	Brazil (100%)
Total		13 324 443	14 652 497	

[a] Consists of a number of species, including *Haliotis discus hannai*, *H. diversicolor*, *H. midae*, *H. rubra* and *H. rufescens*.
[b] Principally *Pinctada fucata martensii* and *P. margaritifera*.
[c] Figures consist of ∼50% Taiwanese *Meretrix lusoria* and the 50% Vietnamese *M. lyrata* and *M. meretrix*.
[d] Consists of a number of species, including *Babylonia areolata*, *B. lutosa*, *B. formosae* and *Hemifusus ternatanus* and *H. tuba*.

infections, and can assist in the development of more robust risk assessments and biosecurity practices, which can help mitigate against and/or minimise the potential impacts of parasite-mediated disease in aquaculture.

MATERIALS AND METHODS

Ranking of aquaculture industries

FAO's FishStatJ has been used as the principal source of data for ranking industries according to their commercial value and tonnage (see Tables 1–6); however, it should be emphasised that some caution needs to be exercised in the interpretation of both the original figures and those provided here given that (1) the species in FishStatJ are listed by common names rather than by a specific Latin binomial nomenclature or by a generic group, e.g. groupers, creating potential errors in correctly identifying and allocating a species to its true class and ascribing an accurate tonnage and value; (2) the values returned for some species are estimated in the absence of precise data and are based on either best knowledge at the time of data submission, the returns submitted for previous years or represent cautious projections based on either national growth trends for each industry or nominal figures intended to demonstrate growth and development; and (3) aquaculture activities in some countries appear to have been omitted, e.g. Australia's production figures for Japanese yellowtail *Seriola quinqueradiata*. In the case of the latter, the figures may have been included and are listed under another category but are not easily identifiable. We have, therefore, attempted to identify national production figures for some of these industries and provide amended values.

Table 1 provides a breakdown of brackish/marine aquaculture by class. In addition to providing production figures and values for the major marine/brackishwater finfish (Table 2), molluscan (Table 3),

Table 4. The top 10 farmed crustacean species ranked by the value of their respective industry. Figures are generated from the FAO FishStatJ databases and are based on identifiable stocks

Common name	Latin name	Tonnage (t) Brackish	Tonnage (t) Marine	Value (US$ × 1000) Brackish	Value (US$ × 1000) Marine	Total value (US$ × 1000)
Whiteleg shrimp[a]	*Litopenaeus vannamei*	2 032 416	278 858	8 113 926	1 054 008	9 167 934
Giant tiger prawn[b]	*Penaeus monodon*	644 376	117 809	2 926 750	541 915	3 468 665
Indo-Pacific swamp crab[c]	*Scylla serrata*	36 668	121 641	166 966	289 015	455 981
Indian white prawn[d]	*Fenneropenaeus indicus*	20 851	21 007	99 411	252 000	351 411
Swimming crab[e]	*Portunus trituberculatus*	–	92 907	–	326 104	326 104
Kuruma prawn[f]	*Marsupenaeus japonicus*	275	52 628	3778	309 247	313 025
Fleshy prawn[g]	*Fenneropenaeus chinensis*	41 646	16	166 584	267	166 851
Metapenaeus spp.[h]	*M. monoceros* + *M. ensis*	35 047	–	124 760	–	124 760
Mud crab[i]	*Scylla* (*paramamosain*?)	109	17 401	431	70 300	70 731
Blue shrimp[j]	*Litopenaeus stylirostris*	–	1929	–	19 771	19 771
Total		2 811 388	704 196	11 602 606	2 862 627	14 465 233

[a] China is the largest brackish producer at 665 588 t; Mexico the largest marine producer at 106 886 t. FAO FishStatJ allocate 76 507 t of Chinese marine-farmed shrimp to 'marine *Penaeus*', it is believed that this may represent China's *L. vannamei* production and has been included within the marine figures.
[b] Vietnam is the largest brackish producer at an estimated 300 000 t; China the largest marine producer at 60 691 t.
[c] Philippines is the largest producer of crabs in brackish waters at 15 731 t; China the largest marine producer at 121 458 t.
[d] Bangladesh is the largest brackish producer at 2364 t; Saudia Arabia the largest marine producer at 21 000 t.
[e] China is the only producer listed.
[f] Taiwan is the largest brackish producer at 178 t; whilst China the largest marine producer at 50 991 t.
[g] China is the largest brackish producer at 41 646 t; Korea the largest marine producer at 16 t.
[h] Bangladesh is the largest producer of identifiable *Metapenaeus* shrimp at 17 777 t.
[i] Taiwan is the only brackish producer at 109 t; China the only nation producing mud crabs in marine waters in 2011 with an annual production of 17 401 t.
[j] Limited information available.

Table 5. Other important cultured marine species. These figures are generated from the FAO FishStatJ databases and are based on identifiable stocks

Common name	Latin name	Tonnage (t)	Value (US$ × 1000)	Largest producer
Ascidiacea				
Sea squirts	*Halocynthia roretzi*	12 369	20 842	Rep. Korea (11 676 t; 94·40%)
Cnidaria				
Jellyfish	*Rhopilema esculentum*	69 749	164 608	China (100%)
Echinodermata				
Echinoidea				
Sea urchins[a]	*Strongylocentrotus intermedius*, *S. nudus*	6791	23 514	China (6756 t; 99·48%)
Holothuroidea				
Japanese sea cucumber	*Apostichopus japonicus*	138 186	482 712	China (137 754 t; 99·69%)

[a] Limited information available on species that are being cultured.

crustacean (Table 4), ascidian, cnidarian and echinoderm (Table 5) industries, we also consider farmed marine ornamental species (Table 6). Identifying global figures for the most popular traded ornamental species, however, has proven more difficult, and here we use information presented by Rhyne *et al*. (2012) on the number of fish imported into the USA during the period May 2004–May 2005 as an indicator. The shipment data, which was extracted from the Law Enforcement Management Information Systems (LEMIS) database maintained by the United States Fish and Wildlife Services (USFWS), was used to list the 20 most popular fish entering the USA. The retail value of each ornamental species, for which a commercial aquaculture production unit could be identified, was determined from the average retail price in the USA determined from a minimum of three outlets.

Estimates of parasite-induced loss

The species rankings provided in Tables 2–6 were then used as a basis for identifying the principal parasite threats that have been reported to have resulted in economic loss. In addition to reporting the estimates of loss cited in peer-reviewed and

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Table 6. The top 12 marine ornamental fish species, for which some commercial production units could be identified that were imported into the USA with details on their average retail price and estimated trade value. As numbers for global production are unknown, here we use numbers imported into the USA during the period May 2004–May 2005 as presented by Rhyne *et al*. (2012) as an indication of the potential size of each industry. Species are ranked by their estimated economic value based on their average retail prices (min. $n = 3$). Common names are taken from the Ornamental Fish International website (http://www.ornamental-fish-int.org/)

Common name	Latin name	Av. price US$ (range)	No. fish p.a. USA[a]	Est. value imported US$
Green Chromis	*Chromis viridis*	10·99 (6·99–12·99)	923 423	10 148 419
False percula	*Amphiprion ocellaris*	20·85 (14·99–39·99)	427 177	8 906 641
Flame angel	*Centropyge loricula*	44·32 (37·99–49·99)	133 634	5 922 659
Blue devil	*Chrysiptera cyanea*	7·32 (4·99–11·99)	729 730	5 341 624
Domino damsel	*Dascyllus trimaculatus*	7·59 (4·99–11·99)	624 625	4 740 904
Banggai cardinal	*Pterapogon kauderni*	27·99 (25·99–29·99)	164 414	4 601 948
Maroon clownfish	*Premnas biaculeatus*	32·84 (23·99–44·99)	117 868	3 870 785
Mandarinfish	*Synchiropus splendidus*	21·49 (18·99–23·99)	141 892	3 049 259
Three-stripe damsel	*Dascyllus aruanus*	6·74 (5·99–6·99)	438 438	2 955 072
Yellowtail damsel	*Chrysiptera parasema*	4·99 (4·99)	393 393	1 963 031
Tomato clownfish	*Amphiprion frenatus*	18·32 (14·99–23·99)	100 601	1 843 010
Royal gramma	*Gramma loreto*	17·49 (13·99–19·99)	91 592	1 601 944
Est. total			4 286 787	54 945 296

[a] Figures extrapolated from the graphics presented in Rhyne *et al*. (2012).

grey literature accounts, we also provide estimates of direct fish loss based on the information given in the published record (i.e. number, size or age class of aquatic animals, tonnage, number of net-pens/culture systems affected, etc.) and the value (US$ kg^{-1}) of the mariculture stock using a combination of the FAO FishStatJ statistics (value divided by tonnage) for the corresponding year of the loss. These latter figures, however, are for harvested, unprocessed stock. The age of stock affected is then corrected for using one of the relevant species listed in Table 7 and assuming a linear increment in the value of stock from the cost per juvenile to harvest-sized stock and a 100% probability of survival to harvest. Additional assumptions relevant to the loss, where appropriate, are provided as part of the entry in Tables 8–12.

RESULTS

Ranking of aquaculture industries

The world's leading aquaculture industries derived from FishStatJ for 2011 are ranked in Tables 2–6 by their market value. These tables include 69 of the 222 unique aquatic animal categories listed in the database and account for approximately 94% (i.e. 22 305 887 t) of the total weight of marine animals produced (i.e. 23 832 381 t) and 93% (i.e. US$ 51 849·962 M) of their total value (i.e. US$ 55 781·97 M). The database, however, also includes a number of general categories, e.g. 'aquatic invertebrates nei', 'marine fishes nei', which potentially embrace a large number of species that are produced in small volumes. The total number of aquatic animals that are reared under brackish and marine aquaculture conditions is, therefore, likely to have been substantially underestimated here. Table 6 ranks the 12 most popular marine aquarium species, for which a commercial production unit could be identified, by their estimated retail value based on numbers imported into the USA (see Rhyne *et al*. 2012).

Tables 8–12 provide a summary of notable parasite-induced events with estimates of the costs incurred.

In 2011, global aquaculture production was 83 729 313 t (all species) of which 44 734 400 t (i.e. 53·43%) were produced in brackish or marine waters (see Table 1). Global aquaculture has increased at a rate of 6·4% year-on-year over the past five years and by 7·2% over that produced in 2010. By comparison, brackish–marine production has increased by 5·7% (over the past five years) and 6·6%, respectively. Of this, Asia produces 39 542 391 t (i.e. 88·39%), although brackish–marine algae represent over half (i.e. 52·46%, 20 743 150 t) of this. In this study, the top 30 fish species listed in Table 2 account for 89·89% by production tonnage of all brackish/marine aquaculture species that were produced in 2011. Likewise, the top 25 molluscs provided in Table 3 account for 94·04% of what was produced and the top 10 crustacean species given in Table 4 for 99·44%.

DISCUSSION

The data presented in Tables 8–12 provide a basic review of some of the major parasite events experienced by these production industries and, where possible, ascribe an estimate of the resultant loss

Table 7. Production details for a range of fish species that are used, in part, for the estimations of loss

Species	Harvest size (kg)	Time to harvest (month)	Stocking density (kg m^3)	Juvenile size (g)	Price juveniles (US$ $fish^{-1}$)	Country	Reference
Dicentrarchus labrax	0·4–0·5	18–24	35–50	2·5	0·39	Across Eur prod	Lupatsch *et al*. (2010); www.fao.org (2014*a*)
Diplodus puntazzo	0·4–0·5	18–22	15	15	0·02	Spain	García García and García García (2010)
Epinephelus spp.	0·93–3·1	24	11·5–18·5	34–168	1·02–2·33	Vietnam	Petersen *et al*. (2011*a*)
Lates calcarifer	0·25–3·0	3–18	1–16 fish m^3	4 (?)	0·12–0·13	Vietnam	Petersen *et al*. (2011*b*)
Oreochromis sp.	0·55	5–6	1·1–2·3 fish m^3	20–25	0·04–0·07	Vietnam	Petersen *et al*. (2010)
Scophthalmus maximus	0·7–2·0	18–20	10 kg m^2	5	1·48–1·57	Across Eur prod	Watanabe and Daniels (2011); www.fao.org (2014*b*)
Rachycentron canadum	6–10	12–18	28 (juv) – 10–15 (ad)	1–1·5	1–2·50	USA	Kaiser and Holt (2005); www.fao.org (2014*c*)
Salmo salar	> 4	24–40	12·5–15	60–100	0·35–0·60	Global	Marine harvest (2013)
Seriola spp.	15–70	12–18	20–30	< 50	4·8 (50 g)–14·3 (600 g)	Japan	Nakada (2008)
Sparus aurata	0·35–0·4	12–16	10–15	2–5	0·14–0·38	Across Eur prod	Koçak and Tatlıdil (2004); www.fao.org (2014*d*)
Takifugu rubripes	> 0·8	18–20	2·0–3·0	2–5	0·02	Japan	Kikuchi (2006); www.was.org

Across Eur prod, figures derived from European producers; ad, adult; juv, juvenile.

where not given in the original work. The tables show that there are elements of both predictability and unpredictability in infection events with elements of both certainty and uncertainty in the consequential economic losses. There are, for example, perennial costs associated with the management of and mitigation against salmon lice, *L. salmonis*, and other caligid species. Despite the apparent rise in the cost of 'sea lice control' in Norway, for example, from US$ 33·4 M p.a. in 1996 (Kvenseth, 1997) to US$ 206 M p.a. in 2009 (Costello, 2009), production over the same period increased by 248% from 297 557 t (1996) to 737 694 t (2008), and yet the price of salmon increased by only 20% (US$ 3·08–3·71 kg^{-1}). During this time, there have also been significant improvements in salmon welfare, and the number of sea lice-related mortalities and the number of fish downgraded as a consequence of sea lice damage has fallen dramatically. To achieve this, the basic costs of sea lice control have increased from 3·64% (1996) of total production costs to 7·53% (2008). As sea lice pose a relatively consistent threat to sea-caged populations of Atlantic salmon, infection can be predicted and, therefore, factored into farm business plans and farm-level treatment strategies. In addition, area management agreements, which form part of national strategies for the control of lice in some countries, e.g. Scotland and Norway, can prompt additional treatments for the area-level management of lice infections. If these are not conducted or the mean lice burden exceeds agreed national threshold levels, then penalties can be imposed in some countries, e.g. Norway (Tallaksen, 2013).

An analysis of unpublished data by the current authors suggests that parasites account for an annual loss of 5·8–16·5% (i.e. US$ 62–175 M; assuming £1 = US$ 1·6) of the value of UK aquaculture production (across all species in both freshwater and marine systems). Although the FishStatJ database lists 17 farmed species for the UK in 2012, parasite-associated losses were largely dominated by the impact of AGD and mitigation strategies against sea lice on the Atlantic salmon industry. Although these estimates are only for UK losses and do not include losses due to bacterial and viral pathogens, they can still be considered low when compared with anecdotal reports suggesting that typical disease losses for certain aquaculture industries in Asia range from 30 to 50%. A significant proportion of these latter losses is attributable to the loss of juvenile stock within the hatchery/nursery phases of production, and for many industries, such losses are commonly factored into and accepted as part of typical production cycles. As a consequence of such fatalistic acceptance of their inevitability, the ubiquity of low-specificity pathogens in some warm-water aquaculture systems and the small-scale nature/lack of diagnostic capacity of some production enterprises,

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Table 8. The estimated economic cost of notable protistan and metazoan parasite events on some of the world's leading marine and brackish water finfish production industries. For each industry, protistans and metazoans are grouped separately and are listed alphabetically within each. The order in which the finfish aquaculture industries are listed is based on their global economic value in 2011 according to FAO statistics and the rank order provided in Table 2. For each parasite-induced event, brief details are provided and an estimate of loss, where possible, has been calculated. Although 'cyprinids' cultured in brackish water are listed in Table 2, it is not possible to identify all the species that are embraced within this and as such are not considered here

Parasite	Impact	Estimated loss (US$)	Reference
(a) Atlantic salmon, *Salmo salar* L.			
Desmozoon lepeophtherii (syn. *Paranucleospora theridion*)	Mortalities (~ 600–1000 fish net-pen^{-1}) in 6 net-pens were seen throughout March–May 2002 in northern Norway. Fish were bleeding from the eyes and each fish had a mass of myxozoan trophozoites covering their pseudobranchs. A value of US$ 2·11 kg^{-1} for harvest-sized Norwegian salmon in 2002 is used to estimate loss	2532	Karlsbakk *et al*. (2002)
	35% of the 200 000 smolts transferred to sea pens in northern Norway in Sept. 2001 were lost by March. An average weight of 250 g fish^{-1} and a value of (US$ 2·11 kg^{-1} for the price of harvest-sized Norwegian salmon in 2002 is used to estimate loss	36 925	Sterud *et al*. (2003)
	Mortalities in northern Norway re-emerge in 2003, with mortalities ranging from low grade to significant (40%). The study uses material collected from 13 *S. salar* sites and 2 *O. mykiss* sites. Loss is estimated on the assumption that a single 1575 m^3 cage at each site stocked at 12·5 kg m^3 was affected with resultant mortalities of between 5 and 10%. The harvest price of Norwegian salmon in 2003, i.e. US$ 2·28 kg^{-1} is applied	33 664–67 328	Nylund *et al*. (2005)
	Study looked at 55 Norwegian farms in 8 counties, 43 of which had either proliferative gill disease (PGI), pancreas disease (PD), heart and skeletal muscle inflammation (HSMI) and cardiomyopathy syndrome (CMS). Analysis found high prevalence and densities of the parasite in farms in southern Norway where PGI and PD predominate. Heavy infections were found in fish with PGI suggesting that parasitic infection may be the primary cause of mortality in fish with PGI	–	Nylund *et al*. (2011)
	A production site in the Scottish Highlands experienced mortalities due to a seasonal gill disease – fish were lethargic and had pale, thickened gill filaments. S1 smolts were stocked into 10 cages in Feb 2009 and mortalities were observed throughout Sept 2009–Jan 2010 with weekly mortalities peaking at 0·36% in Oct 2009. Total site mortality was 8·7%. Loss is based on the assumption that cages measured 15 × 15 × 7 m^3, were stocked at 15 kg m^3, that the size of smolts were 100 g (i.e. 2 362 500 fish stocked), at the time of the event the fish were 400 g and were not graded out prior to the event, and, the harvest price of Scottish salmon in 2010, i.e. US$ 4·42 kg^{-1}, applied to the total lost weight of fish (i.e. 82 215 kg)	363 390	Matthews *et al*. (2013)
Hexamita salmonis	Increased mortality and morbidity in 200–250 g stock held at a farm in northern Norway in Nov 1989 was reported. The smolts had been transferred to sea in August 1989. Impression smears from the kidney, cardiac atrium, spleen, pyloric caeca, posterior gut, eye and brain revealed a large number of flagellates. One month later, another case of systemic hexamitosis was reported in a second Norwegian farm site. The fish at each site had originated from the same freshwater farm but at different time periods. No details relating to the magnitude of losses were provided	–	Mo *et al*. (1990)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	Infections are associated with a severe systemic granulomatous disease resulting in increased mortality of stock and the rejection of up to 60% of the harvested stock in northern Norway. Loss is based on the assumption that at least three 20 t production units were affected, a loss/rejection of 30% of stock, and, the harvest price of Norwegian salmon in 1992, i.e. US$ 4·81 kg^{-1}	86 580	Poppe and Mo (1993)
Hexamita sp.	Infections were found in 4 northern Norwegian sites throughout 1989–1992. Large granulomatous boils were typically found in all the internal organs in 200–250 g post-smolts. At 1 site, boils within the caudal muscle, liver and kidney of 4–5 kg fish were found in 60% of the stock filleted from 1 cage site. The fish from all 4 farm sites originated from the same hatchery in 1988–1989, although the hatchery did bring in several thousand alevins from the south of Norway in 1987. A subsequent infection in 3 classes of fish at a fifth site, situated 200 m from one of the farms and within 100 m of a slaughtering facility, was found in 1992. Infection differs from the gut infections typically seen with *Hexamita salmonis*. Loss is estimated on a 50% downgrade of the infected stock (i.e. 60%) reported from 1 cage of fish (750 m^3; 12·5 kg m^3 stocking density) and the harvest price of Norwegian salmon in 1991, i.e. US$ 4·20 kg^{-1}	11 813	Poppe *et al*. (1992)
Ichthybodo necator	Large mortalities were seen in S2 smolts 6 weeks after their transfer into seawater cages in July 1977. The source of infection was believed to be from parasites surviving a malachite green treatment in freshwater 3 weeks prior to fish transfer. Low summer salinities (min 23‰) and rising sea temperatures (max 16 °C) are considered contributory factors	–	Ellis and Wootten (1978)
Kudoa thyrsites	A mortality rate of 0·57% day^{-1} was seen in smolts ($n = 1200$; av. ~55 g) 5 months following their transfer to a marine site. Although no figures of the total loss are provided, if an av. loss of 0·4% day^{-1} and an av. weight of 70 g $fish^{-1}$ is assumed over 120 days, then a 50% cumulative mortality might have resulted, i.e. the loss of 42 kg of fish. Loss estimates are based on the value harvest-sized fish in the USA in 1986 (first figures available), i.e. US$ 8·33 kg^{-1}. *Kudoa* as the cause of mortality has, however, been questioned	350	Harrell and Scott (1985) Moran *et al*. (1999)
	Processors reported that the prevalence of myoliquefaction in smoked fillets prepared from pen-reared stock can range from 2 to 25%. Loss is based on the assumption that all infected fillets were rejected and on the value of harvest-sized fish produced on the Pacific NE of Canada in 1991, i.e. US$ 5·33 kg^{-1}. Canadian Pacific production in 1991 was 3651 t, industry-wide losses would have been between ~75 and 913 t	5330 t^{-1} of rejected fish or 107–1333 t^{-1} of production. ~0·4–4·8 M across the entire industry	Whitaker and Kent (1991)
	Infection leading to a reduction in fillet quality costs the industry in British Columbia est. US$ 15 M in 2010	15 M	Martell *et al*. (2013)
Myxobolus cerebralis	>90% mortalities in net-pen-reared smolts in Ireland over the summers 1992–1994 were attributed to intracellular presporogonic multicellular developmental stages of	8135 per cage	Rodger *et al*. (1995);

	the parasite-inducing encephalitis. Foci of non-suppurative encephalitis in the myelencephalon significant; appears 26 days post-introduction. Assuming that cages were 125 m^3 and stocked at a min. 15 kg m^3, then loss estimates are based on the value of harvest-sized Irish fish in 1994, i.e. US$ 4·82 kg^{-1}		Scullion *et al*. (1996); Frasca *et al*. (1998, 1999)
Paramoeba perurans (Amoebic Gill Disease, AGD)	Mortality of infected smolts in Tasmania may reach 10% $week^{-1}$, 2–4% $week^{-1}$ in fish weighing 1–2 kg and 1–2% $week^{-1}$ in fish over 2 kg	–	Foster and Percival (1988)
	Mortality variable but can reach 2% day^{-1} and up to 50% in untreated cages. Juvenile fish in the first season usually affected when water temps >12 °C and salinities approach 35‰	–	Munday *et al*. (1990)
	Infection confirmed at 8 Irish farms in post-smolts (450–800 g) in Oct–Nov 1995 resulting in >10% mortality of stock at 2 sites, <5% at a further 3 sites and no significant losses at the remaining 3 sites. Loss is based on the value of harvested Irish salmon in 1995, i.e. US$ 5·00 kg^{-1}	250–500 t^{-1}	Rodger and McArdle (1996)
	Infections account for an estimated 10–20% of production (i.e. 1200–2400 t) in Tasmania in 2001. Production losses are subsequently suggested to be ~14% (i.e. ~1780 t). Annual loss of ~60% stock at 1 Irish site since 1996. Assuming that an unaffected site would harvest 75 000 fish at 4 kg $fish^{-1}$, and that the smolts av. 70 g $fish^{-1}$ transferred in Oct would have an expected min weight of ~450 g $fish^{-1}$ by the following July (i.e. 1·136 g day^{-1} weight gain), a summer loss of 60% of stock would be ~20·25 t. The loss is estimated on the value of harvest-sized fish in Ireland in 2004, i.e. US$ 4·54 kg^{-1}	5–10 M 7·2 M 91 935	Munday *et al*. (2001); Morrison *et al*. (2006) Adams and Nowak (2001) Bermingham and Mulcahy (2004)
	Outbreaks lasting 7–12 weeks at 4 Norwegian farms in the spring of 2006 resulted in mortality rates of 12–20% at 3 of the farms and 82% at the fourth site in 1·0–1·6 kg salmon. Loss is est. on av. 1·3 kg salmon being lost from at least 4 cages (50 × 50 × 20 m^3) stocked at 12·5 kg m^3 at each site with mortality rates of 12, 16, 20 and 82% and using a value of US$ 3·86 kg^{-1} for Norwegian salmon in 2006	12·55 M	Steinum *et al*. (2008)
	Losses at 3 Chilean farm sites in 2007 (all with concomitant *Caligus rogercresseyi* infections) are recorded as 7·7, 5·4 and 1·8%, i.e. 4·9 ± 4·5 loss across all farms with an av. 66% prevalence of amoebae. Highest mortalities coincide with highest salinities and temps. Low feed intake led to a 25% reduction in growth. Loss estimates are based on the value of harvest-sized fish in Chile in 2007, i.e. US$ 7·90 kg^{-1}	142–608 (387 ± 356) t^{-1} of production	Bustos *et al*. (2011)
	Oct 2011, the first loss of Scottish Atlantic salmon (279 000 fish) to AGD is reported	–	Vass (2013)
	Typical losses in Scotland are put at between 10 and 20% but are as high as 70% at certain Scottish sites	–	Marine Scotland (2012)
	Estimate of loss put at > US$ 48 M (i.e. ~9000 t)	> 48 M	Vass (2013)
	According to the Scottish Environmental Protection Agency (cited in FAO Globefish; http://www.globefish.org/salmon-june-2013.html), 13 600 t of dead salmon were disposed of (cost of Scottish salmon=US$ 5·96 kg^{-1} in 2011)	~ 81 M	FAO Globefish (2013)
Spironucleus barkhanus	Systemic infections resulted in increased mortality and morbidity in a cage of 200–250 g post-smolts in northern Norway in Nov 1989 when seawater temperatures were 6 °C. Infections also found as boils in the caudal muscle causing severe lesions in adults (4–5 kg) at 1 site in June 1991; approx. 60% of the stock had lesions. A total of 4 fish farms were affected	–	Mo *et al*. (1990); Poppe *et al*. (1992); Poppe and Mo (1993)
	Fish mortality occurs in both the blood and tissue phases of the disease	–	Guo and Woo (2004)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Tetrahymena sp.	An increased rate of mortality was recorded in ~1-year old salmon stocked in 8 m diameter concrete tanks. No details relating to the pattern or magnitude of loss are provided	–	Ferguson *et al*. (1987)
Trichodina sp.	In July 1982 and 1983, there was a 20% mortality of broodstock in an Irish sea cage when sea temperatures rose to 23 °C and when many of the male fish had begun sexual maturation. There were no appreciable losses in an adjacent cage of younger salmon. Assuming that cages were min. 125 m^3, stocked at 12·5 kg m^3, then the loss of fish would have been >312·5 kg. Figures of loss are based on the harvest price of Irish salmon in 1984, i.e. US$ 6·50 kg^{-1}	2031 per cage	McArdle (1984)
Caligus spp.	Infections and the delousing of harvest fish in Chilean processing plants incur costs of US$ 0·30 kg^{-1}. Loss is based on the reported production of Chilean salmonids of 97 000 t in 1995	29·1 M	Carvajal *et al*. (1998)
Caligus elongatus	Infections on Scottish stock reared in cages are seasonal and peak at 25+ lice $fish^{-1}$ in July–Sept 1991. Infections commonly co-occur with *L. salmonis* (see the entry below)	–	Bron *et al*. (1993)
Caligus elongatus + *Lepeophtheirus salmonis*	Infections on Irish cage-reared salmon were reported to peak at an av. 11·9 ± 5·2 S.D. lice (2:1 *C. elongatus : L. salmonis*) in August 1987 declining to 3·3 ± 3·3 S.D. by mid-Sept. Lice numbers are controlled by organophosphate treatments	–	Tully (1989)
	Infections that were monitored at several Scottish cage sites over the period July 1990–March 1992 were observed to peak at 100+ lice $fish^{-1}$ in Oct 1990 and March 1991. Lice burdens necessitated 9 treatments at single-year class sites and 11 treatments for multi-year class sites across the 20 months monitoring period. Average cost of cage treatment alone is est. to be ~ US$ 10 000 per 200 000 fish (see Mustafa *et al*. 2001)	0·09–0·11 M per 200 000 fish over 20 months	Bron *et al*. (1993)
	92% of salmon at 1 site at Eastport, Maine throughout 1993–1994 were infected with an av. 3·1 lice $fish^{-1}$ in Sept 1993, 99·6% of which were *C. elongatus*. In addition, 87% of smolts were infected with an av. 2·1 lice $fish^{-1}$	–	Shaw and Opitz (1993)
Caligus longirostris	Reported with a prevalence of 1·5% on av. 5·51 kg salmon in 1 Tasmanian cage site and 1·9% on 5·62 kg $fish^{-1}$ in a second, experimental cage site. Low-level infection	Negligible	Nowak *et al*. (2011)
Caligus rogercresseyi	The costs of removing lice from Chilean salmon in processing plants costs ~ US$ 0·30 kg^{-1} according to the Asociación de Productores de Salmón y Trucha de Chile. Loss is based on the 96 675 t of Atlantic salmon produced in 1997	29 M	Carvajal *et al*. (1998)
	Cost to Chilean industry ~ US$ 193·6 M p.a.	193·6 M	Costello (2009)
Caligus teres	Infections were monitored on sea-pen-reared stock in Puerto Montt, Chile over April 2000–Feb 2001. Infections were observed to peak in mid-December with an av. 27 mobile lice and 9 chalimus on 2·3 kg fish. Delousing the 4000 t of stock with ivermectin was conducted at a cost of US$ 0·004 kg^{-1}	16 000	Bravo (2003)
Ceratothoa gaudichaudii	Prevalence of isopod infection on 0·9–1·1 kg salmon in Chile rose from 33·1% (1·37 parasites $fish^{-1}$) in May 1993 to 99·9% (6·05 parasites $fish^{-1}$) in Aug 1994. Infection	1571 per 1000 harvest-sized fish	Sievers *et al*. (1996)

	had a significant impact on growth across the study period with average terminal weights determined as 4·427 kg (0–2 isopods fish^{-1}), 4·151 kg (3–7 isopods fish^{-1}) and 3·763 kg (> 8 isopods fish^{-1}). This equates to loss of 413·4 kg or US$ 1571 (assuming US$ 3·8 kg^{-1} based on 1996 prices for Chilean salmon) per 1000 salmon		
Ergasilus labracis	Ten floating cages (3–6000 fish cage^{-1}), 14‰, 18–20 °C, 100% infection with av. 84·6 parasites fish^{-1} (range 44–2229), severe gill hyperplasia, 90% gill damage, loss of 4000 fish (85–125 mm long) over 4 days. Loss is based on US$ 1 smolt^{-1}	4000	Hogans (1989); O'Halloran *et al*. (1992)
Eubothrium crassum	Cestodes within the pyloric caeca result in a direct economic loss of food uptake impacting detrimentally on growth (infection of av. 71 worms fish^{-1} effects loss of 800 g in 5·2 kg males, whilst 115 worms fish^{-1} effect a loss of 440 g in 4·3 kg females), i.e. a ∼10% loss in the size of market fish. This equates to a minimum loss of ∼ US$ 1848 per 1000 harvest-sized fish (assumes US$ 4·20 kg^{-1} based on Norwegian prices in 1991)	1848 per 1000 harvest-sized fish	Bristow and Berland (1991)
	Potential loss of growth owing to chronic low worm burdens est. at between 10 and 20%. This equates to an average loss of between US$ 2253 and 4506 per 1000 harvest-sized fish (assumes US$ 4·506 kg^{-1} based on Scottish salmon prices in 1993)	2253–4506 per 1000 harvest-sized fish	Mitchell (1993)
	Impact on growth and haematocrit confirmed; no correlation between worm burdens and fish weight	–	Saksvik *et al*. (2001)
Gyrodactyloides bychowskii	Infections of up to several hundred flukes per fish (post-smolts to 2·5 kg fish) were reported at 20 Norwegian sea-cage farm sites between 1989 and 1991. Hypertrophy and hyperplasia of the gill epithelium was commonly observed associated with infections	–	Mo and MacKenzie (1991)
	Parasite burdens of up to 200 flukes per gill arch were observed on 20% of fish examined in June 1999 from a farm site in the Shetland Isles, Scotland. Prevalences of between 0·5 and 10% were observed throughout 1999–2000 on 3 Scottish farm sites. Mild to marked epidermal hyperplasia, slight oedema and hypertrophy was seen at the sites of parasite attachment	–	Bruno *et al*. (2001)
Lepeophtheirus salmonis	Direct losses, treatments and lost growth imposed by 'sea lice', i.e. *C. elongatus* and *L. salmonis* are estimated to cost the Norwegian industry US$ 33·4 M	33·4 M	Kvenseth (1997)
	Fish growth reduced by 5–15%. 5% more feed needed. Total tonnage produced in Scotland in 1997 was 110 917 t suggesting loss production may have been in the region of 5546–16 638 t. Estimates of loss are based on the value of harvest-sized fish in Scotland in 1997, i.e. US$ 2·94 kg^{-1}	16·3–48·9 M	Sinnott (1998)
	Suggested that a Canadian farmer can expect to lose US$ 162 000 per 200 000 fish. Infection accounts for a 5% loss in food conversion necessitating the provision of additional feed; a 1–3% downgrading of carcasses; a 1% loss due to secondary infections; treatment costs (i.e. ∼ US$ 9000 per hydrogen peroxide treatment and US$ 10 800 per azamethiphos treatment) and resultant losses	0·16 M per 200 000 fish	Mustafa *et al*. (2001)
	Cost to Scottish industry US$ 52·9 M in 2000 equal to ∼7–10% of total production value, i.e. control costs US$ 0·39 kg^{-1}	52·9 M	Rae (2002)
	Sea lice are estimated to cost the Canadian salmon industry ∼ US$ 16 M	16 M	Roth (2000)
	Up to 15% of Scottish fish downgraded		Michie (2001)
	Parasiticides, staff and equipment represent 17–30% of the total sea louse control costs	–	Mustafa *et al*. (2001)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	Estimated that the stress of sea louse burdens account for 5% lost growth (i.e. US$ 20·8 M based on the value of the Scottish 130 000 t industry in 2000). Medicines account for a further US$ 6·4–8 M, whilst the remainder is associated with treatment costs (i.e. labour, accidental mortalities during treatment, the downgrading of lice-damaged stock). Costs are based on £1=US$ 1·6	32–48 M	Rae (2002)
	Cost to Norwegian industry ~ US$ 206 M p.a.	206 M	Costello (2009)
	If the estimated costs of sea lice control remain unchanged (i.e. € kg^{-1}) from those given in Costello (2009), then based on salmon production in 2012, sea louse costs for the main producing nations are estimated at US$ 468 M for Norway (0·19 € kg^{-1}; 1·18 M tonnes), US$ 60·5 M for Chile (0·19 € kg^{-1}; 232 700 t) and US$ 55·5 M for Scotland (0·25 € kg^{-1}; 162 223 t)	468 M (Norway) 60·5 M (Chile) 55·5 M (Scotland)	
	Norwegian Food Safety Authority ordered 5 producers operating north of Vikna, Norway to slaughter of 8000 t of fish (3·5–4 kg class) because of treatment failure/resistance/lice burdens exceeding permitted national threshold of 0·5 adult female lice $fish^{-1}$. Failure to comply before the imposed deadline could have incurred a daily penalty of ~ US$ 16 250. Loss estimates here are due to the premature harvest of stock and can be speculated at 0·5–1 kg $fish^{-1}$ (i.e. 1143–2000 t) and are based on the value of harvest-sized fish in Norway in 2011, i.e. US$ 4·58 kg^{-1}	5·23–9·16 M	Tallaksen (2013)
Sea lice[a]	The costs of sea lice control in Chile are estimated at US$ 0·022 kg^{-1}. Loss is estimated on the Chilean production of 253 607 t in 2001	5·58 M	Bravo (2003)
	US$ 480 M p.a. cost to global salmonid industry (incl. costs of parasiticide, impact on growth and food conversion), i.e. av. cost of sea lice control is US$ 0·30 kg^{-1}	480 M	Costello (2009)
(b) Rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792)			
Kudoa thyrsites	A 2·6% infection was found within the cardiac muscle of fresh, dead fish collected from a single hatchery on the coast of British Columbia, Canada in Sept 1987	–	Kabata and Whitaker (1989)
Paramoeba perurans	Mortality of Tasmanian salmonids, including *O. mykiss* in the period 1987–1988, variable – can reach 2% day^{-1} and up to 50% in untreated cages. Details relating to the impact of AGD on the production of Atlantic salmon (53 t in 1987; 240 t in 1988) and rainbow trout (207 t in 1987; 890 t in 1988) not given. Juvenile fish in their first season are usually affected when water temps >12 °C and salinities approach 35‰. Loss is based on an estimated 20% loss of fish numbers both in 1987 (i.e. 17 250 fish) and in 1988 (i.e. 74 166 fish) that first season fish were an av. 200 g, that stock are harvested at 3 kg and on the value of harvest-sized fish in 1987 as US$ 7·49 kg^{-1} and US$ 5·49 kg^{-1} in 1988	Loss of 3·45 t (1987) to 14·83 t (1988) worth 25 840–81 430	Munday *et al*. (1990)
	Chronic loss of fish at 1 Irish sea farm beginning in July 1982 resulting in a >50% loss of stock. Recorded as the driest July on record. Loss is based on the value of harvest-sized Irish rainbow trout in 1984, i.e. US$ 3 kg^{-1}	1500 t^{-1}	Rodger and McArdle (1996)
	Sub-optimal osmoregulatory performance of infected stock in Tasmania in full strength seawater has led to their culture in brackish water	–	Findlay *et al*. (1995)
Trichodina sp.	In July 1982, there was a 20% mortality of 1+ trout in an Irish sea cage when sea temperatures rose to 23 °C and many of the male fish had begun sexual maturation.	600 t^{-1}	McArdle (1984)

	Similar losses were also seen during the summer of 1983. Although *Trichodina* was predominant, some of the infections were a mix of *Trichodina* and *Ichthyobodo*. Loss is based on value of harvest-sized Irish rainbow trout in 1984, i.e. US$ 3 kg^{-1}		
Caligus orientalis	Heavy burdens of up to 188 lice $fish^{-1}$ were found on a cage of 320 fish (av. wt. 597 g) reared in Lake Mokoto on the coast of the Okhotsk Sea, NE Hokkaido, Japan during the summer of 1988 when surface water temperatures ranged from 16 to 23 °C. The fish lost their appetite and most died within a month. Similar infections on stocks reared in Lake Saroma, NE Hokkaido throughout 1986 and 1987 resulted in the stop of production. Loss is based on the assumption that 90% of the Lake Mokoto stock was lost and the harvest price for Japanese freshwater rainbow trout (no figures for marine produced stock) in 1988, i.e. US$ 4·19 kg^{-1}	720	Urawa and Kato (1991)
Caligus teres	Infections were monitored on sea-pen-reared stock in Puerto Montt, Chile over April 2000–Feb 2001. Infections were observed to peak in mid-December with an av. 27 mobile lice and 8 chalimus on 1·7 kg fish	–	Bravo (2003)
Lepeophtheirus salmonis	The lice burdens on stock (300–700 g) reared in sea cages sited in Katsurakoi Harbor near Kushiro on the Eastern Pacific coast of Hokkaido, Japan in 1988 were 0·02 ± 0·15 lice $fish^{-1}$ (prev. 2·2%) in Sept 1988 rising to 3·8 ± 2·5 lice $fish^{-1}$ (prev. 92%) in Nov 1988. Peri-anal haemorrhages were observed but not thought to cause serious disease	–	Urawa *et al*. (1998*a*)
	In Nov 1992, 20 000 juvenile fish (< 1-year old; 103–161 g) were transferred to net-pens in Onmae Bay, Miyagi Prefecture, Japan. One month later, 60% of the stocks were infected. By Feb 1993, all fish were infected with an av. 3·0 lice $fish^{-1}$. Thereafter, lice burdens rose sharply from 5·2 lice $fish^{-1}$ in April to 36·8 lice $fish^{-1}$ (range 19–51 lice $fish^{-1}$) in July 1993. Fish had visible abrasions and haemorrhages. Loss is based on the assumption that fish harvested in July would have been downgraded (1–3%, see Mustafa *et al*. 2001), fish weighed ~300 g; harvest price for stock in 1993 would have been US$ 6·24 kg^{-1}	374–1123	Ho and Nagasawa (2001)
(c) Milkfish, *Chanos chanos* (Forsskål, 1775)			
Amyloodinium ocellatum	An infection resulted in the complete loss of hatchery stock (14 days old; ~8 mm long) in two 10 m diameter tanks at one establishment in Iloilo, the Philippines in June 2001. Loss is estimated on a stocking density of 10 kg m^{-3} (Yap *et al*. 2007) and a value of US$ 0·01 $fish^{-1}$ (~ 0·1 g), i.e. the loss of 2 million fry	20 000	Cruz-Lacierda *et al*. (2004)
Trichodina sp.	Infected juvenile stock sampled from ponds at Pagbilao, Quezon Province and from the Laguna de Bay, Binangonan, Rizal Province, Philippines (salinity range from 2 to 30 ppt) in Sept 1985–April 1986 were found at 5 sites with a prevalence of 8–60%. Flagged as a concern	–	Regidor and Arthur (1986)
Alitropus typus	Infections have been reported to result in the mortality of Filipino held stock	–	Velasquez (1979; cited in Regidor and Arthur 1986)
Caligus sp.	Wild-caught stocks (5–12 kg) caught in Feb–May 1976 were grown on in 10–100 t tanks at a Research Station at Mag-aba, Pandan, Antique, Philippines. When a single fish in this group died in June 1976, the stock was found to be infected with lice. Fish with heavy burdens were emaciated. The infection (av. lice burdens not specified) were controlled by a single 0·25 ppm treatment of Neguvon (2,2,2,-trichloro-1-hydroxyl-phosphoric acid dimethylethol)	–	Laviña (1977, 1978)
Caligus chanos	Heavy lice burdens on Taiwanese stock in the winter of 1980–1981 were reported to cause severe lesions resulting in the death of fish. No details provided	–	Lin (1989)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Caligus epidemicus	Infections were recorded on juvenile fish sampled from 5 sites (salinity range from 2 to 30 ppt) from ponds at Pagbilao, Quezon Province, from others at Molo, Iloilo Province, and, from the Laguna de Bay, Binangonan, Rizal Province, Philippines in Sept 1985–April 1986. Prevalence of infection ranged from 4 to 36% with up to 8·8 ± 13·2 lice fish^{-1}	–	Regidor and Arthur (1986)
Diergasilus kasaharai	Report of a mass mortality of stock within a brackish water pond in a village in Tainan County, Taiwan in Dec 1993 stocked with 20 000 milkfish. Mortalities began with 10 fish day^{-1} rising to 100 fish day^{-1} after a week, each fish had ~130 parasites. No details are provided on the size of fish. Loss is estimated on the assumption that fish were on the lower side of their harvestable size range (i.e. 250 g), and, on their value in Taiwan in 1993, i.e. US$ 1·60 kg^{-1}. Furthermore, it is assumed that a minimum 20% of stock was lost, i.e. 4000 fish	1600	Lin and Ho (1998)
Digenea unidentified sp.	Metacercariae were recorded on juvenile fish sampled from 5 sites (salinity range from 2 to 30 ppt) from ponds at Pagbilao, Quezon Province and from the Laguna de Bay, Binangonan, Rizal Province, Philippines in Sept 1985 to April. Prevalences of infection ranged from 8 to 90% with up to 5·2 ± 5·0 metacercariae fish^{-1}	–	Regidor and Arthur (1986)
Ichthyoxenus sp.	Infections have been reported to kill cultured Filipino held stock. Details unknown	–	Velasquez (1979; cited in Regidor and Arthur 1986)
Transversotrema laruei	Infections were observed at 6 pond sites (2–30 ppt) at Pagbilao, Quezon Province, Philippines in Sept 1985–April 1986 with prevalences of between 8 and 76% with up to 5·2 ± 5·2 parasites fish^{-1}	–	Regidor and Arthur (1986)
Unidentified cymothoid isopod	Reported to have resulted in the mortality of juvenile stock in the Philippines. Details unknown	–	Ronquillo and Caces-Borja (1960; cited in Regidor and Arthur, 1986)
(d) Japanese amberjack/yellowtail, *Seriola quinqueradiata* (Temminck et Schlegel, 1845) and other seriolids			
Ceratomyxa buri	A 100% infection was found in the bile of 0 + aged sea-pen reared stock sampled from Oita Prefecture, Japan in Nov 1999. The relationship between the occurrence of this parasite and the green livers observed in this host requires establishing	–	Yokoyama and Fukuda (2001)
Ceratomyxa seriolae	Examination of the bile from 0 + aged sea-pen reared stock sampled from Oita Prefecture, Japan in Feb 2000 found 70% prevalence. Whether this parasite is responsible for the green livers observed in this host requires investigating	–	Yokoyama and Fukuda (2001)
Ichthyophonus hoferi	Juvenile fish in Mie Prefecture were reported as being infected within the first year of culture. A low incidence of infection was reported but resulting in mortality. No details given	–	Egusa (1983)
Kudoa amamiensis	Infections have impacted on the commercial value of harvested stock. In June 1952, 63·6% of the 0·6–1·3 kg fish (n = 11) that were sampled from Nagaski Prefecture, Japan had infected trunk muscles. In 1970, in Ehime Prefecture, 70 000 fish were reared on a trash fish diet until 400–500 g; almost all the valuable tail sections of the fish were infected.	63 000-80 000	Egusa and Nakajima (1978); Egusa (1983)

	The subsequent examination of a further 100 000 ($\sim$ 400 g) tail muscle sections found that $\sim$ 30% were infected. Figures based on a back projected historical price of harvest stock in 1970 of US$ 2 kg^{-1}		
	A survey of 10 farm sites between 1994 and 1998 indicates that between 90 and 100% of stock in the Motobu area (2 sites) of Okinawa Prefecture, Japan were infected, whereas elsewhere in the Prefecture infection rates are in the region of 0–9% (12 sites). Loss is estimated on the assumption that each site produces 20 t, that infected fish are not sold, and, on the price of Japanese amberjack in 1998, i.e. US$ 7·36 kg^{-1}. Loss in the Mobobu area is calculated to be 37·954 t (i.e. 94·89% of stock), whilst losses for the rest of Okinawa are 1·52 t (i.e. 0·95% of stock)	279 341 for the 2 Motobu sites 11 187 for the remaining 8 Okinawa sites	Sugiyama *et al*. (1999)
Kudoa megacapsula	Disease outbreaks in Oct 1999–Jan 2000 were reported within 4 prefectures in Western Japan. The prevalence of infection was recorded at 12%. Infections appear as unsightly filamentous black cysts in skeletal muscle without consequential myoliquefaction. Loss is estimated on the basis of four, 20 t production units, a 12% loss of market-sized fish and the value of harvest stock in Japan in 2000, i.e. US$ 9·71 kg^{-1}	93 216	Yokoyama *et al*. (2006)
Kudoa pericardialis	Trophozoites were found in the pericardial cavity of stock at numerous farms in Kagoshima, Kouchi, Mie, Miyazaki, Shizuoka and Tokushima prefectures, Japan. Does not affect the harvest price because infections within the heart are inconspicuous	–	Nakajima and Egusa (1978)
Kudoa yasunagai	Infection results in abnormal swimming behaviour (whirling, lying on the bottom of the cage) and scoliosis of the spine. As a consequence feeding and swimming performance is impaired; fish suffer skin damage from swimming into the net. In 2011, a mortality event in a cage of juveniles situated at Wakayama, Japan was recorded 2 months post-transfer. Over 50% of the fish showed signs of infection ultimately resulting in mortalities; prev. of infection >80%. The precise number of fish lost is not specified but experimental trials suggest a low level of loss (< 1%). Loss is estimated on a single cage ($3 \times 3 \times 3$ m^3) of av. 2·5 g fish stocked at 25 kg m^3 (i.e. 270 000 fish) having an 80% survival through to harvest (min. harvest size of 15 kg $fish^{-1}$) but with a 50% reduction (accounts for poor growth, feed inefficiency, specimen condition) on the 2012 market price, i.e. US$ 9·86 kg^{-1}	1·6 M	Shirakashi *et al*. (2012)
	Alternatively, assuming that the 50% of stock that developed scoliosis and fed poorly died, then loss is estimated on the assumption that 270 000 fish were transferred, each with a value of US$ 2·00 $fish^{-1}$ (extrapolated from Table 7)	270 000	Shirakashi *et al*. (2012)
Microsporidium seriolae ('Beko disease')	Disintegration of massive cysts within the trunk muscles causes a shrunken appearance, emaciation and mortality in farm stocks. Cysts appear 2 weeks post-transfer to sea cages, prevalence of infection rising to >90% 6–25 weeks post-transfer. Most fish with light infections recover; suggested that heavily infected juvenile should be disposed of as soon as possible. No details of loss or subsequent downgrading are provided	–	Sano *et al*. (1998); Yokoyama *et al*. (2011)
Myxobolus acanthogobii (syn. *M. buri*)	Infections cause severe scoliosis in up to 30% of 1 + age stock in farms in Shizuoka Prefecture, Japan in 1981. Cysts are frequently found in the cerebral cavities. Loss is based on the per ton assumption that up to 30% of stock may be lost, that fish in their first year are valued at 50% of the harvest price per ton of fish, and, harvest prices in Japan in 1984, i.e. US$ 3953 t^{-1}	up to 593 t^{-1}	Egusa (1985); Yokoyama *et al*. (2005*a*, *b*)
Myxobolus spirosulcatus	Monitoring of net-caged stock (0 + aged fish) in Oita Prefecture, Japan between Aug 1999 and Feb 2000 found a peak of infection (i.e. 80% prevalence) in the bile in Oct 1999. No pathological changes in the host were observed but this parasite may have a relationship with the green livers observed in this host	–	Yokoyama and Fukuda (2001)

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Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
	Heavy mortalities were recorded in 100 g to 1 kg stock in farms near Uwajima, Ehime Prefecture Japan. Fish were emaciated, had skin ulcerations, and at post-mortem were found to have a severe encephalomyelitis, nerve cell necrosis, blood congestion, encephalomeningitis, granulomatous peritonitis, and, a redness to the brain and spinal cord. Unidentified "exotic parasite-like bodies" were found in the seriously damaged spinal cords of 12 of the 65 (i.e. 18%) fish examined. These parasites are later suggested to be *M. spirosulcatus* (Yokoyama *et al*. 2010). Loss is est. on the basis of at least four, 20 t production units, an 18% loss of market sized fish as indicated by the post-mortem study (i.e. 14·4 t), and the value of harvest stock in Japan in 2007, i.e. US$ 6·04 kg^{-1}	86 976	Katagiri *et al*. (2007)
Benedenia seriolae	Considered a serious problem since the advent of cage culture in Japan in the 1950s	–	Harada (1966); Egusa (1983)
	Infections result in severe skin damage, lesions and infections of up to 570 flukes $fish^{-1}$ are reported. Although alludes to mortalities as a consequence of direct and secondary infection, fish with heavy burdens are emaciated and have poor weight gain. The av. weight of fish at 2 heavily infected sites, Kuki and Shiroura, Japan in Oct and Nov, 1963 were 650–750 g and 700–800 g, whilst the av. weight of stock at Lake Shiraishi, where infections were absent, were 800–900 g. No details relating to the total economic cost of this parasite on the Japanese industry are given but here an estimated loss of 10% is assumed. Figures are calculated on the size of the industry in 1963, i.e. 5038 t and an est. harvest price in 1963 of US$ 2·00 kg^{-1} (no figures are available but 50% of the harvest price in 1984, i.e. US$ 3·95 kg^{-1}, the first costs available, is applied)	1 M	Kubota and Takakuwa (1963)
	Parasite accounts for 22% of production costs, i.e. ~ US$ 214 M (based on Japanese production of 153 075 t in 2001 worth ~ US$ 973·9 M). This figure includes production of *S. quinqueradiata, S. dumerili* and *S. lalandi*	214 M	Ernst *et al*. (2002); Whittington *et al*. (2001)
Caligus sp.	Heavy parasite burdens on the gills (10–240 lice $fish^{-1}$; $n = 5$) and within the buccal cavities (2–54 lice $fish^{-1}$) are reported on stock reared at a site in Kuki, Japan. Infections cause fish to rub against nets to the extent that the upper and lower jaw bones become exposed. No details of loss are given but this parasite causes the greatest damage to its host. Loss is estimated on a 10% loss or downgrade of stock at the Kuki site which is assumed to be a 50 t production site and an est. harvest price in 1963 of US$ 2·00 kg^{-1} (no figures are available but 50% of the harvest price in 1984, i.e. US$ 3·95 kg^{-1}, is used)	10 000	Kubota and Takakuwa (1963)
Caligus spinosus	Of the 30 000 fish that were ranched around Goto, Japan in April/May 1967, ~10 000 fish were subsequently lost to lice. Loss is estimated on the suggested av. size of fish as being 6 kg and the harvest price of fish in Japan in 1984 (no figures exist for 1967 and a back extrapolation 1984–1994 ascribes a negative cost for 1967), i.e. US$ 3·95 kg^{-1}	237 000	Fujita *et al*. (1968)
	Caligids usually infect the branchial arches. With heavy infections, fish become emaciated, anaemic and can develop rubbing-induced ulcerations around the mouth which are subject to secondary infection	–	Egusa (1983)
Callotetrarhynchus nipponica	Stock fed raw fish, notably anchovies, *Engraulis japonica*, became infected with larval cestodes (pleurocercoids) which reduced the marketability of the flesh. No details of infections provided	–	Nakajima and Egusa (1972); Ogawa (1996); Hutson *et al*. (2007)

	Trypanorhynch plerocercoid larvae in the abdominal cavity causes physical disturbance impacting on growth	–	Egusa (1983)
Heteraxine (syn. *Axine*) *heterocerca*	Infections result in anaemia and fish death. Study reports almost all the farm sites with only 2 or 3 exceptions within Mie Prefecture, Japan. All sites reported severe damage notably those at Hayada, Kuki and Shiroura. No details of loss are provided but here an estimate of 10% is assumed. Figures are calculated on the size of the Japanese industry in 1963, i.e. 5038 t and an estimated harvest price for 1963 of US$ 2·00 kg^{-1} (no figures are available but 50% of the harvest price in 1984, i.e. US$ 3·95 kg^{-1}, the first costs available, is applied)	1 M	Kubota and Takakuwa (1963)
	Heavy gill infections result in anaemia, emaciation and death	–	Egusa (1983)
Isopoda unidentified sp.	Fish reared in Kuki Bay, Japan with infections on the gills and within the buccal cavity are reported to be emaciated. No details of loss are given	–	Kubota and Takakuwa (1963)
Philometroides seriolae	Nematodes bore through the trunk muscle or reside in the muscle reducing the commercial value of the fish. Although the overall price of the carcass may be downgraded, the affected lesion can be removed during processing	–	Egusa (1983)
Greater amberjack, *Seriola dumerili* (Risso, 1810)			
Cryptocaryon irritans	100% mortality of broodstock held in land-based seawater tanks (6 or 10 m^3) at a stocking density of 8·8 kg m^3. Loss is based on the assumption that 88 kg of fish were lost and the harvest price of Spanish greater amberjack in 1997 as no prices for Greece are listed, i.e. US$ 9·48 kg^{-1}	834	Rigos *et al*. (2001)
	93% of stock (1+ to 3+ aged fish; n = 93/100 fish) at one culture facility on the Spanish Mediterranean coast died 30 days after the first signs of infection. Loss is based on the price of harvest-sized fish in Spain in 2007, i.e. US$ 10 $kg^{-1}$and an av. weight of 5 kg	4650	Montero *et al*. (2007)
Kudoa amamiensis	A survey of 10 farm sites between 1994 and 1998 indicates that between 30 and 90% of stock in the Motobu area (2 sites) of Okinawa Prefecture, Japan were infected, whereas elsewhere in the Prefecture infection rates are in the region of <1% (8 sites). Loss is estimated on the assumption that each site produces 20 t, that infected fish are not sold, and, on the price of Japanese amberjack in 1998, i.e. US$ 7·36 kg^{-1}. Loss in the Mobobu area is calculated to be 24·6 t (i.e. 61·5% of stock), whilst losses for the rest of Okinawa are 0·2 t (i.e. 0·125% of stock)	181 056 for the 2 Motobu sites 1472 for the remaining 8 Okinawa sites	Sugiyama *et al*. (1999)
Microsporidium seriolae ('Beko disease')	Stock transferred to sea cages in Miyazaki Prefecture, Japan in June 2006 were monitored over 2006–2009. Infections in a sub-sample of 20 fish were 100% (av. 16 cysts $fish^{-1}$) in July–Aug 2006 and decreased thereafter but were still 80% by Sept 2007. Most fish recover, although it is suggested that heavily infected fish should be disposed of. No details of loss or fish disposed of are provided	–	Yokoyama *et al*. (2011)
Benedenia seriolae	Parasite accounts for 22% of production costs, a figure which includes the production of *S. quinqueradiata, S. dumerili* and *S. lalandi**	214 M*	Ernst *et al*. (2002); Whittington *et al*. (2001)
Benedenia seriolae / Zeuxapta seriolae	Mixed infections on farmed *Seriola* sp. in Australia in 2003 were responsible for the subsequent loss of 39 t (i.e. ~15 000 fish) of stock	580 000	Kolkovski and Sakakura (2004)
Neobenedenia melleni (syn. *girellae*)[b]	A heavy fluke infection results in the 100% mortality of 0-year-old fish in Okinawa, Japan in July 1992. Inspection of 5 fish consignments entering the country from Hong Kong and Hainan, China which are shown to be infected with a prevalence of 7·7–70% are	192 000	Ogawa *et al*. (1995)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	believed to be the source of infection in Japan. Loss is based on the assumption that a single $10 \times 10 \times 10$ m^3 cage of juvenile fish (~ 50 g) stocked at 20 kg m^3 was lost; that 50 g juveniles are each valued at US$ 4·80 each (see Table 7) assuming no change in prices of stock between 1992 (price of harvest fish=US$ 6·96 kg^{-1}) and 2007 (price of harvest fish=US$ 6·04 kg^{-1})		
	Economic losses due to *N. melleni* may now exceed those of *Benedenia seriolae* with *N. melleni* being more of a problem during the summer months	>200 M	*Pers. comm.* Dr S. Shirakashi
Paradeontacylix-like trematodes	Approx. 80–85% of the Spanish wild-caught juveniles (~ 100 g) that were transferred to at least 3 sea-cage sites along the Tarragona coast and around the Balearic Islands in Sept–Oct began dying over Dec–May. Mortalities were attributed in part to epitheliocystis found in 30% of the Balearic stock and in 90% of those from Tarragona but also to heavy digenean fluke infections in 50% of the fish. Eggs were found in the heart and mortalities were attributed to the accumulation of eggs in the blood vessels of the gills. Loss is based on the assumption of an av. loss of 80% stock across all 3 sites, that each was a 20 t production unit, and, a US$ 4·00 value assigned to each fish est. 250 g	768 000 across 3 Spanish sites	Crespo *et al*. (1994)
Paradeontacylix grandispinus/ *Paradeontacylix kampachi*	Sudden outbreak of disease at several Japanese sites leading to a mass mortality of stock (cumulative 50 to >80% in a month; highest recorded daily mortality $\sim 15\%$) in juvenile 0+ fish in March–May 1993 several months after their importation from Hainan, China. Heavy eggs burdens within afferent gill arteries despite low number of parasites (1–5 fish^{-1}) detected. Loss is estimated on at least 3 farms losing an av. 70% of stock, that each fish was valued at US$ 4·00, and, that each site had 5000 fish as part of their starting stock	42 000	Ogawa and Fukudome (1994)
	Mass mortalities of stock imported from Hainan Island and Taiwan into Japan (12 stocks; 6 shipments; 2 from Hong Kong, 4 from Hainan) first seen in Dec 1983–Mar 1984	–	Ogawa and Egusa (1986); Ogawa and Fukudome (1994)
Sanguinicoliasis	The mass mortality of 0+ stock in sea-cage sites at Majorca, Catalonia and Murcia Spain has been occurring since 1989, typically between Dec and Mar each year. Losses were attributed to a combination of prokaryotic organism inducing epitheliocystis and heavy blood fluke burdens. Losses amounting to 3% of stock, due only to blood flukes, are also reported in 1+ aged stock. No stock or farm details are provided. Loss is based on the death of fish from the single infection, the assumption that cages ($5 \times 5 \times 5$ m^3) were stocked at 20 kg m^3 and the harvest price of market sized fish in Spain in 1992 was US$ 12·90 kg^{-1}	968 per cage	Crespo *et al*. (1992)
Zeuxapta seriolae	Mass mortalities (0·8–1·5% day^{-1}; 50% final) of 400–500 g stock in sea cages sited at Mallorca, Spain across the period Jan–Mar, 2002 were attributed to heavy infections causing anaemia and damage to the gills impairing respiratory function. No stock or farm details are provided. Loss is based on the assumption that cages ($5 \times 5 \times 5$ m^3) were stocked at 20 kg m^3. No data for Spain exists in FishStatJ for 2002, but using a linear scale of values between 1994 (US$ 13 kg^{-1}) and 2010 (US$ 19·28 kg^{-1}), the harvest price of market sized fish is est. at US$ 16·12 kg^{-1}	20 150 per cage	Grau *et al*. (2003)
	Recurrent outbreaks of mortality (33·3–47·2%; 686·7 ± 125·4 parasites fish^{-1}) in 0+ to 3+ aged fish reared in experimental culture tanks in Spain throughout 1998–2000. Loss is based on the 40 fish (av. wt. 558 g) lost during the mortality event and the estimated	212	Montero *et al*. (2004)

	harvest price of Spanish fish in 2000 of US$ 9·50 kg^{-1} (only figures for 1997, i.e. US$ 9·48 kg^{-1}, and 2007, i.e. US$ 10·00 kg^{-1} are available)		
Kingfish, *Seriola lalandi* (Valenciennes, 1833)			
Kudoa (=*Pentacapsula*) *neurophila*	In Nov 2008, 55% of 1 kg stock in 1 cage (i.e. 13 750 out of 25 000) and 80% (i.e. 20 000 out of 25 000 fish) in an adjoining cage in western Australia were lost. Fish were found to have mixed infections: 76·6% of stock had *K. neurophila* in the brains, whilst 66·1% of stock had an infection of *Unicapsula seriolae* within their skeletal muscle. The loss estimate is that provided at the time of the outbreak (i.e. AUS$ 300 000)	280 668	Stephens and Savage (2010)
	A second mortality event in the same site as above, resulted in the loss of 12% of starting stock (i.e. 6480 juveniles out of 54 000); 86·6% of these (i.e. 99/114 fish sampled) had infections in the brain. Loss is estimated on the cost of juveniles given in Table 7, i.e. US$ 4·80 fish^{-1}	31 100	Stephens and Savage (2010)
Unicapsula seriolae	Study suggests that fish on the open market are priced at more than US$ 1·50 kg^{-1} (assuming AUS$ 1=US$ 1) but infected fish sold through Brisbane markets are lower priced because the flesh disintegrates on cooking and releases an unpleasant odour	–	Lester (1982)
	The loss of 33 750 1 kg fish in Nov 2008 was attributed to an infection of *U. seriolae* in in the skeletal muscle of 66·1% of stock and an infection of *Kudoa neurophila* in 76·6% of stock. Losses were recorded at AUS$ 300 000	280 668	Stephens and Savage (2010)
	A second infection in juvenile stock at the same site in western Australia in Nov 2008 resulted in the loss of 6480 fish. A sample of 114 fish revealed that 7 of these had skeletal muscle infections. Loss is estimated on estimated on the price of juvenile fish (see Table 7)	31 100	Stephens and Savage (2010)
Benedenia seriolae	Parasite accounts for 22% of production costs – a figure which includes the production of of *S. quinqueradiata, S. dumerili* and *S. lalandi**	214 M*	Ernst *et al*. (2002); Whittington *et al*. (2001)
	Complications associated with a hydrogen peroxide bath administered in 4 cages for the treatment of parasitic infections in Australia in 2010 resulted in the death of 80 t of fish. No figures for Australian kingfish are listed within FAO FishStatJ and so the market price of Japanese amberjack in 2010 is used as an estimator, i.e. US$ 9·66 kg^{-1}. In addition to the loss of fish, the incident also wiped US$ 3·71 M (AUS$ 4 M) off the farm's market value (loss of share price)	772 800 (fish losses) 3·71 M	McIlwraith (2010)
Caligus chiastos	Lice burdens do not pose a significant threat to the health of captive reared stock, their numbers controlled by the administration of hydrogen peroxide treatments to control monogenean infections (treatment costs approx. US$ 4–5 K cage^{-1} including labour)	4500	Hayward *et al*. (2007); Nowak *et al*. (2011)
Paradeontacylix-like spp.	Infections in juvenile stock in New Zealand are reported from the heart, brain and internal organs resulting in granulomatous pathology in the heart and gills. Infections are associated with low-level mortalities. No details provided in the original report	–	Diggles and Hutson (2005)
Zeuxapta seriolae	Mortality (12·8%) of 223·5 ± 21·7 g experimentally infected fish (n = 91) of Australian sea cage stock between weeks 4 and 8	–	Mansell *et al*. (2005)
Longfin amberjack, *Seriola rivoliana* (Valenciennes, 1833)			
Neobenedenia melleni (syn. *girellae*)[b]	Heavy infection of 1-year-old stock reared in cages Ishigaki Island, Japan. No details on the losses are provided	–	Ogawa *et al*. (1995)
(e) Gilthead sea bream, *Sparus aurata* L.			
Amyloodinium ocellatum	75% mortality (i.e. 30 000) of 10 g juveniles over 48 h in a sea cage in Greece in the summer of 1997; water temperatures 23 to 26 °C. Loss is estimated on US$ 0·10 fish^{-1}	3000	Rigos *et al*. (1998)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	An infection in stock (av. 481 ± 92·9 g) held in 2500 m^3 earthen ponds at 0·75 kg m^3 with an equal weight of meagre resulted in a 29% mortality in 2 days (i.e. 271·88 kg $pond^{-1}$). Loss is estimated on the assumption that a minimum of 2 ponds were affected and on the market price of Portuguese fish in 2011, i.e. US$ 7·67 kg^{-1}	4170	Soares *et al*. (2012)
Brooklynella hostilis	An infection is reported from the gills of moribund stock (av. 150–200 g) held in a floating net-pen in the Gulf of Eilat. Details on the prevalence of infection and mortality are not provided but the fish were co-infected with an enteric bacterium, *Enteromyxum leei* and *Furnestinia echeneis*	–	Diamant (1998*b*)
Ceratomyxa sparusaurati	Prevalence of infection across 3 sites on the western Atlantic coast of Spain ranged from 0 to 59·9%, whilst that at a single site on the southern Atlantic coast of Spain was 3%. Infection resulted in trickling mortalities	–	Palenzuela *et al*. (1997)
	Accounted for low levels of loss (0·5% day^{-1}) in Greece	–	Rigos *et al*. (1999)
	Infections rates of between 6·66–20% were found at 3 separate cage sites within the Adriatic		Mladineo (2003)
Cryptocaryon irritans	56–100% mortality of broodstock held in land-based seawater tanks stocked at 6–10·2 kg m^3. Loss is based on the price of harvest-sized fish in Greece in 2000, i.e. US$ 4 kg^{-1}	2240–4000 t^{-1}	Rigos *et al*. (2001)
Cryptosporidium molnari	Between 1998 and 2000, a total of 346 sea bream sampled from various culture sites along the Atlantic, Cantabric and Mediterranean coasts of Spain, as part of a larger survey of mortality and morbidity events found a 24·4% prevalence of infection within the stomach epithelium. Infected hosts had abdominal swelling, infected zones of epithelium were necrotic which subsequently sloughed and detached from the lumen. Infection is also linked to an early mortality event of fingerlings	–	Sitjà-Bobadilla and Alvarez-Pellitero (2001); Alvarez-Pellitero and Sitjà-Bobadilla (2002)
Enteromyxum leei	Chronic mortalities of 5–10 fish day^{-1} in stock tanks holding 5000 fish (av. 150 g) are reported to have occurred Dec 1991–Jan 1992 in a culture facility in southern Cyprus. Loss is est. on a 7 fish day^{-1} mortality rate, that the event lasted 60 days, and, the price of Cypriot fish in 1992, i.e. US$ 14·44 kg^{-1}	910	Diamant (1992)
	29% loss of stock observed over numerous Greek cage sites covering several geographical regions during the period Sept 1996–Sept 1997. Estimate of loss is based on the harvest price of Greek fish in 1997, i.e. US$ 6·33 kg^{-1}	1836 t^{-1}	Rigos *et al*. (1999)
Henneguya sp.	An infection within the hearts of stock (av. 260 g) reared in seawater, earthen ponds resulted in a low-level of mortality (i.e. 4–5 fish day^{-1})	–	Caffara *et al*. (2003)
Ichthyophonus sp.	Two farm sites in southern Greece had reported mortalities of 25% (farm A) and 15% (farm B). Sampling throughout 1981–1987 found that 15% of the fish from farm A (n = 40; stocked at 15 kg m^3 and fed a mixed diet of pellets and trash fish) and 23·5% of those from farm B (n = 51; stocked at 30 kg m^3 and fed a pellet diet only) were infected. Infection was a common granulomatous response in the liver, heart, kidneys and intestines. Loss is based on the assumption that each site produced 10 t, the size of fish lost	53 160 p.a. across the 2 sites	Athanassopoulou (1992)

	were harvest size, i.e. 0·5 kg, the total mortality at each site can be attributed to *Ichthyophonus*, and, the harvest price of Greek fish in 1987, i.e. US$ 13·29 kg^{-1}		
	Three Spanish culture sites were sampled throughout 1990–1991. A prevalence of 75% was found in stock (3·9–27·9 cm long) in a closed system near Valencia ($n = 185$), 20·8% of hatchery and nursery stock (2–15 cm long) from a site near Cadiz ($n = 49$), and, in 70% of wild stock (26–31 cm long) caught from the wild and then reared on at a site near the River Ebro delta ($n = 10$). No mortalities were reported but the presence of this parasite in stock is considered a threat	–	Franco-Sierra *et al*. (1997)
Kudoa sp.	High mortalities associated with infection reported. No details available	–	Arfara *etal*. (1995 cited in Rigos *et al*. 1999)
Microsporidian: *Pleistophora*-like	Constant low-level mortalities of stock held in floating sea cages in Malta, i.e. 0·06% $week^{-1}$ in fish ~10 g 6–8 weeks post-transfer in Jan–Feb 1994 rising to 0·2% $week^{-1}$ in 1995–1996. In larger fish, infection appears as large white to yellow nodules within the musculature, occasionally granulomatous decreasing marketability of fish. Loss is est. on a single $5 \times 5 \times 5\ m^3$ cage of fish stocked at 15 kg m^3 (i.e. 187, 500 10 g fish), a linear incremental increase in mortality from 0·06 to 0·2% $week^{-1}$ across a 12-month culture period, a linear 35 g weight gain per month, and, the harvest price of Maltese fish in 1996, i.e. US$ 6·24 kg^{-1}. Final estimated losses were 11 840 fish representing a final mortality of approx. 6·3% and 2860 kg of fish	17 846	Abela *et al*. (1996)
Myxidium sp.	Occasional mortalities were attributed to *Myxidium* infections	–	Diamant (1992)
Pleistophora sp.	Muscular infection of av. 75 g stock in Greece in 4 pens of fish resulted in a daily mortality of 0·2% for a period of ~7 days in Feb–Mar 1996. Infected fish were lethargic, emaciated, had discoloured skin and had scoliosis. Mortalities were arrested following a fumagillin treatment. Four cages (assuming $5 \times 5 \times 5\ m^3$) were stocked at 15 kg m^3, loss equates to ~410 fish $cage^{-1}$ (i.e. 30·75 kg) or ~ US$ 270 $cage^{-1}$ (based on US$ 8·767 kg^{-1} harvest price in 1996 for Greek sea bream). Total loss est. at ~ US$ 1080	1080	Athanassopoulou (1998)
Polysporoplasma sparis	Infection rates of between 7·14 and 100% were recorded in ~256 g stock held at 4 different cage sites within the Adriatic Sea	–	Mladineo (2003)
Sphaerospora sp.	Prevalence of infection can reach 80% and cause serious kidney damage, including glomerular destruction and haemorrhagia	–	Sitjà-Bobadilla and Alvarez-Pellitero (1992)
Trichodina sp.	An infection of newly stocked fingerlings (1 fish L^{-1}?) from Bardawil Lagoon, Israel in a 1000 L (?) tank in 1976(?) at a research facility in Eilat, Israel resulted in morbidity and mortality of up to 40–50%	–	Paperna *et al*. (1977)
Ceratothoa oestroides	Infection is reported to have caused high losses in juvenile populations reared in Croatia as a consequence of gill damage and respiratory failure. In older fish, infection results in a 20% reduction in growth. Assuming the 2012 market price of Croatian fish, i.e. US$ 6·50 kg^{-1} infection represents a loss of US$ 1·30 kg^{-1}	1·30 kg^{-1}	Šarušic (1999)
Ceratothoa parallela	Cymothoid isopods were found in the branchial and buccal cavity of 2–2·3 g juveniles when being stocked into cages in Greece. The cumulative mortality over the subsequent 2 months was >50% (i.e. the loss of >120 000 fish; ~258 kg). Loss is based on the value of Greek harvest-sized stock in 2001, i.e. US$ 3·88 kg^{-1}	1000+	Papapanagiotou and Trilles (2001)
Furnestinia echeneis	The study suggests that infections, of up to 239 flukes $fish^{-1}$, on hatchery produced stock (80–130 mm) and on fingerlings from Bardawil Lagoon reared in single 1000 L (?) tanks at a research facility in Eilat, Israel in 1976(?) resulted in the morbidity and mortality of 40–	13·5	Paperna *et al*. (1977)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	50% of stock. Although some details are provided, specifics relating to the mortality event are not clear. It is assumed that fish were stocked at 1 fish L^{-1}. Loss assumes the mortality of 450 (10 g) fish in 2 tanks (i.e. total loss of 9 kg stock) and is based on the harvest price of Israeli freshwater tilapia in 1984 (first figures available), i.e. US$ 1·50 kg^{-1}		
Gyrodactylus orecchiae	Approx. 2–10% mortality in juvenile stock (5–10 g) held in inshore-floating cages in Albania and Croatia; infection of gills and all external surfaces with 1000+ gyrodactylids $fish^{-1}$. Fish were hypermelanotic, lethargic, anorexic with a progressive loss of weight. Loss is based on the assumption that at least 3 cages measuring $5\times5\times5$ m^3, each stocked at 15 kg m^3 were affected (i.e. 187 500 fish $cage^{-1}$), av. mortality was 5% (i.e. 9375 fish $cage^{-1}$), and, a price of US$ 0·05 $juvenile^{-1}$ (see Table 7)	1406	Paladini *et al*. (2009)
	Infection reported from farms in Bosnia-Hercegovina and Italy		Paladini *et al*. (2011)
Lernanthropus kroyeri	Infection at a single 2000 m^3, 1500 t cage production site in Greece producing *D. labrax* and *S. aurata*. Cages are stocked at 12–15 kg m^3 (50–300 g sized fish). Infection accounts for <1% loss over an 8-month period in 200(1?). Losses for each species are not given but assuming an equal production of both species, then mortality is <7 t. Loss figures are based on the value of Greek stock in 2001, i.e. US$ 3·88 kg^{-1}	<27 160	Vagianou *et al*. (2006)
Microcotyle sp.	Anorexia, lethargy, anaemic gills and increased mortalities attributed to a *Microcotyle* infection reported in 200–300 g stock reared in sea cages in southern Spain in Feb 1992	–	Sanz (1992)
Microcotyle sp. & *Lamellodiscus* sp.	Continuous low mortalities in 0+ sea bream in floating cages in NE Spain with mild to severe parasite burdens and proliferative epitheliocystis during the winter of 1993–1994	–	Padrós and Crespo (1995)
Unidentified sanguinicolid	An infection (prev. 82·6%) in net caged stocked (50–400 g body weight) in north-eastern Spain throughout Dec 1998–April 1999 resulted in a low level, chronic pattern of mortality (0·01–0·1% daily). The prevalence of infection through the cold season the following year was found to be 100%. Stocks also were infected with the gill monogeneans *Furnestinia echeneis* and *Microcotyle chrysophrii* (prev. of 35% in 1999 and 20% in 2000). Loss is based on the assumption the site consisted of four $5\times5\times5$ m^3 cages stocked with 50 g fish at 15 kg m^3 (i.e. 180 000 fish as a 9 t production site). Assuming that the mortality event occurred over a 120-day period (i.e. mid-Dec to mid-April), then using the pattern of losses provided a total of 11 880 fish were lost or 6·6% of starting stock. The figure of loss is based on an av. fish wt. of 100 at the time of mortality and the harvest price of Spanish fish in 1999, i.e. US$ 6·00 kg^{-1}	7128	Padrós *et al*. (2001)
Sparicotyle chrysophrii	Infections cause anaemia and high mortality at low intensities (8–10 parasites gill $arch^{-1}$) in fish weighing 10–300 g. No details provided	–	Paladini *et al*. (2011)
(f) Coho salmon, *Oncorhynchus kisutch* (Walbaum, 1792)			
Kudoa thyrsites	A 1·0–11·2% infection within the cardiac muscle of fresh morts collected from 5 different hatcheries along the coast of British Columbia, Canada was found between Aug 1986 and Jan 1988	–	Kabata and Whitaker (1989)

	Processors report that a 60% prevalence of myoliquefaction in smoked fillets prepared from 1 net-pen of stock. Assuming that all infected fillets were rejected, loss is based on the value of harvest-sized fish in Canada in 1992, i.e. US$ 4·44 kg^{-1}	2664 t^{-1} of production or 4440 t^{-1} of rejected fish	Whitaker and Kent (1992)
Loma salmonae	*Loma* combined with a bloom of *Corethron*-like diatoms led to severe inflammatory lesions associated with ruptured xenomas leading to 60% mortality in 100 000 net-pen held smolts (~ 40 g) over a 7-day period in British Columbia in Oct 1987. Estimate of loss is based on price of harvest-sized fish in Canada in 1987, i.e. US$ 4·77 kg^{-1}	11 448	Speare *et al*. (1989)
	Significant gill pathology seen in smolts transferred to net-pens in Washington State; parasite prevalent on 33–65% of gills leading to severe lesions and mortalities throughout the summer	–	Kent *et al*. (1989)
Paramoeba pemaquidensis	25% mortality in stock (no size details) reared net-pens in Washington in 1985. Estimate of loss is based on the value of harvest-sized fish in the USA in 1985, i.e. US$ 3·50 kg^{-1}	875 t^{-1}	Kent *et al*. (1988)
Parvicapsula sp.	Kidney infections resulted in mortalities in juvenile fish held in net-pens in Washington State, USA in 1979	–	Hoffman (1984)
	A 30% mortality observed in marine stock in Oregon State. No details available	–	Johnstone (1984)
Lepeophtheirus salmonis	Lice burdens on 150 g juveniles stocked in sea cages sited in Shizugawa Bay on the Pacific coast of north-eastern Honshu, Japan in Oct 1991 were followed until they were harvested in Aug 1992. Lice burdens peaked in late July to early Aug 1992 at 2·6 ± 2·4 lice $fish^{-1}$ (prev. 84·6%). Peri-anal haemorrhages were observed but not thought to cause serious disease	–	Urawa *et al*. (1998*a*)
	10 000 juvenile fish (~ 1-year old; 420–430 g) were transferred to net-pens in Onmae Bay, Miyagi Prefecture, Japan. Lice infections determined on stock over the period March–July 1993 were low at an av. 3·5 lice $fish^{-1}$ (prev. 73·3%)	–	Ho and Nagasawa (2001)
(g) European seabass, *Dicentrarchus labrax* L.			
Amyloodinium ocellatum	An infection at 2 Italian farms in July 1979 resulted in the loss of at least 600 (av. wt. 80·6 g, 18·5 cm long) fish from 1 tank at 1 site. No specific details relating to the mortalities at the second farm are provided. Loss is estimated on the assumption that at least 1200 fish in total were lost and the price of harvest-sized Italian fish in 1984, i.e. US$ 10·51 kg^{-1} (date at which first figures are available)	1016	Ghittino *et al*. (1980)
Ceratomyxa spp. (*C. diplodae* & *C. labracis*)	The examination of 340+ fish found *C. diplodae* in 10·2% of <1-year-old fish and 3·33–6·97% in 1+ to >4-year-old fish and *C. labracis* in 46·93% of <1-year-old stock and 21·05–71·05% in 1+ to >4-year-old fish. Variable degrees of damage to the gall bladders were seen	–	Alvarez-Pellitero and Sitjà-Bobadilla (1993)
Cryptosporidium molnari	Between 1998 and 2000, a total of 151 fish were sampled from various culture sites along the Atlantic, Cantabric and Mediterranean coasts of Spain, as part of a larger survey of mortality and morbidity events found a 4·64% prevalence of infection within the stomach epithelium. Infection associated losses were suggested.	–	Alvarez-Pellitero and Sitjà-Bobadilla (2002)
Enteromyxum leei	42% loss of stock observed over numerous Greek cage sites covering several geographical regions during the period Sept 1996–Sept 1997	–	Rigos *et al*. (1999)
Ichthyophonus sp.	Infection, with a prevalence of 24·4%, was found in stock (size not specified; *n* = 127) from a Spanish farm near the River Ebro delta, Spain. Infections, notably in the heart and muscle, appeared as granulomas with an intense fibrotic reaction. Severe tissue damage was noted in the trunk kidney. No mortality or morbidity of stock was commented upon	–	Sitjà-Bobadilla and Alvarez-Pellitero (1990)

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Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
	Three Spanish culture sites were sampled throughout 1988–1991. Infections were found with prevalences of 90% in stock (2·4–29·6 cm long) at a grow-out facility near Valencia (n = 82); 78·8% of 2·3–52·3 cm long stock caught from the wild and then reared on at a site on the western Spanish Mediterranean coast (n = 33), and, in 70% of 24–34 cm sized stock ranched from the wild and then grown on in sea cages near the River Ebro delta (n = 10). No losses were reported but the presence of this parasite in stock is considered a threat	–	Franco-Sierra *et al*. (1997)
Loma spp.	Intestinal infections of a microsporidian resulted in the emaciation, poor growth rate and low mortality of stock at 3 Italian inland marine farm sites. No details provided	–	Caffara *et al*.(2010)
Oodinium sp.	[see entry for *Amyloodinium ocellatum*]	1016	Ghittino *et al*. (1980)
Philasterides dicentrarchi	A low level of mortality (i.e. ∼5 morts day^{-1}) was seen in 250 g stock reared in tanks at a French farm site within a Mediterranean laguna in March 1993. Moribund fish had swollen urogenito-anal papillae and congestion of the internal body organs	–	Dragesco *et al*. (1995)
Sphaerospora dicentrarchi	Infection rates of between 7·14 and 100% were found at 5 separate cage sites within the Adriatic	–	Mladineo (2003)
Sphaerospora testicularis	Infections caused significant damage to the testes with significant losses (5–10% day^{-1}) at certain Greek sites during the period Sept 1996–Sept 1997	–	Rigos *et al*. (1999)
Anilocra physodes	A suggested serious parasite problem of juvenile, caged reared stock. No details available	–	Athanassopoulou *et al*. (2001*a*)
Caligus minimus	30 g–2 kg Italian fish infected with ∼40 copepods fish^{-1} were anorexic and lethargic; infection resulted in ∼9% mortality. No details on which size of fish were lost	–	Pavoletti *et al*. (1999) cited in Johnson *et al*. (2004)
Ceratothoa oestroides	Infection is reported to cause high losses in juvenile populations reared in Croatia as a consequence of gill damage and respiratory failure. In older fish, infection results in a 20% reduction in growth. Assuming the 2012 market price of Croatian fish, i.e. US$ 6·74 kg^{-1}, infection represents a loss of US$ 1·35 kg^{-1}	1·35 kg^{-1}	Šarušic (1999)
	A survey of 109 cages at a Turkish site in the Aegean Sea in July 2000 found a 23·11 ± 16·71% prevalence of infection. A later survey of 53 cages in Sept 2000 found 13·51 ± 17·51% prevalence. The study found that there was a 20·1% (i.e. 14 g) difference in the weight of infected ∼290-day-old fish (i.e. >2 parasites fish^{-1}) than in uninfected or those with low parasite burdens (i.e. <2 parasites fish^{-1}). This translates into a 27–46·2 kg t^{-1} difference in production at this stage. Figures of loss are based on the price of Turkish harvest-sized fish in 2000, i.e. US$ 4·13 kg^{-1}	111–191 t^{-1} by day 290 of production	Horton and Okamura (2001)
Diplectanum aequans	Approx. 5–10% of Italian juvenile fish are lost each spring. Loss is estimated on harvest-sized fish being 0·5 kg, that production in 2006 was 8835 t, and, that the price of each juvenile was US$ 0·5, i.e. between 1 850 000 and 3 700 000 fish are lost	0·925–1·85 M	Dezfuli *et al*. (2007)
Emetha audouini	Infection of a cage of 60 000 juvenile (∼ 30 g, 3 months old) in Nov, 1997 in the northern part of Greece resulted in the loss of 10·75% of stock over a 2-week period. Isopods caused extensive, deep skin damage to the cranium and eyes. Adjoining cages of sea bream were unaffected. Loss is estimated on the value of each juvenile, i.e. US$ 0·70 fish^{-1}.	4515	Papapanagiotou *et al*. (1999)

Lernanthropus kroyeri	Infection is reported to be responsible for the mortality of small-sized fish (< 10 g) by asphyxia and anaemia in Greek culture systems. Loss is est. on a 1% mortality rate in stock reared in $5 \times 5 \times 5$ m^3 cages, each stocked at 40 kg m^3 were affected (i.e. 500 000 fish cage^{-1}), and, an est. price of US$ 0·40 juvenile^{-1} (see Table 7)	2000	Athanassopoulou *et al*. (2001*b*)
	Infection at a single, mixed species (*D. labrax* and *S. aurata*), 2000 m^3, 1500 t cage production site in Greece stocked at 12–15 kg m^3 (50–300 g sized fish) accounts for a <1% loss over an 8-month period in 200(1?). Losses for each species are not given but assuming a 50:50 production of both species, then mortality is <7 t. Loss figures are based on the value of Greek stock in 2001, i.e. US$ 4·55 kg^{-1}	< 31 850	Vagianou *et al*. (2006)
Nerocila orbignyi	Mortality of cage-reared stock in Corsica, France rises from 7 to 18% over the period July–Dec 1981; parasite prevalence is ∼90%. Wild mullet are the source of the haematophagous isopods infection establishing in the cages. No details relating to the system or the size of the fish are provided but are assumed to be av. 50 g stocked in a single 125 m^3 cages at a stocking density of 40 kg m^3 (i.e. 100 000 fish cage^{-1}). Loss is est. on a final mortality of 18% of starting stock (i.e. 18 000 fish) but assumes a linear 20 g per month weight gain, and, the price of harvest-sized French fish in 1985 (first figures available), i.e. US$ 11·23 kg^{-1}. Final weight of fish lost is 1450 kg	16 284	Bragoni *et al*. (1984)
(h) Turbot, *Scophthalmus maximus* L.			
Amyloodinium ocellatum	The mortality of 3 tanks of 27 g fish ($n = 27$) within a research facility in Portugal is reported	–	Ramos and Oliveira (2001)
Enteromyxum-like sp.	High levels of mortality, reaching 100% in all infected land-based systems, were seen at a commercial culture site in northern Galicia, Spain during the spring and summer of 1997. A range of stock sizes from 50 g to 2 kg were lost from the systems, each of which typically measured 160 m^2 and were stocked at 25 kg m^3 (i.e. 4000 kg system^{-1}). Figures of loss are based on Spanish prices for harvest-sized fish in 1998, i.e. US$ 9·1 kg^{-1}	36 400 per system	Branson *et al*. (1999)
Ichthyophonus sp.	Three Spanish culture sites along the Cantabric coast were sampled throughout 1989–1991. The study found prevalences of 36·8% in nursery stock (2·9–5·2 cm long) at the first site ($n = 95$), 21% in hatchery and nursery fish (1·7–7·8 cm long) at a second site ($n = 181$), and, 42·4% in nursery, hatchery and grow-out stock at a third, undisclosed site ($n = 118$). No losses were reported but the presence of this parasite in stock is considered a threat	–	Franco-Sierra *et al*. (1997)
Paramoeba sp.	Amoebae caused severe gill damage resulting in the loss of between 5 and 20% of 500 g stock in 20 out of 150 tanks at a culture facility in north-west Spain over a 3-month period (Oct–Dec 1996). No tank sizes were given but loss is based on the assumption that each tank measured 160 m^2, stocked at 25 kg m^3 (i.e. 4000 kg system^{-1}), an av. mortality of 10%, and, the price of Spanish harvest-sized fish in 1996, i.e. US$ 9·78 kg^{-1}	78 240	Dyková *et al*. (1998)
Philasterides dicentrarchi	During the summer of 1999 and the spring of 2000, 2 outbreaks of infection resulted in mortalities. The first event occurred in 2 tanks of >500 g fish, the second in 6 tanks of fish ranging from 150 to 1500 g, with 20–30 morts day^{-1}, rising to 100–150 fish day^{-1}. The infection resulted in the total loss of stock in some tanks. Assuming a 25 kg m^3 stocking density for this species, 4 m^3 culture tanks and a 50% loss across all infected tanks, then the loss of stock would have been ∼400 kg. Figures are based on the price of Spanish harvest-sized fish in 2000, i.e. US$ 8·50 kg^{-1}	3400	Iglesias *et al*. (2001)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Philasterides-like	Several outbreaks at a grow-out facility (av. fish wt. 300 g) in the north of Portugal were reported throughout March 2004–Feb 2005. Mortality reached 3–6% over the period May–Aug 2004. No specific details of loss are provided but it is assumed that the loss occurred in a single 160 m^2 tank stocked at 25 kg m^3 (i.e. 4000 kg system^{-1}). A normal distribution pattern of loss is assumed resulting in the loss resulting in a 21·3% loss of stock (i.e. 2875 fish with a total weight of 862·5 kg). The harvest price of Portuguese stock in 2005, i.e. US$ 8·75 kg^{-1} is applied	7547	Ramos *et al*. (2007)
Tetramicra brevifilum	A chronic, low-level pattern of mortality in juvenile stock (~ 30 g) held in 4 m^3 concrete tanks in Galicia, Spain, resulted in the loss of ~3450 fish (11·5% of stock) over ~100 days, i.e. ~103·5 kg of fish. Infection was evident as small xenomas in a range of host tissues, where aggregations of spores occasionally elicited an inflammatory reaction. Figures of loss are based on the harvest price of Spanish turbot in 1990, i.e. US$ 15·59 kg^{-1}	1614	Figueras *et al*. (1992)
Tetramicra brevifilum + a histophagous ciliate	A 22·5% (i.e. ~675 fish) mortality of stock occurred in a single-holding unit within a grow-out facility holding ~3000 juveniles in north-west Galicia, Spain. The histophagous ciliates were tentatively identified as *Miamiensis avidus* and *Uronema marinum*. No details relating to the size of the fish are provided but av. wt. is assumed to be 50 g. Loss is estimated on the value of harvest-sized Spanish fish in 1993, i.e. US$ 8·39 kg^{-1}	283	Dyková and Figueras (1994)
Unidentified protistan	Seven out of 8 batches of eggs were infected with a large multinucleated protistan (1–2 per embryo; prev. 20·0–21·5%) in the embryos and yolk-sac larvae, which subsequently breaks up into numerous mononucleated organisms. No associated mortality was recorded in this study, unlike the infections observed in wild cod eggs (Pedersen *et al*. 1993)	–	Pedersen (1993)
Uronema-like ciliates	Between 1989 and 1996, a farm in Vest-Agder County, southern Norway had 3 outbreaks in their fry units (av. <0·3 g; 18 °C) in the autumn of each year resulting in the near complete loss on each occasion of stock. It is assumed that 100% of stock, valued at US$ 0·10 fish^{-1}, in a single 160 m^3 tank stocked at 10 kg m^3 was lost	533 000	Sterud *et al*. (2000)
	The same farm also lost 30% of 500–1000 g stock held in on-grower units (15 °C) in Aug, 1998. Loss is est. on the assumption that an av. 30% of stock (av. 750 g) in three 160 m^3 tanks was lost. No prices for Norwegian turbot are available in FishStatJ and so the value of French turbot in 1998, i.e. US$ 8·00 kg^{-1}, is used	11 520	Sterud *et al*. (2000)
(i) Silver sea bream, *Pagrus auratus* (Forster, 1801)			
Anoplodiscus cirrusspiralis	Infections are reported to affect the fins and nasal lamellae of Australian stock. Approx. 10% of experimental stock died when held at higher stocking densities (av. 26·0–43·3 parasites fish^{-1}) despite having similar parasite burdens as those held at lower stocking densities (av. 33·8–36·5 parasites fish^{-1})	–	West and Roubal (1998)
Anoplodiscus tai	Infections were reported at several cultures sites within Fukui and Nagasaki Prefecture, Japan throughout 1989–1993. Heavily infected fish were emaciated and monogenean activity on the fins had led to tissue damage and the partial loss of fins. The study reports that 5-year-old fish with heavy infections were rejected at market. Examination of stock found an av. 41·2 monogeneans per fish (range 26–64 flukes fish^{-1}). No details relating to mortality or the economic loss associated with infections were given	–	Ogawa (1994)

(j) Groupers (general)			
Fish diseases (general)	Over 80% of farmers remarked that disease, including parasites, in small scale cage culture in Thailand (i.e. 1–5 cages) results in the 30–50% loss of stock. Loss is est. on fish being grown in $5\times5\times5$ m^3 cages at a stocking density of 15 kg m^3, and, the value of each 150 g fish is US$ 2·00 (see Table 7)	7500–12 500 per cage	Bondad-Reantaso *et al*. (2001); Kanchanakhan *et al*. (2001)
Parasite (general)	This review suggested that the following parasite species cause problems in grouper culture throughout South-east Asia: *Amyloodinium* sp., *Brooklynella* sp., *Cryptocaryon irritans, Ichthyophonus* sp., *Trichodina* sp., *Benedenia* sp., *Megalocotyloides epinepheli* and *Pseudorhabosynochus epinepheli*	–	Arthur and Ogawa (1996); Bondad-Reantaso *et al*. (2001)
Benedenia sp.	Reported to infect stock of *Epinephelus* spp. reared in sea cages off Pingtung, Taiwan. Flukes caused haemorrhages which were subject to secondary bacterial infection. No details of fish losses were provided	–	Chang and Wang (2000)
Caligus lalandei	Stocks of *Epinephelus* spp. reared in marine cages in the Pingtung area of Taiwan were commonly found infected. Lice activity resulted in lesions, inflammation and ulceration by secondary bacterial infections. No details of loss or downgrading provided	–	Chang and Wang (2000)
Hong Kong grouper or red spotted grouper, *Epinephelus akaara* (Temminck et Schlegel, 1842)			
Pseudorhabdosynochus epinephali	Hatcheries in the southwest Japan produce seed for stock enhancement and aquaculture Broodstock (0·5–1·0 kg) within a hatchery facility in Kagawa Prefecture reported gill infections as being common place and requiring treatment as heavy infections resulted in lower egg production. Moderate mortalities in juvenile stock were reported as a consequence. Loss is estimated on the basis that ‘moderate’ infers a 5–10% mortality and uses the values provided in Table 7 for juvenile fish, i.e. US$ 1·02–2·33 $fish^{-1}$	51–117 (5% loss) to 102–117 (10% loss) per 1000 juveniles	Isshiki *et al*. (2007)
Orange-spotted grouper, *Epinephelus coioides* (Hamilton, 1822)			
Zeylanicobdella arugamensis	A heavy infection of leeches on juveniles (83% infected) and adults (17%) reared in brackish water (22‰) tanks subsequently resulted in the mortality of the adult ($n=1$) 3 days post-infection. The cause of death was suggested to be blood loss, secondary infection and loss of appetite	–	Cruz-Lacierda *et al*. (2000)
Malabar grouper, *Epinephelus malabaricus* (Bloch et Schneider, 1801)			
Cryptocaryon irritans + *Trichodina* sp.	Mixed infections were suggested to be the primary cause of disease outbreaks in juvenile stock ($n=100$; av. 3·6 cm) imported from Thailand to Penang, Malaysia. Disease outbreaks occurred 2–3 weeks post-transfer; 97% of the healthy and 90% of the diseased grouper had *Trichodina* sp. infections	–	Leong and Wong (1990)
Sphaerospora epinepheli	Disease outbreaks in cage cultured stock in 100–800 g sized fish and ~15–20 kg broodstock between May–Aug each year at sites situated on both the Gulf of Thailand and Andaman Sea coastlines. Fish have loss of equilibrium, haemorrhagic regions across the body, the lumen of renal tubules contained masses of spores whilst large numbers of pseudo-plasmodia were seen attached to the epithelium of the tubules, which had become necrotic with evident peritubular fibrosis. Details relating to the magnitude of loss not given	–	Supamattaya *et al*. (1990)
Ergasilus borneoensis	Approx. 18·5% of stock ($n=254$; av. wt. 579·3 g; range 260–920 g) sampled from floating cages in Penang Malaysia were infected with a mean intensity of 177·4 copepods $fish^{-1}$. No details relating to the impact of this parasite on the gills of host fish were provided	–	Leong and Wong (1988)
Ergasilus lobus	Approx. 9000 juveniles were imported from Thailand to brackish water pond site in	3308	Lin and Ho (1998)

Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
	Tainan County, Taiwan in June 1993. Subsequently ~ 3–400 fish day^{-1} died on a daily basis over the following 15 days (i.e. approx. 5250 fish); all fish were infected, the gills had numerous 'vacuoles' and parasites. Loss is estimated on the adjusted value for harvest-sized fish in Taiwan between 1993 (i.e. US$ 4·98 kg^{-1}) and 2011 (i.e. US$ 13·04 kg^{-1}) and the adjusted value for juveniles given in Table 6 (i.e. 38% of their 2011 value). It is assumed that the juveniles weighed 100 g at the time of loss; loss is extrapolated from the value of fish in 2011, i.e. US$ 1·68 $fish^{-1}$, and a value of US$ 0·63 $fish^{-1}$ is used		
Prosorhynchus pacificus	Approx. 97·2% of stock (n = 254; av. wt. 579·3 g; range 260–920 g) sampled from floating cages in Penang Malaysia were infected with a mean intensity of 81·2 parasites $fish^{-1}$. No details relating to the impact of this parasite on stocks were provided	–	Leong and Wong (1988); see also study of Leong and Wong (1990)
Pseudorhabdosynochus epinepheli	All the stock (100% prevalence of infection; n = 254; av. wt. 579·3 g; range 260–920 g) sampled from floating cages in Penang, Malaysia were infected with a mean intensity of 335 flukes $fish^{-1}$	–	Leong and Wong (1988)
	The infection levels in wild fish were three times lower (mean intensity of 126·6 flukes $fish^{-1}$; prevalence of infection 94·3%; n = 35; av. wt. 415·3 g; range 170–900 g)		
	Juvenile stock (n = 100; av. 3·6 cm) imported from Thailand into Malaysia in Dec 1986 were infected (prev. 92·9%) with a mean intensity of 29·5 flukes $fish^{-1}$. Similarly, 92% of a shipment importation from the Philippines (n = 50; av. 15·4 cm) were infected with 51·1 flukes $fish^{-1}$	–	Leong and Wong (1990)
Epinephelus coioides + *E. malabaricus*			
Leeches (unspecified)	A survey of small scale grouper culture in the Philippines (72 farmers +1 co-operative of 65 families) in July–Sept 1999 found a 15·3% occurrence of infection resulting in an av. mortality rate of 30% (up to 100% in some ponds) in nursery and grow-out stock. Loss is est. on a 125 m^3 pond, stocked at 15 kg m^3 with juvenile (av. 100 g) fish, i.e. 18 750 fish $cage^{-1}$, and, the harvest price of Filipino fish in 1992, i.e. US$ 13·00 kg^{-1} (NB: in FAO FishStatJ this is given as a price for seabass and grouper)	~ 7310 per cage	Somga *et al*. (2002)
(k) Olive flounder/Japanese flounder/bastard halibut, *Paralichthys olivaceus* (Temminck et Schlegel, 1846)			
Ichthyobodo sp.	Approx. 17 200 metamorphosed juveniles (av. 0·14 g) were lost over a 4-day period in March 1989 from two 15 m^3 tanks in Okayama Prefecture, Japan which were supplied with 17 °C, 30‰ seawater at a rate of 20 L min^{-1}. Loss is est. on each fish being valued at US$ 0·05, however, Tomiyama *et al*. (2008) suggest that the price of a 10 cm juvenile trawled juvenile is 100 yen (=US$ 1)	860	Urawa *et al*. (1991)
Miamiensis avidus (syn. *Phiasterides dicentrarchi*)	The causative agent of scuticociliatosis in Korean stock at several farm sites is identified from collected brain, gill and ulcerated skin samples. No details of loss throughout the Korean industry are provided	–	Kim *et al*. (2004*a*); Jung *et al*. (2007)
Pseudocohnilembus persalinus	Ciliates causing scuticociliatosis were collected from the brains, gills and ulcerated skin from stock at several Korean farm sites are identified. No details of loss are provided	–	Kim *et al*. (2004*b*)

Unidentified scuticociliatid ciliate	Study makes reference to this parasite as being commonly responsible for the mass mortality of fry and juveniles within Japanese hatcheries. Also reported to occur in commercial-sized fish. No details relating to the economics of loss throughout the Japanese industry are given	–	Yoshinaga and Nakazoe (1993)
Neobenedenia melleni[2] (syn. *girellae*)	A heavy infection of 2000 flukes (fish^{-1} ?) recorded on 310–340 g stock held in floating cages in Oita Prefecture, Japan in Oct 1991. Details of loss not provided. Loss is est. on a 20 kg m^{2} (see http://www.lib.noaa.gov/retiredsites/korea/main_species/flounder.htm) stocking density, a cage area of 100 m^{2} (see Yoon, 2008), the assumption that heavy burdens resulted in a 50% loss of stock, and, the price of Japanese stock in 1991, i.e. US$ 20·32 kg^{-1} (see the entry in FAO FishStatJ under bastard halibut)	20 320	Ogawa *et al*. (1995)
Neoheterobothrium hirame	Infections in the buccal cavity cause anaemia in spawning stock maintained in tanks and in fish reared in off-shore nets	–	Michine (1999); Ogawa (1999)
Uronema marinum	Mass mortality of farmed fry and high cumulative mortality of juveniles frequently observed in numerous farms. Loss is based on at least one 2000 t cage (i.e. 10 × 10 m^{2}) at 5 sites each stocked with 100 000 juveniles experiencing a loss of 50%. The value of each fish is est. at US$ 0·10	50 000	Jee *et al*. (2001)
(l) Pompano, *Trachinotus* spp.			
Lepeophtheirus spinifer	Lice on market-sized (∼ 350 g) reared in floating cage-reared *Trachinotus blochii* in Battan Province Central Luzon, Philippines, caused lesions and scale loss reducing the market value of fish	–	Cruz-Lacierda *et al*. (2011)
(m) Flathead grey mullet, *Mugil cephalus* L.			
Amyloodinium-like	Infection within a culture facility resulted in 6 mortalities; the remaining 3 moribund fish (40–51 cm) were sampled to determine the cause of mortality	–	Baticados and Quinitio (1984)
Myxobolus parvus	Mild to heavy gill and visceral infections seen in stock kept in ponds (11–13‰); no morts	–	Paperna (1975)
Benedenia monticelli	Skin and mouth infections caused mass mortality of cultured grey mullet (80–100 mm long) in Eilat; captured fish with typically <6 parasites fish^{-1} stocked in 0·75–1 m^{3} open, seawater culture tanks, die within 2 weeks of stocking. It is assumed that a 50% mortality occurred in three 1 m tanks stocked at 10 kg m^{3} with av. 5 g (10–12 cm) and the value of individual wild-caught fish was US$ 0·05 fish^{-1}	150	Paperna (1975); Paperna *et al*. (1984)
Ergasilus lizae	Mortalities in brackish ponds (11–13‰) in Israel, 90% infection with av. 10–70 parasites fish^{-1}on fish >50 mm long. Loss is assumed that the loss occurred in similar 250 m^{3} ponds referred to in Paperna *et al*. (1977), stocked at 3 fish m^{3}, that the av. size of infected fish was av. 5 g (10–12 cm), av. mortality was 12%, and, the value of individual wild-caught fish was US$ 0·05 fish^{-1}. It is assumed that at least 10 ponds were affected and were the basis of the report	45	Paperna (1975)
Pseudocaligus apodus	Open sores on dead fish held in a seawater pond at the Dor Fisheries Research Station situated in the coastal plain of Israel. The entire stock was lost. It is assumed that the single pond measured 250 m^{3} in capacity, stocked at 3 fish m^{3} (av. 5 g), each valued at US$ 0·05 fish^{-1}	38	Paperna (1975)
(n) Barramundi, *Lates calcarifer* (Bloch, 1790)			
Fish diseases gen. spp.	Over 80% of farmers remarked that disease, including parasites, in small scale cage culture in Thailand (i.e. 1–5 cages) results in the 30–50% loss of stock. Loss is est. on fish being grown in 5 × 5 × 5 m^{3} cages at a stocking density of 15 kg m^{3}, and, the value of each 150 g fish is US$ 2·00 (see Table 7)	7500–12 500 per cage	Bondad-Reantaso *et al*. (2001); Kanchanakhan *et al*. (2001)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Cryptosporidium-like	A total of 12 000 out of 35 000 (i.e. ~34%) 9-week-old fry (av. 35–45 mm) were lost from an Australian hatchery over a 2-week period. Loss is based on the US$ 0·12 fish^{-1} value given in Table 7	1440	Gabor *et al*. (2011)
	A low-level mortality (10–20 fish per 10 000 day^{-1}) and emaciation in 2% of the hatchery stock (30–40 mm long) prompted an investigation which found a *Cryptosporidium*-like infection in 29% of the fish that were sampled. Shortly thereafter, moderate lymphocytic and plasmacytic gastroenteritis in the fish resulted in losses rising to 1100 fish day^{-1} with a total loss of 20 000 fish. Loss is based on the US$ 0·12 fish^{-1} value provided in Table 7	2400	Gabor *et al*. (2011)
Eimeria sp.	A cumulative mortality of up to 30% was reported in 2·5–7 cm juveniles stocked in 5 nurseries (each stocked with 3000–5000 fish) in Ca Mau, Vietnam. *Eimeria* infections were seen in more than 60% of the diseased fish sampled from each site. Loss is est. on an av. 30% mortality within 20 000 fish valued at US$ 0·12 fish^{-1} (see Table 7)	720	Gibson-Kueh *et al*. (2011)
Trypanosoma sp.	High mortalities were recorded in sea cage reared stock in the Northern Territory, Australia in July, 2005. Fish were lethargic, anaemic and blind with intra-ocular haemorrhages, there were large haemorrhagic ulcers on the skin, fish had massively enlarged spleens with huge numbers of trypanosomes in the blood. No details relating to the number and size of fish lost are given; however, an image provided in the report would suggest the fish were 30–40 cm in size (est. av. 1·5 kg). It is assumed that a 'high' mortality infers ~10%, that at least four 5×5×5 m^3 cages stocked at 10 kg m^3 were affected, and, the fish were valued at the av. harvest price for Australian fish in 1995, i.e. US$ 6·69 kg^{-1}	3345	Schipp *et al*. (2007)
Caligus epidemicus	Infections on juvenile fish (100% prevalence; av. 12·7 lice fish^{-1}; range 6–35) resulted in the loss of appetite, lethargy and poor growth performance. Fish were stocked in floating net cages within earthen ponds at Dumangas, Iloilo, Philippines	–	Cruz-Lacierda *et al*. (2011)
	The prevalence of infection of stock across 6 Malaysian sites was determined to be 55·85% (i.e. 267/456 fish) with a mean intensity of 14·3 ± 23·8 lice fish^{-1}. Although *C. epidemicus* is one of many *Caligus* species found on stock, it is the most prevalent species and is reported to be a serious problem in production	–	Muhd-Faizul *et al*. (2012)
Cirolana fluviatilis	An infection on fingerlings (8–12 cm, 12–22 g) stocked in 3 cages 5 × 2×2 m^3 at a density of 2 kg m^3 (i.e. 130 fingerlings m^3) at a site in Cochin, India resulted in a 35% mortality after 2 months and 45% after 6 months (i.e. 1127 fish, Nov 2006–May 2007). Loss is est. on a value of US$ 0·5 fish^{-1}	564	Sanil *et al*. (2009)
Diplectanum latesi	The mortality of 4·5–7·0 kg broodstock held at an experimental station at Muttukkadu, India in Nov–Dec 1989(?) is attributed to heavy monogenean burdens on the gills. No details regarding the number of fish lost are provided. Loss is estimated on the mortality of 50 fish av. wt. 5 kg and the harvest price of Thai fish in 1999 (as no figures exist for India), i.e. US$ 2·69 kg^{-1}	807	Rajendran *et al*. (2000)
Neobenedenia melleni	The infection of stock in sea cages within Hinchinbrook Channel, Australia in Aug 2000 resulted in the loss of ~50 t of fish (i.e. ~200 000) worth an est. US$ 277 000	277 000	Deveney *et al*. (2001)

	Fluke numbers were observed at >400 fish^{-1}. Low seawater temps (i.e. ∼19 °C) regarded a contributory factor	–	
Pseudorhabdosynochus latesi	This monogenean is reported to occur at high intensities on stock sampled from floating cages in Penang, Malaysia	–	Leong and Wong (1986, 1988, 1990)
(o) Cyprinids			
From FAO FishStatJ the 100 000 t of 'cyprinids' cultured in Egyptian brackish waters ranks as the world's 15th largest brackish/marine finfish aquaculture industry, however, this figure results from the production of multiple species (possibly *Cyprinus carpio, Hypophthalmichthys molitrix, Ctenopharyngodon idellus*). As the precise tonnage of each species cannot be identified, they are not considered here as part of this review			
(p) Red seabream *Pagrus major* Temminck et Schlegel, 1843			
NB: In the absence of Latin binomials within the FAO FishStatJ database to identify species, finding accurate data for this species has proven difficult			
Enteromyxum leei	Low but consistent mortality due to enteromyxosis seen in cages of ∼350 g fish in Greece in 1994. The study comments that most of the fish were removed and removed during post-processing. This event occurred alongside a mortality event in 2 cages of *Puntazzo puntazzo* which resulted in the loss of 30% of stock over a 6-month period. In the absence of details, it is assumed that at least two 125 m^3 cages were affected with an equivalent 30% loss (a combination of direct mortality and subsequent carcass rejection; i.e. 1125 kg), that cages were stocked at 15 kg m^3, and, that the fish would have achieved the av. harvest price for Greek fish in 1994, however, this species is not readily identifiable from the FAO FishStatJ database and so a value of US$ 8·66 kg^{-1} is used (i.e. the av. value of red porgy at US$ 7·83 kg^{-1} and gilthead sea bream at US$ 9·49 kg^{-1})	9743	Le Breton and Marques (1995)
Henneguya pagri	Infections followed after the importation of Chinese seabass seed into Japan in the early 1990s. A chronic pattern of mortality is reported in juveniles (50–90 g). Infected fish which typically have anaemic gills, an enlarged *bulbus arteriosus* and suffer internal haemorrhages in the pericardial cavity. It is assumed that at least two 125 m^3 cages stocked at 15 kg m^3 with 50 g fish (i.e. 12 500 fish cage^{-1}) were affected each year, that the price of juveniles followed those given in Imai (2005), i.e. ¥4000–15 000 kg^{-1} live fish (=US$ 39·10–146·62) equivalent to US$ 1·96 to 7·33 fish^{-1}. Loss is based on the assumption that chronic infections resulted in 2·5% of starting stock (i.e. 625 fish across 2 cages)	1225–4581 p.a.	Yokoyama *et al*. (2005*a*, *b*)
Kudoa iwatai	Infection identified from farm specimens collected in Kinko Bay, Japan	–	Egusa and Shiomitsu (1983)
Microsporidium seriolae	Juvenile sea bream (2·5–3·5 cm) collected from off shore cages; muscle liquefaction around cysts masses; morbidity ∼20% but mortality lower than this. Loss is based on 2 cages of 125 m^3 cages stocked at 15 kg m^3 with 2 g fish (i.e. 937 500 fish cage^{-1}) that the value of each fish is 70% of that given in Imai (2005), i.e. US$ 0·003–0·01 fish^{-1}. A lower figure based on 5% mortality (i.e. loss of 46 875 fish cage^{-1}) and an upper figure of 20% morbidity is given (i.e. subsequent loss of 187 500 fish cage^{-1}). The upper and lower value of the fish for each is provided	282–938 (5% mortality) 1125–3750 (20% morbidity)	Egusa *et al*. (1988)
Unidentified scuticociliatid ciliate	Study makes reference to this parasite as being responsible for the mortality of Japanese fry and fingerlings in Hiroshima Prefecture, and also of commercial sized fish (unpublished data). Loss is based on an est. 10% mortality in both 2 g juveniles and 350 g harvest-sized fish stocked in a 125 m^3 cage stocked at 15 kg m^3, and, based on the juvenile price suggested by Imai (2005) and in the absence of a harvest price in FA FishStatJ, an av. price based on other Japanese sea breams produced and sold in 1992, i.e. US$ 9·85 kg^{-1} (i.e. blackhead sea bream, *Spondyliosoma cantharus**, at US$ 13·53 kg^{-1}; crimson sea bream, *Evynnis japonica*, at US$ 8·04 kg^{-1}; and, silver sea bream, *Diplodus argenteus* spp., at US$ 7·99 kg^{-1})	282–938 (for 2 g juveniles) 1847 (harvest size)	Yoshinaga and Nakazoe (1993)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
*Again the lack of Latin binomials in the FAO FishStatJ is a source of confusion as it is believed that this species should be black sea bream, *Acanthopagrus schlegeli*			
Anoplodiscus tai	5-year-old farm fish rejected at market. Heavily infected fish (26–64 parasites fish^{-1}; 98·5% on the fins) are emaciated with partial fin loss. Parasites induce epithelial hyperplasia and loss of epithelium at sites of attachment	–	Ogawa (1994)
Caligus sclerotinosus	A survey of sea ranched stock reared in net cages at a farm site at Tongyeong, Gyeongsangnamdo, South Korea throughout June to Nov. 2011 found severe infections (100% prev., mean intensity 7·06 lice fish^{-1}, range 2–49 lice fish^{-1}). No mortalities were reported in this study the authors make reference to winter mortalities within farms at Yeosu, Jeollanamdo but it is not clear if these can be directly attributed to *C. sclerotinosus*. This parasite was reported to have been introduced to Japan from Hong Kong in a shipment of brood stock (see Miyazaki *et al*. 1986)	–	Venmathi Maran *et al*. (2012)
Larval gnathiids	21 broodfish (0·45–1·1 kg; 2–4 yrs old) reared in concrete tanks in Italy, were killed by 3 episodes of infection. Average infection was ~30 parasites fish^{-1} with up to 146 parasites recorded on 1 fish	–	Patarnello *et al*. (1995)
(q) Korean rockfish, *Sebastes schlegelii* (Hilgendorf, 1880)			
Microcotyle sebastis	High seasonal water temperatures, high prevalences of infection (77·8–100%) and parasite burdens (0–2120 fish^{-1}) are suggested to be factors underlying the mass mortality of cultured stocks in South Korea. Estimates of loss are based on the Korean price of harvest-sized fish in 2011, i.e. US$ 7·91 kg^{-1}	7910 t^{-1}	Yoon *et al*. (1997)
	The in-feed administration of praziquantel (20 g kg^{-1} commercial feed fed to 14 g fish as 1% ration on alternate days for a total of 4 treatments) was effective in the near complete removal of gill monogeneans. Assuming that failure to treat would otherwise result in the complete loss of stock, then 800 g praziquantel would be required for four 1-day treatments (assuming 1 kg of drug costs ~ US$ 110; Xian Wango Biopharm Co. Ltd.)	88 t^{-1}treated	Kim and Cho (2000)
(r) Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum, 1792) and other species of *Oncorhynchus*			
Hexamita salmonis	18–43% mortality in 1–2 kg stock at a net-pen farm in British Columbia in Sept 1991, fish were anaemic, had enlarged kidneys, spleens and congested livers, and, swollen abdomens with serosanguinous ascites. Loss is based on the value of harvest-sized fish in Canada for 1991, i.e. US$ 3·74 kg^{-1}. Assumed cage volume is min 125 m^3 stocked at ~12·5 kg m^3, i.e. 1562·5 kg biomass	1050–2510 per infected cage	Kent *et al*. (1992)
Kudoa thyrsites	An infection rate of 4% was found within the cardiac muscle of fresh morts in Oct. 1987 at 1 of the 3 hatcheries that were sampled along the coast of British Columbia, Canada	–	Kabata and Whitaker (1989)
Loma salmonae	An infection within a stock of 337 869 hatchery fish at a hatchery in Anchorage, Alaska throughout March to mid-May 1980 resulted in the mortality of 9·95% (i.e. 33 618 fish). No details relating to the size of the fish are provided but it is est. that the fish were 2–5 g valued at US$ 0·10 fish^{-1}	3362	Hauck (1984)
Nucleospora salmonis (previously *Enterocytozoon salmonis*)	Elston *et al*. (1987) found that an intranuclear microsporidium of haematopoetic cells (47% of haemoblast nuclei were infected) was responsible for acute anaemia in 3-year-old salmon reared in net pens in Washington State, USA. Features of this infection were similar to a case plasmacytoid leukaemia in adult chinook salmon reared in seawater reported by Kent and Dawe (1990) that resulted in severe mortalities (no details provided) that occurred at several sites in British Columbia. An experimental infection by Hedrick	6615	Elston *et al*. (1987); Kent and Dawe (1990); Hedrick *et al*. (1991)

	et al. (1991) resulted in 100% mortality 53–60 days post-injection. An estimate of loss is provided for the study of Kent and Dawe (1990) which assumes that at least two $10 \times 10 \times 10\ m^3$ cages stocked at $15\ kg\ m^3$ were infected resulting in a 10% mortality, and, the value of Canadian fish in 1990, i.e. US\$ 4·41 kg^{-1}		
Sphaerothecium destruens	80% mortality of 3-year-old broodstock held in a net-pen Puget Sound, US over an 8-month period between 1983 and 1984. All fish had enlarged kidneys and spleens. Loss is based on the value of harvest-sized fish in Canada for 1984 as no figures are available for the US, i.e. US\$ 3·59 kg^{-1}. Assumed cage volume is min $125\ m^3$ stocked at $\sim 12{\cdot}5\ kg\ m^3$, i.e. 1562·5 kg biomass	4490	Harrell *et al*. (1986)
Gilquinia squali	Trypanorhynch metacestodes within the vitreous humor (1–2 parasites eye^{-1}) resulted in blindness and a 10% mortality in a single net-pen. Loss is based on the value of harvest-sized fish in Canada for 1988, i.e. US\$ 5·40 kg^{-1}. Assumed cage volume is min $125\ m^3$ stocked at $\sim 12{\cdot}5\ kg\ m^3$, i.e. 1562·5 kg biomass	845	Kent *et al*. (1991)
Chum salmon, *Oncorhynchus keta* (Walbaum, 1792)[c]			
Ichthyobodo necator	Parasite survives transfer to seawater (33‰), can cause severe epidermal destruction, drastically reduced tolerance to seawater and juvenile mortality (60–70%, 4–6 weeks after transfer).	–	Urawa and Kusakari (1990); Urawa (1995)
	Experimental trial demonstrates that infected fry ($n = 1000$; av. wt. 0·75 g) can be transferred from freshwater into 33 ppt seawater and that the flagellates survive and can reproduce. A total of 17 426 flagellates were found on 10 fry 1 week post-transfer. After two 2 weeks, the fish began to die and final mortality exceeded 40%. In March and April 1986, approx. 30 million hatchery reared fry were released into the Chitose River, Hokkaido, Japan. The prevalence of infection was 34% in the hatchery but following formalin treatments was reduced to 2%. The prevalence of infection on fry in the river in April and May was found to be 20 and 34% respectively, whilst samples taken from the mouth of the Ishikari River were determined to be 32 and 27% in the same months. Loss estimates are based on an av. infection of 28·25% on the fry released into the river, the assumption that 40% of these infected fish will die (i.e. 3 390 000 fry), and, the individual est. value of released fry in 1990, i.e. US\$ 0·002 $fish^{-1}$. An upper estimate is also provided based on the assumption that all infected fish die, i.e. 8 475 000 fry	67 800–169 500	Urawa and Kusakari (1990)
	Trial demonstrates that 60–70% of infected fish transferred to seawater die within 4–6 weeks. Treatment with 250 ppm formalin (1 h) is effective in reducing mortalities. Without treatment ~30% of transferred fry die. Following treatment, a total of 9 million hatchery fish were subsequently released 4 weeks post-treatment. Loss is based on the assumption, that in the preceding year, the Yoichi River Hatchery in western Hokkaido, lost 30% of fish (i.e. ~ 3 850 000 fry), and, the the individual est. value of released fry in 1987–1988, i.e. US\$ 0·002 $fish^{-1}$	77 000	Urawa (1993, 1995)
Pink/humpback salmon, *Oncorhynchus gorbuscha* (Walbaum, 1792)[c]			
Kudoa thyrsites	An infection rate of 1% was found in the cardiac muscle of fresh morts in Sept 1987 at a single hatchery situated on the coast of British Columbia, Canada	–	Kabata and Whitaker (1989)

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Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
(s) Large yellow croaker, *Larimichthys crocea* (Richardson, 1846)			
Cryptocaryon irritans	Study infers that infections are a problem in culture but does not provide specific details	–	Lin *et al*. (2013)
(t) Red drum, *Sciaenops ocellatus* L.			
Enteromyxum leei	Stock (23–117 g) held in an Israeli culture facility are shown to be susceptible to infection by co-habitation with infected *S. aurata* (45·8%) or by exposure to effluent water from the tanks holding infected stock (35·0%)	–	Diamant (1998*a*)
(u) Tiger pufferfish, *Takifugu rubripes* (Temminck et Schlegel, 1850)			
Enteromyxum fugu (syn. *Myxidium fugu*) + *Leptotheca fugu*	Infections in the intestine which result in emaciation disease have been reported since 1996 resulting in mortalities, typically of 1-year-old stock, between May/June through to Aug/Sept).The resultant mortality is variable (prev. <20 to >60% at different farm sites). A 10% mortality in a single 125 m^3 cage stocked at 2·5 kg m^3 is assumed, and, the harvest price of Japanese fish between 1996 to 2002 (the latter date being that of the report), i.e. US$ 22·00 (virtually constant throughout this period), is used to estimate loss	688 per cage	Tun *et al*. (2000, 2002); Ogawa and Yokoyama (2001)
Enteromyxum leei	Reported to be highly pathogenic and one of the causative agents of emaciation disease	–	Yanagida *et al*. (2005)
Ichthyobodo sp.	Infections were said to frequently occur in spring in net reared stock (av. 226–463 g) along the western coast of Okayama Prefecture, Japan	–	Urawa *et al*. (1998*b*)
Kudoa shiomitsui	Infection first described from the pericardial cavity of farm reared fish (135–360 g) collected from Kagoshima prefecture, Japan		Egusa and Shiomitsu (1983)
Leptotheca fugu hyperparasitised with a microsporean	The host inflammatory response in individuals infected with hyperparasitized *L. fugu* is reported to be more severe than with infection of *L. fugu* alone	–	Tun *et al*. (2002)
Heterobothrium okamotoi	Infections in the gills and wall of the branchial cavity lead to anaemia. This parasite was believed to be the cause of major mortalities seen in Japanese farms throughout the 1950s–1960s. No details of loss are provided but it is assumed that major mortality events allude to the loss of >20% stock	–	Okamoto (1963)
	Losses due to heavy infections are reported to be rising with expansion of the industry. Infection was first noted 5 months after the fish were transferred (i.e. in Nov). No details relating to the magnitude of loss are provided but losses of 10% in 125 m^3 cages stocked at 2·5 kg m^3, with a harvest price of US$ 22·00 (1996–2002), are assumed	688 per cage	Ogawa and Inouye (1997); Ogawa *et al*. (2005*b*)
	Parasites produce eggs in strings that can exceed 2 m in length. These become caught in the net mesh, accumulating and representing a source of infection. Regular net changes are required as part of parasite management	–	Ogawa and Yokoyama (1998)
	Recurrent problems seen in early 2000s in floating net-pens	–	Ogawa (2002)
Bullseye pufferfish, *Sphoeroides annulatus* (Jenyns, 1842)			
Amyloodinium ocellatum	Severe infections can result in the sig. mortality of cultured stocks – no losses are provided but a 5% mortality, in a 125 m^3 cage stocked at 2·5 kg m^3, and a harvest	78 per cage	Fajer-Ávila *et al*. (2003)

	price of US$ 5·00 kg^{-1} (see García-Ortega *et al*. 2002) for Mexican fish in 2002 is applied		
Heterobothrium ecuadori	Heavy infections can result in the significant loss of stocks – no details provided	–	Fajer-Ávila *et al*. (2003)
Lepeophtheirus simplex + *Neobenedenia* sp.	Report that dual infections can cause skin lesions, anorexia and mortality of juvenile stock. No details are provided	–	Fajer-Ávila *et al*. (2008)
(v) Porgies, sea breams			
Black porgy, *Acanthopagrus schlegelii* (Houttuyn, 1782)			
Alella macrotrachelus	Infections on farm stock at a site at Tashima, Japan were followed over Aug. 1978 to Aug. 1980; fish typically reach 100–150 g in 12 months. Infections reached 100% within 3–4 months with up to 15 females fish^{-1} resulting in hyperplasia, oedema and haemorrhages of the gill lamallae. These copepods posed the greatest threat in the first winter when the fish were of a smaller size but infections were at their peak. The study does not allude to the loss of stock	–	Muroga *et al*. (1981)
Caligus acanthopagri	Fish reared in ponds at Chi-Ku village Tainan County, Taiwan in March 1983 had an abnormal feeding condition, were emaciated and black in appearance. Daily mortality of 5–10 fish day^{-1}. A total of 713 adult lice were removed from the body surface of 3 moribund hosts. No details relating to the total loss of stock are provided. Loss is estimated on the assumption that the mortality event lasted at least 14 days, occurred in 3 ponds, fish had an av. wt. of 250 g, and, the price of Taiwanese harvest-sized stock was US $ 6·00 kg^{-1} (no figures available for 1983; first figures available are for 1989 when the price was US$ 7·27 kg^{-1})	473	Lin *et al*. (1994)
Caligus multispinosus	There was a rising daily mortality of 10–30 fish in pond held stock at Pei-Men Village Tainan County, Taiwan in Nov. 1992. A total of 22 adult lice and many juveniles were removed from the gills and buccal cavity of 4 moribund hosts. Loss is estimated on the assumption that the mortality event lasted at least 14 days, occurred in 3 ponds, fish had an av. wt. of 250 g, and, the price of harvest-sized fish in Taiwan was US$ 7·95 kg^{-1}	1670	Lin *et al*. (1994)
Sharp-snout sea bream, *Diplodus puntazzo* (Walbaum, 1792)			
Amyloodinium ocellatum	100% mortality (i.e. 50 000) 12 g juveniles lost over 48 h in a sea cage in Greece in the summer of 1997 when sea water temperatures were 23 to 26 °C. Loss is based on the unchanged value of stock, i.e. US$ 0·02 fish^{-1} (see Table 7)	1000	Rigos *et al*. (1998)
Ceratomyxa diplodae	A survey of 109 fish (49–650 g) conducted between Dec 2000 and Jan 2002 found infections with a prevalence of 51% in the gall bladder and 2% in the intestines	–	Merella *et al*. (2005)
	A tank of 32 fish (av. wt. 206 g) began dying 35 days after a treatment with 17b-estradiol for sex inversion. All fish were lost within 90 days. Loss is based on the price of harvest-sized fish in 2011, the first figures available, i.e. US$ 8·16 kg^{-1}	54	Katharios *et al*. (2007)
Ceratomyxa sparusaurati	Low levels of loss, i.e. 0·1% d^{-1}, observed in Greece.	–	Rigos *et al*. (1999)
	An infection rate of 30% was found at a single cage site within the Adriatic	–	Mladineo (2003)
Cryptocaryon irritans	100% of stock (n = 59; 324–410 g) at one culture facility on the Spanish Mediterranean coast died within 15 days of the first observed mortalities. Loss is based on an av. size of 350 g fish^{-1} and the av. price of Mediterranean sharp-snout sea bream in 2000,	188	Montero *et al*. (2007)

Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	i.e. US$ 9·12 kg^{-1} (harvest price for Cyprus was US$ 4·83 kg^{-1}; price in Italy was US$ 13·41 kg^{-1})		
Enteromyxum leei	In July 1994, mortalities of 30–50 fish day^{-1} from 2 cages of 15 000 (30–60 g) fish in western Greece. After 6 months 35+% of stock lost with chronic losses of 20–30 fish $week^{-1}$. Fish were emaciated with swollen abdomens, pale livers with high numbers of spores in the bile; 90% of the fish were found to be carriers of infection. Loss is estimated on the value of 150 g fish, i.e. US$ 1·50 $fish^{-1}$	15 750	Le Breton and Marques (1995)
	Approx. 80% loss of stock reported from 8 farm sites in central and southern Greece during the summer of 1997 when sea temperatures exceeded 22 °C. Fish lost were at the fattening stage and an av. fish wt. of ~400 g is assumed. Loss is estimated on the assumption that each farm produced min. 10 t, and, on the harvest price of Italian fish in 1997, i.e. US$ 8·23 kg^{-1}, as no figures for Greek fish/production are available	526 720	Athanassopoulou *et al*. (1999)
	9% loss of stock observed over numerous Greek cage sites covering several geographical regions during the period Sept 1996–Sept 1997 when summer seawater temperatures rose to 24–25 °C. Losses at some sites were 1–5% day^{-1} with a chronic pattern of mortality over 3–6 weeks. Loss of 30–70% of stock at certain sites. Loss is based on the assumption that at least 5 sites were affected, production at each was a minimum of 10 t, and on the harvest price of Italian fish in 1997, i.e. US$ 8·23 kg^{-1}, as no figures for Greek fish/production are available	~37 000	Rigos *et al*. (1999)
	A total of 13 000 juveniles (av. 25 g) were stocked in to a single 250 m^3 cage in the Gulf of Sardinia in July 2000. A monogenean infection in the winter of 2001 reduced the stock by ~1450. In Aug –Nov 2001, a second major mortality event due to *E. leei* resulted in daily mortalities of 0·26–0·38% and a final loss of 32% of stock (i.e. ~1800 fish). Parts of the stock were sold in Aug reducing the stock to 50%. Total losses following both events were 25% (i.e. ~3250/13 000). A subsequent survey conducted Dec 2000 to Jan 2002 looked at a total of 109 fish. *Enteromyxum* was found with a prevalence of 33% in the gall bladder and 41% in the intestines. Loss is based on the assumption that the av. wt of each fish at the time of the event was ~250 g and the price of harvest-sized fish in Italy in 2001, i.e. US$ 5·13 kg^{-1}	2309	Merella *et al*. (2005)
	Reference is made to the severe mortalities of Mediterranean stocks that devastated production. A total of 464 t (i.e. Cyprus 64 t, Italy 400 t) were produced in 2001, this fell to 401 t in 2003 (i.e. Cyprus 1 t, Italy 400 t), and then no tonnage recorded for the period 2004 to 2006. If the decline in production is attributed to this one pathogen, then loss can be estimated using the harvest price of Italian fish in 2003, i.e. US$ 6·56 kg^{-1}	413 280 (in 2003) 2·63 M (in 2004)	Mladineo (2006)
Polysporoplasma sparis	An infection of 20% was found at a single cage site within the Adriatic	–	Mladineo (2003)
Atrispinum salpae	A total of 13 000 juveniles (av. 25 g) were stocked into a single 250 m^3 cage in the Gulf of Sardinia in July 2000. In Jan–Feb 2001, high prevalence and intensity of parasites resulted in daily mortalities of 0·19–0·22% and a final cumulative mortality of 11·4% (i.e. ~1450 fish). A subsequent survey conducted Dec 2000 to Jan 2002	930	Merella *et al*. (2005)

	looked at a total of 109 fish. *Atrispinum salpae* was found on the gills with a prevalence of 93% (range 1–1370 flukes $fish^{-1}$). Loss is based on the assumption that the av. wt of each fish at the time of the event was ∼125 g and the price of harvest-sized fish in Italy in 2001, i.e. US\$ 5·13 kg^{-1}		
Lamellodiscus sp.	43% of stock at 8 farm sites (50+g fish) infected	–	Athanassopoulou *et al*. (1999)
Lamellodiscus bidens + *L. ergensi*	Five wild fish caught off Crete were examined to determine the pathology associated with infections. The prevalence of infection was 100% with each gill arch having an av. 100·2 ± 40·1 flukes (40% *L. bidens*; 60% *L. ergensi*). These burdens resulted in hyperplasia and a proliferation of the gill epithelium notably at the base of the secondary lamellae where there are chloride cells. There was also fusion and destruction of the secondary lamellae. Although no losses were recorded, the study alludes to the risks of infections under intensive aquaculture conditions, which include potential economic loss as a result of reduced growth and/or loss of fish as a consequence of respiratory distress	–	Katharios *et al*. (2006)
Microcotyle sp.	70% of stock at 8 farm sites (50+ g fish) infected	–	Athanassopoulou *et al*. (1999)
White sea bream, *Diplodus sargus* L.			
General parasitic infection	Three Greek farm sites reported total mortalities of 12, 32 and 42%. Nephrocalcinosis infection seen in all sampled fish but mortalities attributed to *Kudoa* and *Myxobolus* infections. Samples taken Oct 2002–Oct 2003 had the following:	638–2234 t^{-1}	Golomazou *et al*. (2006)
	Enteromyxum leei 8·0 ± 12·8 (0–40); prevalence of infection (range)		
	Kudoa sp. 8·0 ± 16·6 (0–60)		
	Myxobolus 33·1 ± 33·6 (0–90)		
	Furnestinia sp. 63·6 ± 30·1 (0–80)		
	Microcotyle sp. 8·4 ± 14·4 (0–40)		
	Loss estimates are based on the value of harvest-sized fish in 2003, i.e. US\$ 5·32 kg^{-1}		
Blackspot sea bream, *Pagellus bogaraveo* (Brünnich, 1768)			
Ceratomyxa sparusaurati	An infection rate of between 6·66 and 33% was found at a single-cage site within the Adriatic	–	Mladineo (2003)
(w) Atlantic bluefin tuna, *Thunnus thynnus* L.			
Anisakis simplex	21·86% of the 183 tuna (5–12 kg) that were sampled from 3 Adriatic sites throughout 2003–2006 bore infections with a mean abundance of 3·05 nematodes $fish^{-1}$. Although the worms were not responsible for mortalities, the presence of these zoonotic nematodes raises public health concerns for those consuming fresh products	–	Mladineo *et al*. (2008)
Cardicola forsteri	A sample of 52 harvest-sized fish reared off the Island of Braè in the Adriatic revealed that the eggs of this sanguinicolid caused granulomas and a marked inflammatory response, primarily in the kidney, and to a lesser extent in the heart and gills, of 63·34% of those examined	–	Mladineo and Tudor (2004)
	A total of 62 fish from a site off Brač Island, Croatia were sampled in Jan 2003 and during a mortality event in July 2003. Eggs were found with a prevalence of 63·34% in the gill, heart and kidney. The study comments that there was inflammation associated with infection. No details relating to the mortality event were provided	–	Mladineo (2006)

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Table 8. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Didymocystis wedli	The gills of 73·68% (i.e. 38/52) harvest-sized fish that were sampled and held off the Island of Braè in the Adriatic were infected with an av. 13·26 encysted adults fish^{-1}. It was suggested that heavy burdens reduce respiratory function imposing an additional stress upon fish	–	Mladineo and Tudor (2004)
	A total of 183 tuna (5–12 kg) from 3 Adriatic sites were sampled throughout the winter of 2003 to the summer of 2006. Infections were found at a prevalence of 61·75% and an abundance of 28·91 flukes fish^{-1}. The presence of these didymozoid digeneans was reported to elicit a marked host reaction but were not attributed to mortality events	–	Mladineo *et al*. (2008)
Euryphorus brachypterus	Heavy infections have been reported on the pseudobranchs of wild fish result in bleeding and ulceration. Lesions were also reported on the skin and gills of wild fish. Infections may pose a threat to captive ranched stock	–	Williams and Bunkley-Williams (1996)
Hepatoxylon trichiuri	Sixty-two fish from a farm off Brač Island, Croatia were sampled on 2 occasions, i.e. Jan 2003 and during a mortality event in July 2003. Plerocercoids were attributed as the cause of haemorrhages within the mucosa and stomach. This cestode was found in 12·4% of tuna post-mortemed with a mean abundance of 0·12 cestodes fish^{-1}	–	Mladineo (2006)
Koellikerioides intestinalis	An infection was determined in 54·64% with an abundance 10·96 digeneans fish^{-1} in the 183 tuna (5–12 kg) that were sampled from 3 Adriatic sites throughout 2003–2006. There was a marked host inflammatory response at the site of parasite attachment. These parasites were not, however, attributed to observed mortalities throughout the study	–	Mladineo *et al*. (2008)
Oncophora melanocephala	Stock (n = 62) from a farm off Brač Island, Croatia were sampled in Jan 2003 and during a mortality event in July 2003. Adult nematodes were prevalent in 57·89% of hosts with a mean abundance of 1·74 worms fish^{-1}. Haemorrhaging was associated with nematode infection in the pyloric caeca and mucosa. The study concludes that this parasite poses a potential threat to the host	–	Mladineo (2006)
(x) Cobia, *Rachycentron canadum* (Lamarck, 1766)			
Protista gen. spp.	*Amyloodinium ocellatum*, *Coccidia* spp., *Ceratomyxa*, *Cryptocaryon irritans*, *Epistylis* spp., *Kudoa* spp., *Myxidium* spp. and *Trichodina* spp. are all identified as potential pathogens to cobia culture	–	McLean *et al*. (2008); FAO (2014*c*)
Brooklynella hostilis	Is reported to have caused a Caribbean-wide mass mortality of wild stocks in 1980 but in Oct 2002, a consignment of 30 000 fingerlings (6·0–8·4 cm total length) being sent from a facility in Florida to Puerto Rico died as a consequence of heavy infections. Loss is based on the estimated value of juvenile fish, i.e. US$ 2·00 (see Table 7)	60 000	Bunkley–Williams and Williams (2006)
Cryptocaryon irritans	A shipment of juveniles (n = 15; 8·4–11·2 cm) sent from Florida were stocked in a marine cage culture facility in Puerto Rico before quarantine checks were complete. A moderate infection on the gills resulted. It is suggested that the infection did not result in the loss of stock	–	Bunkley–Williams and Williams (2006)

Ichthyobodo sp.	In June 2003, a shipment of 7 juveniles (3·5–5·2 cm total length) received from a culture facility in Florida were added to cage stock in Puerto Rico before quarantine checks were complete. Some fish died during transit. A moderate infection on the skin and gills of cage stock was subsequently found. No further loss of stock was suggested	–	Bunkley–Williams and Williams (2006)
Sphaerospora-like myxozoan	90% mortality (i.e. loss of 49 500 fish) of 45–80 g juveniles beginning 1 month post-transfer to sea cages in Taiwan. Loss occurred over a 30-day period in 1999. Fish were anaemic, had grossly enlarged kidneys and had ascites; extrasporogonic and sporogonic stages were found in the blood, glomerulus, renal tubules and renal interstitium. Loss is calculated on the value of harvest-sized fish in Taiwan in 1999, i.e. US$ 5·04 kg^{-1} and an av. fish weight of 60 g	14 969	Chen *et al*. (2001)
	Sporogonic stages were found in the lumen of renal tubules but infections were low and there was no obvious kidney damage	–	Lopez *et al*. (2002)
Caligus lalandei	Stocks reared in marine cages in the Pingtung area of Taiwan are reported as susceptible to the occasional infection	–	Chang and Wang (2000)
Neobenedenia melleni[b] (syn. *girellae*)	Oct 2000 and Feb 2001 juvenile stock reared in sea cages off the Penghu islands of Taiwan are reported to have severe ulceration of the cranium as a result of monogenean infection (av. 15–20 flukes $fish^{-1}$) resulting in a 40% mortality of stock. No farm production details or size of the fish lost are provided. Loss is estimated on the assumption that av. wt. of fish were 100 g, that at least three 500 m^3 cages on at least 2 production sites were affected, fish were stocked at 20 kg m^3, and, that value of each fish was US$ 3·00 (see Table 7)	1·8 M	Lopez *et al*. (2002)
	A mass mortality of stock on Liu-chiu Hsu Island, Taiwan occurred over the period Oct 2002–Jan 2003. Freshwater baths were given at 1 week intervals to control infections. Subsequent sampling of the 0+ stock (12–37 cm long) in March 2003 found an av. 12·6 parasites $fish^{-1}$ (range 1–33) localized principally on the dorsal surface of the cranium (59·7%) and on the eyes (23·7%). No details relating to the mass mortality are provided but loss is estimated on the mortality of 10% of stock, an av. fish wt. of 100 g, that at least three 500 m^3 cages were affected, fish were stocked at 20 kg m^3, and, that value of each fish was US$ 3·00	0·9 M	Ogawa *et al*. (2006)
Parapetalus occidentalis	In 2000, infections are reported in the gill cavities of stock being reared in offshore cage-nets around Penghu Islands, Taiwan. The study reports that 17 females were collected from cage stock to augment existing material for a taxonomy-based study but provides no indication of overall infection levels	–	Ho and Lin (2001)
(y) Meagre, *Argyrosomus regius* (Asso, 1801)			
Amyloodinium ocellatum	An infection in stock (av. 423 ± 110·5 g) held in 2500 m^3 earthen ponds at 0·75 kg m^3 with an equal weight of gilthead sea bream resulted in 1·2% mortality (i.e. 11·25 kg $pond^{-1}$). Loss is estimated on the assumption that a minimum of 2 ponds were affected and on the market price of Portuguese fish in 2011, i.e. US$ 8·90 kg^{-1}	200	Soares *et al*. (2012)
Benedenia sciaenae	In the first season of commercial Turkish production, farmers at Akbük, western Turkey in April 2005 reported scale loss and skin damage on stock (av. 5·63 ± 0·89 kg). A total of 9088 parasites were recovered from 40 fish (mean intensity 227 ± 77·5; range 84–386 flukes $fish^{-1}$). No production figures (tonnage or value) are listed for Turkey in FAO FishStatJ, but figures for France (i.e. US$ 8·72 kg^{-1}), Italy (i.e. US$ 8·41 kg^{-1}) and for Portugal (i.e. US$ 12·78 kg^{-1}) for 2005 are available. Production in the first year is assumed to be 5 t, that infections resulted in a 20% downgrading in price, and, that the price of harvest-sized were similar to those sold in Italy	8410	Toksen *et al*. (2007)

Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
Sciaenocotyle panceri	Two batches of meagre (av. wt. 8·3 g) were stocked in adjacent 4000 m^3 floating cages (93 442 fish stocked Aug 2005; 45 000 fish stocked July 2006) at 30 m depth off north-east Sardinia. In May 2007, both stocks were combined (av. wt. 750 and 200 g). In Sept 2007, the fish were lethargic, emaciated and anaemic, mortalities began thereafter. Prevalence of infection was 100% in both age classes, the older stock had a mean intensity of 367 flukes $fish^{-1}$ and the younger stock 200 flukes $fish^{-1}$. Mortality in the older stock was 5–10% (i.e. loss of 4670–9340 fish; 3·5–7·0 t lost) and <2% in the younger stock (i.e. <500 fish; 100 kg). Loss is estimated on the value of Italian fish in 2005, i.e. US$ 8·41 kg^{-1}	29 435–58 870 (older year class) 841 (younger year class)	Merella *et al*. (2009)
	A Corsican multi-year class farm in the Gulf of Ajaccio consisting of 8 cages of meagre and 12 of sea bass reported heavy mortalities in Aug 2005 as a consequence of heavy burdens of gill monogeneans. The prevalence of infection on a sample ($n = 47$) of <300 g (6 months old) fish was 95·7% (mean abundance 58·7 ± 30·5 flukes $fish^{-1}$; mean intensity 61·3 ± 28·4 flukes $fish^{-1}$). Although heavy mortalities are reported, no details were provided. It is assumed that each cage measured 125 m^3, stocked at a min. 15 kg m^3 and that total mortality across all 8 cages was 50%. Loss is estimated on the price of French harvest-sized fish in 2005, i.e. US$ 8·72 kg^{-1}	65 400	Ternengo and Katharios (2008); Ternengo *et al*. (2010)
(z) Atlantic cod, *Gadus morhua* L.			
Loma morhua	From a sample of 41 (40–52 cm long) cod acquired from a sea ranching facility in Newfoundland in July 1987, 78% had macroscopic xenomas on the gills. Of these, 26 (i.e. 63%) died in Sept 1987 when sea temperatures rose from 11 to 16 °C. Fish had been lethargic, were emaciated and at necropsy all 41 fish had pale gills and a massive infection of xenomas within the gills, heart, spleen and, occasionally, the inner body wall	–	Khan (2005)
	Following the loss of Newfoundland hatchery reared stock (av. 23 cm long; 2 years old) in Sept 2000, the post-mortem examination of 14 specimens revealed that 29% had macroscopic xenomas in the heart; all had microscopic xenomas on the gills and in their hearts. Further losses in Nov 2003, revealed that 21% (i.e. $n = 5$) of the specimens that were post-mortemed had gill and heart xenomas	–	Khan (2005)
	Major outbreaks reported at numerous aquaculture sites including land-based systems	"100s of 1000s"	O'Neill *et al*. (2011)
	Throughout Newfoundland, New Brunswick and New Hampshire. No details provided	–	
Pseudobranchial X-cell	Of a total of 1 795 000 wild cod juveniles (∼ 2 g) caught in Isafjardardup fjord, NW Iceland (2002–2004), reared in land-based tanks to ∼80–100 g in size, <1% of these fish had pseudotumours; however, a prevalence of 2–15% was found in emaciated/moribund fish. Levels in wild-caught juveniles caught in 1998–2000, by comparison, were higher with 7% of 6 months old (6·5–13 cm long), 23% of 22 months old (18·5–27 cm long) and 7% in 2+ year-old fish having pseudotumours	–	Eydal *et al*. (2010)
Trichodina cooperi + *T. murmanica*	Infections on wild fish, caught off Isafjordur, West Iceland and then grown on in shore-based tanks, were monitored over a 9-month period. Two cohorts of fish (∼ 5 cm) were transferred in Sept of 2002 and 2003. Infections were low on each fish at the time of transfer. The prevalence of *T. cooperi* reached near 100% on both cohorts within 2 months (60% of the fish had mild infections, i.e. 1–10 parasites in a skin scrape measuring 1·5 cm^2;	–	Kristmundsson *et al*. (2006)

	25% medium, i.e. 11–50 parasites; and, 15% heavy, i.e. > 50 parasites). After approx. 4 months post-transfer although, i.e. Jan/Feb, the numbers of *T. cooperi* began to reduce but the number of *T. murmanica* was observed to increase towards a peak prevalence of 95–100% with similar parasite burdens to those recorded for *T. cooperi* in Nov/Dec The heaviest parasite burdens of *T. murmanica*, however, were observed in just one cohort in April when <5% of fish had no infection, over 35% had mild infections, 20% had medium infections, and, 40% had heavy infections. Mortalities were recorded but it is difficult to say whether these were due to parasite infections, stress following post-transfer or the subsequent cannibalistic tendencies of the stock		
Trichodina murmanica	A sharp rise in temperature from 6–8 °C to 15–16 °C as a result of defective cooling unit in a cod hatchery in Newfoundland, Canada in Aug 2002 was the stressor linked to the subsequent mortality of >100 000 juvenile cod (av. 4·3 cm body length) over a 4-week period. Each fish was determined to have an av. 62 parasites mm^{-2}. Loss is estimated on the value of each fish, i.e. US$ 0·50	50 000	Khan (2004)
Trypanosoma murmanensis	By experimental transmission, it is demonstrated that infection can result in the mortality of 65% of 0 +, 19% of 1 +, 11% of 2 + and 7% of 3 + aged fish with most deaths occurring between 22 and 38 days post-infection	–	Khan (1985)
Lernaeocera branchialis	482 cod (32–76 cm TL) died within 5 days of their transfer from traps to sea cages in Newfoundland in July 1988. 44% of the mortalities were infected with *L. branchialis*. Assessment of the remaining 1500 cod, 1 month later revealed that 8·5% were infected. Loss is estimated using an av. weight of 1 kg $fish^{-1}$ and the harvest price of Canadian cod in 1988, i.e. US$ 7·17 kg^{-1}	3456	Khan *et al*. (1990)
(aa) Lefteye flounders, *Psettina breviritcis* (Alcock, 1890)			
No records of parasitic infection resulting in the major loss of farmed stocks of this species could be found. There are some concerns surrounding the identity of this species from its common name as listed in the FAO FishStatJ database. It is also possible that Chinese left eye flounder refers to *Paralichthys olivaceus*, which is also known as the bastard halibut, the olive flounder or the Japanese flounder and not *Psettina breviritcis* as it is listed here			
(ab) Southern bluefin tuna, *Thunnus maccoyii* (Castelnau, 1872)			
Uronema nigricans	Infection, seen as parasitic encephalitis, resulted in the loss of between 5 and 10% of the wild-caught fish (∼ 15–35 kg) that were fattened on in sea cages for a period of 3–8 months before harvesting. The annual harvest in 1993 was 636 t, assuming that the figures quoted were representative of the entire industry, then this represents a loss of between 31·8 and 63·6 t. Loss estimates are based on the value of harvested fish in Australia in 1993, i.e. US$ 16·32 kg^{-1}	518 976–1 037 952	Munday *et al*. (1997)
	Prior to 1993, the mortality and morbidity rates were suggested to be 5% in captive fish. These were reported to have fallen to 1·34% in 1995 and were <1% in 2001	–	Munday *et al*. (2003)
	During the 2003 season, total loss was 4%, i.e. 94·9 t valued at US$ 22 450 t^{-1}	2·13 M	Deveney *et al*. (2005)
	Infection was found with a prevalence of 58% in 31 morts and in 2 fish displaying signs of 'swimmer syndrome'. Fish, weighing 25–50 kg, were from a commercial grow-out facility in Spencer Gulf, east of Port Lincoln, South Australia. Loss (0·5–1 t) is based on the value of Australian stock in 2005, i.e. US$ 22·45 kg^{-1}	11 225–22 450	Deveney *et al*. (2005)
Caligus chiastos	In May 2005, 4–6 weeks after transfer to cages in Spencer Gulf, Australia, 55% of the ranched stock had an av. 5·77 lice per infected fish. Lice activity over the head and eyes and subsequent net collisions as a consequence of irritation-induced flashing resulted in observable eye pathology on 32·5% of stock (av. eye scores were 3·5, i.e. extremely cloudy	–	Hayward *et al*. (2008, 2009)

Table 8. (*Cont*.)

Parasite	Impact	Estimated loss (US$)	Reference
	to erosion of the cornea. Authors estimate the value of each fish at US$ 500. Consequential losses unknown but are suggested to be significant		
Caligus chiastos and *Cardicola forsteri*	Tuna (av. 22·5 kg) ranched in the Great Australian Bight looked at the relationship of both parasite species on tuna health for 12 weeks after transfer into and between cages. The *Caligus* infection was 100%, peaking at 265·8 lice fish^{-1} about 4 weeks post-transfer. Lice numbers were positively correlated with gross eye pathology scores and negatively correlated with condition factor. *Cardicola* infections, which were correlated with lice burdens, reached 100% (highest av. burden 268·3 flukes fish^{-1}) within 4–6 weeks post-transfer, with epizootics peaking near the start of mortalities ~7 weeks after ranching. The cumulative mortality in the 2 cages were ~40% (n = 474 fish) and 47% (n = 89 fish). Loss in the 2 cages (i.e. 232 fish) is based on the harvest price of Australian stock in 2008, i.e. US$ 16·37 kg^{-1}	1·4 M	Hayward *et al*. (2010)
Caligus elongatus	Suggested that grazing activity of the parasite on captive reared stock may result in ocular damage	–	Rough *et al*. (1999); Munday *et al*. (2003)
Cardicola forsteri	The hearts of 84 ranched tuna (size of host and number infected not specified) farmed in sea cages were found to be off Port Lincoln, Australia, were found to be infected with an estimated 19 000 to 1·7 M eggs per heart. Infection resulted in hypertrophy of the ventricle spongiosa. Eggs were also found within the afferent filamentary arteries and lamellae vasculature. The study concluded that infections do not appear to cause mortality	–	Colquitt *et al*. (2001)
	A further study of 210 tuna (19·9–31·7 kg) from net pens around Port Lincoln, Australia found that infections peaked 2 months after transfer (May 2004) with a prevalence of 100% and an av. 27 flukes fish^{-1} (range 0–99). Infections declined thereafter suggesting that fish are able to control parasite numbers	–	Aiken *et al*. (2006)
(ac) Mozambique tilapia, *Oreochromis mossambicus* (Peters, 1852) and Nile tilapia, *Oreochromis niloticus* L.			
Amyloodinium ocellatum	An infection in Salton Sea, a 980 km^2 hypersaline (i.e. 46 ppt) water body in California, USA throughout May 1997 to Nov 1998 resulted in the mass mortality of juvenile *O. niloticus* (1·0–13·0 cm length). Infection reached 100% in June/July of each year as water temperatures approached 40 °C. Massive numbers of heavily infected dead fish were noted in shallow waters. The tilapia in Salton Sea are exotic, details relating to the nature and purpose of their introduction are unknown and although this event is not linked to identifiable aquaculture activities, given the global significance of tilapia culture, this event is worth reporting. Loss is estimated on the volume of Salton Sea (9 300 000 dam^3), a tilapia biomass of 11 kg h^{-1} reported in 2000 (Riedel *et al*. 2002), a moderate (20%) and high (50%) level of mortality, and, the value of harvest-sized American stock in 2000, i.e. US$ 3·31 kg^{-1}	6·77 M (20% mortality) 16·93 M (50% mortality)	Kuperman and Matey (1999)
Caligus epidemicus	Nile tilapia stock held in ponds in Iloilo (av. 8·6 cm, av. 15·0 g) and in Quezon (av.	–	Natividad *et al*. (1986)

	11·4 cm, av. 29·1 g), Philippines were found to be heavily infected (prev. 100%, av. 111·7 copepods fish^{-1}, range 7–548 on Iloilo stock; prev. 92%, av. 34·3 copepods fish^{-1}, range 1–138 on Quezon stock)		
	Infected Mozambique tilapia stock reared in saltwater ponds in Taiwan resulted in mortalities. No details regarding the specific loss of fish are provided	–	Lin and Ho (1993)
Neobenedenia melleni[b] (syn. *girellae*)	Mozambique tilapia stock (~ 18 cm TL) held in 1 m^3 floating sea cages in Kaneohe Bay Hawaii (1981–1984) were infected with, in certain cases, >400 flukes fish^{-1} over the entire body surface and eyes resulting in multi-focal petechial haemorrhages, scale and skin damage, buphthalmos, corneal, ulceration scarring and blindness. Exact losses not specified but infection was sufficiently severe that the patterns of mortality and morbidity impeded preliminary breeding cycles. In estimating loss, it is assumed that a 50% mortality occurred in at least 4 cages, stocked at 15 kg m^3, and the harvest price of American tilapia in 1985 (first figures available), i.e. US$ 14·00 kg^{-1}	420	Kaneko *et al*. (1988)
(ad) Mangrove red snapper, *Lutjanus argentimaculatus* (Forsskål, 1775)			
Amyloodinium ocellatum	An infection resulted in 2-month old hatchery stock (av. wt. 0·12 g; 19 mm long) reared in seven 5 t cement tanks in Iloilo, the Philippines in June 2003. Final mortality was 100%, infected fish had an av. 80–100 trophonts on their skin and fins and 40–50 trophonts on their gills. Loss is estimated on a stocking density of 10 kg m^{-3} and a value of US$ 0·01 fish^{-1}, i.e. the loss of 2·9 million fry	29 000	Cruz-Lacierda *et al*. (2004)
Caligus epidemicus §	A total of 16 site visits to pond and cage sites in Guimaras and Iloilo, Philippines were made between Dec 1999 and Aug 2003. Stock typically had mixed infections, however, only *C. epidemicus* was found on 2 visits (n = 14 fish) with prevalences between 2·0 and 12·5 lice fish^{-1} (range 1–4 lice per infected host). No details regarding the impact of infections on the host were provided	–	Ho *et al*. (2004)
Caligus epidemicus + *Caligus quadratus*	Mixed infections were found on stock (n = 94) during 8 of the 16 visits detailed above (§)	–	Ho *et al*. (2004)
	The prevalence of infection ranged from 53 to 100% (av. 90·3%), mean intensities 2·5–14·5 lice fish^{-1} (av. 6·3 lice fish^{-1}), range 1–20 lice per infected host	–	–
Caligus epidemicus + *Caligus quadratus* + *Pseudocaligus uniartus*	A mixed infection was found only once during the study detailed above (§). The prevalence of infection was 100% (n = 15 fish), with a mean intensity of 3 lice fish^{-1} (range 1–5)	–	Ho *et al*. (2004)
Caligus quadratus + *Pseudocaligus uniartus*	A single mixed infection with a prevalence of 100% (n = 10 fish; mean intensity 16 lice fish^{-1}, range 9–39) was found during the study detailed above (§)	–	Ho *et al*. (2004)
Caligus quadratus	During the study above (§), single infections were found on 3 occasions with the prevalence of infection ranging from 53 to 95% (av. 76%), with mean intensities of between 1·5 and 4·5 lice fish^{-1} (av. 2·8 lice fish^{-1}), range 1–8 lice per infected host	–	Ho *et al*. (2004)

[a] Encompasses a complex of caligid species.
[b] There is an ongoing debate as to whether *Neobenedenia girellae* and *N. melleni* represent separate discrete species or should be accepted as *N. melleni*.
[c] Given the importance of salmonids in global marine aquaculture Chum and pink salmon are included here.

Table 9. The estimated economic cost of parasitic infections on the world's leading mollusc production industries. For each parasite-induced event, brief details are provided and an estimate of loss, where possible, has been calculated

Parasite	Impact	Estimated loss (US$)	Reference
(a) Pacific cupped oyster, *Crassostrea gigas* (Thunberg, 1793)			
Haplosporidium sp.	Isolated occurrences and low levels of infection in California State, Washington State, France and Matsushima Bay, Japan. Low-level infection in 1989–1990 (10% of seed brought to California from Japan were infected). Species unknown, but impacts may be similar to *H. nelsoni* and *H. costale*. Sporocysts break down epithelial cells of digestive system resulting in some tissue necrosis. More resistant to infection than *Crassostrea virginica,* but based on impacts of *Haplosporidium* sp. on *C. virginica*, and the exhibition of hemic response similar to that in *C. virginica* as a result of early systemic infections, authors conclude that this is likely to have negative pathogenic impacts	–	Pereya, (1962); Friedman *et al*. (1991); Bower *et al*. (1994); Kamaishi and Yoshinaga (2002); Dégremont *et al*. (2010)
Marteilia (syn. *Marteilioides*) *chungmuensis*	Ovarian protozoan parasite causing nodule-like structures on the gonads and/or enlarged gonads and disfiguring. Substantial economic losses in Korean and Japanese aquaculture as infected oysters cannot be sold. Prevalence increases in summer and decreases autumn–spring. 76% mortality in experimental infection	–	Bower *et al*. (1994); Itoh *et al*. (2004); Tun *et al*. (2008)
	Losses in Okayama Prefecture, Japan in ~2000 estimated at ¥ 2–300 M and later updated in 2009 (?) to an estimated € 0·5 M	2–3 M (2000) 680 000 (2009)	Itoh *et al*. (2002); Itoh (2009)
Mikrocytos mackini (mikrocytosis or Denman Island disease)	Protistan parasite of unknown taxonomic affiliation. Diseased oysters characterized by green pustules making them unmarketable. Mortality up to 53% but severity fluctuates annually. Infection thought to be via the digestive tract and gills, with subsequent colonization of other tissues. Requires long periods at low temperatures (< 10 °C) to cause disease; mostly expressed during the spring in more northerly locations. First reported in 1960, when 17–35% of the oysters in Henry Bay, Denman Island British Columbia died. Experiments indicate mortality occurs approx. 18 weeks after infection. Known range between southern British Columbia to Washington State. Severe infections confined to older oysters (up to 30% at low tide levels). No figures of loss (value or tonnage) are available so loss is est. at 10% of current production which in 2012 was 7165 t at US$ 1425 t^{-1}	1·02 M	Quayle (1961, 1982); Farley *et al*. (1988); Elston (1993); Bower *et al*. (1994); Hervio *et al*. (1996); Hine *et al*. (2001); Bower *et al*. (2005)
Perkinsus marinus	Widely distributed protistan parasite causing high mortalities in oyster populations. Under intensive cultural conditions, the mortality rate in larval oysters exceeded 90% in Washington State, USA. Occurs at water temperatures of 20–30 °C and salinities of 13–28 ppt. Highest mortalities (up to 95%) occur in the summer months on the East coast of America from Massachusetts to Brazil. American production, for example, in 1987 was 40 449 t, assuming this level of output would have been maintained in the absence of the parasite and that *Perkinsus* is the only factor responsible for loss, then approx. 2180 t worth an est. US$ 14·21 M was lost between 1988 and 1992. Production in 1993 had returned to close to the 1987 level at 39 053 t	14·21 M (1988–1992)	Leibovitz *et al*. (1978); Elston (1980); Andrews (1984, 1988); Perkins (1993); Bower *et al*. (1994); Burreson (1996); Oliver *et al*. (1998); La Peyre *et al*. (2003); Dégremont *et al*. (2010)

Protista incertae sedis (Humboldt egg parasite)	First observed in 1966 in *C. gigas* in Humboldt Bay, California. Occurs in the cytoplasm of maturing ova. Superficially resembles *Steinhausia, Ovicola* and *C. mytilovum*. Infection in females variable, from <1–77%. Heavily infected females show necrosis in ova and an inflammatory response, possibly reducing reproductive potential. There was no indication, however, that infection kills the mature host. Also recorded in Korea, Northern Territory Australia and Marennes France	–	Becker and Pauley (1968*a*, *b*); Bower *et al*. (1994)
Cliona spp.	Clionid sponges are distributed globally and cause damage by boring through the shell, and if the shell cannot be repaired quickly enough, may weaken the adductor muscle and death may eventually occur. Can affect other oysters, scallops and mussels growing on bottom substrates	–	Bower *et al*. (1994)
Gymnophalloides tokiensis	Trematode infecting *C. gigas* and *C. virginica* in Japan, but other unconfirmed species of same genus recorded in British Columbia and Atlantic Canada. Where infection intensity is high, oysters have a high water content, reduced glycogen, protein and fat, lower growth and survival rates	–	Bower *et al*. (1994)
Polydora sp. (Spinonidae)	Shell-boring polychaete occuring globally. Causes blistering and shell weakness. Induces oxidative stress, reduces growth and often results in mortality. *Polydora haswelli* and *P. aura* found abundantly in cultured *C. gigas* throughout Asia, and *P. uncinata* infects *C. gigas* cultured in Southeastern Korea	–	Chambon *et al*. (2007); Sato-Okoshi *et al*. (2012, 2013)
Mytilicola orientalis	Introduced to Pacific coast of the USA and Europe from *C. gigas* transported from Japan. Considered a serious pest of cultured bivalves. Causes damage to digestive tract epithelium (where it attaches)	–	Elston (1993); Torchin *et al*. (2002); Kim and Sato (2010)
Myicola ostreae	Severe gill erosion. Found in Europe, eastern and western USA and British Columbia	–	Lauckner (1983); Bower *et al*. (1994)
(b) Japanese carpet shell, *Ruditapes philippinarum* (Adams et Reeve, 1850)			
Perkinsus atlanticus	Pathogenic protist, synonymous with *P. olseni,* that infects *Ruditapes* sp. In *R. decussatus*, causes formation of cysts on gills, foot and mantle when infections are high intensity, and associated high mortalities. Laboratory experiments show mortality from heavy infections start to occurs after 4 weeks. Parasitized clams documented to be more susceptible to opportunistic infections. Distributed in the Mediterranean Sea and NW Spain	–	DaRos and Canzonier, (1985); Azevedo (1989); Bower *et al*. (1994); Almeida *et al*. (1999); Lee *et al*. (2001); Montes *et al*. (2001); Shimokawa *et al*. (2010)
Perkinsus marinus	Thought to be responsible for decline in harvest of *R. philipinarium* in Korea since 1990s due to annual mass mortality events. Effects on host include tissue atrophy, reduced energy and growth, reduced reproductive potential, organ necrosis and often mortality (up to 100% when infection is high). Appears to favour high salinity and water temperature. Korean production in 1990 was near its peak at 61 713 t, assuming that the subsequent decline in production can be attributed only to *Perkinsus* and that year on year tonnage could have been maintained, then it can be est. that across the period 1991–2012, *Perkinsus* was responsible for the loss of 900 744 t (av. 40 943 t p.a.) worth approx. US$ 1460 M (av. US$ 66·385 M p.a.)	1460 M (1991–2014) 66·385 M p.a.	Park and Choi (2001); Ngo and Choi (2004); Park *et al*. (2005)
Ostrincola koe	Parasitic copepod infecting mantle cavity, causing widespread damage and mortality. Has been responsible for mass mortality events in other cultured molluscs (e.g. *Meretrix meretrix*)	–	Kim (2004)
Cercaria tapidis	Bucephalid trematode commonly infecting cultured clams in Korea and Japan. High levels of infection causes reduced growth and degeneration or castration of gonads. No obvious seasonality, but prevalence of infection higher in autumn	–	Ngo and Choi (2004)

Table 9. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
(c) Yesso scallop, *Patinopecten yessoensis* (Jay, 1857)			
Perkinsus qugwadi	Caused significant mortality (up to 98%) in juveniles (< 5 cm shell height, <1-year old) and adults (up to 60%) between 1988 and 1995 in British Columbia, Canada. May be native to British Columbia; not found elsewhere. Pathogenic at low temperatures (8–15 °C). Formerly known as Scallop Protozoan X (SPX). Assuming that infection caused a 20% loss in production, then across the period 1988–1995, an est. 99 t were lost valued at US$ 92 605	92 605	Bower *et al*. (1992, 1994, 1998); Blackbourn *et al*. (1998); Itoh *et al*. (2013)
Cliona sp.	Globally distributed, shell-boring sponges that burrow under shells of bivalves. Scallops able to repair damage; however, if adductor muscle is damaged, impaired feeding may result causing mortality	–	Bower *et al*. (1994); Lauckner (1983); McGladdery *et al*. (2006)
Dipolydora alborectalis (Spionidae)	Shell-boring polychaete (Spionidae) that bores visibly into the shells of *P. yessoensis*; often highly abundant in Japanese cultures. Causes blistering, shell weakness, reduces growth and often results in mortality	–	Sato-Okoshi *et al*. (2012)
Pectenophilus ornatus	Highly modified parasitic copepod with brood-pouch that infects gills. Reduces market condition of scallops and thought to infect 100% of Japan's scallop stock. Prevalence also increases with host size. Found to be highly transformed member of the family Mytilicolidae. Loss is est. on a 5–10% downgrading in the value of Japanese stock which in 2012 was 184 287 t worth an est. US$ 503·76 M	28–56 M	Nagasawa *et al*. (1988); Nagasawa and Nagata (1992); Bower *et al*. (1994); Huys *et al*. (2006); Suzuki and Matsutani (2009)
Polydora brevipalpa (Spionidae)	Highly prevalent, shell-boring polychaete causing large shell defects and some mortality in eastern China and on the west coast of Japan. Host-specific to *P. yessoensis*	–	Mori *et al*. (1985); Sato-Okoshi *et al*. (2012)
Polydora websteri (Spionidae)	Shell-boring polychaete causing up to 84% mortality in British Columbia's scallop grow-out sites from 1989 to 1990. According to FishStatJ, production on the Pacific coast fell from 10 t (US$ 8565 t^{-1}) in 1989 to 0 in 1990. If, however, the 10 t in 1989 represents the 16% of viable stock that was sold, then this suggests that 52·5 t of production was lost	85 650 449 660	Bower *et al*. (1992)
(d) Chilean mussel, *Mytilus chilensis* (Hupé, 1854)			
syn. *Mytilus edulis* (see Gray *et al*. 1999) – see the entry below			
(e) Abalone, *Haliotis* spp.			
Candidatus Xenohaliotis californiensis (Rickettsiae)	Withering syndrome appeared in Californian *H. cracherodii* Leach, 1814 after 1983 El Niño event. Caused high mortality in *H. rufescens* Swainson, 1822 (90% prevalence) and *H. fulgens* Philippi, 1845 (37·5% prevalence) in southern Californian and Mexican farms during El Niño event of 1997. Also causes high mortality in *H. iris* Gmelin, 1791 in New Zealand. Associated with elevated water temperatures >20 °C. Chronic wastage of foot and visceral tissues reduces ability to adhere to substrata. Impairment of digestion due to high infection of pathogen in gut	–	Haaker *et al*. (1992); Lafferty and Kuris (1993); Kismohandaka *et al*. (1995); Friedman *et al*. (1997); Antonio *et al*. (2000); Cáceres Martínez *et al*. (2000); Friedman *et al*. (2000); Moore *et al*. (2000, 2002, 2009); Diggles *et al*. (2002); Hine *et al*. (2002); Braid *et al*. (2005)
Paua haplosporidosis	Unknown haplosporidian causing paua (abalone) haplosporidosis. Causes lethargy, lack of orientation and surface adhesion and chronic mortality of juveniles (av. shell length	–	Diggles *et al*. (2002); Diggles and Oliver (2005)

	14 mm) in summer months (up to 80–90% in one farm hatchery located on the South Island of New Zealand)		
Labyrinthuloides haliotidis	Protozoan parasite-infecting hatcheries on the west coast of Canada. Destroys head and foot of juvenile abalone. Resulting mortality may be up to 100%. Infection contributed to the closure of the only commercial abalone aquaculture unit	–	Bower (1987*a*, *b*); Bower *et al*. (1994); Bower and Meyer (2005)
Perkinsus olseni	Pathogenic protist, synonymous with *P. atlanticus*. Spreads rapidly although tissues; thought to cause mortalities in abalone in the Gulf of St. Vincent, Australia	–	Almeida *et al*. (1999); Bower *et al*. (1994); Goggin and Lester (1995)
Spionid mudworms (Spionidae) (*Boccardia knoxi, Polydora hoplura, Polydora haswelli, Terebrasabella heterouncinata* and *Boccardia proboscidea*)	Shell-boring polychaetes causing blistering of shell. *Boccardia knoxi* and *P. hoplura* caused 50%+ mortality in abalone farms in Tasmania and S. Australia in 1995–2000. In South Africa, *B. probscidea, P. hoplura* and *T. heterunicintata* cause high levels of infestation leading to decreased growth, decreased flesh condition and increased mortality in cultured *H. midae* L. Heavy infestations in cultured *H. discus* Reeve, 1846 in Asian waters cause blistering, shell weakness, reduced growth and often mortality. Common parasites of *H. rufescens* in California; increased mortality due to heavy infections or subsequent predation. Only data for blacklip abalone in 1999 (21 t) and 2000 (40 t) are available in FishStatJ. Assuming that only 50% of surviving stock was harvested this suggests that approx. 60 t were lost worth an est. US$ 26 302 t^{-1} (1999) to US$ 29 117 t^{-1}	0·55–1·16 M p.a.	Lleonart *et al*. (2003); Simon *et al*. (2006, 2010); Sato-Okoshi *et al*. (2012, 2013); Maguire and Rogers-Bennett (2013)
Evalea tenuisculpta	Pyramidellid snail infecting *H. rufescens* at certain sites along coast of California where up to 82% have been infected. Although little is known about effects of infection in this host, they can cause shell damage, reduced growth rates, transmission of bacterial disease and mortality	–	Maguire and Rogers-Bennett (2013)
(f) Chinese razor clam, *Sinonovacula constricta* (Lamarck, 1818)			
Monorchis xiamenensis	Metacercaria of this trematode worm infect both juvenile and mature clams, causing destruction of organs including gonads, digestive gland, gills and mantle	–	Lei (2000)
Vesicocoelium solenophagum	Trematode worm completing its life cycle in the razor clam (after eggs have been carried and passed out by gobiid fish). Infects number of tissues including reproductive organs causing serious damage and mortality to second-year clams. Infection seen in first-year clams during July and Aug. Increases in April–June when host damage becomes more serious. Known as 'black root disease'	–	Chungti and Zhenzu (1979); Shi and Wang (2001)
(g) Peruvian scallop, *Argopecten purpuratus* (Lamarck, 1819)			
No mass mortality events recorded for scallops in Chile and very little information available (Lohrmann, 2009). All known parasites for *A. purpuratus* have benign effects on the host			
(h) Blood cockle, *Anadara granosa* L.			
Nematopsis sp.	Oocysts parasitize connective tissue of gills. Heavy infections thought to reduce filtering efficiency and weaken condition in juveniles resulting in loss of culture. Poor environmental conditions may increase vulnerability to infection; several mass mortality	–	Pookasawan *et al*. (1982); Tuntiwaranuruk *et al*. (2004); Uddin *et al*. (2011)

Table 9. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	events of *A. granosa* in Phuket, Thailand. Prevalence of *Nematopsis* sp. is dependent on season and environmental conditions (e.g. salinity)		
Digenetic trematode	Sporocysts infect gonads, mantle, stomach epithelium, digestive glands and foot. Heavy infection destroys the gonads and reduces glycogen content. Recorded in stocks in Malaysia (Straits of Malacca). No clear seasonality in prevalence of infection, but appears to favour more saline conditions	–	Sayuthi (1993); Uddin *et al.* (2011)
(i) Mediterranean mussel, *Mytilus galloprovincialis* (Lamarck, 1819)			
Marteilia refringens (Marteiliosis/ Aber disease)	*M. refringens* causes mortality in cultured mussels in Galicia, NW Spain. Also previously observed in Europe in *Ostrea edulis, Mytilus edulis* and *Crassostrea gigas*. High levels of parasitism observed in the Thermaikos Gulf (Greece). Extensive mortality in oysters cultured in France and Spain in 1960s–1970s. Mortalities occur from May onwards and peak in June, July and Aug. Causes lesions in digestive tubules, which results in wasting of digestive gland and eventual death. Inhibits gonadal development in *M. galloprovincialis* and reduced total carbohydrate levels. Mortality often between 50 and 90%. Long-term infections may result in 100% mortality. Assuming that the av. prevalence of infection (12·06 ± 12·06) across 5 sites in Galicia, NW Spain given in Villalba *et al.* (1997) resulted in mortality, then the loss of production applied to the tonnage in 1988 (i.e. 243 010 t) equates to a loss of 29 307 t worth an est. US$19·05 M	19·05 M	Lodeiros *et al.* (1987); Figueras *et al.* (1991); Villalba (1993); Villalba *et al.* (1993); Bower *et al.* (1994); Robledo and Figueras (1995); Robledo *et al.* (1995); Villalba *et al.* (1997); Thébault *et al.* (1999); Zrnčić *et al.* (2001); Balseiro *et al.* (2007); Karagiannis and Angelidis (2007); Carella *et al.* (2010)
	Assuming that the 1988 levels of Spanish production could have been maintained in the absence of parasitic infection and that parasites were the sole cause of loss, then the subsequent drop in production over the period of 1989–1997 equates to a loss of 692 977 t worth an est. US$ 387·56 M	387·56 M	
Mytilicola intestinalis	Parasitic copepod. Endemic along inshore European coasts. Infection of adults occurs in gut where eggs are laid, hatched and are expelled. Nauplii develop through 2 pelagic stages before infecting new mussels. Mortality occurs when infection is high; thought to be associated with mass mortalities. Causes overall reduction of condition (e.g. lower total carbohydrate levels), which affects the quality of meat in marketable mussels	–	Korringa (1951); Lauckner (1983); Andrews (1984); Dethlefsen (1985); Davey and Gee (1988); Davey (1989); Blateau *et al.* (1992); Bower *et al.* (1994); Robledo *et al.* (1994*a*, *b*); Villalba *et al.* (1997); Buck *et al.* (2005); Pogoda *et al.* (2012)
Proctoeces maculatus (syn. *Cercaria tenuans*)	Trematode worm causing a number of symptoms including valve weakness and difficulty attaching to substrates. Main impact is atrophy of reproductive organs and inhibited gametogenesis. Widespread distribution in temperate and tropical waters. Thought to be responsible for mass mortality event of mussels in southern part of Laguna Veneta, Italy	–	Munford *et al.* (1981); Lauckner (1983); Figueras *et al.* (1991); Bower *et al.* (1994); Robledo *et al.* (1994*a*, *b*); Villalba *et al.* (1997)
	Assuming that the av. prevalence of infection (0·68 ± 0·66) across 5 sites in Galicia, NW Spain given in Villalba *et al.* (1997) resulted in mortality, then the loss of production applied to the tonnage in 1988 (i.e. 243 010 t) equates to a loss of 1652 t worth an est. US$ 1·07 M	1·07 M	

(j) Atlantic mussel, *Mytilus edulis* L.			
Coccidia sp.	Protozoan parasite infecting and damaging kidneys. Mortalities occur when infection is heavy in mussels grown in artificial conditions	–	Bower (1992); Bower *et al*. (1994)
Marteilia refringens	Causes mortality in cultured mussels in Galicia, NW Spain. Also previously observed in Europe in *Ostrea edulis*, *Mytilus edulis* and *Crassostrea gigas*. Extensive mortality in oysters cultured in France and Spain in 1960–1970. Mortalities occur from May onwards and peak in June, July and August. Causes lesions in digestive tubules, which results in wasting of digestive gland and eventual death. Mortality often 50–90% and long-term infections may result in 100% mortality. Synonymous with *Marteilia maurini*	–	Villalba (1993); Villalba *et al*. (1993); Bower *et al*. (1994); Robledo and Figueras (1995); Thébault *et al*. (1999); Zrnčić *et al*. (2001); Balseiro *et al*. (2007); Carella *et al*. (2010)
Cliona spp.	Globally distributed sponges causing damage by boring through shell and, if the shell cannot be repaired quickly enough, may weaken the adductor muscle and death may eventually occur. Infection has been recorded for *M. edulis* on bottom substrates in Scandinavia and North America	–	Lauckner (1983); Bower *et al*. (1994)
Mytilicola intestinalis	Parasitic copepod found in digestive tract of several molluscs. Endemic along inshore European coasts from Denmark to Italy. Infection of adults occurs in gut where eggs are laid, hatched and are expelled. Nauplii develop through 2 pelagic stages before infecting new mussels. Mortality of mussels occurs when infection is high (5–10 parasites per mussel); thought to be associated with mass mortalities. Causes reduction in feeding rate resulting in overall reduction of condition, which affects quality of meat in marketable mussels	–	Korringa (1951); Lauckner (1983); Andrews (1984); Dethlefsen (1985); Davey and Gee (1988); Davey (1989); Blateau *et al*. (1992); Elston, (1993); Bower *et al*. (1994); Buck *et al*. (2005); Pogoda *et al*. (2012)
Polydora ciliata	Shell-boring polychaete occuring globally. Causes blistering, weakens and deforms shell, reducing overall condition. In Europe, *P. ciliata* is associated with reduced market quality and mortalities	–	Kent (1979, 1981); Bower *et al*. (1994); Buck *et al*. (2005)
Proctoeces maculatus	Trematode worm causing a number of symptoms including valve weakness and difficulty attaching to substrates. Heavy infections reduce glycogen levels and circulation, and gametogenesis is either impaired or completely stopped. Some cases report associated mortalities. Widespread distribution in temperate and tropical waters; seasonal prevalence with epizootic episodes in autumn and winter	–	Lauckner (1983); Bower *et al*. (1994); Sunila *et al*. (2004)
Edotia doellojuradoi	Isopod infecting cultured mussels in Chile and causing gill damage to host. Damage increases with parasite abundance	–	Valencia and George-Nascimento (2013)
(k) New Zealand green-lipped mussel, *Perna canalicula* (Gmelin, 1791) (syn. *Perna canaliculus*)			
Apicomplexan parasite X (APX)	Only occurs in NZ. Affects *P. canalicula* in farms in Marlborough Sound. More common to *Ostrea chilensis*. Heavy infections cause chronic wastage and reduction of gametes and eventually death	–	Diggles *et al*. (2002)
Nepinnotheres novaezelandiae	Parasitic pea crab thought to be symbiotic with host; however, recent research has identified detrimental impacts including 30% reduction in shell height and wet mass and erosion of the gills, causing reduced rates of oxygen consumption	Annual loss of US$ 2·16 M	Trottier and Jeffs (2012); Trottier *et al*. (2012)
(l) Pearl oyster, *Pinctada* spp.			
Unknown parasite	Mass mortalities in 1985; 50–80% of cultured *P. margeritifera* L. in coastal lagoons in French Polynesia. Symptoms include mantle lesions, lack of growth and excessive secretion of mucus. Assuming that in the absence of the parasite production would have increased by 0·21–0·84 t, then loss can be est. at US$ 8·50–34·02 M	8·50–34·02 M	Cabral (1989*a*, *b*)

Table 9. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Unknown protozoan parasite	Caused high mortalities in cultures of *P. margeritifera* in the Red Sea in 1969 and 1973	–	Nasr (1982); Cabral (1989*b*)
Bucephalus sp.	Trematode affecting the formation of pearls. In *P. radiata* (Leach, 1814), *Bucephalus* has been reported to destroy female gonads, and overall infections can reduce ability to withstand environmental stress	–	Sakaguchi (1968*a*, *b*); Bower *et al.* (1994); Lee *et al.* (2001)
Shell-boring worms and sponges	Examples of recorded infections include *Polydora vulgaris* in *P. margeritifera* in Kuwait, and *Polydora ciliata* and *Cliona margeritiferae* in *P. fucata* (Gould, 1850) in Sri Lankan pearl banks. Shell-boring parasites are huge problem in pearl oyster culture worldwide, causing damage, reduction in condition and, in some cases, mortality	–	Velayudhan (1982); Bower *et al.* (1994)
(m) Asiatic hard clam, *Meretrix* spp.			
Ostrincola koe	Parasitic copepod responsible for mass mortality of *Meretrix meretrix* L. in 1988–1989 in Southern Jiansu, China. Infects mantle cavity of the clam	–	Ho and Zheng (1994)
Peritrichous ciliate *Myxospozoa Epicomplexa*	Protozoan parasite found in diseased clams with mantle hypertrophy disease'. Symptoms include fleshy, swollen mantles, degraded tissues and abnormally increased mucus production	–	Ren *et al.* (2005)
(n) Sea snails *Babylonia*/*Hemifusus* spp.			
Haplosporidium babyloniae	Occurs on *Babylonia areolata* (Link, 1907) (ivory shell snail) in southern coastal areas of China. Most organs become badly damaged and develop serious lesions as a result of infection	–	Peng *et al.* (2011)
(o) Asiatic clam, *Corbicula fluminea* (Müller, 1774)			
Most of the literature describing *Corbicula fluminea* focuses on its status in many countries as an invasive non-native species and its function as a vector for parasites that impact other wild and cultured species and in humans (Williams Jr. *et al.* 2001; Graczyk *et al.* 2003; Sousa *et al.* 2008*a*, *b*, *c*; Karatayev *et al.* 2012). Mass mortality events have been recorded for this species; however, these have been attributed to environmental conditions (Werner and Rothhaupt, 2008; Vohmann *et al.* 2010); the authors have been unable to find any recorded economic impacts of protozoan or metazoan parasites for this species			
(p) Hard clam, *Mercenaria mercenaria* L.			
Quahog parasite X (QPX) (Phylum: Labyrinthulomycota)	Undescribed parasite but from family Thraustochytridae. Documented in hatcheries in Gulf of St. Lawrence, Canada, Virginia and Massachusetts. Mortalities of 80–90% recorded for juvenile hatchery stock and up to 92% for seed transported from South Carolina to New Jersey during 1995–1998. Infects mantle, gills, foot and connective tissues (and other organs) eventually causing necrosis, decomposition of tissue by bacteria/fungus and mortality; highest prevalence occurs in November and May. Temperature thought to be a determining factor in prevalence of QPX	–	Bower *et al.* (1994); Calvo *et al.* (1998); Ragan *et al.* (2000); Ford *et al.* (2002); Dahl *et al.* (2010); Perrigault *et al.* (2009, 2011); Hégaret *et al.* (2010)
QPX-like parasite	Observed in 2 sites of *M. mercenaria* culture in Massachusetts in 1995. Infected clams suffered poor condition and reduced growth followed by mass mortalities in stock 1·5–2 years old	–	Smolowitz *et al.* (1998)

(q) American cupped oyster, *Crassostrea virginica* (Gmelin, 1791)			
Haplosporidium costale (SSO disease) (syn. *Minchinia costalis*)	Found on East Coast of North America from Chesapeake Bay, Virginia to Nova Scotia. Infections restricted to high salinity (⩾ 25 ppt) occur in autumn and remain histologically undetectable until following spring when mortalities occur (sharp increases May–June). Low prevalence but 20–75% mortality in affected populations. Regular sporulation throughout connective tissues causing prompt oyster mortality. Infection site usually epithelia of digestive tract; causes damage to digestive epithelium and affects gonad development	–	Meyers (1981); Andrews (1982, 1984, 1988); Bower *et al*. (1994); Dégremont *et al*. (2010); Ford (2011)
Haplosporidium nelsoni (MSX disease)	Occurs on mid-Atlantic Coast of USA: Massachusetts to South Carolina and Florida. Less prevalent in low-salinity water (< 18‰), but enzootic in high salinity (> 20‰). >90% mortality occurred in Delaware and Chesapeake Bay 1957–1959. During years of drought (1981–1982), *H. nelsoni* invaded areas of low salinity (where oysters are mostly grown). Life cycle largely unknown. Oysters acquire new infections in spring and mortalities occur in summer. Deaths in infected oysters sometimes delayed by temperature (e.g. late summer infections cause death the following summer). Initial site of infection is epithelial tissues of gills and mortality may begin within 6 weeks of infection and occurs quickly. Continued prevalence of *H. nelsoni* greatly reduces potential for oyster culture in Chesapeake Bay area although selective breeding improves resistance. Since initial outbreak in the 1950s, MSX has followed cyclical patterns, peaking at 6–8 years	–	Haskin *et al*. (1966); Andrews (1967, 1984); Sinderman (1976); Ford and Haskin (1982); Haskin and Ford (1982); Ford (1985); Ford and Haskin (1987); Barber *et al*. (1991); Perkins (1993); Bower *et al*. (1994); Burreson *et al*. (2000); Hofmann *et al*. (2001); Sunila and LaBanca (2003); Dégremont *et al*. (2010); Wilbur *et al*. (2012)
	In 1950, 2·881 M bushels (=576·2 M oysters) were landed in Maryland (valued at US$ 5·53 M) and 3·357 M bushels (671·4 M oysters valued at US$ 12·02 M) in Virginia. In 1960, although the landings were little changed, i.e. 2·354 M bushels valued at US$ 3·86 M for Maryland and 3·357 M bushels valued at US$ 10·88 M for Virginia, if these represent the 10% of the stock that survived, then the combined losses can be estimated at US$ 132·64 M.	132·64 M	Mackenzie (1996)
Mikrocytos mackini (mikrocytosis)	Protozoan parasite that has been placed within the Class Ascetospora. Known to infect *C. virginica* and cause mikrocytosis (see *C. gigas*)	–	Bower *et al*. (2005)
Perkinsus marinus	Widely distributed protistan parasite causing high mortalities in oyster populations. Disseminates slowly from a centre of infection via snail vector *Boonea impressa*. Highest mortalities (up to 95%) in summer months on east coast of America from Massachusetts to Brazil. Estimated 50% annual mortality. Increases most readily at 25 °C, but infections recorded in more northerly areas (implications for warmer conditions due to climate change) and at higher salinity. Causes reduction in bodily soft tissue, overall condition and growth rate. Growth rate may be reduced by 60% or more in moderate salinity and 80% at high salinity. Lethal threshold is 10^6 pathogen cells g^{-1} tissue wet weight	–	White *et al*. (1987); Andrews (1988); Crosby and Roberts (1990); Paynter and Burreson (1991); Burreson (1996); Cook *et al*. (1998); Oliver *et al*. (1998); La Peyre *et al*. (2003); Dungan *et al*. (2012)
	Infection of oysters in Maryland and Virginia throughout the late 1980s and early 1990s resulted in high mortality rates. American production in 1987 was 80 893 t, assuming that this level of output would have been maintained in the absence of the parasite and that *Perkinsus* is the only factor responsible for loss, then approx. 2720 t worth an est. US$ 62·83 M was lost between 1988 and 1991. Production in 1992 had returned pre-1988 levels at 83 544 t	62·83 M (1988–1991)	Burreson and Ragone Calvo (1996)
Bucephalus cuculus	Larval trematode; causes castration, starvation and eventually death. Occurs on East Atlantic coast of USA (Maryland). Infections of *Bucephalus* sp. documented to result in	–	Tripp (1973); Andrews (1984); Bower *et al*. (1994)

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Table 9. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
	castration and hermaphroditism. Overall infections can reduce ability to withstand environmental stress		
Myicola ostreae	Generally harmless parasitic copepod, although can cause gill lesions and severe gill erosion. Found in Europe, eastern and western USA and British Columbia	–	Lauckner (1983); Bower *et al*. (1994)
(r) Grooved carpet shell, *Ruditapes decussatus* L. (syn. *Tapes decussatus*)			
Perkinsus atlanticus	Pathogenic protistan, synonymous with *P. olseni,* infecting *Ruditapes* sp. Documented in *R. decussatus* to cause formation of cysts on gills, foot and mantle when infections are high intensity and associated high mortalities. Laboratory experiments show mortality from heavy infections start to occur after 4 weeks. Parasitized clams more susceptible to opportunistic infections. Distributed in the Mediterranean Sea and NW Spain	–	DaRos and Canzonier (1985); Azevedo (1989); Bower *et al*. (1994); Almeida *et al*. (1999); Montes *et al*. (2001); Shimokawa *et al*. (2010)
Bacciger bacciger	Sporocysts and cecariae heavily infect gonads and visceral mass of *R. decussatus* in St. Gilla Lagoon, Sardinia. Responsible for mortality of carpet shells (alongside infections of *Perkinsus marinus*) cultured in Venice Lagoon over 2 years (10% in year 1 and 25% in year 2)	–	Breber (1985); Culurgioni *et al*. (2006)
Nematopsis sp.	Infects intestinal tissues where it reproduces in host connective tissue and gills causing lysis of the nearby gill cells. Severe mortality attributed to *Nematopsis* infection in other bivalve species in Asia; however, some discrepancy in literature as to pathological impacts in bivalves	–	Canestri-Trotti *et al*. (2000); Culurgioni *et al*. (2006)
Paravortex cardii	Turbellarian found in intestinal lumen, digestive glad and gonads. Also common parasite of cockle *Cerastoderma edule*. Heavy infection causes widespread host damage and castration	–	Carballal *et al*. (2001); Culurgioni *et al*. (2006)
(s) Sydney rock oyster, *Saccostrea glomerata* (Gould, 1850) (syn. *Saccostrea commercialis*)			
Bonamia (syn. *Mikrocytos*) *roughleyi* (Australian winter disease)	Protozoan causing pustules, ulcerations and abscesses in gills, gonads and mantle. Mortalities up to 70% in mature oysters in third winter before marketing. Linked to low temperatures and high salinities (30–35‰). If an av. mortality of 20% mortality is applied across the industry and to the av. tonnages produced across the period 1988–1994 (i.e. 5760 t; the dates of the 2 reports), then loss can be est. at 1152 t p.a. worth ~ US$ 4·56 M p. a. or a total loss of ~8064 t across the period worth an est. US$ 31·91 M	4·56 M p.a.	Farley *et al*. (1988); Bower *et al*. (1994)
Marteilia sydneyi	Causes QX disease. High mortalities in oyster cultures recorded in eastern Australia. Outbreaks often occur following heavy summer rains in southern Queensland and New South Wales	–	Potter (1983); Lester (1986); Wesche (1995); Hine and Thorne (2000)
Paramarteilia (syn. *Marteilioides*) *branchialis*	Protozoan causing lesions in gills. Along with infections of *Marteilia sydneyi*, high levels of mortalities may occur in tray-cultured oysters throughout autumn	–	Bower *et al*. (1994)
Korean mussel, *Mytilus coruscus* (Gould, 1861) (syn. *Mytilus crassitesta*)			
Dipolydora giardia (Spinoidae)	Shell-boring polychaete infecting Asian cultures of *M. coruscus*. Causes blistering, weakened shells, reduced growth and often mortality of host	–	Sato-Okoshi *et al*. (2012)
Modiolicola gracilicaudus	Parasitic copepod infecting *M. coruscus* in Sea of Japan. Known to cause considerable damage to hosts, which may result in mortality	–	Ho (1980); Kim (2004)

Mytilicola orientalis	Parasitic copepod spread from Eastern Asia to mussel and oyster cultures in Europe and USA. Negative effects on host occur when environmental conditions are extreme and infection is high (> 25 copepods per host). Infection occurs in intestine	–	Ho (1980); Pogoda *et al*. (2012)
(t) Winged pearl oyster, *Pteria penguin* (Röding, 1798)			
Tylocephalum metacestodes	Larval tapeworm. Encysts in connective tissue of digestive gland	–	Hine and Thorne (2000)
Boring polychaetes, sponges, molluscs and isopods (e.g. *Polydora* sp., *Cliona* sp.)	Cultured *P. penguin* in Philippines suffer from heavy fouling reducing shell quality and survival	–	Bondad-Reantaso *et al*. (2007)
(u) Geoduck, *Panopea generosa* (Gould, 1850)			
Isonema-like flagellate	Only found in geoduck larvae in USA hatcheries. Flagellate enters mantle and multiplies within coelom causing death when infection is heavy	–	Kent *et al*. (1987); Bower *et al*. (1994); Bower and Blackbourn (2003)
(v) Inflated ark or blood clam, *Scapharca broughtonii* (Schrenck, 1867)			
Perkinsus sp.	Low-level infections were found in specimens taken from Komsoe Bay, S. Korea where Manila clams, *Ruditapes philippinarum*, were found to be moderately infected (i.e. 1 M+ hypnospores clam^{-1}) at levels that might impair growth and reproduction	–	Park *et al*. (1999)
(w) Pen shell, *Atrina* spp.			
The authors have been unable to find any recorded economic impacts of protozoan or metazoan parasites for this species			
(x) South American rock mussel, *Perna perna* (Linnaeus, 1758)			
Bucephalid (Digenea) sporocysts and *Proctoeces* sp.	Brown mussels from Hougham Park and Kowie Point, South Africa are commonly infected with digeneans (*Proctoeces* sp. and bucephalid sporocysts; prev. 50%). *Proctoces* infection has an impact on mussel growth whilst the presence of bucephalid sporocysts result in castration of their hosts	–	Calvo-Ugarteburu and McQuaid (1998)

Table 10. The estimated economic cost of notable protistan and metazoan parasite events on the 10 leading crustacean marine and brackish water-based aquaculture industries

Parasite	Impact	Estimated loss (US$)	Reference
(a) Whiteleg shrimp, *Litopenaeus vannamei* (Boone, 1931) (syn. *Penaeus vannamei*)			
Agmasoma penaei	A microsporidian infection was found in 2% of the culture stock at a farm in Yucatan, Mexico	–	Vidal-Martínez *et al*. (2002)
Apiosoma sp.	Infection found with a 6–57% prevalence on stock held at a farm in Yucatan, Mexico	–	Vidal-Martínez *et al*. (2002)
Epistylis sp.	Ciliates were prevalent on 2–29% of stock at a site in Yucatan, Mexico	–	Vidal-Martínez *et al*. (2002)
	A survey of 149–191-day-old juvenile stock (carapace length 1·47–2·21 cm) at an intensive culture farm at Sisal, Yucatan throughout Dec 2001–Nov 2002 stocked in ponds at 98–136 shrimp m^2 found infection on 22–100% of shrimp with a mean intensity of infection of 13 ± 28 to 126 ± 124 parasites shrimp^{-1}	–	López-Téllez *et al*. (2009)
Haplosporidian sp.	Imported *L. vannamei* juveniles from Nicaragua into Cuba and held in a quarantine facility between Oct 1985 and March 1986 were subsequently found to have an hepatopancreatic infection which was detected in 31 out of 53 (58·5%) shrimp that were sampled	–	Dyková *et al*. (1988)
	During the winter season Sept 2004–Feb 2005, stock in ponds in Belize showed slow growth and reduced survival	–	Nunan *et al*. (2007)
	Progressive mortalities of juvenile (< 1-month-old stock) rising to 60–90% in severely affected Indonesian hatcheries due to infections of intracellular haplosporidians have, since 2007, been estimated to have cost the national industry US$ >5 M. Infections result in atrophy of the hepato-pancreas, retarded growth, melanization of the cuticle and a flaccid body. Infected shrimp, however, were frequently co-infected with *Vibrio* spp.	> 5 M	Utari *et al*. (2012)
Sirolpidium spp.	Study comments that this phycomycete fungus has been responsible for severe mortalities in Larval cultures. No details of loss provided	–	Carr (1996)
Thelohania sp.	Twenty to 25 days post-stocking infections were first observed in shrimp stocked at 125 post-larvae m^2 in three 8000 m^2 ponds in Thailand. The prevalence of infection rose to 25–28% on day 60 but had decreased to 3–5% when the stocks were harvested. The study demonstrated that the severity of infection impacts on growth performance and survival	–	Prasertsri *et al*. (2009)
Zoothamnium sp.	Ciliates were observed on 2–65% of farm stock at a site in Yucatan, Mexico	–	Vidal-Martínez *et al*. (2002)
	A survey of juvenile shrimp (carapace length 1·47–2·21 cm) throughout Dec 2001–Nov 2002 at an intensive culture farm at Sisal, Yucatan found ciliates with a prevalence of between 0 and 87% with a mean intensity of infection of between 0 to 144 ± 132 parasites shrimp^{-1}	–	López-Téllez *et al*. (2009)
(b) Giant tiger prawn, *Penaeus monodon* (Fabricius, 1798)			
Fusarium sp. + luminescent bacteria (*Vibrio* sp.)	Infections are reported to result in the heavy mortality of mysis and post-larvae in hatcheries on the coast of Andhra Pradesh, India. No details relating to the scale of loss are provided	–	Siva Kamari and Ramesh Babu (2001)
Haliphthoros philippinensis	Suggested that infections within the hatchery production of larvae can be devastating	–	Lio-Po and Sanvictores (1986)

Isochrysis galbana	100% prevalence on the gills and appendages of post-larvae causing fouling. Infection within closed tanks in an Indian hatchery resulted in >80% mortality	–	Aravindan *et al*. (2007)
Lagenidium sp.	Infections are suggested to be the basis of heavy losses in hatcheries	–	Lio-Po and Sanvictores (1986)
Lagenidium callinectes	Infections are reported to affect the eggs and larvae of marine Crustacea. A culture facility in India stocked six 5000 L tanks with a total of 3·84 M nauplii. There was a 5·33 + 0·55% mortality between nauplii and zoea, a subsequent 24·68 ± 4·58% mortality of zoea 5 days after stocking, and, a total mortality of 47·89 ± 0·27% of mysis 10 days after stocking, i.e. the mortality of 1·84 M larval stages. No figures for the value of stock at that time are available; however, the current cost of 1 M *L. vannamei* nauplii in Thailand (as of May 2014) is approx. 10 000 THB (=US$ 309)	569	Ramasamy *et al*. (1996)
Lagenidium thermophilum	Fungal infection of eggs and larvae at hatcheries within Chachensao Province, Thailand result in high mortalities. The study provides no details relating to the scale of losses but the economic losses follow those given for *L. callinectes* above, i.e. US$ 309 per 1 M nauplii (i.e. 100 nauplii per 1 Thai baht (THB)) or US$ 3087–4322 per 1 M post-larvae (i.e. 1–1·4 THB per 10 PL)	309–4322 per 1 M juveniles lost	Muraosa *et al*. (2006)
(c) Indo-Pacific swamp crab, *Scylla serrata* (Forsskål, 1775)			
Haliphthoros milfordensis + *Halocrusticida baliensis* + *Lagenidium callinectes*	Seed production at a research station in Bali, Indonesia has been hampered since 1992 by fungal infections resulting in almost 100% mortality of zoeae. Eggs were derived from spawning adults (200–300 g) brought in from Probolinggo, East Java in July 1997 and held in a 16 m^3 tank. The number of zoeae lost is not detailed but almost all the zoeae were lost on each occasion to fungal agents. It is assumed that 16 female broodstock crabs were held (i.e. 1 crab m^3), that each crab produced an av. 3 million eggs and spawned three times, that the same protocol was used throughout 1992–1997, and, in the absence of livestock prices the current minimum wage for an Indonesian labourer, i.e. US$ 73·72 $month^{-1}$ (=850 000 Indonesian rupiah; see http://en.wikipedia.org/wiki/List_of_minimum_wages_by_country) is used for an animal husbandry for a period of 6 months (based on 3 spawnings with a 41–46-day interval between each; see FAO 2014*e*)	442 p.a. 2652 over the 6 years programme	Hatai *et al*. (2000)
Hematodinium sp.	A case of yellow water disease (or milky disease) was recorded in the mud crab reared in the Shanmen area of Zhejiang, China resulting in a high mortality of stock. The infected crabs were thin with heavy parasitic burdens within the gills, heart, muscle and hepatopancreas	–	Xu *et al*. (2007*a*)
	A low-salinity culture area (< 9 ppt) covering 7000 ha in Guangdong Province, southern China, producing approx. 2000 t of crab, has had recurrent infections of milky disease since 2005. Infections typically breakout in Sept–Nov as the crab approaches maturity with high mortalities resulting (> 60%). Loss is estimated on the 60% of stock lost annually throughout this region (i.e. 3000 t) using the harvest price of Chinese mud crab in 2005, i.e. US$ 3·85 kg^{-1}, to 2008, i.e. US$ 4·04 kg^{-1}	11·55–12·12 M p.a. (=46·35 M total loss for the region 2005–2008)	Li *et al*. (2008)
	If, however, a 60% mortality is typical of the losses throughout the entire industry, then loss can be calculated on the 40% produced in 2005 through to 2008, i.e. 12 075, 13 132, 16 898 and 18 694 t. This represents national losses of 18 112 t (2005), 19 698 t (2006), 25 347 t (2007) and 28 041 t (2008). Estimates are based on the harvest price of crab in each year, i.e. US$ 3·85, 3·96, 3·60 and 4·04 kg^{-1}, respectively	69·73 M (2005) 78 M (2006) 91·25 M (2007) 113·29 M (2008)	
Thraustochytrid sp.	Two cases of egg infection by an epiparasite during a broodstock research programme resulted in 100% mortality. Berried females were collected from the Ross River, South Townsville, Queensland, Australia. Sequencing of the unidentified parasite suggested similarities to *Dermocystidium* sp. and *Rhinosporidium seeberi*	–	Kvingedal *et al*. (2006)
(d) Indian white prawn, *Fenneropenaeus indicus* (Milne-Edwards, 1837) (syn. *Penaeus indicus*)			
Amyloodinium ocellatum	Mortality rates can reach 100% under laboratory conditions	–	Aravindan *et al*. (2007)

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Table 10. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
Gymnodinoides caridinae	Infection over the gills and appendages on post larvae results in a heavy accumulation of mucus on the gills with high percentages of resultant mortality	–	Aravindan *et al*. (2007)
Leptomonas-like parasite	Infections by an amoeboflagellate are reported to cause the mortality of protozoea and mysis in hatcheries at Narakkal, near Cochin, India. A total of 14 incidences throughout a 2-year period were reported with mortalities ranging from 70 to 90%. No mortalities were reported in naupliar and post-larval stages. Assuming that at least a single 1000 L larval culture tank stocked at 500 mysis L^{-1} were affected on each occasion, by applying an av. mortality rate of 80% and an est. current cost of US$ 2500 per 1 M mysis, then the 7 M mysis that were lost can be estimated	17 500	Sahul Hammed (1996)
Microspiridia sp.	The study reports that microsporidian infections represent a significant loss to the industry but does not specify whether reference is being made to aquaculture	–	Ramasamy *et al*. (2000)
Nitzschia closterium	Nine separate episodes of dinoflagellate infection between Jan and March 1986 in a commercial hatchery at Narakkal, near Cochin, India resulted in mortalities of between 75 and 100% of larval stock. No details relating to the culture system (other than the 1000 L size of the algal culture tanks) are provided. Assuming that at least three 1000 L larval culture tanks stocked at 500 post-larvae L^{-1} were affected on each occasion, by applying an av. mortality rate of 87% and current costs of US$ 3087–4322 per 1 M post-larvae, then the 11·745 M post-larvae that were lost can be estimated	36 256–50 762	Sahul Hammed (1995)
(e) Swimming crab, *Portunus trituberculatus* (Miers, 1876)			
Hematodinium sp.	A case of milky disease resulting in the high mortality of stock in July–Sept 2004 was reported from Zhoushan, Zhejiang Province	–	Xu *et al*. (2007*b*)
	Ten percent (n = 4) of the crabs (108–220 g; n = 40) sampled from polyculture sites along the Shandong Peninsula, coastal Southern China from July to Nov 2012 were found to be infected. These crabs were lethargic and had watery haemolymph. The experimental inoculation of 15 crabs found that the dinoflagellate was infectious and resulted in 60% mortality. Mortalities in this region of China have been reported since 2004, which contributes approx. a third of the industry's national income. If 10% mortality in the region is assumed, then between 2216 and 3688 t were lost each year between 2004 and 2012. Estimates are based on the harvest price of crab in 2004, i.e. US$ 3·00 kg^{-1}, and 2012, i.e. US$ 3·51 kg^{-1}	6·65–12·94 M p. a. (2004–2012)	Li *et al*. (2013)
	If it is assumed that production in the Shandong Peninsula represents a third of national production, then the total loss in production in the region can be calculated from 2004, when mortalities were first reported, to 2012 (the date of the study), using the harvest price for each year, i.e. a total loss of approx. 9331 t	31·63 M (2004–2012)	
	If losses in this region are representative of the losses throughout the industry, then over the period 2004–2012, a total of 83 982 t of production was lost	284·97 M	
(f) Kuruma prawn, *Marsupenaeus japonicus* (Spence Bate, 1888) (syn. *Penaeus japonicus*)			
Cothurnia sp.	Two 9000 m^2 ponds stocked with juvenile prawns (1·1–12·5 g) at 40 and 60 prawns m^2 were followed over a growth cycle. Infection on stock occurred with a prevalence of 76·7–84·7% with an av. 21·3–35·9 ciliates $gill^{-1}$ (range 0–116·2 ciliates $gill^{-1}$)	–	Hudson and Lester (1992)
Dermocystidium sp. + *Lagenidium* sp.	Infection resulted in the large scale mortality of hatchery reared shrimp within 2–3 days	–	Cook (1971 cited in Overstreet, 1973)

Ephelota sp.	Juvenile stocks (1·1–12·5 g) in two 9000 m^2 ponds in Brisbane Australia were followed over an extended growth cycle from Feb to Sept 1990. An average 0·3–0·7 ciliates $gill^{-1}$; prev. 12·0–16·7%; mean intensity 2·0–5·6 ciliates $gill^{-1}$, were recorded. Infections can cause larval stages to continuously flick their tails leading to fatigue and death (see Overstreet, 1987)	–	Hudson and Lester (1992)
Haematonectria haematococca (syn. *Fusarium solani*)	The agent responsible for black gill diseases can result in serious mortalities of pond cultured stocks	–	Bian and Egusa (1981)
Microsporidia sp.	Four 10 000 L tanks in Australia in 1997 were stocked with the progeny of spawners collected from the wild. Each tank had 1 M larvae (100 larvae L^{-1}), 92% of which had trailing faecal casts. Following the mortality of 60% first stage nauplii larvae, a subsequent histological investigation found multifocal hepatopancreatic degeneration and necrosis associated with basophilic staining bodies that resembled sporocyst stages of a microsporidian. Loss is est. on the mortality of 2·4 M larva using current value of *L. vannamei* nauplii in Thailand (as of May 2014), i.e. 10 000 THB (=US$ 309) per 1 M nauplii	742	Hudson *et al*. (2001)
Zoothamnium sp.	Infections on juvenile (1·1–12·5 g) stock in two 9000 m^2 ponds in Brisbane, Australia, stocked at 40 and 60 prawns m^2, were monitored over a growth cycle from Feb to Sept 1990. An av. 13·5–16·3 ciliates $gill^{-1}$ (range 0–85·4 ciliates $gill^{-1}$), prev. 67·3–87·3%; mean intensity 18·8–20·6 ciliates per $gill^{-1}$, were found. Although no direct losses were recorded in this study, large infections can cause stress and lead to mortality (see Overstreet, 1973)	–	Hudson and Lester (1992)
(g) Fleshy prawn, *Fenneropenaeus chinensis* (Osbeck, 1765) (syn. *Penaeus chinensis*)			
Paranophrys sp.	Ciliate disease has been reported in larvae and overwintering adults frequently causing 100% mortality in infected tanks. No details relating to the numbers of prawn lost or their value are available, however, loss can be estimated by applying contemporary prices for *L. vannamei* nauplii (1 M=US$ 309) and post-larvae (1 M=US$ 3087 to 4322), and, the harvest price for *F. chinensis* in 2012, i.e. US$ 4·00 kg^{-1} in China and US$ 16·69 kg^{-1} in South Korea	309 per 1 M nauplii; 3087–4322 per 1 M PL; 4000 to 16 685 t^{-1}	Bower *et al*. (1994)
(h) *Metapenaeus* spp., e.g. *Metapenaeus monoceros* (Fabricius, 1798) + *M. ensis* (De Haan, 1844)			
Orbione bonnieri	The study suggested that 10% of the shrimp produced in Thailand are infected with bopyrid isopods	–	Printrakoon and Purivirojkul (2012)
(i) Mud crab spp. e.g. *Scylla* (*paramamosain* Estampador, 1949)			
No details relating to major parasite-induced losses are available			
(j) Blue shrimp, *Litopenaeus stylirostris* (Stimpson, 1874) (syn. *Penaeus stylirostris*)			
Pleistophora sp.	In 1987, a culture facility in Baja California, Mexico had infections that rose from 2% to 10% over the period April–Nov 1987 resulting in the destruction of abdominal striated muscle. In the absence of harvest prices for Mexico, an av. price (i.e. US$ 9·23 kg^{-1}) is est. from sales in 1987 in Ecuador, i.e. US$ 7·20 kg^{-1}, in El Salvador, i.e. US$ 12·00 kg^{-1}, and, Panama, i.e. US$ 8·50 kg^{-1}	923 t^{-1}	Alarcon-Gonzalez (1990)

Table 11. The estimated economic cost of notable protistan and metazoan parasite events on other large-scale commercial aquaculture industries.

Parasite	Impact	Estimated loss (US$)	Reference
(a) Ascidiacea: sea pineapple, *Halocynthia roretzi* (Von Drasche, 1884)			
Azumiobodo hoyamushi	Over the past decade, the mortality of sea squirts attributable to soft tunic syndrome in the Tongyoung region of South Korea has ranged from 60% to 90%, i.e. 13 000–50 000 t of morts, accounting for a loss of 30 M	30 M	Han *et al.* (2012); Kim *et al.* (2014)
Kinetoplastid protistan	Production began in Korea in 1982 with 39 t, increasing to 42 800 t in 1994 but then decreasing to 4500 t in 2004 due to the mass mortality of stock during the winter season. Loss is based on the assumption that the production of 42 800 t could have been maintained and the yearly value of Korean stock (i.e. av. loss of 33 216 t p.a. or a total estimated loss of 564 671 t between 2004 and 2011	Est. total loss of 763·65 M from 1995 to 2011; av. loss of 44·92 M p.a.	Kumagai *et al.* (2010, 2011)
	Outbreaks were observed resulting in the mass mortality (17–100%) of stock at 3 farm sites throughout Miyagi Prefecture, Japan in 2007, 6 sites in 2008, and, 14 sites in 2009. Losses were primarily in 2 + and 3 + year-old individuals, occasionally in 1 +. Details relating to the magnitude of each loss were not provided but loss is given the price per tonne of Japanese stock in 2007–2009	Loss of 1102 t^{-1} in 2007; 1328 t^{-1} in 2008; and, 1465 t^{-1} in 2009	Kumagai *et al.* (2010)
(b) Cnidaria: edible jellyfish, *Rhopilema esculentum* (Kishinouye, 1891)			
No details relating to major parasite-induced losses are available, however, the studies of You *et al.* (2007) and Dong *et al.* (2009) provide comprehensive overviews of the Chinese *R. esculentum* aquaculture, with mortality details in the latter relating to the release of stock and thereafter			
(c) Echinoidea: Sea urchins: *Strongylocentrotus intermedius* (Agassiz, 1863) and the Dalian purple urchin, *S. nudus* (Agassiz)			
No major losses due to parasitic agents are recorded for these species; however, the mass mortality of *Strongylocentrotus droebachiensis* in Nova Scotia in 1982 is documented in the study of Scheibling and Stephenson (1984). Although the authors were unable to identify the specific cause of mortality, they refer to the findings of Li *et al.* (1982) and their suggestion that an amoeboid protist, tentatively identifed as *Labyrinthomyxa* sp., was the cause of an early mortality event. Further, recent mortality events in the same area have been attributed to the amoeba *Paramoeba invadens* (see Feehan *et al.* 2013)			
(d) Holothuroidea: Japanese spiky sea cucumber or Japanese sea cucumber, *Apostichopus japonicas* (Selenka, 1867)			
Fungi	Although infections between April and Aug each year are common in pond culture, they do not typically result in large-scale mortalities. Infected animals can appear discoloured and develop oedema. No details relating to loss are provided	–	Wang *et al.* (2004)
Boveria labialis	Large numbers are reported attaching to the inner wall of the respiratory tree of both young and adult specimens in offshore ponds (20 °C, 27 ppt) near Dalian, China. Infected animals are sluggish but infections do not generally cause a serious mortality problem. No figures of loss are provided	–	Wang *et al.* (2004); Long *et al.* (2006)
Platyhelminthes	Can cause heavy damage to the skin of both aestivated juveniles (1 + cm) and to adults leading to ulceration and death. Mortality rates of up to 90% within a month are reported. Loss is estimated on the harvest price of Chinese produced sea cucumbers in 2003, i.e. US$ 3·00 kg^{-1}	2700 t^{-1}	Wang *et al.* (2004)

losses are typically underreported, hiding the severity and true impact of certain parasites, e.g. *Amyloodinium, Cryptocaryon* and *Trichodina* spp.

Some parasitic diseases, whose continuous or predictably repeated infection levels and difficulty of treatment have caused major economic impacts, have driven particular industries to the point of near collapse. The impact that a kinetoplastid protist responsible for soft tunic syndrome has had on the ascidian *Halocynthia roretzi* industry throughout South Korea and Japan is an appropriate example (Kumagai *et al.* 2011). In Korea, infections have resulted in a serious decline in the industry from 42 800 t (valued at US$ 34·17 M) in 1994 to just 4500 t (worth US$ 8·92 M) in 2004 (Kumagai *et al.* 2010; FAO FishStatJ, 2013). Assuming that the 1994 levels of production could have been maintained in the absence of the flagellate, then it can be

Table 12. The estimated economic cost of notable protistan and metazoan parasite events on some of the world's leading marine and brackish water ornamental fish production industries

Parasite	Impact	Estimated loss (US$)	Reference
(a) Blue green damselfish, *Chromis viridis* (Cuvier) – Pomacentridae			
Cryptosporidium sp.	This is only a report of several infected *Chromis viridis* specimens, with the identification of new genotypes from aquarium fish	–	Zanguee *et al*. (2010)
Hysterolecitha nahaensis	*Chromis viridis* has been recorded to be infected by this digenean, but no details on the pathogenicity are reported	–	Barker *et al*. (1994)
Kudoa amamiensis	This species was described from several fish species, including *Chromis isharai* and *Chromis notatus*. Only one to 3 cysts, 2 mm long, were found to infect the skeletal musculature. Fish were collected from Amami-Ohshima and Okinawa coasts (Japan). No mortalities were reported, however, infected hosts were not marketable, due to the cysts distributed throughout the skeletal muscle. Fish response involved fibrous connective tissue surrounding the cyst	–	Egusa and Nakajima (1980); Moran *et al*. (1999)
(b) Clown anemonefish, *Amphiprion ocellaris* (Cuvier) – Pomacentridae			
Amyloodinium ocellatum	Mortality caused by this protozoan in aquarium conditions. Destruction of epithelial cells of the skin and the gills	–	Bower *et al*. (1987); Woo (2006)
Brooklynella hostilis	Acute mortality, skin discoloration, lethargy, inappetance, mucus hyperproduction	–	Lom and Nigrelli (1970); Fenner (1998); Noga (2010)
Cryptocaryon irritans	Acute mortality, white spots on the skin, ragged fins, skin discoloration, mucus hyperproduction	–	Colorni and Burgess, 1997
(c) Flame angel, *Centropyge loricula* (Günther) – Pomacanthidae			
Amyloodinium ocellatum	Infection report, no details on pathogenicity	–	Landsberg *et al*. (1994)
Uronema marinum	Reddish skin lesions with deep ulcers on *Centropyge flavissima*	–	Bassleer (1983)
(d) Sapphire devil, *Chrysiptera cyanea* (Quoy and Gaimard) – Pomacentridae			
Amyloodinium ocellatum	Infection report, no details on pathogenicity	–	Landsberg *et al*. (1994)
Cryptosporidium sp.	*Chrysiptera hemicyanea* has been found to be infected with *Cryptosporidium* sp., although no pathogenicity has been reported	–	Zanguee *et al*. (2010)
(e) Threespot dascyllus, *Dascyllus trimaculatus* (Rüppell) – Pomacentridae			
No details relating to major parasite-induced losses are available			
(f) Banggai cardinal fish, *Pterapogon kauderni* Koumans – Apogonidae			
No details relating to major parasite-induced losses are available			
(g) Spinecheek anemonefish, *Premnas biaculeatus* (Bloch) – Pomacentridae			
Uronema marinum	Skin lesions with deep ulcers and white patches	–	Bassleer (1983)
(h) Mandarinfish, *Synchiropus splendidus* (Herre) – Callionymidae			
No details relating to major parasite-induced losses are available			
(i) Whitetail dascyllus, *Dascyllus aruanus* L. – Pomacentridae			
Aponurus sp.	Digenean reported in the stomach with no pathogenicity details	–	Cédrik *et al*. (1998)
Haliotrema sp.	Monogenean reported in the gills with no pathogenicity details	–	Cédrik *et al*. (1998)
Hysterolecitha nahaensis	Digenean reported with no pathogenicity details	–	Barker *et al*. (1994)
Scolex polymorphus	Cestode report in the caecum with no pathogenicity details	–	Cédrik *et al*. (1998)
Tulinia microrchis	Report of this digenean on *Dascyllus aruanus* with no pathogenicity details	–	Barker *et al*. (1994)

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Table 12. (*Cont.*)

Parasite	Impact	Estimated loss (US$)	Reference
(j) Goldtail demoiselle, *Chrysiptera parasema* (Fowler) – Pomacentridae			
Kudoa amamiensis	This species was described from several fish species, including *Chrysiptera assimilis*. Only 1–3 cysts, 2 mm long, were found to infect the skeletal musculature. Fish were collected from Amami-Ohshima and Okinawa coasts (Japan). Infected hosts were not marketable, due to the cysts distributed throughout the skeletal muscle. Fish response involved fibrous connective tissue surrounding the cyst	–	Egusa and Nakajima (1980); Moran *et al.* (1999)
(k) Tomato clownfish, *Amphiprion frenatus* (Brevoort) – Pomacentridae			
Cladosporium sp.	Deep dermal ulcers reported on stock cultured in North Carolina (USA).	–	Silphaduang *et al.* (2000)
Uronema marinum	Skin lesions with deep ulcers and white patches	–	Bassleer (1983)
(l) Royal gramma, *Gramma loreto* (Poey) – Grammatidae			
No details relating to major parasite-induced losses are available			

estimated that infections have cost the Korean industry approximately US$ 764 M between 1994 and 2011 (Table 10). Infections at three Japanese farms were subsequently reported in 2007, which rose to 14 farms in 2009 (Kumagai *et al.* 2010).

Many of the instances of parasite infection provided in Tables 8–12 are derived from case reports for unexpected mortality events. These represent sporadic parasite infection events that have resulted in significant economic losses at a single or small number of sites or within a single season. For example, a *Uronema nigricans* infection of ranched southern bluefin tuna, *Thunnus maccoyii*, in Australia resulted in the loss of between 5 and 10% of stock, worth an estimated US$ 0·5–1 M (Munday *et al.* 1997). This illustrates that it is impossible to control parasite exposure in the wild phase, with stock typically belonging to mixed age classes and sizes and ranging over a wide area. As there is no standard crop, disease events are, thus, extremely unpredictable.

Many of the smaller magnitude, sporadic mortality events can be attributed to some of the less specific diseases, which can result from low water quality or poor fish handling and welfare and that might, therefore, be ameliorated simply through improved husbandry practices. Although most of these disease events go unreported, either because of the smaller scale of the losses incurred or the general acceptance that they fall within the typical, accepted margins of loss in production, their collective impact on global mariculture production is significant, and the value of fish lost may arguably exceed the economic impact of many of the major parasite pathogens listed in Tables 8–12. Deterioration in water quality can occur through overstocking, inappropriate feeding regimes, low water current speeds/poor flushing or generally poor site hygiene practices. For example, net fouling can result in organic enrichment within culture systems, facilitating the increase of many opportunistic species, which, if unregulated and unmanaged, can result in health impacts due to infection by low-specificity pathogens, e.g. *Trichodina* spp., *Zoothamnium* spp. Heavily biofouled cage nets can cause reduced flow-through rates resulting in increased retention times of infective stages, net deformation and welfare impacts for caged stock (Lader *et al.* 2008). Decreased flow rates can also result in lower dissolved oxygen and increased ammonia levels and in extreme events, the asphyxiation of stock (Douglas-Helders *et al.* 2003; Madin *et al.* 2010). Fouled nets may also serve as a reservoir for pathogenic agents such as *Paramoeba* (syn. *Neoparamoeba*) *pemaquidensis* (see Tan *et al.* 2002) and the polyopisthocotylean monogenean *Heterobothrium okamotoi*, which infects the gills of the tiger puffer, *Takifugu rubripes*, reared in floating cages. These flukes are extremely fecund with up to 1500 eggs *in utero* producing 50–360 spindle-shaped eggs per day that are extruded in strings of up to 2·8 m in length (Ogawa, 1997; Ogawa and Inouye, 1997; Ogawa *et al.* 2005*a*). These egg strings readily become entangled within the nets representing a source of reinfection that requires regular net changes to minimise the infection of stock (Ogawa and Inouye, 1997; Ogawa and Yokoyama, 1998; Ogawa, 1999; Ogawa *et al.* 2005*a*).

Looking through the timeline of parasite episodes, notably those detailed in Table 8, it is interesting to examine some of the underlying husbandry practices that were either directly responsible for or facilitated disease events and to consider whether the magnitude of the subsequent losses may have provided an impetus for change. Some of the earlier reports allude to the use of trash fish feed, e.g. *Kudoa amamiensis* in Japanese amberjack, *S. quinqueradiata* (see Egusa and Nakajima, 1978); the lack of health screening prior to the movement of stocks to new

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sites, e.g. the establishment of *Neobenedenia girellae* and *Paradeontacylix* infections on Japanese populations of farmed greater amberjack, *Seriola dumerili* (Ogawa and Egusa, 1986; Ogawa and Fukudome; 1994; Ogawa *et al*. 1995); improvements following the implementation of fallowing and site rotation, e.g. resulting in improved management of *L. salmonis* including a lower number of treatment interventions (Bron *et al*. 1993; Grant and Treasurer, 1993); a shift away from the use of multi-year class sites to an 'all in, all out' single-year class approach (Bron *et al*. 1993); and evident improvements in fish welfare practices, e.g. lower morbidity and mortality rates from *U. nigricans* in ranched tuna (Munday *et al*. 2003). The risks of infection from mixed-species sites have also been previously commented upon (Vagianou *et al*. 2006).

There are, however, a number of concerns associated with the expansion of global aquaculture, much of which is concentrated within the coastal zone, and the potential for an increased incidence of disease events. The human population is set to reach 9·55 billion by 2050 (United Nations, 2012) and there is a general migration towards coastal zones resulting in increasing population density (e.g. in 2000, 53% of the US population resided in 17% of the land area designated as coastal with an expected 24·4% increase in the size of the population residing in the US coastal states between 2000 and 2025 (Boesch *et al*. 2000)), and as a consequence of increased anthropogenic activity along the coastal zone, there will be increase in the levels of nutrients passing into local marine ecosystems and the impacts that these have upon the general marine environment and aquaculture in particular (Halpern *et al*. 2008; Callaway *et al*. 2012). Likewise, the greater globalisation of the trade in aquatic animals and their products, reviewed in Bondad-Reantaso *et al*. (2005), may facilitate the spread of pathogens into new environments. At the same time, in an era of changing climatic conditions, there will be alterations to land run-off, coastal water chemistry/temperature and changes in sea levels and oceanic/coastal currents all of which will have anticipated impacts on current aquaculture production practices, aquaculture systems, the interactions between wild and farmed aquatic stocks, parasite life cycles, transmission pathways and the prevalence and severity of disease events (Overstreet, 2007; Callaway *et al*. 2012). Cook *et al*. (1998) and Hofmann *et al*. (2001), for example, demonstrate links between increasing sea temperatures and the spread of *Perkinsus marinus* and *Haplosporidium nelsoni*, respectively, in the eastern oyster, *Crassostrea virginica*, as do Bermingham and Mulcahy (2004) who indicate that temperature is also an important risk factor in the incidence of amoebic gill disease. Although raised temperature profiles may accelerate the life cycle of some aquatic pathogens, it may also lead to the decreased prevalence of others as certain parasite species move out of their temperature optima. At the same time, increased water temperatures may preclude the use of certain drug treatment regimes requiring the development of novel strategies for the management and control of parasite pathogens (see Shinn and Bron, 2012).

This study provides a review of the top 69 aquatic species cultured in brackish and marine waters, which accounted for ~94% of the total tonnage derived from mariculture in 2011 and then provides estimates for losses incurred as a consequence of key parasite-associated disease events reported worldwide. Although it has not been possible to provide a single resolved value for the economic impact of parasites on global mariculture, this study clearly demonstrates that parasitic infections remain an important source of economic loss. Without a step-change in management priorities and a concerted move towards more IPMS, it is evident that as the global aquaculture industry grows and intensifies, the level of parasite infections will similarly rise as will the attendant economic costs of parasitism.

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