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Asian Shrimp Production and the Economic Costs of Disease

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Abstract

Using FAO aquaculture production statistics, the global production of cultured crustaceans for 2018 is predicted to be ~8.63 million tonnes. The growth of the shrimp industry, however, is impacted by episodes of disease resulting in huge national income losses (despite compensatory price rises in response to supply shortage), amounting to billions of dollars annually. To illustrate this, the current study reviews losses over the past 40 years and then focuses on current disease problems in Asia, notably AHPND (acute hepatopancreatic necrosis disease caused by pathogenic isolates of *Vibrio parahaemolyticus*), the microsporidian *Enterocytozoon hepatopenaei* (EHP), and WSSV (white-spot syndrome virus). The impacts of AHPND in affected countries, with particular focus on Thailand and the changes in the number of farm operators, land use and production, is investigated. The economic loss from decreased production is followed through the volume of product traded through Mahachai Market, one of Thailand's principal seafood markets, throughout 2010–2017 and is estimated to be US$ 7.38 billion with a further US$ 4.2 billion in export losses. Shrimp disease-related losses within the Vietnamese Mekong Delta were, in the absence of detailed production data, estimated using an assumption-based exercise. Losses due to AHPND in 2015 were determined to be >US$ 26 million, while the costs of WSSV in the same year were >US$ 11 million.

Keywords: acute hepatopancreatic necrosis disease, economic losses, *Enterocytozoon hepatopenaei*, shrimp disease, *Penaeus vannamei*, white-spot syndrome virus

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Introduction

Asia's combined aquaculture production currently exceeds 99.10 million tonnes and yet despite its 6.58 % per annum growth, it is marred by episodes of disease that continue to result in major economic loss. Asia's farmed shrimp and prawn industry, which consists of at least 18 classes of product as categorized by FAO (2017), is expected to exceed 5.37 million tonnes in 2018 (ave. 2010-2015; 4.91% year-on-year growth) compared to a global estimated production of 6.25 million tonnes based on a 5.15 % year-on-year growth (ave. 2010–2015; 22 shrimp-prawn groups).

However, national feed sales and aquaculture statistics, as independently verified by industry specialists, would suggest that the figures submitted for the People`s Republic of China, Indonesia and Viet Nam are over-estimated. By adjusting the production figures for these countries by using feed sales data, then global production in 2018 looks set to be ca. 4.15 million tonnes, of which 3.26 million tonnes would be produced in Asia. The disagreement in production figures lies in the manner in which the figures are compiled and edited by the different agencies. It is also dictated by local interpretations of what constitutes "production"; who is registered, who is required to register and what percentage of the industry is captured by registration; and the return rate and accuracy of submission data regarding output and land use versus submissions based on forecasting.

Shrimp production over the last four decades has been erratic and characterized by a series of apparent boom-bust cycles which have been shaped by a plethora of major disease events. Figure 1 presents year-on-year growth for both global and Asian production (1970–current) and additionally, begins to summarize some of the major disease outbreaks with the associated estimates of economic loss. Using the feed sales adjusted production data, it can be seen that there has been negative growth since 2010 (ave. -4.69 ± 2.16 %; 2010–2015), with the year-on-year growth notably plummeting to -8.10 % in 2014 at a time when the Thai production of whiteleg shrimp (*Penaeus vannamei* Boone 1931) was at its very nadir.

The graph highlights the effect of viral pathogens (e.g. yellow head virus – YHV, Taura syndrome virus – TSV and white-spot syndrome virus – WSSV) on production throughout the 1980s and 1990s, and then during the last five years, the impact of bacterial agents (e.g. isolates of *Vibrio parahaemolyticus* with a toxin gene-bearing plasmid responsible for acute hepatopancreatic necrosis disease (VP_{AHPND}); 2010–present) and the fungal microsporidian *Enterocytozoon hepatopenaei* (EHP). Although the final production statistics for 2016 and 2017 are still outstanding, the year-on-year growth for Asia for the period between 2010 and 2015 has been consistently negative. While globally, production averages are at -2.87 % per annum, for Asia, the annual growth appears to be -4.69 %.

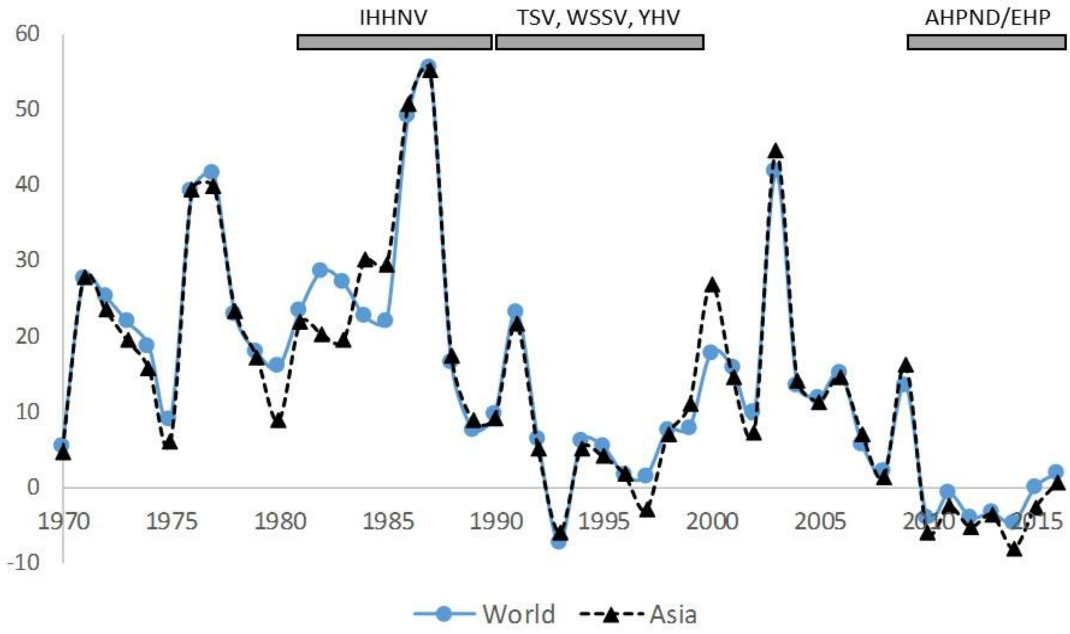


Fig. 1. The percentage year-on-year change in the growth of Asian and global shrimp production. Episodes of disease that have been a key factor in shaping growth of the shrimp aquaculture sector are summarized in Annex 1.[1,]

[1] Data from FAO FishStatJ (2017) and national feed sale figures (where available) are used.

[2]AHPND = acute hepatopancreatic necrosis disease, EHP = *Enterocytozoon hepatopenaei*, IHHNV = infectious hypodermal and haematopoietic necrosis virus, TSV = Taura syndrome virus, WSSV = white-spot syndrome virus, YHV = yellow head virus.

Using FAO FishStatJ statistics, Asia's entire crustacean aquaculture production, not just shrimp and prawns, is ca. 6.56 million tonnes (46 categories) of which 3.16 million tonnes is *P. vannamei* (based on the latest data available which is for 2015), an industry worth an estimated US$ 14.00 billion and employing >2 million people including casual or seasonal labour. It is estimated that the value of Asia's *P. vannamei* industry will rise to US$ 19.15 billion in 2018 when assuming an average year-on-year increase of 11.00% (2010-2015), while the value of the global whiteleg shrimp industry is expected to be US$ 26.48 billion when an average year-on- year growth of 11.90% is applied. Shrimp disease has, however, resulted in huge national income losses despite compensatory price rises in response to supply shortage, amounting to billions of dollars annually (Fig. 1).

AHPND and EHP-ASSOCIATED losses in Asia

The current disease status within Asia's shrimp aquaculture industry is summarized in Table 1, however, this study will focus principally on some of the economic losses associated with AHPND and, to a lesser degree, on EHP.

Table 1. Summary of the last known report of each significant shrimp disease in countries and territories in the Asia-Pacific Region.[1,2]

	Shrimp disease [4]										
	AHPND	**ASDD**	**ATM-WFD**	**BMGN**	**CMNV**	**EHP**	**HPD**	**HPH**	**IHHNV**	**IMNV**	**LSNV**
Australia	2016 [3]					2001?	2007		2015/16*		
Brunei Darussalam									2010		
China PR	2018		2014		2015	2018	2007		2016	2015	
Fiji									2007		
French Polynesia									2009		
India	2018?		2018	2003	2015	2018	2017		2017	2017	
Indonesia		2006	2014?			2016?	2007	2009/2016?	2015	2015	
Iran									2011		
Israel							2007				
Japan				2000							
Kuwait							2007				
Malaysia	2011/17*	2006	2014?			2017	2007		2015/16*	2012/16*	
Myanmar									2012/15*		
New Caledonia									2013		
Papua New Guinea									2010		
Philippines	2016						2007		2016	2015	
Republic of Korea				2000			2007		2015*	2015	
Singapore							2007				
Sri Lanka									2013	2007?	
Taiwan POC	2016*						2007		2013/16*		
Thailand	2018	2008	2018		2015	2018	2007		2015		2011
Viet Nam	2018		2018?			2018					

Table 1. Continued.

	MSGS	MVD	NHP	NPB	SHIV	SIMS	SB (PMTB)	TBV (BP)	TSV	WSSV	WTD (MrNV)	YHV
Australia		2007		2000		2006	2009			2018	2008/16*	2008
Bangladesh										2018		2015
Brunei Darussalam										2013	2013	2010
China PR					2018				2013	2015	2013	2015
Fiji		2007					2007	2007				
Hong Kong SAR										2013/16*		
India	2016*						2017		2017	2017	2012/16*	2006
Indonesia							2006		2013	2015		2011
Iran										2013		
Japan										2015/16*		
Malaysia		2007	2012/16*				2004	2004	2012/16*	2015/16*	2013/16*	2012/16*
Myanmar									2012/16*	2012/16*	2017	2012/16*
New Caledonia							2006					
Philippines						2006	2009			2016		2010/16*
Republic of Korea									2013?	2013/15*		
Saudi Arabia										2013		
Singapore							2008			2016		
Sri Lanka							2010			2013	2007	2013
Taiwan POC							2008	2008	2016	2013/16*	2012/16*	2013
Thailand	2011	2007			2018		2008		2013	2018	2015	2015
Viet Nam	2016*	2007	2013				2008			2018	2016*	2013/16*

[1]No data are available for other countries and territories in the region.

[2]Data are drawn from a variety of resources including NACA-OIE-FAO (2015–2017), Cefas (2018), and white and grey literature.

[3]*Abbreviations:* In Australia known as *Penaeus monodon* mortality syndrome (PMMS); * = not officially reported but the disease is known to occur.

[4]AHPND = acute hepatopancreatic necrosis disease; ASDD = abdominal segment deformity disease; ATM-WFD = aggregated transformed microvilli and white faeces disease; BMGN = baculoviral midgut gland necrosis; EHP (HP) = *Enterocytozoon hepatopenaei* (hepatopancreatic microsporidiosis); CMNV (CMD) = covert mortality nodavirus (covert mortality disease); HPD = hepatopancreatic parvovirus disease; HPH = hepatopancreatic haplosporidiosis; IHHNV = infectious hypodermal and haematopoietic necrosis virus (also now known as *Penaeus stylirostris* densovirus, PstDNV); IMNV = *Penaeus monodon*-type baculovirus; LSNV = Laem Singh virus; MSGS = monodon slow growth syndrome; MVD = mourilyan virus disease; NHP = necrotising hepatopancreatitis; NPB = nuclear polyhedrosis baculoviroses (reference here is made to MBV or *Penaeus monodon*-type baculovirus or more accurately to PmSNPV or singly enveloped nuclear polyhedrosis virus from *P. monodon*); SB (Pmtb) = spherical baculovirus (*Penaeus monodon*-type baculovirus); SHIV = shrimp hemocyte iridescent virus; SIMS = spawner-isolated mortality syndrome; TBV (Bp) = tetrahedral baculovirosis (*Baculovirus penaei*); TSV = Taura syndrome virus; WSSV = white-spot syndrome virus; WTD (MrNV) = white tail disease (also known as (*Macrobrachium rosenbergii* nodavirus, *Mr*NV); YHV = yellow head virus.

Acute Hepatopancreatic Necrosis Disease

AHPND of *P. vannamei* and of giant tiger prawn (*Penaeus monodon* Fabricius 1798) has had a devastating impact on shrimp production (see Pakingking et al. 2016) and is now reported from at least eight Asian territories (see Table 1), and from Costa Rica, Honduras and Mexico (Shinn et al. 2018). The impact of infection on production in the People's Republic of China, Malaysia, Mexico, Thailand and Viet Nam is presented in Fig. 2, with losses estimated on the farm-gate value of stock (i.e. values do not include losses to feed, processing, export and other support industries).

In Thailand, production fell from a peak of 611 194 tonnes in 2011 (Table 2) to ca. 200 000 tonnes by 2014/15; productivity fell from a peak of 11.19 tonnes.ha^{-1} in 2010 to only 6.14 tonnes.ha^{-1} in 2014 following the AHPND outbreak (Table 2). When pre-AHPND (i.e. 2009) production is compared to that in 2014 (last date for which comprehensive figures are available), then it can be seen that in addition to total production having dropped by 53.91 %, there were also 16.16 % fewer farms in production, and the land area used for shrimp culture was down by 10.45 % (Table 3; Fig. 3). To determine whether the losses estimated and presented for Thailand in Fig. 2 were accurate, the value of lost product was independently assessed by evaluating the volume and value of *P. vannamei* passing through Mahachai Market in Samut Sakhon Province, Thailand throughout 2010–2017.

Figure 4 shows the number of six-tonne containers passing through the seafood market on a daily basis, which when summarized and presented as annual trends (Fig. 5) shows that there has been a consistent yearly decrease in volume. This decline is particularly marked when the average for 2010–2012 is compared to that for 2013–2017 (Fig. 6). The daily price of the shrimp (number per kg; Thai baht (THB) per kg) was also tracked by following a LINE (a communication app) group hosted by the Thai Shrimp Centre and then used to define an accurate average farm gate price of product (Fig. 7), and consequentially the loss from the decreased volume of container traffic moving through Mahachai Market. From this, the consequential impact of the AHPND outbreak on the volume of shrimp passing through Mahachai Market (2010-2016) is estimated to be US$ 7.38 billion.

It should be stressed that not all this decreased trade can be attributed to only AHPND, and while AHPND may be responsible for a significant proportion of the losses, other concurrent shrimp infections also account for a percentage of the losses. The additional revenue lost on exported shrimp products was also determined by calculating the yearly difference in exported volume from its peak in 2010, and by looking at trend data relating to the value added to export data and the percentage of product that was exported (Table 4). From the data, the additional Thai export losses are determined to be US$ 4.2 billion. National losses to date are put at more than US$ 11.58 billion (2010–2016), with an estimated 100 000 jobs lost as a result of infections. A recent study conducted by Flegel and co-workers (Flegel 2016) looked at the causes of early mortality in 196 shrimp ponds in Thailand and confirmed AHPND by histology and polymerase chain reaction (PCR) within 21.4 % of ponds.

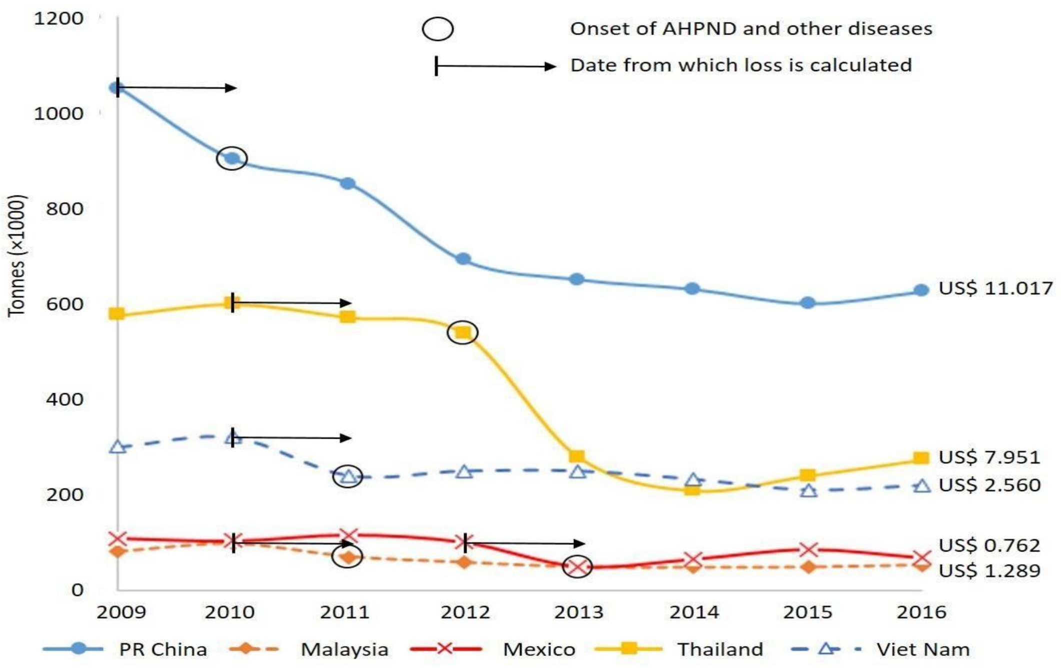


Fig. 2. Whiteleg shrimp (*Penaeus vannamei*) production and the subsequent losses (US$ billion) due to shrimp disease in countries in which AHPND has been reported. The first date of reported losses attributable to AHPND for each country is marked as a black circle, while losses are calculated from the black arrow. Data are drawn and averaged from three independent sources.

Table 2. Shrimp industry production data for Thailand over the period 2000 to 2014 giving the number of farms in operation, total land area used for culture (ha) and total shrimp production (tonnes) with details given for *Penaeus monodon* (*P.m.*) and *P. vannamei* (*P.v.*).[1,2]

Year	Farms	Area (ha)	Production (tonnes)	Tonnes.ha^{-1}	*P. m.* (tonnes)	*P. m.* tonnes.ha^{-1}	*P. v.* (tonnes)	*P. v.* (tonnes.ha^{-1})
2000	34 979	81 120	309 862	3.82	304 988	3.82		
2001	31 839	76 941	280 007	3.64	274 330	3.64		
2002	31 179	74 381	264 923	3.56	260 573	3.56		
2003	34 977	82 019	330 725	4.03	194 909	3.67*	132 365	4.58
2004	33 411	71 200	360 289	5.06	106 884	3.67*	251 697	5.98
2005	33 444	71 825	401 250	5.59	26 055	3.67*	374 487	5.79
2006	30 732	67 772	494 401	7.30	13 986	3.67*	480 061	7.51
2007	30 311	68 402	523 226	7.65	14 317	3.67*	508 446	7.88
2008	25 041	54 758	506 602	9.25	4 745	3.67*	501 394	9.38
2009	25 131	52 811	575 098	10.89	3 533	3.67*	571 189	11.02
2010	23 333	50 911	559 644	10.99	5 105	3.67*	553 899	11.19
2011	23 675	58 023	611 194	10.53	6 514	3.67*	603 227	10.72
2012	23 832	58 820	609 552	10.36	20 558	3.67*	588 370	11.06
2013	21 668	49 854	325 395	6.53	14 279	3.67*	310 705	6.76
2014	21 071	47 291	279 907	5.92	16 292	3.67*	263 245	6.14

[1]an asterisk indicates that no figures relating to the total area used for each species are available and so for 2003–2014, an average figure of 3.67 tonnes.ha^{-1} is assumed for *P. monodon* culture so that approximate production figures for *P. vannamei* (*P.v.* tonnes.ha^{-1}) can be determined.

[2]Data are extracted from the Fisheries Statistics of Thailand Yearbooks 2000–2014.

Updated Table 3

Table 3. A comparison of the number of farms, the land area used and the tonnage resulting from shrimp production in the main shrimp-producing provinces of Thailand in 2009 (pre-AHPND) and 2014 (on-going AHPND infection and for which the latest complete figures are available). Part of the data is drawn from the Fisheries Statistics of Thailand Yearbooks for 2009 and 2014. The "map code" follows that given in Fig. 3a.

		2009							2014						2009 versus 2014	
Map code	**Province**	**No. farms**	**Area (ha)**	**Total shrimp (tonnes)**	**Map code**	**Province**	**Farm no. (% diff)**	**Area (ha) (% diff)**	***P. vannamei* production (tonnes) (% diff)**	***P. monodon* production (tonnes)**	***P. vannamei* production (tonnes)**	**Map code**	**Province**	**Farm no. (% diff)**	**Area (ha) (% diff)**	***P. vannamei* production (tonnes) (% diff)**
	Coastal zone 1	2 565	7 635	132 271		Coastal zone 1	10.64	8.71	-49.91	305	65 749		Coastal zone 1	10.64	8.71	-49.91
1	Trat	690	2 029	46 935	1	Trat	-18.70	-26.92	-54.21	-	21 400	1	Trat	-18.70	-26.92	-54.21
2	Chanthaburi	1 500	3 916	64 336	2	Chanthaburi	28.33	47.49	-45.77	214	34 455	2	Chanthaburi	28.33	47.49	-45.77
3	Rayong	375	1 690	21 000	3	Rayong	-6.13	-38.34	-52.89	91	9 894	3	Rayong	-6.13	-38.34	-52.89
	Coastal zone 2	10 234	14 200	62 361		Coastal zone 2	-8.87	51.59	-21.55	2 792	47 882		Coastal zone 2	-8.87	51.59	-21.55
4	Chon Buri	146	168	600	4	Chon Buri	118.49	100.67	122.39	-	1 321	4	Chon Buri	118.49	100.67	122.39
5	Chachoengsao	7 350	5 810	32 617	5	Chachoengsao	-56.03	-50.42	-42.68	149	18 409	5	Chachoengsao	-56.03	-50.42	-42.68
6	Prachin Buri	400	800	2 970	27	2 943	431	758	4 408	-	4 408	6	Prachin Buri	7.75	-5.30	49.78
7	Samut Prakan	600	2 400	2 584	432	2 152	1 928	5 506	5 018	890	4 070	7	Samut Prakan	221.33	129.43	89.13
8	Bangkok Metropolis	197	515	106	29	48	936	2 525	951	508	443	8	Bangkok Metropolis	375.13	390.16	822.92
9	Samut Sakhon	800	2 317	10 071	50	9 774	1 291	4 233	10 968	191	10 771	9	Samut Sakhon	61.38	82.68	10.20
10	Samut Songkhran	291	1 326	1 215	0	1 215	423	2 838	1 529	145	1 296	10	Samut Songkhran	45.36	114.01	6.67
11	Phetchaburi	450	864	12 198	9	12 189	766	2 449	8 173	909	7 164	11	Phetchaburi	70.22	183.29	-41.23
	Coastal zone 3	3 521	12 788	128 154	546	127 608	1 360	3 679	41 641	2 117	39 524		Coastal zone 3	-61.37	-71.23	-69.03
12	Prachuap Khiri Khan	786	3 990	32 239	92	32 147	537	1 079	13 247	178	13 069	12	Prachuap Khiri Khan	-31.68	-72.96	-59.35
13	Chumphon	500	1 600	34 116	47	34 069	303	766	9 272	1 019	8 253	13	Chumphon	-39.40	-52.13	-75.78
14	Surat Thani	2 235	7 198	61 799	407	61 392	520	1 834	19 122	920	18 202	14	Surat Thani	-76.73	-74.52	-70.35

Table 3. Continued.

2009							2014							2009 versus 2014		
Map code	**Province**	**No. farms**	**Area (ha)**	**Total shrimp (tonnes)**	**Map code**	**Province**	**Farm no. (% diff)**	**Area (ha) (% diff)**	***P. vannamei* production (tonnes) (% diff)**	***P. monodon* production (tonnes)**	***P. vannamei* production (tonnes)**	**Map code**	**Province**	**Farm no. (% diff)**	**Area (ha) (% diff)**	***P. vannamei* production (tonnes) (% diff)**
	Coastal zone 4	4 205	7 864	97 059	405	96 654	2 757	3 442	31 100	1 592	29 508		Coastal zone 4	-34.44	-56.23	-69.47
15	Nakhon Si Thammarat	2 000	4 000	37 909	60	37 849	1 383	1 903	13 891	592	13 299	15	Nakhon Si Thammarat	-30.85	-52.42	-64.86
16	Songkhla	1 800	2 880	47 989	330	47 659	1 243	1 239	14 156	808	13 348	16	Songkhla	-30.94	-56.99	-71.99
17	Phatthalung	200	320	2 127	0	2 127	35	68	698	19	679	17	Phatthalung	-82.50	-78.85	-68.08
18	Pattani	200	640	8 624	15	8 609	90	203	2 183	173	2,010	18	Pattani	-55.00	-68.23	-76.65
19	Narathiwat	5	24	410	-	410	6	29	172	-	172	19	Narathiwat	20.00	20.00	-58.05
	Coastal zone 5	2 406	6 964	134 887	497	134 390	1 548	3 619	50 349	9 486	40 863		Coastal zone 5	-35.66	-48.03	-69.59
20	Ranong	150	694	8 032	0	8 032	111	553	9 264	1 012	8 252	20	Ranong	-26.00	-20.28	2.74
21	Phang Nga	376	1 285	30 329	39	30 290	239	666	9 026	1 298	7 728	21	Phang Nga	-36.44	-48.14	-74.49
22	Phuket	100	304	4 202	90	4 112	65	144	2 382	553	1 829	22	Phuket	-35.00	-52.79	-55.52
23	Krabi	330	1 010	24 274	58	24 216	290	591	8 661	2 463	6 198	23	Krabi	-12.12	-41.46	-74.41
24	Trang	850	1 769	34 000	293	33 707	475	746	11 219	2 851	8 368	24	Trang	-44.12	-57.86	-75.17
25	Satun	600	1 901	34 050	17	34 033	368	919	9 797	1 309	8 488	25	Satun	-38.67	-51.68	-75.06
	Others	2 200	3 360	20 366	130	20 236	3 242	6 725	39 719	-	39 719		Others	47.36	100.14	96.28
	Total	25 131	52 811	575 098	3 533	571 189	21 071	47 291	279 907	16 292	263 245		Total	-16.16	-10.45	-53.91

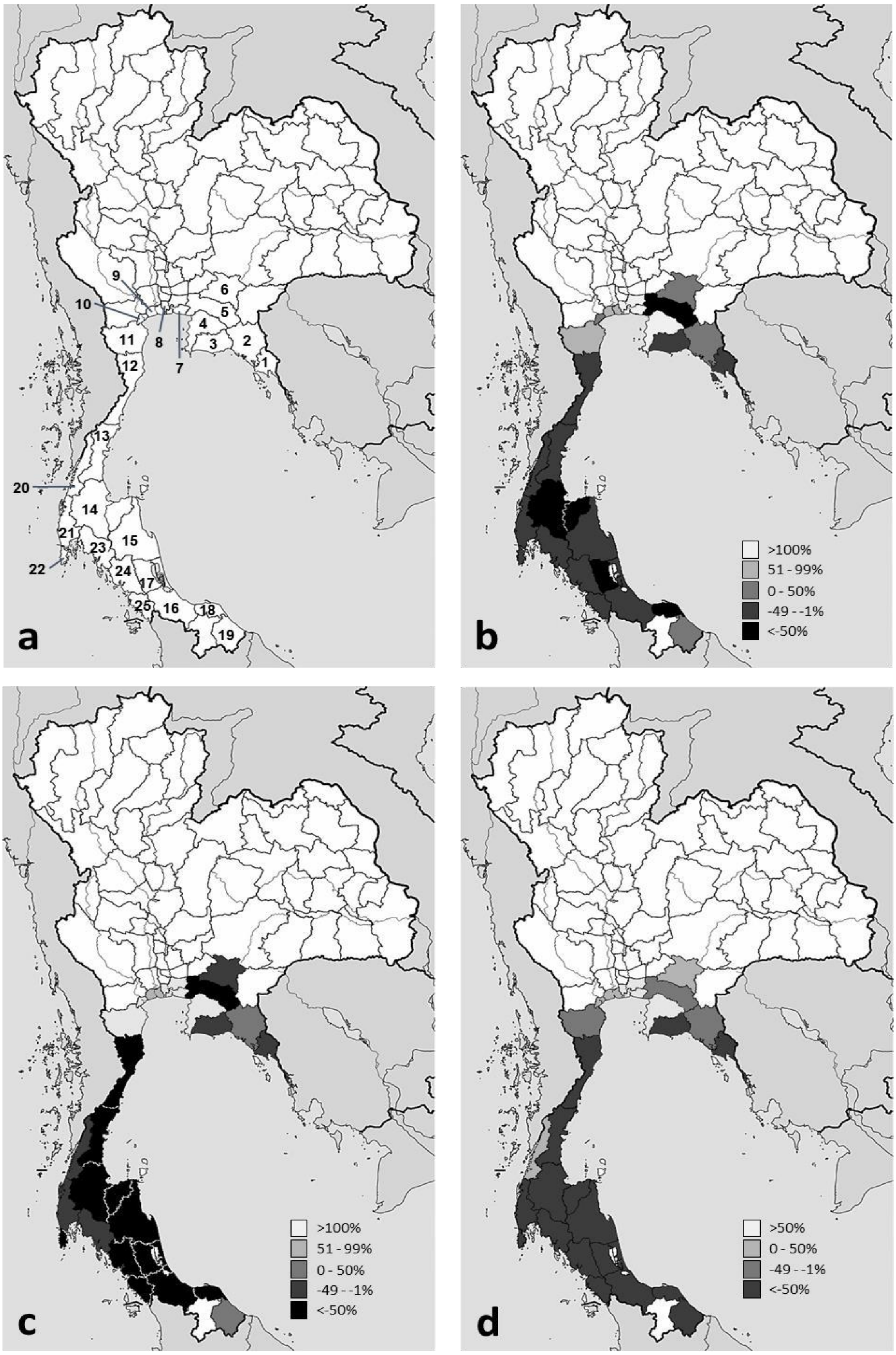


Fig. 3. Changes to the production of whiteleg shrimp (*Penaeus vannamei*) over the period of 2009 (i.e. pre-outbreak of AHPND) to 2014 (i.e. peak of infection) in the main farming provinces of Thailand. (a) The main provinces producing *P. vannamei.* (b) The percentage change in the number of registered farms producing *P. vannamei* in 2009 compared to that in 2014. The percentage change in the land area used for the culture of *P. vannamei* between that used in 2009 and that used in 2014.

For both (b) and (c) the observed changes range from over a 100 % increase to a 50+ % decrease in the number of farms or land area used for shrimp culture in 2009. (d) The percentage change in the total tonnage of *P. vannamei* produced in 2009 with that in 2014. Provincial figures range from a 50+ % increase to 50 % cut or lower in production.[1,2]

[1] 1 = Trat; 2 = Chanthaburi; 3 = Rayong; 4 = Chonburi; 5 = Chachoengsao; 6 = Prachinburi; 7 = Samut Prakan; 8 = Bangkok Metropolis; 9 = Samut Sakhon; 10 = Samut Songkhran; 11 = Phetchaburi; 12 = Prachuap Khiri Khan; 13 = Chumphon; 14 = Surat Thani; 15 = Nakhon Si Thammarat; 16 = Songkhla; 17 = Phatthalung; 18 = Pattani; 19 = Narathiwat; 20 = Ranong; 21 = Phang Nga; 22 = Phuket; 23 = Krabi; 24 = Trang; 25 = Satun.

[2] Data presented in Table 3 are used to construct the maps; the raw data are taken from the Fisheries Statistics of Thailand (2000–2014).

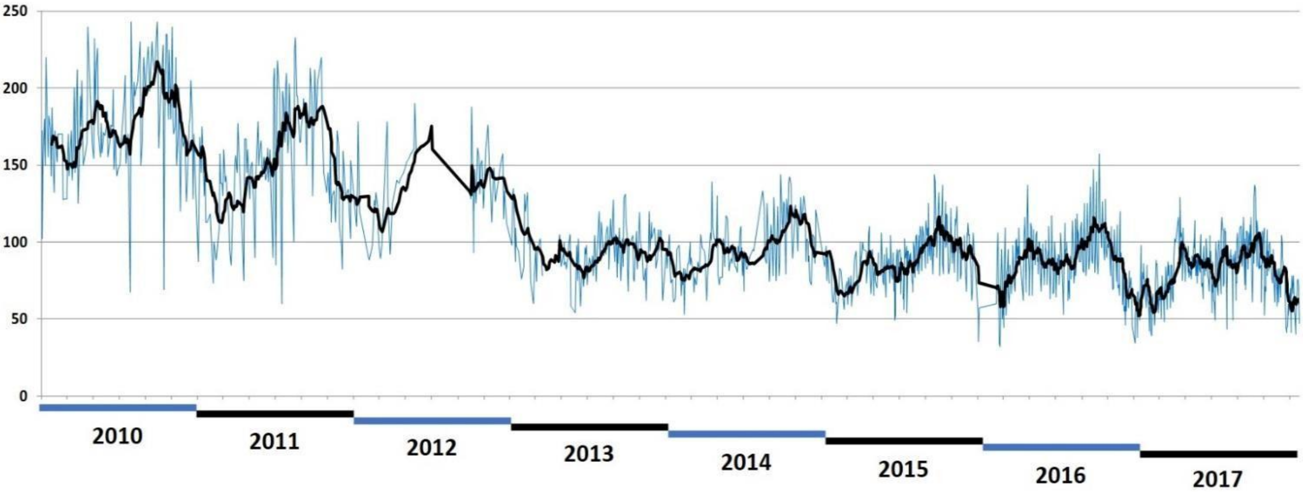


Fig. 4. The number of six-tonne containers passing through Mahachai Market in Thailand each day from January 2010 to December 2017.

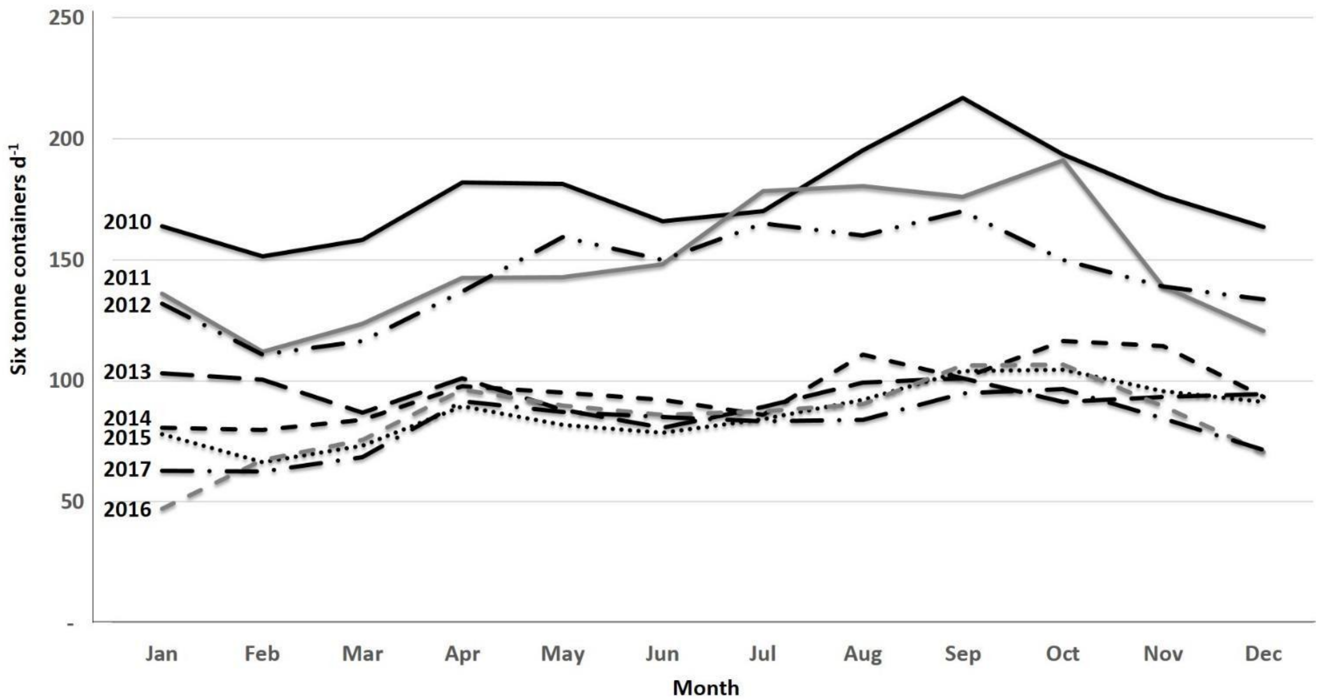


Fig. 5. Monthly summary of the number of six-tonne containers passing through Mahachai Market, Thailand throughout the period January 2010 to December 2017.

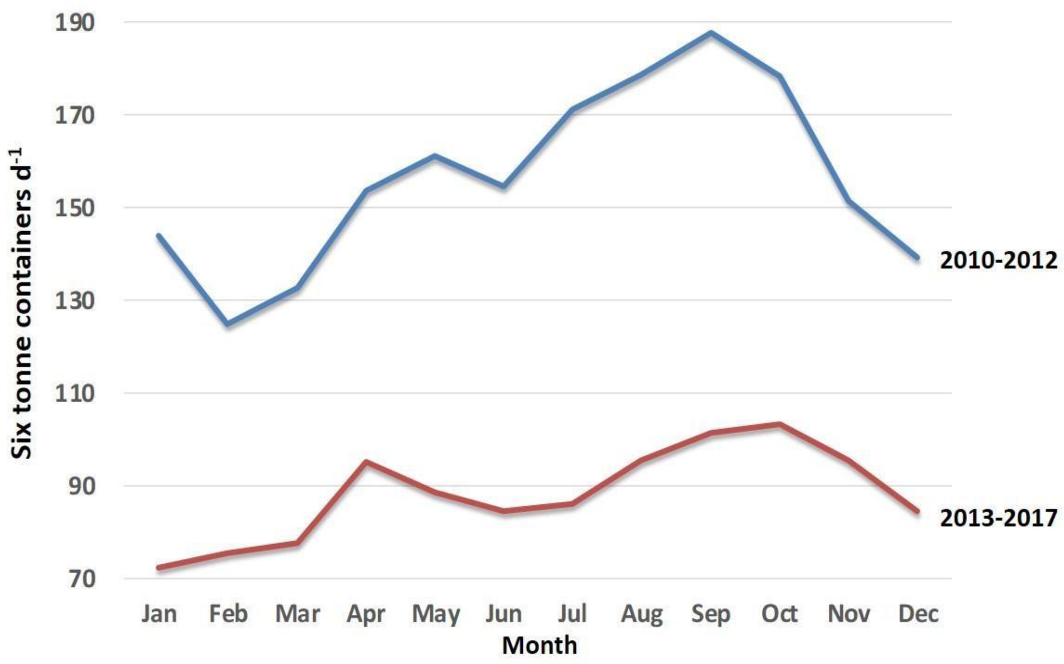


Fig. 6. The volume of six-tonne containers passing through Mahachai Market in Thailand in 2010 to 2012 compared to the decreased volume in 2013 to 2017.

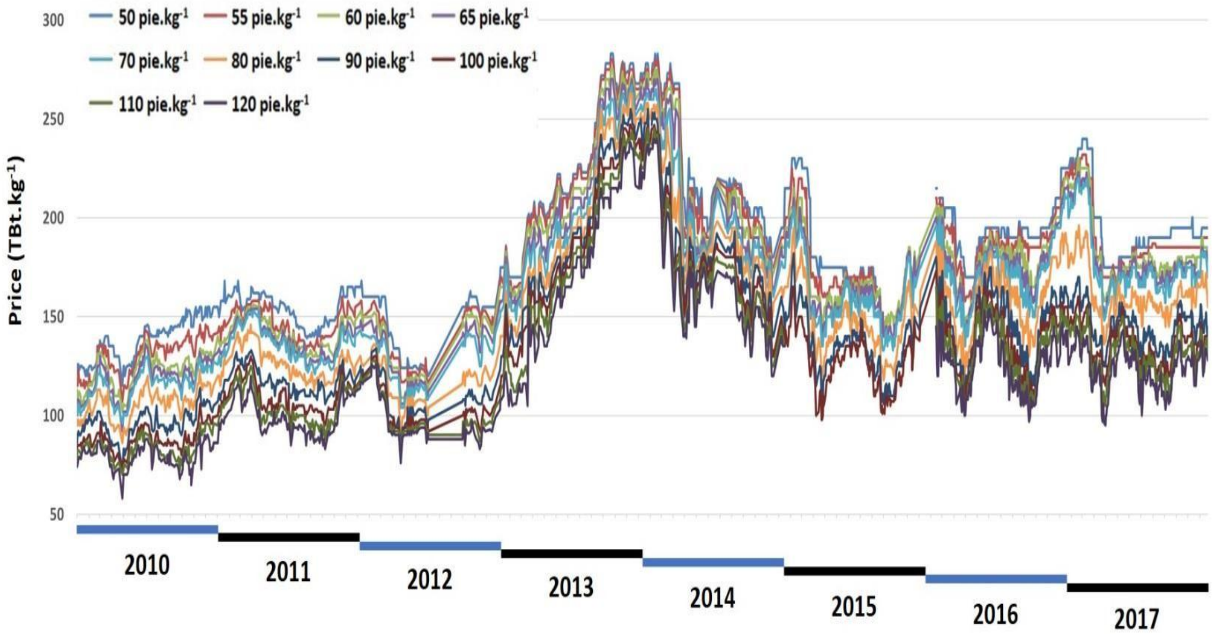


Fig. 7. Value of the shrimp pond bank in Thailand (US$ 1 = THB 31). The graph shows the daily price of the shrimp product (given as TBt.kg^{-1}; pie.kg^{-1}) fetched at Mahachai Market in Thailand throughout January 2010 to December 2017.

Table 4. The value of Thailand's national shrimp and prawn production and exports for the period 2005 to 2016. For each year, the volume (tonnes) of shrimp/prawns harvested from commercial fisheries and from aquaculture is given together with their total value and price per tonne. Following the outbreak of AHPND in 2012, the fall in production (i.e. volume and value) from aquaculture is given. The volume and value of exported product is also given and the subsequent loss in revenue following the AHPND outbreak and peak in trading in 2010 is given.[1]

	Year					
	2005	2006	2007	2008	2009	2010
Capture fisheries (tonnes)	81 569	75 782	63 201	53 991	54 682	54 420
Aquaculture (tonnes)	401 250	494 401	523 226	506 602	575 098	559 644
Tot. production of shrimp & prawns (tonnes)	482 819	570 183	586 427	560 593	629 780	614 064
Total value (US$ x 1000)	1 496 160	1 607 396	1 763 509	1 784 055	1 958 997	2 073 397
Value (US$ / tonne)	3 099	2 819	3 007	3 182	3 111	3 377
Lost tonnage from 2011 peak						
Value of lost tonnage (US$ x 1000)						
Exports						
Total volume of product exported (tonnes)	159 117	180 116	196 372	197 787	211 615	242 724
Total value of exports (US$ x 1000)	1 013 034	1 142 486	1 327 816	1 316 927	1 337 334	1 688 911
Value of export (US$ / tonne)	6 367	6 343	6 762	6 658	6 320	6 958
Percentage of production that is exported	32.96	31.59	33.49	35.28	33.60	39.53
Value added on exports (US$ / tonne)	3 268	3 524	3 755	3 476	3 209	3 582
Lost export tonnage from 2010 peak						
Add. revenue lost on exports (US$ x 1000)						
Exchange rates applied (1 US$ = x THB)	37.5	37.9	32.2	32.6	34.6	31.5

	Year					
	2011	2012	2013	2014	2015	2016
Capture fisheries (tonnes)	48 646	45 479	41 327	40 339	40 339	40 339
Aquaculture (tonnes)	611 194	609 552	325 395	279 907	240 000	273 000
Tot. production of shrimp & prawns (tonnes)	659 840	655 031	366 722	320 246	280 339	313 339
Total value (US$ x 1000)	2 702 321	2 647 785	2 041 367	1 773 972	1 552 911	1 735 711
Value (US$ / tonne)	4 095	4 042	5 567	5 539	5 539	5 539
Lost tonnage from 2011 peak		1 642	285 799	331 287	371 194	338 194
Value of lost tonnage (US$ x 1000)		6 637	1 590 907	1 835 132	2 056 193	1 873 393
Exports						
Total volume of product exported (tonnes)	202 339	178 850	92 062	75 447	70 085	78 335
Total value of exports (US$ x 1000)	1 740 168	1 458 605	918 860	880 734	818 137	914 444
Value of export (US$ / tonne)	8 600	8 155	9 981	11 674	11 674	11 674
Percentage of production that is exported	30.66	27.30	25.10	23.56	25	25
Value added on exports (US$ / tonne)	4 505	4 113	4 414	6 134	6 134	6 134
Lost export tonnage from 2010 peak	40 385	63 874	150 662	167 277	172 639	164 389
Add. revenue lost on exports (US$ x 1000)	181 928	262 729	665 076	1 026 101	1 058 993	1 008 387
Exchange rates applied (1 US$ = x THB)	30.2	31.1	31.3	32	34	35

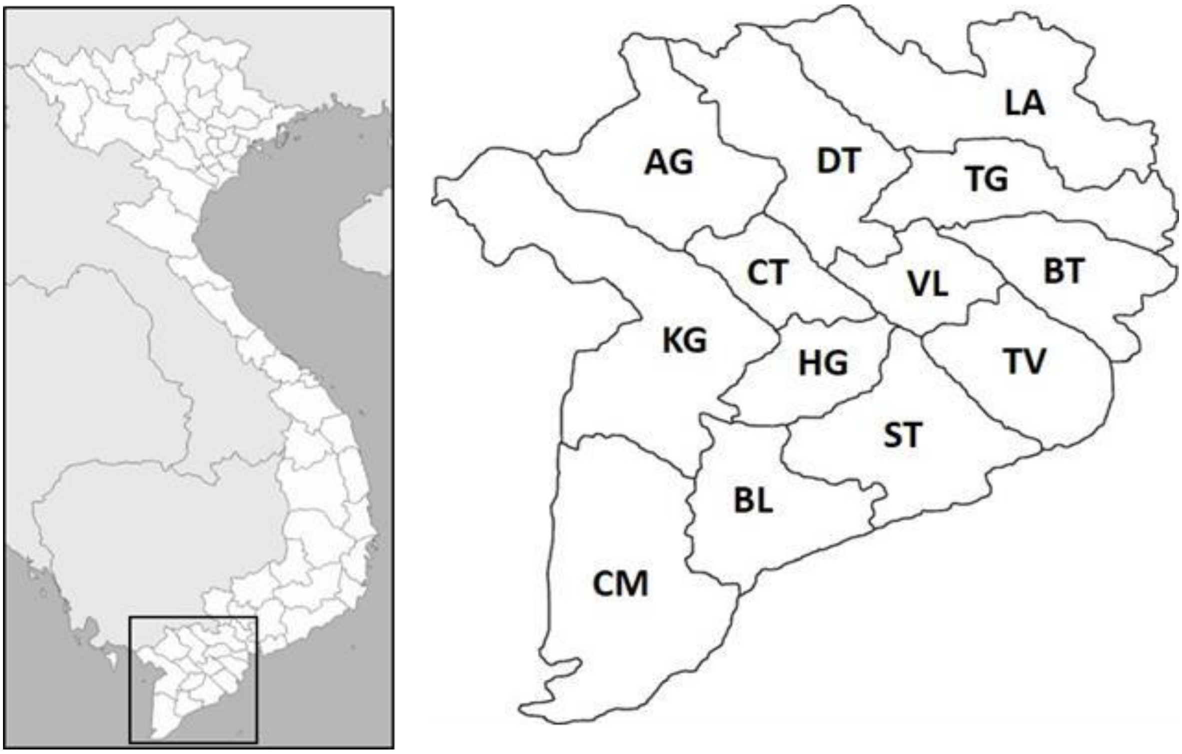
[1] Data drawn from various sources including the Fisheries Statistics of Thailand Yearbooks 2000–2014 and FAO (2016). No data for 2015–16 are available (shaded columns); predictions are estimated on selected parameters given for 2014.

Elsewhere, in the Vietnamese Mekong Delta, 8.72 % of *P. monodon* ponds (i.e. 47 574 ha) and 32.48 % of *P. vannamei* ponds (i.e. 18 966 ha) in 2014 were reported to have been affected by shrimp disease (Table 5). In 2015, the area of *P. monodon* ponds affected by AHPND was reported to be 5 875 ha, while a further 5 509 ha of ponds used for *P. vannamei* culture were infected. In the absence of detailed production data and information relating to losses, a series of assumptions based on national husbandry practices were used to estimate national losses (see Table 6).

In calculating the value of lost stock, it was assumed that only a single crop of shrimp was lost from any one pond in the year. From this, the combined AHPND-associated losses for both species were estimated to be over US$ 25.98 million for the year. Hien et al. (2016) also reported on the occurrence of AHPND within Viet Nam and suggested that losses were of the order of US$ 97.96 million (i.e. US$ 10 352 per tonne), however, no details relating to how the losses were calculated were provided.

White-spot syndrome virus (WSSV) still remains the most significant viral pathogen of cultured shrimp – infections are rapid and typically result in an 80–100 % loss of stock. Infections in 5 370 ha of *P. monodon* and *P. vannamei* culture ponds in the Mekong Delta in 2015 were determined using a similar series of assumptions based on local practices and estimated at US$ 11.02 million (Table 6). Again, these differ from those provided by Hien et al. (2016), who suggested WSSV associated losses were US$ 55.58 million.

Table 5. The area of shrimp ponds (ha) reported to be affected by shrimp disease in 2014 in the key shrimp-producing provinces of the Vietnamese Mekong Delta.



Code	Province	*Penaeus monodon*			*Penaeus vannamei*		
		Infected (ha)	Total (ha)	%	Infected (ha)	Total (ha)	%
AG	An Giang						
BL	Bạc Liêu	13 485	119 996	11.24	2 054	8 076	25.43
BT	Bến Tre	3 314	27 000	12.27	993	5 113	19.42
CM	Cà Mau	11 802	262 915	4.49	1 027	6 600	15.56
CT	Cần Tho						
DT	Đồng Tháp						
HG	Hậu Giang						
KG	Kiên Giang	7 325	88 648	8.26	14	1 915	0.73
LA	Long An	303	1 000	30.30	1 622	5 700	28.46
ST	Sóc Trăng	7 103	19 736	35.99	11 704	27 017	43.32
TG	Tiền Giang	151	2 599	5.81	414	1 380	30.00
TV	Trà Vinh	4 091	23 841	17.16	1 138	2 600	43.77
VL	Vĩnh Long						
Total		454	545 735	8.72	18 966	58 401	32.48

The figures presented here, however, are in marked contrast to the losses presented in Fig. 3 for Viet Nam, which indicates that since 2011, when AHPND was first reported in the country, shrimp disease including AHPND has cost the country US$ 2.56 billion (ca. US$ 437 million per annum). As already stated, caution must be exercised in that not all the reported losses can be ascribed to a single pathogen, i.e. VP_{AHPND}. The case study presented here begins to calculate losses for ponds where an infection of VP_{AHPND} was confirmed, using a conservative, very simple series of assumptions (i.e. only one crop from any one pond is lost; loss occurs within 40 days post-stocking; that the percentage of semi-intensive versus extensive ponds infected follows the national ratio; that the number of ponds with an infection is close to the actual situation; that the values assigned for each parameter are accurate). From this, however, there appears to be a huge underestimation in the calculation of loss. Such models, however, are dependent on the quality of farm data available.

With the addition of further details relating to, for example, the number of crops lost, confirmed diagnosis of the pathogen responsible for the loss, the stocking density used/degree of farm intensification, the point at which infection occurred and, the impact on the crop that was harvested etc., only then can we begin to design better models to compute the value of loss. For some studies, loss is simply estimated on the total pond area affected by pathogen "×" multiplied by the value of the expected tonnage to be harvested, which overestimates loss. Part of the challenge in calculating disease losses lies in: the sheer magnitude of the problem; the complexity of the data; untangling the complications of co-infections and assigning loss to particular pathogens; and, respectfully, a lack of resources to collate and process the data. While the approach used in this study attempts to provide loss estimates linked to primary production, calculating the additional losses through the value chain and to satellite industries adds further complexity.

Table 6. Losses due to acute hepatopancreatic necrosis diseases (AHPND) and white-spot syndrome virus (WSSV) in the Vietnamese Mekong Delta for 2015. Calculations are based on the assumptions provided and that only a single crop was lost. [1]

AHPND	
Penaeus monodon	***Penaeus vannamei***
5 875 ha affected	5 509 ha affected
Assumptions	Assumptions
38 % of production is semi-intensive; 62 % extensive	52.7 % of production is semi-intensive.; 47.3 % extensive
100 % of one crop up to 40 d poststocking lost	100 % of one crop up to 40 d poststocking lost
Stocking 15 PL.m^{-2} (semi.); 8 PL.m^{-2} (exten.)	Stocking 100 PL.m^{-2} (semi.); 70 PL.m^{-2} (exten.)
110 d production cycle	110 d production cycle
1 000 PL = $6.30	1 000 PL = $4.30
$Tmort_{50}$ = 20 days	$Tmort_{50}$ = 20 days
10 % per day increment in feed/growth	10 % per day increment in feed/growth
Feed = US$1.5 kg^{-1}	Feed = US$1.3 kg^{-1}
Labour = ca. 12.5 % of total production (US$5.77 ha.d^{-1})	Labour = ca. 12.5 % of total production (US$5.77 ha.d^{-1})
Farm gate price = US$7.65 kg^{-1}	Farm gate price = US$3.83 kg^{-1}
Harvest = 2.74 tonnes.ha^{-1} (semi.); 1.5 tonnes.ha^{-1} (exten.)	Harvest = 12 tonnes.ha^{-1} (semi.); 9 tonnes.ha^{-1} (exten.)
Loss = US$4 675 709	Loss = US$21 303 962
WSSV	
Penaeus monodon	***Penaeus vannamei***
3 447 ha affected	1 923 ha affected
Assumptions	Assumptions
38 % of production is semi-intensive; 62 % extensive	52.7 % of production is semi-intensive; 47.3 % extensive
2 % loss per day between 9 and 109 d poststocking	2 % loss per day between 9 and 109 d poststocking
Stocking 15 PL.m^{-2} (semi.); 8 PL.m^{-2} (exten.)	Stocking 100 PL.m^{-2} (semi.); 70 PL.m^{-2} (exten.)
110 d production cycle	110 d production cycle
1 000 PL = US$6.30	1 000 PL = US$4.30
10 % per day increment in feed/growth	10 % per day increment in feed/growth
Feed = US$1.5 kg^{-1}	Feed = US$1.3 kg^{-1}
Labour = ca. 12.5 % of total production ($ 5.77 ha.d^{-1})	Labour = ca. 12.5 % of total production ($5.77 ha.d^{-1})
Farm gate price = US$7.65 kg^{-1}	Farm gate price = US$3.83 kg^{-1}
Harvest = 2.74 tonnes.ha^{-1} (semi.); 1.5 tonnes.ha^{-1} (exten)	Harvest = 12 tonnes.ha^{-1} (semi.); 9 tonnes.ha^{-1} (exten.)
Loss = US$3 250 775	Loss = US$7 770 624

[1]Data are drawn from various sources including the Directorate of Fisheries Viet Nam, from Fistenet and from industry contacts.

Enterocytozoon hepatopenaei

Spreading infections of the fungal microsporidian parasite *Enterocytozoon hepatopenaei* (EHP), the causative agent of hepatopancreatic microsporidiosis (HPM) in shrimp, which is reported to result in severe growth retardation, morbidity and, in heavily infected individuals, mortality, is also causing serious concern within the industry. Infections in *P. vannamei* and *P. monodon* are reported from Australia, the People's Republic of China, India, Indonesia, Malaysia, Thailand and Viet Nam, where the parasite infects not only the tubule epithelial cells of the hepatopancreas as previously reported but is also found within the intestinal cells (J. Jiravanichpaisal unpublished data). Despite the growing number of reports of EHP, details relating to the economic impacts that this parasite has on production are scant. EHP spores are extremely small (ca. 1 × 0.67 μm), persistent and can be readily transmitted horizontally between shrimp. A Thai survey of 196 ponds reporting early mortality in stocked shrimp found EHP in 119 of the ponds (i.e. prevalence at 60.7 %; Flegel 2016).

The consequential slowed growth or growth arrest in heavily infected stock means that either the entire stock is lost (i.e. culled out if found to be heavily infected and ca. 7–9 g) or forces an early harvest, in which event the production costs may not be covered. Under normal production, a typical 110-day culture (i.e. PL10 to 18 g) with an anticipated harvest of 12 tonnes.ha^{-1} and a value of ca. US$ 5.30 kg^{-1} against production costs of ca. US$ 3.58 kg^{-1} might be assumed. For EHP-infected sites with poor or arrested growth, the shrimp may not grow beyond 12 g, resulting in a lower than anticipated harvest yield of 9 tonnes.ha^{-1}. The value of the harvested shrimp (e.g. at 12 g may fetch US$ 3.50 kg^{-1}) may be lower than the costs invested at this point in production, e.g. US$ 4.00 kg^{-1}. Under such circumstances, production costs are not covered and so losses per hectare may range between US$ 4 500 and US$ 32 100 over normal practice economics, depending on the proportion of stock affected and at what point the decision to harvest is made.

If, however, a 60.7 % level of infection remains a reflection of current infection levels and is applied across the Thai industry and an anticipated production for 2018 of 345 000 tonnes of *P. vannamei* is attained, then approximately 209 415 tonnes could be infected. If, however, it is assumed that 20 % of the value of this is lost as a consequence of undersized stock and a value of US$ 5 539 per tonne (see Table 4) is applied, then losses to the Thai economy, not including the additional consequential losses of feeding stock that have arrested growth, could be in the order of US$ 232 million per annum.

This estimate, however, requires substantiating through a structured survey and a comparative evaluation of industry production data between infected and uninfected sites. Elsewhere, an interview conducted with a farmer from India reported losses of ca. US$ 5 000 per ha, while another from Indonesia suggested that his EHP-related losses were US$ 7 538 ha^{-1}. The management and containment of EHP lies in strict biosecurity practices and regular disease testing.

The faeces from broodstock and/or larger shrimp can be screened for EHP spores either by molecular and/or by histochemical means, while batches of smaller-sized shrimp should be regularly screened by PCR at key steps in commercial production, e.g. on leaving the hatchery/nursery and before entering on-growing sites. Preventative measures against the acquisition and/or the establishment of EHP infections are discussed in Pakingking et al. (2016) and elsewhere in this volume.

International Movement of Live Stocks

The global aquaculture production of crustaceans for 2018 is estimated to be 8.63 million tonnes and includes 40 categories. Production for 2018 is forecasted from FAO FishStatJ data by applying an average 5.49 % year-on-year growth as seen for the period 2010–2015. This production is dominated by *P. vannamei*, which represents over 50 % of the volume produced, while *P. monodon*, ranking fourth behind Chinese mitten crabs, *Eriocheir sinensis* H. Milne-Edwards 1853, and red swamp crayfish, *Procambarus clarkii* (Girard 1852), represents less than 10 % of global production. *Penaeus vannamei* is currently produced in 35 territories (16 in Asia; 81.37 % by volume) based on countries providing returns to FAO in 2015 (FAO 2017) and is truly a pantropical species of major significance. Figure 8, which provides somewhat of a summary of its current distribution, maps some of the historical international movements linked to the culture of *P. vannamei*.

As key aquaculture species, i.e. those for human consumption and the ornamental trade, are exchanged globally, the inherent risks of pathogen transfer and introduction also increase with the number of translocation events and the volume of live species that are moved (Fig. 9). This is demonstrated by the global movement of Nile tilapia (*Oreochromis niloticus* Linnaeus 1758) and its parasite fauna into new territories (García-Vásquez et al. 2011).

There remains, therefore, concern regarding the movement of any shipment of non-native species into new environments and the rigour of biosecurity practices in detecting potential pathogen threats. Within the Sub-phylum Crustacea, crayfish are notorious invasive species (Ahjong and Yeo 2007; Gherardi and Acquistapace 2007). Worryingly, crayfish, e.g. *Procambarus* spp., are known to be hosts to chytrid fungus, *Batrachochytrium dendrobatidis*, a pathogen of global significance that is decimating amphibian populations (Crawford et al. 2010).

Their significance as potential vectors are evidenced by a recent survey of farmed and native populations of *Procambarus clarki* in Louisiana, United States of America where *B. dendrobatidis* was found at a low prevalence and intensity of infection that mirrored the seasonal patterns of infection seen within the local amphibian population (Brannelly et al. 2015). *Batrachochytrium dendrobatidis* has also been reported as an infection of the Malaysian giant freshwater prawn *Macrobrachium rosenbergii* (De Man 1879) (see Paulraj et al. 2016), however, this finding has been rejected after the results were found to be incomplete and inconsistent with previous descriptions of the pathogen (Pessier and Forzan 2017).

Fig. 8. International movement of *Penaeus vannamei*. The graphic summarizes the information listed in DIAS (2016) and is supplemented by additional reports from the literature. The information provided, however, is by no means complete and most likely captures less than 50 % of the movements that have taken place. The direction of the translocation is given, as is the natural range of *P. vannamei* – denoted by a red line.

Although there are no statistics on crayfish production for Thailand listed within the FAO FishStatJ database, there is an active aquaculture and ornamental industry. Two species have been introduced for aquaculture, namely *P. clarkii* (introduced from the United States of America ca. 1987, and the Australian red claw crayfish (*Cherax quadricarinatus* Von Martens 1868), which was brought in from Australia in 1995. Numerous other species of *Procambarus* and *Cambarellus* are commonly encountered on sale as ornamentals. Populations of *C. quadricarinatus*, for example, were introduced and raised in rice fields in Chiangmai Province as an initiative under a royal project (Srisaad and Thinkhaonoi 2015). Crayfish are now cultivated in several Thai provinces including Chiangmai, Chonburi, Khonkaen, Nakhon Ratchasima, Pathumthani, Prae, Srakaew and Supanburi. From these culture activities, however, wild populations of *C. quadricarinatus* have already established in Buriram, Chiangmai, Kanchanaburi, Sisaket and Sra Keaow provinces, while wild communities of *P. clarkii* are reported from the Kwaiyai and Kwainoy rivers in Kanchanaburi Province (Wanjit and Chaichana 2013). While FAO FishStatJ does not provide the details of which live species are being exported and imported, in general terms it would appear that the volume of live products being imported into Asia (see Fig. 9) is falling, while exports are rising. While this particular study does not enter into a discussion on the mechanisms and routes of pathogen introduction, the results presented in Fig. 9 highlight that there is still active traffic in the movement of live crustaceans and that vigilance and strict biosecurity measures at the regional, national and international levels (Galli et al. 2014a, b, 2015) must be upheld.

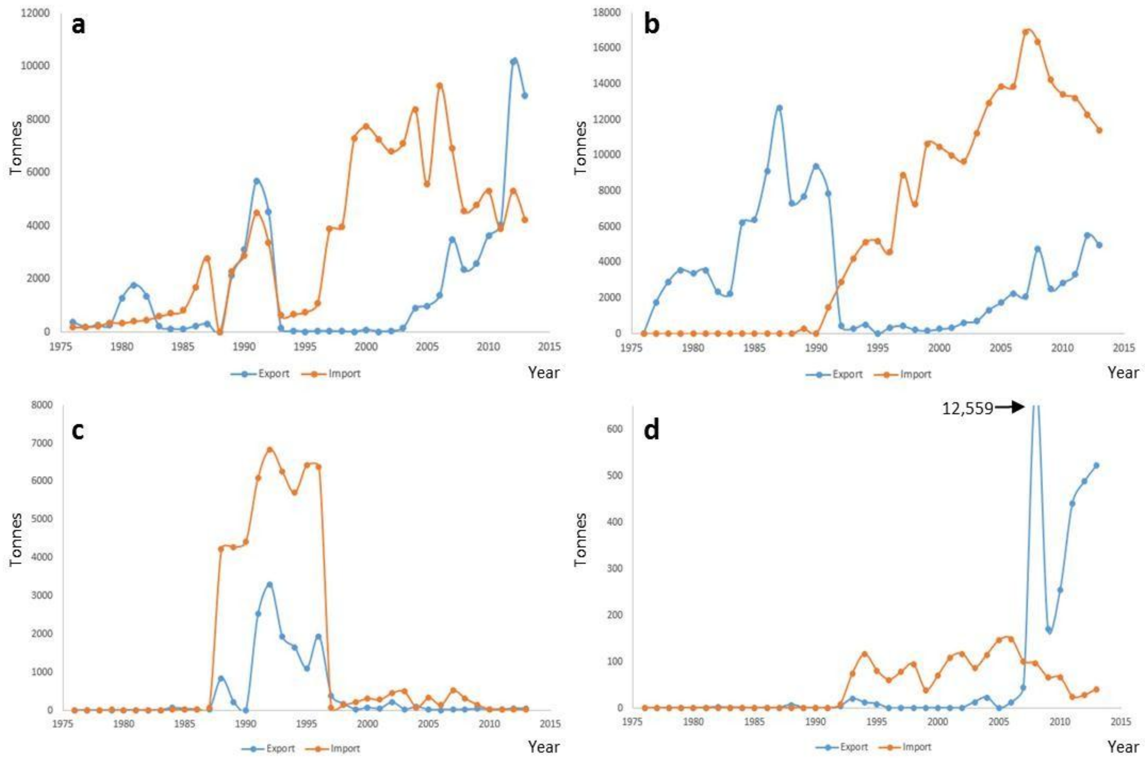


Fig. 9. The export-import trade of live crustaceans throughout Asia. (a) Trade in live prawns and shrimp; (b) trade in live crabs; (c) trade in live crustaceans for breeding etc.; and (d) trade in live crustaceans for human consumption. Data are drawn from FAO (2016).

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Annex 1

Some of the Disease Episodes that have been a Key Factor in Shaping Growth of the Shrimp Aquaculture Sector

Since 1981: Infectious hypodermal and haematopoietic necrosis virus (IHHNV) in the Americas (including the fishery in the Gulf of California) has cost the collective economies US$ 0.5–1 billion (Lightner et al. 2012). **1987–89:** Taiwanese *P. monodon* production crashes from 78 500 to 16 600 tonnes due to various factors including viral agents (Briggs et al. 2005). **1988:** *Penaeus monodon*-type baculovirus (MBV) infection of Malaysian *P. monodon* PL results in up to 100 % mortality (Yang et al. 2001); similar mass mortalities are reported in the Philippines (Albaladejo 2001). **1988:** MBV in Sri Lanka results in a 64 % drop in production (from 5.3 $tonnes.ha^{-1}$ to 1.9 $tonnes.ha^{-1}$) with a US$ 6 million loss in foreign income (Siriwardena 2001).

1990s: Taura syndrome virus **(**TSV) in Latin America results in losses of US$ 1–1.3 billion in the first three years (Briggs et al. 2005). **1990–1991:** Yellow head virus (YHV) is reported as causing extensive losses of *P. monodon* in Thailand (Briggs et al. 2005). **Since 1991:** YHV in Asia has resulted in US$ 0.5 billion of loss (Lightner et al. 2012). **Early 1990s:** YHV and white- spot syndrome virus (WSSV) result in losses in Indonesia, the Philippines and Thailand (Briggs et al. 2005). **1991–92:** TSV in the Americas results in ca. US$ 1–2 billion (Lightner 2003; Lightner et al. 2012). **1992:** TSV results in 30 % drop in Ecuadorian production from 100 000 to 70 000 tonnes; losses are estimated at US$ 400 million (Lightner, 1996). **1992:** Southern Thailand reports significant losses to YHV (Briggs et al. 2005). **1992:** WSSV reported from farmed *P. japonicus* (Spence Bate 1888) in Japan using PL imported from the People's Republic of China (Nakano et al. 1994). **1992/3:** Losses due to WSSV in Asia put at >US$ 6 billion and at US$ 1–2 billion throughout the Americas in 1999 (Lightner et al. 2012). Total collective losses, however, are estimated at US$ 15 billion (i.e. US$ 0.8 billion per annum – 5 % of the total harvest value of US$ 16.7 billion in 2010) (Lightner et al. 2012). **1992–1993/4:** Chinese production falls from 207 000 to 64 000 tonnes due to WSSV (Briggs et al. 2005). **1993:** WSSV affects 85–90 % of the *P. chinensis*, *P. japonicus* and *P. monodon* culture area in the Chinese provinces of Wenzhou, Xiamen, Jiangsu and Shanghai and 70–80 % of that in Shangdong, Liaoning and Hebei; national production falls by 60 %, i.e. a loss of 123 000 tonnes valued at US$ 250 million. WSSV epizootic in the People's Republic of China affects 1 million people (Jiang 2001). **1993:** MBV, WSSV and YHV induced losses in Viet Nam put at US$ 100 million (Khoa et al. 2001). **1993:** TSV infection at two Peruvian sites receiving PL from Ecuador results in US$ 2.5 million loss (Talavera and Vargas 2001). **1993:** Necrotising hepatopancreatitis (NHP) affects two-thirds of Peruvian shrimp culture area resulting in a ca. 50 % loss of sales valued at US$ 20 million. Five farms (450 ha) close (Talavera and Vargas 2001). **1994:** WSSV and TSV losses in Thailand put at US$ 240 million per annum but estimate of annual loss in 1997 rises to US$ 650 million per annum (Chanratchakool et al. 2001). **1994:** WSSV causes Chinese shrimp production to fall to 53 000 tonnes (Jiang 2001).

1994: Rosenberry (1993, 1994) and Lundin (1996) calculate and summarize shrimp disease losses (tonnes × 1 000; US$ million) as: Bangladesh (5; 25); People's Republic of China (180; 900); Ecuador (34; 170); India (25; 125); Indonesia (50; 250); Mexico (1; 5); Philippines (57; 284); Thailand (130; 650); Taiwan POC (100; 500); United States of America (4.5; 60); and Viet Nam (10; 50). **1994 *et seq.*:** WSSV suggested to cost Asian production US$ 1 billion per annum (Briggs et al. 2005). **1994–1995:** Two outbreaks of WSSV and YHV throughout India result in loss of 10 000–12 000 tonnes; the second episode valued at US$ 17.6 million (Mohan and Basavarajappa 2001). **1994–1996:** TSV in Honduras causes shrimp survival to drop to 15 %, reducing production by 18 % in 1994, 31 % in 1995 and 25 % in 1996 (Corrales et al. 2001). Honduran losses are calculated as a loss of 1 943, 1 868 and 3 278 tons in the three years priced at US$ 6.61, 6.61 and 7.02 kg^{-1} which equates to losses of US$ 12.84, 12.35 and 23.01 million. Losses resulted in an 18 % cut in labour costs (Corrales et al. 2001). **1995:** Viral infections throughout Andra Pradesh and Tamil Nadu, India result in a US$ 64 million loss (Hugh-Jones 1995). **1994–1996:** 80 % of Malaysian farms are hit by WSSV (Yang et al. 2001). **1994–1996:** Widespread WSSV infection in Bangladesh in almost all semi-intensive farms in Khulna (37 400 ha) and Cox's Bazaar; losses are estimated at 3 400 tonnes, US$ 10 million and 500 jobs. PL imported from Taiwan POC and Thailand are implicated as the source of infection (Rahman 2001). **1994–1998:** Mid Crop Mortality Syndrome (MCMS) costs the Australian industry US$ 32.5 million (Walker 2001). **1995:** WSSV outbreak in Nicaragua results in 5–10 % survival of stock (Drazba 2001). Assuming a 10 % survival, 2 305 tonnes were produced in 1995 valued at US$ 15 213 000 (i.e. US$ 6.60 kg^{-1}. Loss is estimated at 20 745 tons valued at US$ 136.92 million. **1995–1999:** Malaysian losses to WSSV are US$ 25 million per annum (Yang et al. 2001). **1996:** TSV detected in Panama. Infection results in a 285 tonne (i.e. 30 %) decrease in production (Morales et al. 2001). Panamanian losses are calculated at US$ 1.85 million (i.e. US$ 6.50 kg^{-1}). **1996:** WSSV puts 90 % of Sri Lankan farming units out of production valued at US$ 18.5 million in foreign income (Siriwardena 2001). **1996:** Lundin (1996) suggests total disease-related losses are 540 000 tonnes valued at US$ 3 billion; i.e. 40 % of total tropical production per annum (Stentiford et al. 2012). **1998–1999:** WSSV and YHV in Sri Lanka reduce the area for production to 9.5 % (i.e. 264 ha), of which 55.5 % was infected (Siriwardena 2001). **1998–2000:** WSSV causes shrimp exports from Ecuador to fall from 115 000 to 38 000 tonnes (Cámara Nacional de Acuacultura; Briggs et al. 2005). Ecuadorian losses are 77 000 tonnes with an av. shrimp price of US$ 5.28 kg^{-1} (1998-2000) which represents a loss of US$ 406.56 million. **1999:** WSSV in Panama results in loss of 4 400 tonnes (40 % of production) of *P. vannamei*; export loss is ca. US$ 40 million (Morales et al. 2001). The direct losses are estimated at US$ 23.23 million based on US$ 5.28 kg^{-1}. Nauplii production falls to 45 % of that in 1998. Only 29 % (2 638 ha) of ponds in operation. Infection results in direct loss of 1 500 jobs and a further 3 500 in ancillary services (Morales et al. 2001). **1999:** WSSV in Ecuador in first year causes loss of 63 000 tonnes (42 % of production) of *P. vannamei* and *P. stylirostris* (Stimpson 1871) worth US$ 280 million (Alday de Graindorge and Griffith 2001). **1999:** In Latin America, TSV in 1993 and then WSSV from 1999 result in direct losses of ca. US$ 0.5 billion per annum (Briggs et al. 2005). Losses to WSSV throughout the Americas are estimated at US$ 1–2 billion (Lightner et al. 2012). **1999:** WSSV infections in Honduras result in a 13 % reduction in the workforce (Corrales et al. 2001). **1999:** WSSV results in closure of 87.5 % of Peruvian ponds (i.e. 2 800 of 3 200 ha) (Talavera and Vargas 2001). Survival in affected ponds drops to 6–52 %

(Talavera and Vargas 2001). Peruvian production of whiteleg shrimp fell from 6 080 tonnes in 1997 to just 614 tonnes in 2000. If the entire loss is attributed to WSSV, then losses were 2 618 tonnes in 1998, 1 768 tonnes in 1999 and 5 466 tonnes in 2000. Using prices of US$ 6.83, 9.57 and 7.32 kg^{-1} respectively for the three years, then losses were US$ 74.76 million. **1999:** Kunang kunang disease (“fireflies’ disease”) caused by *Vibrio harveyi* affects 70 % of Indonesian PL production with resultant losses of ca. US$ 8.75 million (Rukyani 2001). **1999:** Indonesian shrimp crop failures are estimated at US$ 300 million to date. Approximately 90 % of hatcheries are affected by *V. harveyi*, with losses estimated at US$ 100 million per annum (Rukyani 2001).

1999: Shrimp disease losses in India are valued at US$ 100 million (Mohan and Basavarajappa 2001). **1999:** TSV imported from Latin America causes mortalities in Taiwan POC (Tu et al. 1999; Yu and Song 2001). **Since 1999:** TSV infections throughout Asia are estimated at US$ 0.5–1.0 billion (Lightner et al. 2012). **1999–2003:** WSSV losses in Ecuador are ca. 267 000 tonnes valued at US$ 1.8 billion. Results in loss of 26 000 jobs (13 % of labour force), closure of 74 % of hatcheries, 68 % reduction in sales and production for feed mills and packaging plants and 64 % lay off at feed mills. Indirect losses result in the loss of 150 000 jobs in the sector (Alday de Graindorge and Griffith 2001).

2000s

2001–02: Monodon slow growth syndrome (MSGS) infections in Thailand result in a loss of *P. monodon* valued at US$ 400 million (this study). **2001:** The Global Aquaculture Alliance estimates yearly losses of 22 % due to shrimp disease (60 % due to viruses, 20 % due to bacterial infections), i.e. US$ 1 billion per annum. **2002:** Shrimp disease costs the Asian shrimp industry an estimated US$ 400 million in direct losses (Briggs et al. 2005). **2002:** WSSV outbreaks in Cambodia result in losses of ca. US$ 14.5 million per annum (Tana and Todd 2002). **2002–2006:** Infectious myonecrosis virus (IMNV) in Brazil results in a US$ 100–200 million loss (Lightner 2011). **2004:** Losses due to IMNV throughout the Americas are put at US$ 100–200 million (Lightner et al. 2012). **1990–2005:** Losses due to shrimp disease are estimated at US$ 15 billion (Flegel et al. 2008). **2006:** Losses due to IMNV in Indonesia are estimated at US$ 1 billion (Lightner et al. 2012). **2008:** Kuruma shrimp losses in Japan are estimated at US$ 8.8 million (53 % due to vibriosis; 31 % due to WSSV; 16 % due to fusariosis) (Yuasa et al. 2016). **2009:** Early mortality syndrome/acute hepatopancreatic necrosis disease (AHPND) results in an 80 % loss of production in the Chinese provinces of Fujian, Guangdong, Guangxi and Hainan (Leaño and Mohan 2012). **2010**: IMNV-associated losses in Brazil to date were expected to exceed US$ 1 billion (Lightner et al. 2012).

2010 onwards

2011: AHPND infections in Malaysian *P. vannamei* are estimated at US$ 100 million (FAO 2013). **2011:** Vietnamese Mekong Delta, unprecedented losses in 40 000 ha of *P. monodon* ponds. In Bac Lieu, over 11 000 ha used for shrimp culture are destroyed. The loss of 330 million shrimp in 6 200 ha of ponds in Tra Vinh is valued at US$ 0.6 million. Loss of ca. US$ 75 million worth of *P. monodon* stock in 20 000 out of 25 000 ha of ponds in Soc Trang Province, Viet Nam is attributed to AHPND (Lyon et al. 2013). **1981–2012:** Estimate of disease losses in cultured shrimp is US$ 12–19 billion (Lightner et al. 2012). **2012:** Stentiford et al. (2012) estimate that the top five viral pathogens (i.e. IHHNV, IMNV, TSV, WSSV and YHV) result in an annual loss of 15 % of production valued at US$ 1.5 billion. **2011–2013**: Prevalence of AHPND in Malaysia throughout 2011–2013 was 50 %, 26 % and 73 % (Kua et al. 2016). **2011–2014:** Total production losses in Malaysia to AHPND are estimated at US$ 490 million (Kua et al. 2016). **2010–2016:** Shrimp disease in Thailand results in direct losses of ca. US$ 7.4 billion with a further US$ 4.2 billion in export losses (this study).

2010–2016: Collective losses due to AHPND and other shrimp diseases throughout the People's Republic of China, Malaysia, Mexico, Thailand and Viet Nam are estimated at US$ 23.6 billion (i.e. 4.8 million tonnes; this study) with a further loss of US$ 7 billion in feed sales (this study); export losses are estimated at US$ 13.4 billion (this study). Infection losses account for 40 % of the value of the total harvest in 2016, i.e. US$ 10.3 billion (this study). **2014:** Data for the Mekong Delta indicate that 8.72 % (i.e. 47 574 ha) and 32.48 % (i.e. 18 966 ha) of the area used for the culture for *P. monodon* and *P. vannamei*, respectively, were affected by episodes of disease (Directorate of Fisheries Viet Nam; this study). The production of *P. monodon* is 17 561 tonnes lower than in 2013, valued at US$ 8.78 million (this study). **2015:** Vietnamese Mekong Delta – Hien et al. (2016) estimate losses due to AHPND to be US$ 97.96 million and US$ 55.58 million for WSSV. **2015:** In the Vietnamese Mekong Delta, 5 875 ha used for *P. monodon* culture and 5 509 ha used for *P. vannamei* are recorded as being infected with AHPND (Hien et al. 2016). Losses are put at US$ 4.7 million and 21.3 million, respectively (this study). A further 3 447 ha used for *P. monodon* and 1 923 ha for *P. vannamei* experience episodes of WSSV (Hien et al. 2016). Losses are estimated at US$ 3.3 million and 7.8 million, respectively (this study). **2016:** Annual shrimp losses in Indonesia are estimated at US$ 298.4 million (US$ 191 million for WSSV; US$ 95.6 million for IMNV; US$ 7.6 million for vibriosis) (Hastuti and Haryadi 2016). **2016:** Losses due to *Enterocytozoon hepatopenaei* (EHP) in Thailand are not known but it is speculated that they could be as high as US$ 180 million per annum (this study). **1980–2016:** Collective losses due to shrimp disease to date are estimated at US$ 42 billion (direct losses), US$ 24 billion (export losses) and US$ 13 billion (feed sales) (this study). **2018:** EHP-related losses in Thailand could be as high as US$ 232 million per annum (this study). Indian state authorities report that 21% of farms in Andhra Pradesh are infected with EHP.