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Review article

A global review of seahorse aquaculture

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ABSTRACT

Seahorses (*Hippocampus* spp.) are flagship species for many issues in marine conservation including overexploitation, incidental bycatch and habitat loss. Aquaculture has been proposed as one solution to address unsustainable trade for traditional medicine, aquarium fishes and curios. Here we review historical and current information on global seahorse aquaculture including characteristics of aquaculture operations, species in culture, contribution to international trade and technical issues associated with raising seahorses in captivity. We found that prior to the 1990s, seahorse aquaculture was plagued by problems with disease and feeding. In the late 1990s and early 2000s there was considerable expansion in the number and size of aquaculture operations and the number of species in culture. This was reflected in an increasing contribution of captive-bred seahorses to the aquarium trade but not in the larger traditional medicine market. Currently, the majority of seahorse aquaculture involves small-scale operations in developed countries, employing relatively few personnel and selling live animals for the home aquarium market. Although, there are still considerable technical problems with diseases and with breeding and raising some species, others are performing successfully in aquaculture. There are currently at least 13 species in commercial culture or under research for their culture potential. However, economic viability remains a concern to many current aquaculture operations including price competition with wild-caught animals. Large-scale aquaculture to supply the traditional medicine market or as a livelihood venture has not yet been demonstrated to be commercially viable, although it is being actively researched.

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1. Introduction

World aquaculture (food fish and aquatic plants) has grown significantly during the past half-century. From a production of below 1 million tonnes in the early 1950s, production in 2006 was reported to have risen to 66.7 million tonnes (51.7 million tonnes excluding aquatic plants, with a value of US$85.9 billion (US$78.8 billion excluding aquatic plants) (FAO, 2008). In 2006, countries in the Asia and the Pacific region accounted for 89% of the production quantity and 77% of the value. There are signs that the rate of growth for global aquaculture may have peaked, although high growth rates may continue for some regions and species (FAO, 2008). Aquaculture for the aquarium hobbyist trade, however, is a rapidly growing sector of the industry (Tlusty, 2002) and there is directed effort and increasing pressure within the ornamental trade to develop reliable and sustainable hatchery procedures for the captive breeding of many reef fish species (Moe, 2003; Wabnitz et al., 2003). The value of the world ornamental imports has increased markedly too, from US$50 million to US$250 million over the past two decades (Olivier, 2003).

Over half of all aquaculture production of fish, crustaceans and molluscs is from the freshwater environment, with 34% coming from mariculture and the remainder from brackish systems (FAO, 2008). These figures are even more skewed for ornamental aquaculture, with approximately 90% of freshwater fish cultured (Dawes, 1998), but only 2% of marine ornamentals coming from aquacultured sources (Moe, 2001). Marine ornamentals offer higher value per kg (Hoff, 1996), but their aquaculture is considerably less advanced and sources of commercial quantities of marine species have been slow to develop (Moe, 2001). It has been estimated that 100 of the 800 marine species traded in the pet industry are routinely bred in captivity (Dawes, 1999), with only 21 of these species being commercially feasible (Schiemer, 2001).

Ornamental fish aquaculture has many similarities to food fish aquaculture (Tlusty, 2002). Food production aquaculture is often criticized as having a goal of creating a high-value end product that does not significantly add to overall global food supplies (Naylor et al., 2000). Similarly, the ornamental fish industry produces a luxury item and fish keeping is a hobby that is practiced mainly in industrialized countries (Olivier, 2003). Between 1.5 and 2 million people worldwide are believed to keep marine aquaria (Wabnitz et al., 2003) with the main importing countries being the United States, Japan and Europe (particularly Germany, France and the United Kingdom). However, as opposed to other luxury items but similar to aquaculture production in general, the ornamental fish industry can have, under the proper developmental scenario, a positive impact on the global economy, particularly in less developed areas (Tlusty, 2002). Over 50% of the world's supply of ornamental fish comes from Asia (Olivier, 2003), and 60% of the fish in this industry originate from developing countries (Bartley, 2000).

In general, the benefits of aquaculture are considered to be increased global production of food, lessened impacts on wild stocks, more efficient production, and economic support of smaller coastal communities, and the production of both juvenile and market-size fish of a wide variety of species year round (Landau, 1992; New, 1996; Olsen, 1996; Pillay, 1996; Wabnitz et al., 2003). However, there are also numerous well-documented detrimental effects on the environment over the past few decades (e.g. Eng et al., 1989; Páez-Osuna, 2001; Grosholz, 2002; Gyllenhammar, and Hakanson, 2005; Utter and Epifanio, 2002; Primavera, 2005; Pullin and Sumaila, 2005; Weir and Grant, 2005). The risks from food fish aquaculture include nutrification of water bodies, addition of antibiotics and other chemicals to the ecosystem, introduction of non-native species, user conflicts, impacts on wild fish stocks through sourcing of broodstock or harvesting for fish meal production and consequent effects on wild predators (Raa and Liltved, 1991; Goldburg and Trippet, 1997; Kautsky et al., 1997; Naylor et al., 2000). Although generally unstudied, most of these benefits and risks apply to the aquaculture of ornamental species.

To achieve sustainable aquaculture, environmental impacts on water quality and use, land use, biological pollution, feeds, diseases and treatments and escapes need to be recognized and minimized (Boyd et al., 2005). Sustainability can only be attained when environmental conditions are appropriate and maintained, and this includes ecological, socio-anthropological and economic aspects of the environment (Frankic and Hershner, 2003; Dempster et al., 2006; Pomeroy et al., 2006). Aquaculturists, especially those working at the production level, often have little knowledge about the environmental and social issues related to aquaculture (Boyd et al., 2005). However, there are a comprehensive set of policies and associated regulatory frameworks that are emerging that support sustainable aquaculture (Frankic and Hershner, 2003). In addition, there is a move to develop codes of practice (Boyd, 2003), international principles (FAO et al., 2006) and certification and ecolabelling schemes (Boyd et al., 2005; Yamamoto, 2007) for aquaculture production facilities, in response to the concerns about negative environmental and social impacts, as well as food safety. Such certification schemes require development through the involvement of stakeholders and verification by independent certification companies. The Marine Aquarium Council (www.aquariumcouncil.org) has now developed such standards for marine ornamental aquaculture: The Mariculture and Aquaculture Management (MAM) International Standard addresses the propagation, collection, and culturing of marine aquarium organisms, and specifies requirements from broodstock/post-larvae receipt through to grow-out for market; packaging and transport of cultured marine ornamentals. Such certification schemes will help ornamental aquaculture companies to meet internationally defined and recognized standards and promote sustainable practices.

Aquaculture involves a huge diversity of production systems which range from intensive systems where all food is provided, to extensive aquaculture where predators and competitors are controlled. In each case, the benefits and risks need to be understood, but criticism has particularly focussed on intensive systems in coastal areas e.g. shrimp and salmon farming (Naylor et al., 2000; Naylor and Burke, 2005; Primavera, 2006). Ornamental aquaculture tends to be conducted in closed tank systems or ponds, often in developed areas where there is sufficient capital investment for infrastructure development and close to an airport for easy transportation (Tlusty, 2002). Elucidating the position of ornamental fish production in the overall aquaculture scheme will assist in determining where further development would be most beneficial, and where it should be developed cautiously.

2. Seahorses — a case study

Seahorses, *Hippocampus* spp., are highly unusual marine fishes that have provided a focus for global conservation efforts. Their unique body morphology, with horse shaped head, large eyes, curvaceous trunk and prehensile tail, has made them charismatic icons for issues such as overfishing, bycatch or habitat destruction (Lourie et al., 1999). Many of their specialized life history traits including male pregnancy, lengthy parental care, small brood sizes, strict monogamy in most species, low mobility, small home ranges and sparse distribution may make seahorse populations particularly susceptible to anthropogenic disturbance (e.g. Foster and Vincent, 2004; Martin-Smith & Vincent, 2005; Vincent et al., 2005; Curtis and Vincent, 2006; Freret-Meurer and Andreata, 2008).

At least 46 species of seahorses are currently known, found worldwide in tropical and temperate shallow coastal habitats including seagrass beds, coral reefs, mangroves and estuaries (Kuiter, 2001, 2003, 2009; Lourie and Randall, 2003; Lourie et al., 2004; Piacentino and Luzzatto, 2004; Lourie and Kuiter 2008; Gomon and Kuiter, 2009; Randall and Lourie, 2009). Although our understanding of seahorse biology has improved greatly since the early 1990s, there are still large gaps in our knowledge for many species (see review by Foster and Vincent, 2004). Similarly, species identification remains challenging, with some of the taxonomy unresolved (Lourie et al., 1999; Kuiter, 2001, 2009). The first comprehensive taxonomic identification guide was not published until 1999 (Lourie et al., 1999) which has subsequently been updated (Lourie et al., 2004). There are remaining issues surrounding taxonomic identification of seahorses, partly because species do not vary greatly from one another and partly due to the variation within species e.g. seahorses can change colour and grow and lose skin filaments. Some species e.g. *Hippocampus kuda* are recognized to be a species complex, the taxonomy of which has not yet been resolved. Over 120 scientific names have been cited and many more common names are in use (Lourie et al., 1999). It seems likely that more seahorse species will be confirmed or described as genetic techniques are applied to seahorses in problematic groups (e.g. Teske et al., 2005; Lourie, 2006).

Dried seahorses are used extensively in traditional medicine, particularly traditional Chinese medicine (TCM), and, to a lesser extent, as curios, while live seahorses are traded as aquarium fishes (Vincent, 1996). Investigations into the seahorse trade started in the mid 1990s, and demonstrated that some species and populations had already been overexploited (Vincent, 1996; McPherson and Vincent, 2004; Giles et al., 2006). Initially, the scale and volume of the trade was not appreciated because of its artisanal and highly distributed nature (Vincent, 1996). However, more detailed investigation showed that the volume of seahorses traded and the number of countries involved has steadily increased. At least 32 countries had traded seahorses and their relatives by 1995, but this increased to nearly 80 countries during 1996–2001, with much of the expansion in Africa and Latin America (McPherson and Vincent, 2004; Baum and Vincent, 2005). Trade in Asia alone was inferred to be more than 45 t of dried seahorses in 1995, but official data, trade surveys, and qualitative evidence suggested that the Asian trade in dried seahorses in 2000 may have been considerably greater (Giles et al., 2006).

Concerns over the unsustainable nature of trade in some species of seahorses led to all species being listed on Appendix II of CITES (Convention for the International Trade in Endangered Species of Wild Fauna and Flora, www.cites.org) in November 2002 with implementation in May 2004. From this date, all Parties to CITES must demonstrate that international trade in seahorses does not threaten wild populations.

For many years, seahorses have been cultured by experienced marine hobbyists on a small scale, primarily motivated by an interest in many aspects of seahorse husbandry including breeding (e.g. Giwojna, 1990). Over the last few years, however, the interest in seahorse and other syngnathid aquaculture projects around the world has increased dramatically. Commercial aquaculture of seahorses has been repeatedly proposed as one solution to replace wild-caught animals, provide economic opportunities for fishers in developing countries and to meet any future increases in global demand (e.g. Forteath, 1997; Payne and Rippingale, 2000; Job et al., 2002, 2006). Global trends certainly suggest that aquaculture needs to be part of the solution, at least, for species in trade (Olivier, 2003). However, the ecological and social implications of aquaculture are not always straightforward and an a priori analysis of benefits and risks is necessary (Tlusty, 2002).

Our aim in this study was to document the history and current state of global seahorse aquaculture, in particular identifying the common factors leading to successful outcomes and some of the present and future technical, economic and social challenges. This was carried out using the following approaches i) a literature review to document the history of seahorse aquaculture; ii) analyses of available trade data and iii) questionnaires to seahorse aquaculture facilities to document the current status.

2.1. The history of seahorse aquaculture

Attempts to breed seahorses have probably been undertaken for as long as they have been held in captivity (Fig. 1). The facility to produce the first captive-born seahorse (*Hippocampus trimaculatus*) in South China in 1957 was the Shantou mariculture Test Farm in Guangdong Province (Fan, 2005). However, the first serious efforts to breed seahorses commercially started in the 1970s, particularly in China. By the early 1980s, literature from mainland China conveyed the impression that seahorse culturing was well understood (e.g. Aquaculture Institute of Shanghai, 1982; Wu and Gu, 1983; Shandong Marine College, 1985; Publicity and Education Committee, China's Aquaculture Society, 1990). However, problems with vulnerability to disease and providing the correct diet (e.g. Xu, 1985), or economic failure (CNSA, 2002 in Fan 2005) meant that these facilities remained experimental rather than commercially viable (Fan, 2005). The restructuring of China's economy in the 1980s led to widespread closure of seahorse farms, just at a time when China's demand for seahorses accelerated (Vincent, 1996).

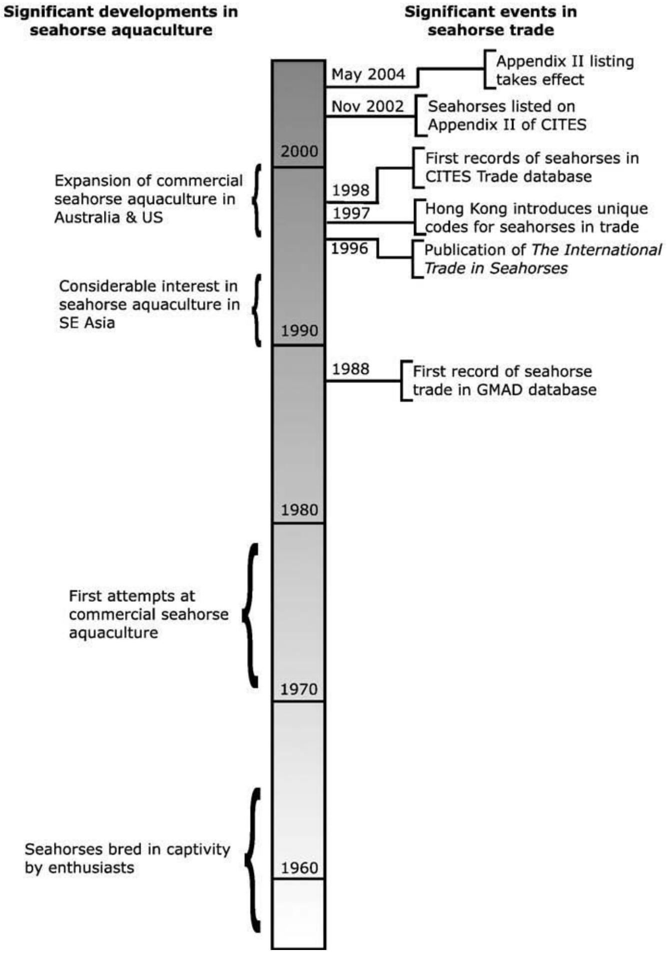


Fig. 1. Timeline of significant developments in seahorse aquaculture and seahorse trade reporting from 1960–2009.

Similarly, experimental breeding and rearing of seahorses was attempted in other countries (e.g. Australia, Japan, Venezuela) during the 1970s and 1980s, often in small-scale systems in research institutes, public aquariums (e.g. Soichi and Kimura, 1978; Correa et al., 1989; Lawrence, 1989; Scarett, 1996). As far as we are aware, none of these ventures were commercialized. There was also interest in the hobby aquarist community in many aspects of seahorse husbandry including breeding (e.g. Herald and Rakowicz, 1951; Anon, 1956; Straughan, 1961; Giwojna, 1990; www.breedersregistry.org).

The potential of seahorse aquaculture was first documented in 1995 (Prein, 1995), with recognition of the potential for syngnathid culture on a larger scale. While Prein (1995) recognized that there were potential advantages to culturing syngnathids compared to many other marine fish species (relatively few, larger eggs, advanced young, high value), he also stated that the problems of scaling up culture from a laboratory to commercial scale should not be underestimated. Commercial development and considerable expansion of seahorse aquaculture occurred in the 1990s particularly in Australia, New Zealand and the USA. As technical advances were made on a small scale for some species of seahorse, particularly the big-bellied seahorse, *H. abdominalis* (Woods, 2000a,b), ambitious proposals were developed for large-scale seahorse farms (e.g. Forteath, 1997). In particular, one project in Australia developed a business plan to breed and export hundreds of thousands of *H. abdominalis* individuals for the TCM market. In addition, relatively large-scale government funding was made available for research and development on the environmental factors controlling reproduction of seahorses in aquaculture in Australia. At the same time, interest was growing in seahorses as new aquaculture species in Southeast Asia (e.g. Hafiz al Qodri, 1995; Prein, 1995), particularly in Vietnam (Dao and Hoang, 1991; Pham, 1992, 1993; Truong and Doan, 1994; Truong and Ton, 1995; Truong, 1998). The growing interest was reflected in two workshops held in 1998 to discuss a) the culture and management of marine species used in traditional medicine (Moreau et al., 1998) and b) the husbandry, management and conservation of seahorses in public aquariums (Lunn et al., 1999).

At this stage, there was little information available on seahorse biology, behaviour and life history, and this undoubtedly affected the success of seahorse aquaculture. For example, the operational sex ratios of seahorses and its influence on reproductive rates was first described in 1991 (Clutton-Brock and Vincent, 1991) and the monogamy observed in most seahorse species was only reported in 1995 (Vincent and Sadler, 1995). Considerable technical difficulties remained in breeding and rearing many seahorse species because of difficulties in feeding and outbreaks of disease (e.g.; Vincent and Clifton-Hadley, 1989; Pham and Dao, 1991; Fenner, 1998; Hargrove, 1998; Truong, 1998). However, there was considerable research effort for a number of species in late 1990s and early 2000s and the subsequent publication of much relevant information (Fig. 2; e.g. Payne and Rippingale, 2000; Woods, 2000a,b; Adams et al., 2001; Payne, 2001; Job et al., 2002; Shapawi and Purser, 2003; Woods, 2003a,b,c,d; Woods and Valentino, 2003; Woods, 2005; Wilson et al., 2006; Martinez-Cardenas and Purser, 2007).

2.2. Seahorse trade and aquaculture

The first report on the international trade in seahorses was published in 1995 (Vincent, 1995). The subsequent production of an influential report (Vincent, 1996) created awareness of the scale and value of trade in seahorses.

Considerable advances in the collection and recording of trade data for seahorses were initiated in the years 1997–1998, allowing more detailed analysis of sources, destinations and volumes of seahorses traded internationally. Unique codes for dried and live seahorses were introduced in Hong Kong, one of the largest trading jurisdictions, in 1997. The European Union added seahorses to Annex D of legislation on wildlife trade on 1 June 1997, requiring import declaration for live animals and for dead animals that are substantially whole. Australia also introduced trade controls on syngnathids in 1998 including records of the source of animals (wild-caught vs. captive-bred). Furthermore, the first records of seahorses in the United Nations Environment Program–World Conservation Monitoring Centre (UNEP–WCMC) CITES trade database were in 1997 (http://sea.unep-wcmc.org/citestrade/), although CITES data for seahorses were only required from trading countries following the implementation of their Appendix II listing in 2004. These data document a number of variables including the species of seahorse, countries of origin, import and export, source (e.g. wild, captive-bred, ranched, confiscated) and type of import (e.g. live, bodies, specimens, derivatives) (UNEP–WCMC, 2004).

Another source of information on live seahorses in the aquarium trade is the Global Marine Aquarium Database (GMAD). Established in 2000 by UNEP–WCMC and the Marine Aquarium Council (MAC), this provided a publicly accessible database of records which includes seahorses (http://www.unep-wcmc.org/marine/GMAD.html). GMAD harmonized the data from 45 representative wholesale exporters and importers of marine aquarium species and thus can only give estimates of relative change not absolute numbers traded. GMAD only contains data until 2003 when the project was put on hold due to funding limitations.

We interrogated both the CITES trade database and GMAD for all records of *Hippocampus* trade. The CITES trade database had 3788 individual records covering the period 1997–2008 while GMAD had 786 individual records from 1988 to 2003 (note that an individual record represents a shipment and may refer from 1 to many thousands of seahorses). There are limitations in these data; for example they may contain duplication if individual countries did not record their data in the same manner (UNEP–WCMC, 2004) and many of the species names used are inaccurate, with species recorded as wild-caught far from their known distribution (see Green and Hendry, 1999). There are also discrepancies in the data where different quantities are reported for re-export than were originally imported and uncertainties in units where these have not been reported. However, these are the only data available to examine temporal trends and changes in supply due to aquaculture and so we have used them with appropriate caution. Other trade data

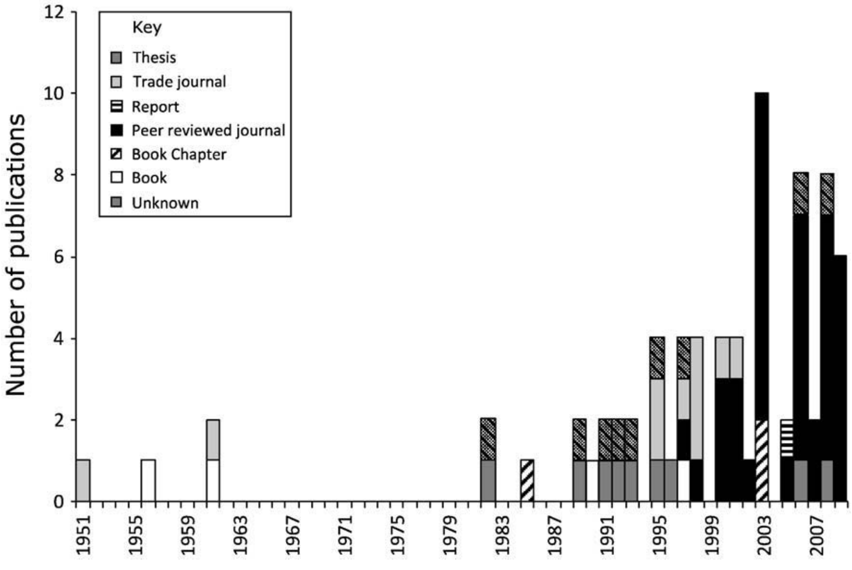
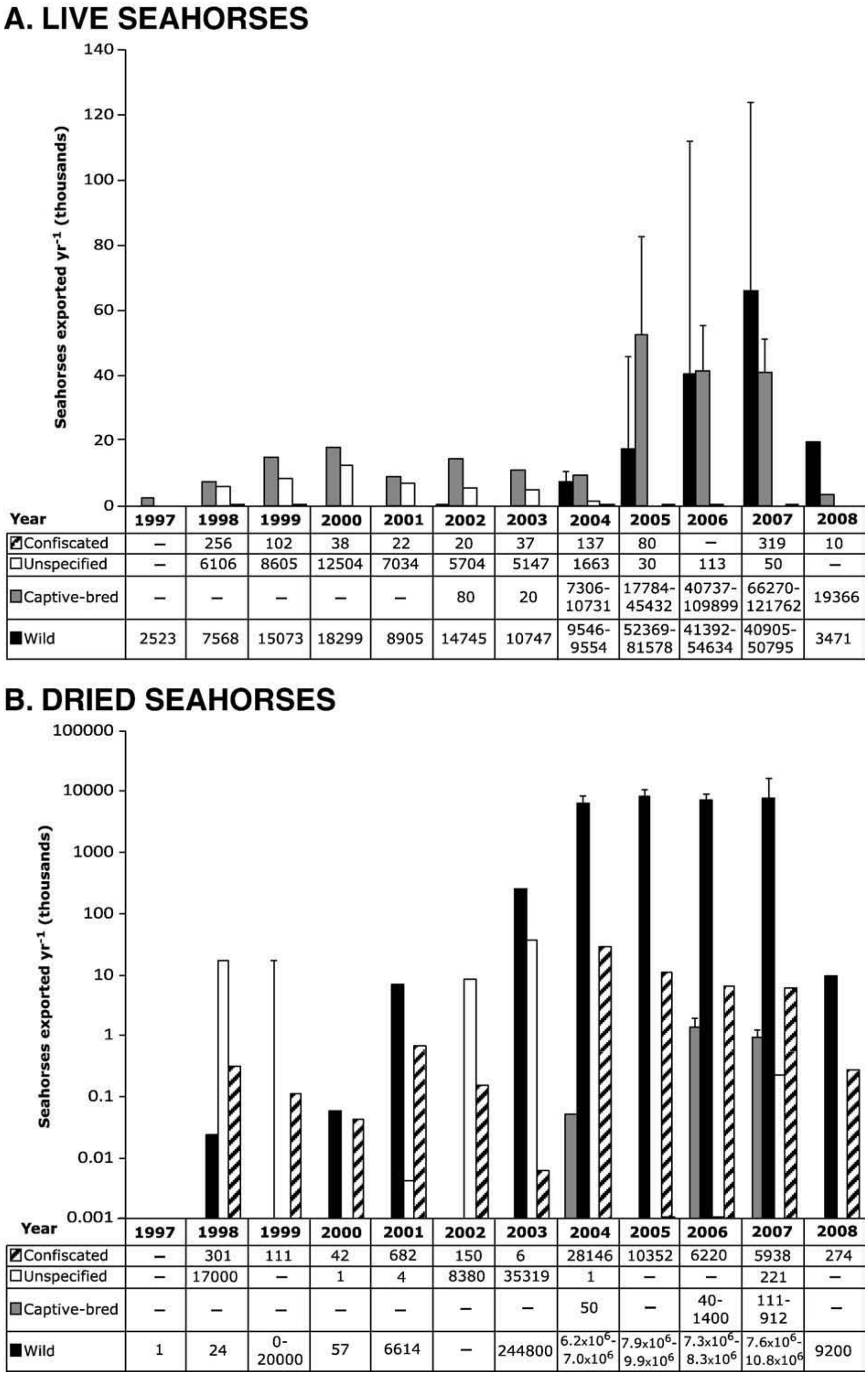


Fig. 2. Seahorse aquaculture publications from 1951 to 2009 by type.



Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
▨ Confiscated	–	256	102	38	22	20	37	137	80	–	319	10
☐ Unspecified	–	6106	8605	12504	7034	5704	5147	1663	30	113	50	–
▩ Captive-bred	–	–	–	–	–	80	20	7306-10731	17784-45432	40737-109899	66270-121762	19366
■ Wild	2523	7568	15073	18299	8905	14745	10747	9546-9554	52369-81578	41392-54634	40905-50795	3471

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
▨ Confiscated	–	301	111	42	682	150	6	28146	10352	6220	5938	274
☐ Unspecified	–	17000	–	1	4	8380	35319	1	–	–	221	–
▩ Captive-bred	–	–	–	–	–	–	–	50	–	40-1400	111-912	–
■ Wild	1	24	0-20000	57	6614	–	244800	6.2×10^6-7.0×10^6	7.9×10^6-9.9×10^6	7.3×10^6-8.3×10^6	7.6×10^6-10.8×10^6	9200

Fig. 3. International trade in seahorses as recorded in the CITES trade database held by UNEP–WCMC over the period 1997–2008. (A). Live seahorses by declared source as shown in table below year. (B). Dried seahorses by declared source as shown in table below year. Note logarithmic scale on ordinal axis. Error bars indicate maximum estimate where there are discrepancies in quantities between import and re-export.

provide a snapshot at a point in time and, while arguably more accurate, are limited in their use to investigate temporal changes in aquaculture (e.g. McPherson and Vincent, 2004; Baum and Vincent, 2005; Giles et al., 2006).

All live trade in the databases was recorded as numbers of seahorses whereas records of dried trade were given as weight in the majority of cases or as numbers. For consistency we converted weight to approximate numbers using a nominal weight of 2.5 g for a medium-sized dried seahorse (Baum and Vincent, 2005; Martin-Smith and Vincent, 2006). Where there were discrepancies in the quantities imported and then re-exported we have calculated both the minimum and maximum quantities.

Using the CITES trade database, mean live seahorse exports were between 35,400 (±32,700 sd) and 52,700 (±62,800) yr^{-1}, representing at least 33 declared species (31 accepted by the recognized CITES species identification guide, Lourie et al., 1999 and subsequent additions), traded by 46 exporting countries. Recorded trade in live seahorses increased from 1997 to 2000, perhaps reflecting the implementation of the various record-keeping mechanisms detailed above. The recorded trade in live seahorses remained approximately constant from 2001 to 2004 with a sharp five–eight fold increase in 2005–2007 (data for 2008 may not be complete yet because of delays in reporting) (Fig. 3a). Seahorses were only definitely recorded from captive-bred sources for the first time in 2002, comprising <1% of the total, whereas in 2004–2008 this had increased to 25–84% (mean 57%) of the total (Fig. 3a). Interestingly, the apparent volume of wild-caught seahorses increased following the implementation of the CITES listing which was potentially an artifact of better reporting rather than an actual increase in trade.

In total 11 countries–Australia, Brazil, Hong Kong, Ireland, Mexico, New Caledonia, New Zealand, Sri Lanka, UK, USA and Viet Nam–were recorded as the source of captive-bred seahorses. However, the source of live seahorses was recorded as unknown for up to 45% of individuals and it is highly probable that some of these were from aquaculture. For example, there were no recorded captive-bred seahorses from Australia in the CITES trade database in 2000, yet other official data stated that more than 3000 captive-bred seahorses were exported to the EU and USA (Martin-Smith and Vincent, 2006). There was a clear indication of increasing participation in international trade in aquaculture over the period 2002–2005 as described in Section 2.1 (Fig. 4a). The number of species of wild-caught seahorses traded internationally remained reasonably constant over the period 1997–2008 while the number of species that were captive-bred increased over the period 2002–2004, indicating increasing participation in captive breeding, increased success in dealing with technical challenges and/or diversification within existing operations (Fig. 4b). Seven of these species, *H. abdominalis*, *H. barbouri*, *H. breviceps*, *H. comes*, *H. ingens*, *H. kuda* and *H. reidi* accounted for more than 99% of the internationally-traded, captive-bred, live animals (Table 1). Wild-caught individuals of other species such as *H. coronatus*, *H. erectus*, *H. guttulatus*, *H. hippocampus*, *H. histrix*, *H. kelloggi*, *H. spinosissimus*, *H. takakurae* and *H. zosterae* were traded in large numbers and may represent an opportunity for further diversification within the aquaculture industry (Table 1). In most years there were wild-caught or unspecified source seahorses that were just

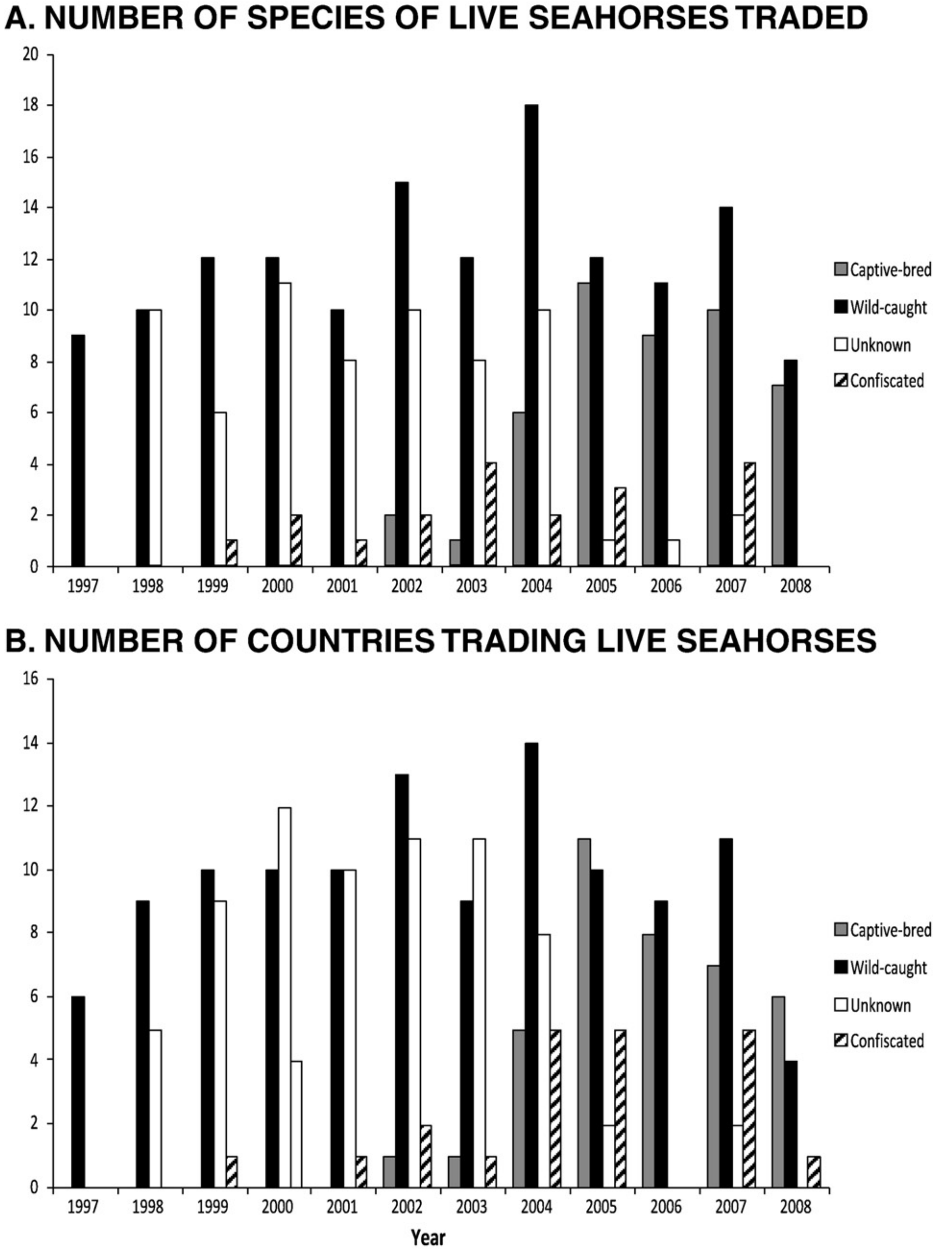


Fig. 4. International trade in live seahorses as recorded in the CITES trade database held by UNEP–WCMC over the period 1997–2008. (A) Number of species of live seahorses traded by source (captive-bred, wild-caught, unspecified or confiscated). (B) Number of countries involved in trade of live seahorses by source.

Table 1
Number of live seahorses traded internationally as recorded in the CITES trade database by declared species and source. Ranges are given where there are conflicting values in the database. Species shown in grey represent those that we consider to be probable misidentifications although there are likely others in the data.

Species	Source Captive	 Wild	 Unknown
H. abdominalis	10,938–12,472	1340–1450	632
H. aimei[a]	80		
H. algiricus		890	
H. angustus	534	642	96
H. barbouri	2328–2648	18,462–31,768	130
H. borboniensis	100		
H. breviceps	1970–2196	532	
H. camelopardalis	2		
H. capensis		20	
H. comes	2704–6000	13,500–26,718	0–22
H. coronatus		2078	454
H. denise		1608–4200	
H. erectus	160	59,156–62,114	13,650
H. fuscus	60	20	
H. guttulatus		3400	
H. hippocampus	400	3574	7994
H. histrix		20,006–31,696	0–40
Hybrid	200		
H. ingens	1220–2240	682–1062	2016
H. japonicus		100	124
H. jayakari		200	102
H. kelloggi		24,242–36,890	
H. kuda	123,751–259,922	217,180–258,178	45,522
H. minotaur	1000		
H. montebelloensis		100	
H. ramulosus[b]		4074	1178
H. reidi	148,766–317,522	20,478–22,662	2476
H. spinosissimus		12,704–17,250	116
H. spp.	8764–8804	37,424–37,440	17,260
H. subelongatus	40	790–802	
H. takakurae		5460	1256
H. trimaculatus		660–700	
H. whitei	100	8	
H. zebra		144	
H. zosterae		1572	584

[a] Considered to be *H. barbouri* or *H. spinosissimus* in Lourie et al. (2004).
[b] Considered to be *H. guttulatus* in Lourie et al. (2004).

described as *Hippocampus* sp. which is unsurprising considering the challenges with accurate species-level identification.

GMAD data extend further back in time (to 1988) than the CITES trade data (Fig. 5). Seahorse exports were reasonably constant from 1989 to 1998 with an increase in 1999–2001 and a sharp decrease in 2002–2003. Although it may not be possible to determine the total overall number of seahorses traded we believe the trends are reflective of the real situation since the GMAD and CITES data (derived from different sources) were highly correlated for most of the period during which the data overlapped (Spearman's Rank Correlation Coefficient (SRCC) = 1.000, $p = 0.008$ for 1997–2001, SRCC = 0.657, $p = 0.088$ for 1997–2002). Unfortunately GMAD data do not give species names so it is not possible to cross-correlate these with the CITES trade data.

Recorded exports of dried seahorses were much more variable, ranging from 1 to more than 10 million seahorses yr^{-1} (Fig. 3b). The apparent increases in 2003 and 2004 were potentially the result of increasing awareness of the forthcoming CITES listing in 2003 while declarations became mandatory in May 2004. Similar to live seahorses, reporting may have improved following the CITES listing leading to the apparent increase in dried seahorse trade in 2005–2007. Dried seahorses sourced from captive breeding in Australia, New Zealand and an unknown country were recorded in 2004, 2006 and 2007 but comprised an insignificant proportion of international trade (<0.02%) (Fig. 3b).

In addition to these data collected by national authorities, additional trade surveys were conducted over the period 1993–1995 in China, Taiwan, Hong Kong, India, Indonesia, Philippines, Thailand, Vietnam and 1998–2001 in Australia, Bangladesh, central America, China, European Union, Hong Kong, India, Indonesia, Japan, Korea, Malaysia, Mexico, New Zealand, North America, Pakistan, Singapore, South Africa, South America, Taiwan, Thailand and Vietnam (see McPherson and Vincent, 2004; Baum and Vincent, 2005; Giles et al., 2006; Martin-Smith and Vincent, 2006 for details on how these data were collected). Some of these data remain unpublished, but are becoming accessible on the HippocampusInfo website (www.hippocampusinfo.org).

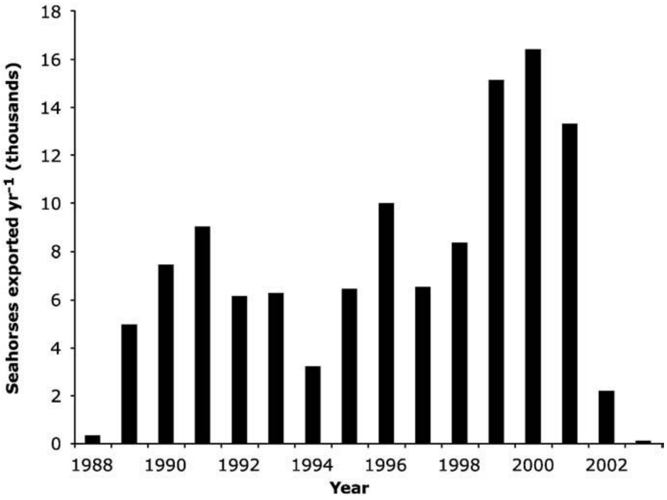


Fig. 5. International trade in live seahorses as recorded in the GMAD database over the period 1988–2003.

We found seahorse aquaculture occurring in 12 countries with 22–24 individual operations during these trade surveys (Table 2, Fig. 6). We found no seahorse aquaculture operations in Bangladesh, Central America, Hong Kong, Japan, Korea, Malaysia, Pakistan, Singapore, South America, South Pacific and Taiwan. Nine species of seahorse were being cultured and a further two species were proposed. Australia and New Zealand were major centres of seahorse aquaculture, defined by the number of operations, with Mexico and China also with multiple operations (Fig. 6).

Table 2
Seahorse aquaculture ventures that were operating at the time of seahorse trade surveys. Australian data from Martin-Smith and Vincent (2006), Vietnam data from Giles et al. (2006). All other data are unpublished.

Country/region	Year	# Operations	Species cultured	Comments
Australia	2001	5	*H. abdominalis*, *H. barbouri*, *H. subelongatus*, *H. whitei*	
China	2000	3	*H. kuda*	Possibly other species
Ireland and UK	2001	2	(*H. guttulatus*, *H. hippocampus*)[a]	Other unidentified species cultured
India	1999	(1)	*H. kuda*	Abandoned for lack of funds
Indonesia	1999	1	*H. comes*, *H. kuda*	
Mexico	2000	4	*H. ingens*	
New Zealand	2000	4	*H. abdominalis*	
USA	2000	1	*Not reported*	
South Africa	2001	(1)	*H. capensis*	Status of operation unclear
Thailand	1998	1	*H. kuda*, *H. mohnikei*	
Vietnam	2001	1	*H. kuda*	

[a] Proposed.

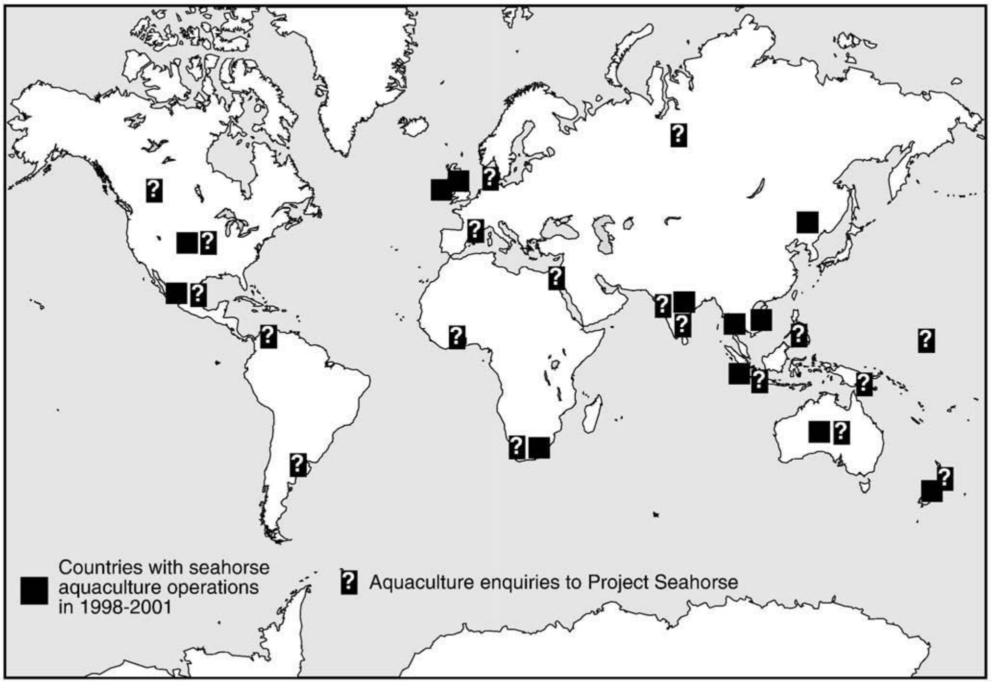


Fig. 6. Geographic distribution of seahorse aquaculture operations known to have been active prior to 2005 and of other enquiries about seahorse aquaculture received by Project Seahorse over the period 1998–2005.

3. Current status of seahorse aquaculture

To determine the current status of seahorse aquaculture we sent a targeted questionnaire to all individuals or organizations held in a Project Seahorse database of actual or potential seahorse aquaculture operations. This questionnaire consisted of about 45 questions on the operation infrastructure (size, location, water treatment, number of employees, funding source, years of operation), markets for product and details on species cultured (identity, number of broodstock, source, number of offspring and survival rate) (see Appendix A for example of blank questionnaire). The questionnaire was designed in consultation with the Human Research Ethics Committee at the University of Tasmania (Approval Number H8421) and all participants were supplied with an Information Sheet describing the study and a Consent Form. We sent the questionnaire and associated documentation to 90 individuals or organizations in our database as well as to a further 44 individuals who participated in a workshop entitled “Regional Technical Consultation on Stock Enhancement of Species

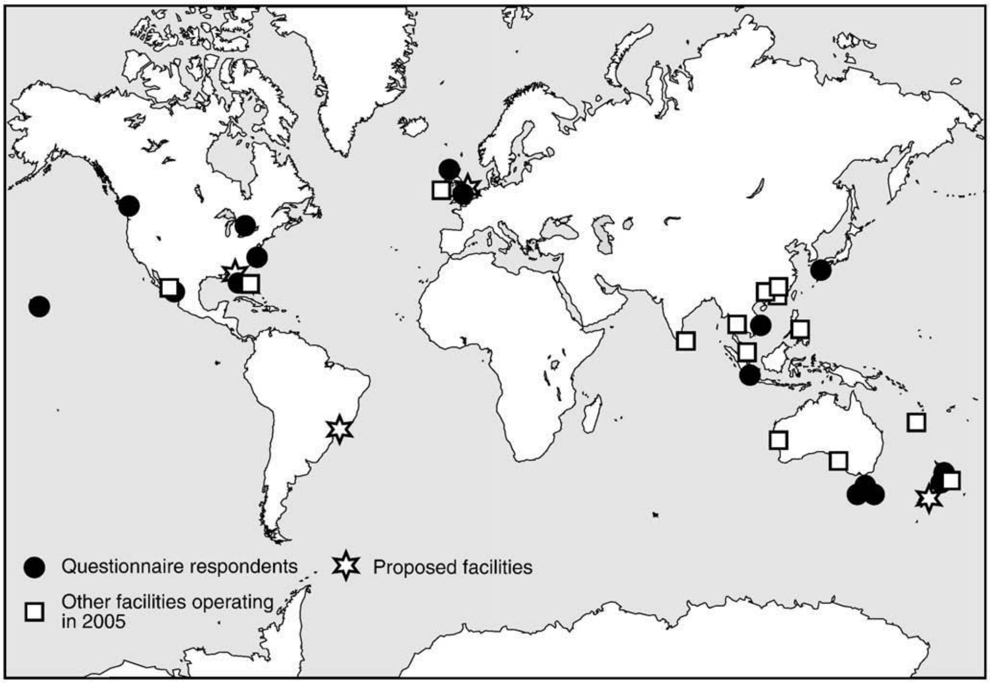


Fig. 7. Geographic distribution of seahorse aquaculture operations in 2005 including those responding to a Project Seahorse questionnaire.

Under International Concern" hosted by the Southeast Asian Fisheries Development Center from 13 to 15 July 2005 in Iloilo, Philippines.

We divided our questionnaire responses into two categories: commercial operations that sold or were intending to sell seahorses and research-only/not-for-profit operations, as we considered a priori that there might be differences between these two groups, based on previous studies that assessed the motives for marine ornamental aquaculture (Moe, 2003). With these data, we used coded dummy variables for our nominal data (e.g. size of operation). We investigated the relationship among nominal variables using cross-tabulation with Spearman Rank Correlation Coefficients (SRCC). For our other interval or scale variables, these were all significantly non-normally distributed. Thus we used the median as our measure of central tendency along with the interquartile (IQ) range as our measure of variability. All of our analyses were conducted using SPSS 11.0.4.

Of the 90 questionnaires that we distributed, ten did not reach their intended recipients. A further eight respondents replied that they were no longer or had never been involved in seahorse aquaculture. Of the remaining 72 questionnaires, we received a total of 16 completed, with respondents from eight countries (Fig. 7). We supplemented this information with data gathered from web searches using the search term "seahorse aquaculture". We found a further 12 operations in ten countries that were or claimed to be producing captive-bred seahorses (Fig. 7) and data were included on the basis of information on their websites. Overall we estimate that in 2005–2006 there were at least 28 seahorse aquaculture operations in 15 countries.

Table 3
Selected characteristics of aquaculture operations surveyed by questionnaire.

Characteristic	Category	Type of aquaculture operation	
		Commercial ($n=13$)	Research ($n=3$)
		Number of respondents[a]	
Location	Coastal (adjacent to water body)	8	2
	Inland	5	1
Size	Small ($<200\ \text{m}^2$ or 4×10^4 l)	9	2
	Medium (200–1000 m^2 or 4–20$\times10^4$ l)	3	1
	Large ($>1000\ \text{m}^2$ or 20×10^4 l)	1	0
Number of employees ($n=12$ for commercial, $n=2$ for research)	Full-time	1 (0–3)	1
	Part-time	1 (0–13)	2 (1–3)
	Volunteer	0 (0–4)	0
Waterflow system	Open	3	1
	Semi-closed	3	1
	Closed	7	1
Type	Private	11	1
	Aquaculture institute (government)	2	2
	University	2	1
Stated market for seahorses	Traditional medicine	1	n/a
	Aquarium	13	n/a
	Curio	1	n/a
	Other	1	n/a
Destination ($n=12$ for commercial)	Domestic	11	n/a
	International	6	n/a
		Median % (Range)	
Funding source ($n=11$ for commercial)	Private investment	100 (10–100)	0
	Research grant	0 (0–10)	100 (0–100)
	Other	0	0 (0–100)
Food source	Local-sourced live food	0 (0–50)	0 (0–10)
	Distant-sourced live food	35 (0–50)	30 (0–90)
	Frozen or dried food	55 (0–90)	60 (10–100)
		Median (Range)	
History ($n=10$ for commercial)	Year operation commenced	2001 (1994–2004)	1997 (1994–1998)
	Year seahorses first sold from operation	2003 (1995–2004)	n/a

[a] Note that multiple answers were possible to some questions and thus the number of respondents may sum to greater than the overall total.

The majority of the questionnaire respondents were operating small facilities with two-thirds of the operations smaller than $200\ \text{m}^2$/40,000 l with no difference between commercial and research operations (Table 3). These operations also typically employed a small number of people, usually only one full-time employee and one part-time employee. Almost all of the funding for the commercial operations was private investment as opposed to research grants and other funding for the research/not-for-profit operations. A variety of aquaculture systems were in operation with open, semi-closed and closed water circulation represented in both groups. All of the closed systems were small (SRCC between size of operation and type of water circulation $=-0.707$, $n=16$, $p=0.002$).

Most commercial operations had been in business for a relatively short period of time (<5 years) although the research/not-for-profit operations had been operating for longer (7–11 years) (Table 3, Fig. 8). There were no correlations between the age of the operation and its size, number of employees or whether seahorses were sold internationally. The questionnaire did not ask about the level of grant funding, subsidies, or other financial benefits that were being received by the facility, either during the start-up phase or for ongoing operations.

Sale of live seahorses for aquariums was the dominant market for aquaculture seahorses with all of the questionnaire respondents selling to this market (Table 3). Similarly, all of the operations found in web searches were selling seahorses for the aquarium market. Only one operation also sold dried seahorses for traditional medicine while one other operation also sold curios and operated tourism visits. The volumes of these sales are unknown. At least three other operations found in web searches also operated as tourist attractions. Domestic markets were more important than international markets and there was a significant positive correlation between the size of the operation and international exports with only medium and large operations selling internationally (SRCC between size of operation and market $=0.588$, $n=12$, $p=0.044$).

Thirteen species of seahorses were cultured commercially, two species in research-only operations (Table 4). About half of the commercial operations were in range states of their aquaculture species i.e. that species occurs naturally in the territorial waters of the country. The most popular species for aquaculture were *H. barbouri* and *H. kuda* (6 operations each), *H reidi* (4) and *H. erectus* (4) while a number of species were only cultured in single operations (Table 4). A number of other operations which did not complete questionnaires had stated through websites or promotional material that they were

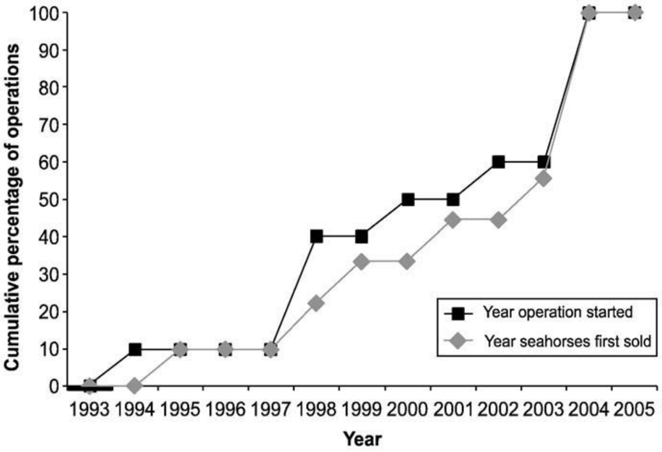


Fig. 8. Cumulative distribution of start-up date and date when seahorses were first sold by aquaculture operations responding to Project Seahorse questionnaire.

Table 4
Species of seahorse in aquaculture, all in the genus *Hippocampus*. All quantitative data were from questionnaire responses with varying sample size among species, ranging from $n = 1$ to $n = 6$. Blanks indicate no data were provided. Range States are countries or political jurisdictions where the species is known to occur naturally. Abbreviations for source of broodstock are L = locally sourced (wild-caught), A = sourced from aquaculture and O = from other sources e.g. zoos. IQ range = interquartile range.

A. Commercial operations		# Operations		Broodstock		Production (yr^{-1})			# Other operations
Scientific name	Common names	Range state	Non-range state	Median # (IQ range)	Source	Median # offspring (IQ range)	Median % survival to maturity (IQ range)	Median adult production (IQ range)	
H. abdominalis	Big belly seahorse, pot belly seahorse	2	0	1050 (900–1200)	L, A	20,000		12,000	2
H. barbouri	Barbour's seahorse, zebra snout seahorse	0	6	21 (17–43)	A	84 (17–400)	60 (0–70)	1350 (1200–1500)	1
H. breviceps	Short–headed seahorse	1	1	27 (14–40)	A, O	200	40		1
H. capensis	Knysna seahorse	0	1	12	O	250	70	175	
H. comes	Tiger-tail seahorse	0	1	3	A, O		60		
H. erectus	Lined seahorse	4	1	50 (5–120)	L, A	800 (100–1500)	80	6000	
H. ingens	Pacific seahorse	1	0	6	L	4000			
H. kuda	Yellow seahorse, spotted seahorse	2	4	40 (10–225)	L, A, O	6750 (200–22 000)	40 (30–70)	5000 (800–5000)	2
H. reidi	Longsnout seahorse	2	2	19 (8–43)	A, O	300 (100–500)	50 (0–60)	900 (0–8000)	1
H. spinosissimus	Hedgehog seahorse	0	1	3	O				
H. trimaculatus	Three-spot seahorse	1	0	20	L	200	0		
H. whitei	White's seahorse	1	1	40	O	1000			1
H. zosterae	Dwarf seahorse	3	1	13	L, A	300	80		

B. Research operations		# Operations		Broodstock		Production (yr^{-1})		
Scientific name	Common names	Range state	Non-range state	Median # (IQ range)	Source	Median # offspring (IQ range)	Median % survival to maturity (IQ range)	Median adult production (IQ range)
H. abdominalis	Big belly seahorse, pot belly seahorse	3	0	60 (21–200)	L, A, O	2000 (300–5000)	45 (20–70)	730 (50–1400)
H. barbouri	Barbour's seahorse, zebra snout seahorse	0	1		A			

culturing six of these species (Table 4). Broodstock numbers were generally fairly small (<100 adult individuals), the exception being two operations culturing *H. abdominalis* which had over 1000 individuals. The source of broodstock was varied, coming from local populations, other aquaculture operations or zoos and public aquariums. Average survival rates to maturity varied from species to species but were generally declared to be greater than 50%. Offspring and adult production also varied by species but was generally over 1000 individuals yr^{-1}. Questions to provide details of the age and stage were not included in the questionnaire.

4. Economic challenges

Commercial viability is obviously a key attribute determining the characteristics of seahorse aquaculture operations and the level of supply of aquaculture seahorses to world markets. The costs of production will be dependent on many factors including initial investment (land, building costs, equipment, depreciation), fixed and variable ongoing costs (electricity, labour, food, chemicals, maintenance) and distribution and marketing (Engle and Quagrainie, 2006). Similarly, income will be dependent on availability and size of markets, consumer preferences and willingness to pay (Engle and Quagrainie, 2006). Costs and income will vary considerably from case to case and thus the overall attractiveness of seahorse aquaculture as a business proposition.

As far as we are aware detailed assessment of the commercial viability of seahorse aquaculture has only been undertaken by individual aquaculture operations as part of their commercial-in-confidence planning processes and is therefore not available for general review. To assist our interpretation of seahorse aquaculture we subsequently sent a follow-up questionnaire to our respondents from commercial aquaculture operations asking four general questions about the economic viability and challenges to their operations (Appendix B). We received responses to ten of the 12 questionnaires we sent out although one of the respondents from a developed country indicated that they were no longer culturing seahorses, citing price competition from other countries together with high freight costs as the primary reasons why their business was no longer viable.

There was a clear difference in answers from respondents in developing countries versus those in developed countries. The biggest challenge to viability of seahorse aquaculture in developed countries was considered to be the cost of production relative to sale price (5/6 responses) while rearing and disease were considered more important in developing countries (3/3 responses). Similarly aquaculture operations in developed countries had trouble competing on price with wild-caught seahorses (5/6 responses) while this was not considered an issue in developing countries (3/3 responses). Regardless of location, all respondents thought that most customers would pay more for captive-bred seahorses (8/9 responses), although one respondent commented that this was market-specific with North American and European customers willing to pay a premium but not so in Singapore.

Additional factors that were considered important included consumer awareness (7/9), the size of the home aquarium market (6/9), eco-certification (4/9), receiving a premium for aquaculture seahorses (2/9) and availability of feed (1/9).

5. Technical challenges and solutions

5.1. Seahorse culture facilities

Seahorse broodstock are held in facilities that range from standard glass or acrylic aquarium tanks (e.g. Wilson and Vincent, 1998; Job et al., 2002; Koldewey, 2005, Planas et al., 2008), cylindrical drums (Payne, 2005), to large concrete ponds (Koldewey, pers. obs.; Ortega-Salas and Reyes-Bustamante, 2006). Juveniles are removed after birth and placed into rearing tanks that include glass aquariums (e.g. Payne, 2003), cylindrical polyethylene vessels (e.g. Wilson and Vincent, 1998; Woods and Martin-Smith, 2004), bowls (e.g. Gardner et al., 2005), pseudo-kreisels (e.g. Curttright, 2005), fiberglass circular cone-bottom tanks (e.g. Brittain, 2005), or circular unpainted concrete nursery tanks (e.g. Job et al., 2002). Tank height is important to enable successful courtship and transfer of the eggs from the female to the males' brood pouch (Woods, 2003d; Koldewey, 2005). Holdfasts are necessary and include plastic plants, rope, tubes or pipes. Increasing the density of artificial holdfasts may enable an increase in stocking density, but will increase material costs and potentially the labour time and costs of cleaning (Woods, 2003d).

Questionnaire responses indicated that the current functional approach for seahorse aquaculture is a small-scale intensive system (<200 m^2/40,000 l) culturing seahorses for the aquarium market. Intensive systems are those defined as having the most extreme levels of human control; with high stocking density, extensive use of artificial feeds (often supplemented with vitamins, essential elements, antibiotics and close environmental control (Allsop, 1997). This equates to most mariculture projects for the ornamental trade, which have also been developed on a relatively small scale as attempts at closing life cycles repeatedly in closed systems have proved technically challenging for most species (Sadovy and Vincent, 2002).

However, there is ongoing research, particularly in developing countries, on increasing the scale of operations with recent reports of large-scale rearing of *H. kuda* and *H. trimaculatus* in the Philippines and India (Okuzawa et al., 2008; Garcia and Hilomen-Garcia, 2009; Murugan et al., 2009). Although the Indian experiments used standard 2000 l FRP tanks (broodstock) and 30 l rearing tanks (Murugan et al., 2009), the Philippines' operation showed some success in trialling arrays of floating bamboo and nylon mesh cages to grow-out juveniles (Garcia and Hilomen-Garcia, 2009).

It is important that seahorse aquaculture does not cause similar negative impacts and learns from other examples of detrimental aquaculture (e.g. Naylor et al., 2000; Tlusty, 2002; Vincent and Koldewey, 2006). To avoid adding to conservation concern, it must assess potential damage to the marine environment and implement mitigation programmes before seahorse culturing is initiated. Full environmental impact assessments (EIA) should be part of every seahorse aquaculture operation, using well established guiding principles for best practice e.g. by UNEP or the International Association for Impact Assessment (IAIA). Most developed nations have imposed effluent regulations in aquaculture and many also regulate land and water use, sites, predator control, worker safety etc. (Read and Fernandes, 2003; Tacon and Forster, 2003; Boyd et al., 2005) that often includes an EIA. As most (6/12 commercial, 2/3 research) culture operations had either open or semi-closed systems, issues relating to effluent, water use and escapes are all pertinent to seahorse culture. As seahorse aquaculture is operating in both developed and developing countries, it is important that national regulations be followed and where these are not in place, appropriate standards be adopted. Some seahorse aquaculture facilities actively promote a responsible approach to seahorse farming on their websites, through regulating water discharges, sale of exotic species, and broodstock collection and this should be encouraged. Certification of aquaculture facilities under the new MAC Mariculture and Aquaculture Management (MAM) International Standard is also recommended.

5.2. Seahorse culture methodology

5.2.1. General husbandry

Seahorses are found in both temperate and tropical waters and the culture environment should reflect the natural temperature range that the culture species would experience. At extremes of temperature tolerance, seahorses may be able to survive but some aspects of breeding may be compromised (Woods, 2003d; Lin et al., 2008). Optimisation of culture temperature should also consider economic factors such as local electricity costs, water volumes and heating unit efficiency (Woods, 2003d).

Growth of seahorses in aquaculture is difficult to compare with growth in the wild as there are so few measurements of the latter. Currently, there are only two species where data exist on growth rates in the wild and aquaculture; *H. abdominalis* (Woods, 2003b, 2005; Martin-Smith, unpublished data) and *H. guttulatus* (Curtis and Vincent, 2006; Palma et al., 2008). For *H. abdominalis*, these rates are similar at similar temperatures.

There have also been a few studies relating to the effect of environmental parameters on seahorse culture. *Hippocampus abdominalis* was shown to be tolerant of raised ammonia levels (Adams et al., 2001), while *H. kuda* and *H. trimaculatus* juveniles were tolerant of both decreased and increased salinities (Hilomen-Garcia et al., 2003; Murugan et al., 2009). Increased temperature decreased the hatching time in *H. kuda* (Lin et al., 2007), and there may be optimal temperatures for embryonic development and survival (Lin et al., 2006). Seahorses process food very rapidly which can quickly lead to fouling in the culture environment if faeces are not removed, so good maintenance regimes are required. The need for water changes will depend on whether the system is open or closed and on the density of seahorses. High stocking density has been shown to have a negative effect on growth and survival (Woods, 2003d). As with all good aquarium husbandry, routine water quality monitoring should be in place, and seahorses respond best to the aquaculture environment when strict control is applied to water quality, cleaning and feeding regimes (Planas et al., 2008).

The husbandry parameters from all peer-reviewed publications on seahorse aquaculture are summarised in Table 5. Further information on general husbandry is provided for twelve seahorse species commonly held in public aquariums (Koldewey, 2005). This husbandry manual is compiled in the form of species chapters, and provides information from a wide range of aquariums in Europe, North America and Australia.

5.2.2. Breeding

The life history of seahorses is comprehensively reviewed by Foster and Vincent (2004). In summary, seahorse reproduction is unusual in that the males become pregnant, incubating the young in a brood pouch. In addition, most seahorse species appeared to be monogamous within a single breeding cycle, the male accepting eggs from only one female (Kvarnemo et al., 2000; Wilson and Martin-Smith, 2007). There is evidence of mate choice, with males selecting larger females (Mattle and Wilson, 2009; Naud et al., 2009) and male body size, pouch size and function, may influence the future fitness and survival of the offspring (Dzyuba et al., 2006). Size can also be a method of predicting sexual maturity (Thangaraj et al., 2006). The duration of the male's pregnancy (gestation duration) ranges from approximately 9 to 45 days, depending on species and water temperature. Males of most seahorse species produced about 100–300 young per pregnancy, with the range between five and 2000 young per cycle. Newborn sizes range from approximately 2 to 20 mm, which then reach maturity between 4 months and 1 year (Foster and Vincent, 2004).

Recent experimental work has investigated the influence of a number of different parameters, including feeding regime and rearing conditions, on gonad development and reproductive behaviour (Lin et al., 2007; Faleiro et al. 2008; Murugan et al., 2009). While these studies have not been undertaken in full-scale commercial operations, they will help inform the development of successful large-scale seahorse aquaculture.

Seahorse culture has advanced over the last five to 10 years, with the closure of the life cycle of several species over a number of generations (e.g. Pham, 1993; Wilson and Vincent, 1998; Burhans and Melechinsky, 2000; Payne and Rippingale, 2000; Woods, 2000a,b; Job et al., 2002; Koldewey, 2005; Job et al., 2006; Lipton et al., 2006). Thirteen species were reported in commercial culture from the

Table 5
Husbandry parameters for seahorse aquaculture research published in peer-reviewed journals arranged by species. Studies grouped together with shading indicate that they were all conducted at the same research facilities. For meaning of abbreviations please see footnotes to table.

					Husbandry parameters					Food items	
Reference	Species	LH stage[a]	Tank size (L)	Tank material	Water flow[b]	Water temp	Salinity	pH	Photoperiod	Adult	Juvenile
Adams et al 2001	*abdominalis*	A	500	Glass		18±1	35	8.2±0.2	12L:12D		
	abdominalis	J	60			18±1	35	8.2±0.2	12L:12D		Enriched *Artemia* (Super Selco)
Martinez-Cardenas & Purser 2007	*abdominalis*	J		Fibreglass	R (2.5L h^{-1})	17.1–17.5	32–36	7.8.8.0	12L:12D		Enriched *Artemia* (Super Selco)
Martinez-Cardenas et al 2008	*abdominalis*	A, J	1000			17			12L:12D	Frozen mysids	Enriched *Artemia*
Shapawi & Purser 2003	*abdominalis*	J	25	Fibreglass	R	18			12L:12D		Enriched *Artemia* (5 treatements)
Wilson et al 2006	*abdominalis*	J	25		R (174 L h^{-1})	15.9±0.4	32.6±1.4	8.1±0.1	12L:12D		Enriched *Artemia*, frozen mysids, pelleted feed
Woods 2003a,b, Woods & Valentino 2003	*abdominalis*	J	9	Plastic	R (15 L h^{-1})	18 15.0±0.2	33.8±0.1	8.2±0.1	12L:12D		Enriched *Artemia*, frozen copepods
	abdominalis	J	20	Plastic	R (30 L h^{-1})	18			12L:12D		Enriched *Artemia*
Woods 2005a	*abdominalis*	J	60	Plastic		14.9±0.5 16.8±0.3	34.9±0.1 35.3±0.1	8.1±0.1 8.2±0.1	12L:12D		Enriched *Artemia*, frozen mysids
Woods 2005b	*abdominalis*	A	23	Plastic	R (15 L h^{-1})	15.9±0.1	35.2±0.1	8.1±0.1	12L:12D	Frozen mysids	
Woods 2000, Woods & Martin-Smith 2004	*abdominalis*	A	75	Plastic	R (60 L h^{-1})	17.1±0.2	34.6±0.2	8.1±0.1	14L:10D	Enriched *Artemia*, shrimp, amphipods	
		J	2	Plastic		16.0±0.9	34.3±0.2	7.9±0.1			*Artemia* nauplii, enriched *Artemia*
		J	60	Glass	R (60 L h^{-1})	14.1±0.2	34.2±0.1	8.2±0.1			
Wilson & Vincent 1998	*barbouri, fuscus, kuda,*	J	35, 135	Plastic	R (120 L h^{-1})	26-27	35	8.2	14L:10D		Enriched *Artemia*, copepods, frozen mysids
Job et al 2006	*comes*	A	500	Glass	R	29±0.5	31.2±0.2	8.3±0.1	13.5L:10.5D	Live and frozen *Acetes*	
	comes	J	3500	Concret	R (1200 L h^{-1})	30±0.2	31.7±0.3	8.3±0.1	12L:12D		Wild zooplankton to 10d, enriched *Artemia* 7-63d
Lin et al 2008, 2009a,b	*erectus*	A	432		F (30-48 L h^{-1})	28±0.5	35±1.0	7.8±0.3	14L:10D	Fozen mysid, live *Artemia*	
	erectus	J	38	Glass		28±0.5	35±1.0		16L:8D		*Artemia* nauplii to 15d, enriched *Artemia* 16-40d, frozen mysid 41-61d
Faleiro et al 2008	*guttulatus*	A	170, 180		R	24-25	34-35	8.2-8.3	14L:10D	Live *Artemia*, frozen enriched *Artemia*, mysids	
Palma et al 2008	*guttulatus*	A	500	Plastic						Live shrimp, mysids, *Artemia*	
	guttulatus	A	90	Plastic	R (20 L h^{-1})	19.7±0.1	37.6±0.1		12L:12D		Frozen shrimp, mysids, *Artemia*
Planas et al 2008	*guttulatus*	A	160	Plastic	R (360 L h^{-1})	15–17.5	37±2	8.0±0.2	15.5L:8.5D 10L:14D		Enriched *Artemia*

Ortega-Salas and Reyes-Bustamante 2006	*ingens*	J	60, 1000	Glass, cement		17–23					Rotifers and *Artemia* nauplii to 35d, live adult *Artemia* to >60d
Choo & Liew 2006	*kuda*	A				26–30	24-28		12L:12D	Live and frozen *Acetes*	
	kuda	J	150	Plastic		29.7±1.9	24.5±2.8	7.4±0.3			Rotifers, harpacticoids copepod nauplii, to 25d, mysids 25-60d, frozen *Acetes* >60d
Garcia & Hilomen-Garcia 2009	*kuda*	J		Concrete, fibreglass							Enriched rotifer, *Artemia* nauplii, *Artemia*, live mysids, mixed copepods
	kuda	J	1300	Bamboo and plastic net	O	27–30	32–35				Thawed *Acetes* or natural food
Hilomen-Garcia et al 2003	*kuda*	J	250	Fibreglass		26.5–28.2	32–33	8.0–8.6	11.6L:12.4D		Enriched rotifer, copepods, enriched *Artemia*
Job et al 2002	*kuda*	J	3500		R	30±0.2	31.7±0.3	8.3±0.1	12.4L:11.6D		Wild zooplankton to 10d, *Artemia* >7d, wild mysids >12d
	kuda	J	147	Glass	F (150 L h^{-1})	30±0.2	31.7±0.3	8.3±0.1			Enriched *Artemia* (3 treatments)
Lin et al 2007	*kuda*	A	54000	Concrete	R	26	32			Live and frozen mysids, *Acetes*	
Thangaraj et al 2006	*kuda*	A, J	1000	Plastic		26.5–28.0	36.5–37.0	7.8–8.3	12L:12D		*Artemia*, mysids
Storero & Gonzalez 2009	*patagonicus*	A, J	50						14L:10D	Wild decapods, amphipods	
Cividanes da Hora & Joyeux 2009	*reidi*	J	50, 120, 200	Glass	R (50, 120, 200 L h^{-1})	22.0–26.6	26.5–29.0	8.2–8.4	12L:12D		Wild zooplankton to 6d, enriched Artemia (Super Selco) 3-22d, wild mysid >22d
Olivotto et al 2009	*reidi*	A	200		R	28±0.5	30	8.0–8.2	14L:10D	Frozen *Artemia* and mysids	
	reidi	J	20		R (7 L h^{-1})	28±0.5	30	8.0–8.2			Enriched copepods, rotifers, *Artemia*
Chang & Southgate 2001	sp.	J	10			24–26	31				Enriched *Artemia* (3 treatments)
Payne & Rippingale 2000	*subelongatus*	A	15,30	Glass	R	23±0.5	35	8.1–8.3	12L:12D		
	subelongatus	J	15	Glass	R	23±0.5	35	8.1–8.3	12L:12D		Enriched copepod and *Artemia* nauplii
Murugan et al 2009	*trimaculatus*	A	2000	Plastic		30.2±0.5	32±1.5	7.6±0.3	16L:8D	Amphipods, *Acetes*, insect and fish larvae,	
	trimaculatus	J	80	Plastic							Rotifers to 6d, *Artemia* nauplii 7-13d
	trimaculatus	J	45	Plastic					24L:0D		Rotifers, *Artemia*, wild zooplankton
	trimaculatus	J	188						16L:8D		*Artemia* nauplii, copepodites
Sheng et al 2006	*trimaculatus*	J	1000	Plastic		26			14L:10D		Rotifers, copepods, *Moina*
Wong & Benzie 2003	*whitei*	A	300	Glass		20			12L:12D		Frozen mysids
	whitei	J	10	Plastic	R (60 L h^{-1})	17.0±0.5, 20.7±0.5, 23.0±0.5, 25.8±0.3					*Artemia*, enriched *Artemia*

[a] A = adults, J = juveniles.

[b] R = recirculating, F = flow-through, O = ocean.

questionnaire results (Table 4) and aquaculture information for the same number of species is cited in the peer-reviewed literature (Table 5). These species are largely the same as those reported in the CITES data (Table 1) However, technical challenges remain notably in disease, nutrition and the development of species-specific culture techniques.

5.2.3. Feeding

Wild seahorses eat a varied diet, dominated by amphipods, decapods and mysids (Teixeira and Musick, 2001; Woods, 2002; Kendrick and Hyndes, 2005; Kitsos et al., 2008; Storero and Gonzalez, 2008), with algae also reported (Kitsos et al., 2008). Feeding and nutrition provided some of the initial challenges for seahorse aquaculture, primarily due to the ontogenetic changes in diet (reviewed in Foster and Vincent, 2004; Murugan et al., 2009). These issues appear to have been largely overcome in a number of species, particularly *H. abdominalis*, where considerable work has been done, particularly at the National Institute of Water and Atmospheric Research (NIWA) in New Zealand and the School of Aquaculture, University of Tasmania (Australia) on natural diets (Woods, 2002), different types of diets (Woods, 2003b; Woods and Valentino, 2003), diet enrichment (Shapawi and Purser, 2003; Payne, 2003; Woods, 2003c), feeding conditions (Woods, 2000a,b; Wardley, 2006; Martinez-Cardenas and Purser, 2007) and growth (Filleul, 1996). Some similar work has been done with other species including *H. barbouri* (Payne, 2001; Wilson and Vincent, 1998), *H. breviceps* (Kendrick and Hyndes, 2005), *H. capensis* (Lockyear et al., 1997), *H. erectus* (Lin et al., 2009a,b) H. *fuscus* (Wilson and Vincent, 1998), *H. guttulatus* (Palma et al., 2008), *H. kuda* (Lin et al., 2007; Wilson and Vincent, 1998), *H. reidi* (Olivotto et al., 2008; Cividanes da Hora and Joyeux, 2009), *H. patagonicus* (Storero and Gonzalez, 2009), H. *subelongatus* (Payne and Rippingale, 2000; Kendrick and Hyndes, 2005), *H. trimaculatus* (Murugan et al., 2009), *H. whitei* (Wong and Benzie, 2003) and an unidentified species (Chang and Southgate, 2001), with studies of feeding behaviour in *H. reidi* (Felício et al., 2006; Roos et al., 2008), *H. trimaculatus* (Sheng et al., 2006) and unidentified species (Van Wassenbergh et al., 2009). This is summarised in Table 5, with further information on feeding for twelve species of seahorse provided in the husbandry manual developed for seahorse species commonly held in public aquariums (Koldewey, 2005).

5.2.3.1. Adults. Most attempts at seahorse culture have relied on cultured live food such as brine shrimp (*Artemia*), copepods, mysid shrimps, rotifers and amphipods, as well as wild collected food (Correa et al., 1989; Forteath, 1995; Lockyear et al., 1997; Martinez-Cardenas et al., 2008; Wilson and Vincent, 1998; Payne and Rippingale, 2000; Woods, 2003d, Olivotto et al., 2008; Cividanes da Hora and Joyeux, 2009; Murugan et al., 2009; Table 4). Culturing large quantities of live food can be difficult, time-consuming and expensive (Gardner, 2003; Payne, 2003; Woods, 2003d) and may also have associated disease problems (Rhodes, 1999). Sourcing live food for seahorses can be unreliable in quantity and quality and may introduce unwanted pests to the culture system (Gardner, 2003). Feeding frozen or artificial diets can be problematic in seahorses accepting inert foods and the lack of understanding of the nutritional profile required from a commercial diet (Woods, 2003d). Successful weaning of seahorses onto frozen mysids, copepods, shrimps and *Artemia* has been reported (Garrick-Maidment, 1997; Payne, 2003; Koldewey, 2005; Woods, 2003d; Palma et al., 2008; Lin et al., 2009a,b). The mode of presentation of inert diets is important, particularly keeping it in suspension (Payne, 2003). The decision on whether seahorses are fed live, inert, or mixed diets depends on the location and type of culture facility. Studies show a variety of diets have been developed for different species, but both juvenile and adult seahorses benefit from enriched food. Low cost supplements may also be locally available as an effective enrichment for seahorses (Job et al., 2002).

5.2.3.2. Juveniles. The relatively large size of seahorse juveniles (compared to most other marine fish larvae) should make them easier to rear but their ontogenetic changes in diet require a chain of live food to provide the necessary nutrition in the first few weeks after release from the pouch. In general, newly released juveniles are fed 2–7 times a day with some combination of (a) newly hatched *Artemia*, (b) 24–48 h enriched and decapsulated *Artemia* nauplii, (c) rotifers, (d) haparticoid copepods, and/or (e) mysid larvae (e.g. Woods, 2003a,b; Woods and Valentino, 2003; Koldewey, 2005; Choo and Liew, 2006; Cividanes da Hora and Joyeux, 2009; Garcia and Hilomen-Garcia, 2009; Table 4). Co-feeding (combined feeding of live and inert diets) may be advantageous in weaning juvenile seahorses onto an inert diet (Woods, 2003d) although *H. barbouri* has been reared to adulthood with high rates of survival without the use of any live food (Payne, 2003).

5.2.4. Diseases

As with many fish species in culture, seahorses do not respond well to being kept at high densities and are prone to stress and that makes them more vulnerable to infection. Laboratory and aquaculture observations have noted a variety of diseases (reviewed in Arca-Ruibal and Sainsbury, 2005), including cestodes (*H. abdominalis*: Lovett, 1969), microsporidians (*H. erectus*: Blasiola, 1979; Vincent and Clifton-Hadley, 1989), fungi (*H. erectus*: Blazer and Wolke, 1979), ciliates (*H. erectus*: Cheung et al., 1980; *H. trimaculatus*: Meng and Yu, 1985), trematodes (*H. trimaculatus*: Shen, 1982), and marine leeches (*H. kuda*: de Silva and Fernando, 1965). The particular diseases of concern for seahorses are vibriosis (e.g. Alcaide et al., 2001; Greenwell, 2002) and mycobacteriosis (Koldewey, 2005). Vibriosis can be treated with antibiotics, though these range in effectiveness according to the bacterial strain. There are bivalent and multivalent vaccines available, but limited testing has been done to challenge vaccinated seahorses with pathogenic field isolates to test their effectiveness (partly due to regulatory and ethical implications) and no published information is available. Specific vaccines are being developed specifically from bacterial isolates at the facility where the pathogens have been found, which has proved an effective approach for those facilities, although this is costly (M. Geach, pers. comm.). Live food may be a source of vibriosis and decapsulation of *Artemia* cysts and/or treatment of food with antibiotics has been used to reduce this route of infection (Rhodes, 1999). There are no effective treatments for mycobacteriosis, yet this is considered a disease of special concern for syngnathids (Koldewey, 2005).

The other major health issue for seahorses in culture is gas entrapment problems or ‘gas bubble’ disease. This typically presents as either gas entrapment in the brood pouch, subcutaneous emphysema of the tail segment and/or over-inflation of the swim bladder. Gas supersaturation and/or infectious agents have been proposed as causative agents, though this remains unresolved. Treatment is possible, by aspiration of the bubbles and use of antibiotics (Koldewey, 2005).

Seahorses do offer some unique challenges for health care due to their anatomy and behaviour. Injections are difficult through the hard, bony-plated body and the ‘semi-closed’ branchial chambers make gill biopsies prohibitive. The best way to manage disease is through prevention and quarantining of new animals arriving at the culture facility should be carried out as routine. The provision of optimal environmental parameters and a good diet will also reduce health problems. It is clear that the lack of information on the treatment of the common diseases experienced in seahorse culture is a major constraint to the viability of seahorse culture and more research is urgently required.

6. Discussion

At present, all seahorse aquaculture facilities who responded to the questionnaire (13/13) are targeting the live aquarium market, with only one supplying TCM and one the curio market. Most species cultured were tropical (*H. barbouri*, *H. kuda*, *H reidi* and *H. erectus*) which are preferred in home aquarium tanks. There is likely to be a smaller market for temperate species, such as *H. abdominalis* and *H. guttulatus*. This suggests that the ornamental market is the most commercially viable at present.

Members of the TCM community have indicated a willingness to accept aquaculture animals, although there is a view that these may be less efficacious than those that are wild-caught (Moreau et al., 1998). In fact, many TCM traders are looking to aquaculture to meet the supply of animals they require (Hong Kong Chinese Medicinal Merchants Association, pers. comm.). However, cultured seahorses will only be viable in the TCM market if they can be produced at a competitive price that is comparable to wild-caught animals. Wild-caught seahorses, particularly dried animals, are very cheap (<US $0.50 to US$1.50 per individual) at the point of capture as the majority are caught as bycatch in tropical shrimp fisheries (e.g. Baum and Vincent, 2005; Giles et al., 2006; Meeuwig et al., 2006) with no direct costs. Thus, production costs for aquaculture have to be kept extremely low in order to compete economically with wild-caught individuals, perhaps explaining why there are no large-scale operations supplying the dried market. One of the questionnaire respondents from a developing country was selling live seahorses for US $1.20 and indicated that they wished to move into the TCM market where they felt they would be price-competitive.

Conversely, in the marine ornamental aquarium trade, seahorses are relatively valuable (Bruckner, 2005; Martin-Smith and Vincent, 2006). However, even for the ornamental trade, the high price commanded by some cultured aquarium fishes compared to those wild-caught often undermines their economic viability (Sadovy and Vincent, 2002). Aquaculture fish can, however, be a more attractive product to buyers when production is more predictable, in terms of supply and price (Watson, 2000). Analysis of the financial feasibility of marine ornamental aquaculture for clown fish in the Philippines demonstrated that production could be profitable despite relatively high start-up and operating costs (Pomeroy and Balboa, 2004; Pomeroy et al., 2006). Similarly, Lindsay et al. (2004) concluded that culture of a limited number of marine ornamental species was a viable economic prospect for the Pacific region.

Commercial viability was hard to assess from the approach used in this study, although most commercial facilities were less than five years old. The fact that research/not-for-profit facilities were older (7–11 years) may reflect the research funding sources that support these facilities and because their motives are research-driven rather than market-driven.

Anecdotal evidence suggests that cultured seahorses tend to be more desirable as they are better adapted to an *ex situ* environment so tend to be less prone to stress-related diseases and are more adaptable to available aquarium feeds. This is supported by reports that rearing aquarium fish in closed systems is likely to lead to the production of hardier species, which fare better in captivity and survive longer (Ogawa and Brown, 2001; Olivier, 2003). The higher quality and life expectancy of farmed fish can justify the mark-up and thus profitability of farmed marine fish (Olivier, 2003). Some facilities culturing seahorses for the aquarium market have developed a range of colours and sizes designed to appeal to home hobbyists.

Although costs of production for seahorse aquaculture will be considerably higher in developed countries this may be offset by consumers willing to pay a premium for aquacultured animals (Alencastro, 2004; Alencastro et al., 2005). Consumers in the USA showed a strong preference for tank-raised ornamental fish while price was only a secondary factor influencing their purchasing behaviour (Alencastro, 2004). Thus, it would appear that these consumers would be willing to pay extra for aquacultured seahorses. However, our study showed that the biggest challenge facing seahorse aquaculture facilities in developed countries was the cost of production compared to the sale price. Until the costs of production can be optimised or the market price increased, expansion of seahorse aquaculture in developed countries may be limited.

In contrast, the biggest challenge for seahorse aquaculture in developing countries related to technical problems, such as rearing and disease. Seahorse aquaculture faces the same problems as most intensive fish monoculture: outbreaks of disease due to the increased vulnerability to infection caused by high stocking densities and elevated stress levels; provision of the appropriate diets at a viable growth rate/cost balance; and environmental issues (Jennings et al., 2001). Significant improvements have been made in the culture of seahorse species over the last decade, and many of the issues relating to feeding in particular have been resolved for some species. However, live food culture can be expensive in staff time, equipment and consumables and are a significant cost for a seahorse aquaculture operation, particularly with the high demands of frequency of feeding (2–7 times per day). Estimates suggest that labour costs represent more than one third of the total cost of production for an ornamental breeding farm (Olivier, 2003). A frozen food diet may be the best choice where live foods are only seasonally available or where the seahorses are destined for the live aquarium trade, as hobbyists often only limited access to live food. Some culture facilities have solved the problems of ensuring that hobbyists have the right food source by providing proprietary diets for seahorses when they sell the animals.

Disease problems remain a considerable challenge for seahorse aquaculture and may be a significant reason that large-scale culture has not yet been successful. Priority areas for research include a) disease treatment and improved health management; b) determination of the nutritional requirements for seahorses that can be replicated in artificial inert diets; and c) genetic management of species in culture to reduce dependence on wild-caught broodstock and maintain productivity over multiple generations. Seahorse aquaculture appears to be similar to other marine ornamental aquaculture, which remains comparatively problematic, both from a technical and a socioeconomic point of view (Rosamond et al., 2000). Reducing the environmental impact of aquaculture practices has become one of the main research problems that need to be addressed before further expansion can occur in the industry (Jennings et al., 2001). However, many of these impacts can be minimized or mitigated through careful, proactive planning (Frankic and Hershner, 2003). Sustainable sourcing of broodstock and food sources are particularly important.

For seahorses, the CITES listing should increase the sustainability of aquaculture operations. CITES seeks to achieve sustainable international trade in Appendix II species by requiring exporting Parties to restrict trade in Appendix II species to levels that are not detrimental either to species' survival, or to their role within the ecosystems in which they occur (known as the “non-detriment finding”). Where a Management Authority of the country of export is satisfied that any specimen of an animal species was bred in captivity (F2 generation or greater), a certificate by that Management Authority to that effect will be accepted in lieu of any of the permits or certificates required under Article IV. CITES does, however, require non-detriment findings for aquaculture operations producing F1 specimens from wild-origin broodstock.

A CITES technical workshop concerned with the implementation of the CITES listing for seahorses made specific recommendations concerning seahorse aquaculture operations (Bruckner et al., 2005) for consideration by the 169 Parties (which has since increased to 175). These included the certification or registration of captive breeding facilities and developing methods to tag captive-bred seahorses to differentiate them from wild-caught animals. Until marking methods are developed, a paper trail is required to distinguish wild and aquaculture (F2 generation or greater) seahorses. General criteria for acceptable and “non-detrimental” aquaculture operations were also recommended, with emphasis on capacity to rear offspring to reproductive age, prevention of release of aquaculture product into the wild, lack of reliance on wild broodstock, and controls to minimize disease and mortality.

In 2004, CITES recommended a 10 cm minimum height as a way for Parties to make non-detriment findings for all seahorse species taken from the wild and entering international trade. A single minimum permissible height appears to be both biologically appropriate and socially acceptable (Martin-Smith et al., 2004), until Parties are able to define management tools more specifically (Foster and Vincent, 2005). There is no recommendation to impose a standard minimum export size for aquaculture seahorses (Bruckner et al., 2005).

Increasing awareness of the threats to wild seahorse populations may motivate consumers to choose cultured over wild-caught animals. Seahorse aquaculture ventures need to recognise the special responsibilities inherent in working with threatened species. The conservation benefits of seahorse aquaculture still need to be evaluated. The Convention of Biodiversity (CBD, www.biodiv.org) has over 180 signatory countries. Its three goals are: conservation of biological diversity; sustainable use of the components of biological diversity; and the fair and equitable sharing of the benefits arising from the use of genetic resources. At present, the trend is for marine ornamental culture facilities to be based in developed countries (Wabnitz et al., 2003). This was also found to be the case with seahorse aquaculture, with the majority of existing (20/30) and proposed (3/4) facilities being based in developed countries. This trend was also reflected in the trade data, which reported cultured seahorses being traded by seven countries, only two of which were developing countries. This may alter the relationships between the marine ornamental trade distribution network, possibly depriving local fishers of employment and losing the community- and national level benefits the trade provided (McAllister, 1989, 1999). Achieving effective conservation and sustainable use are only likely to be lasting if programmes are implemented in the context of local cultures, livelihoods and development needs (United Nations Millennium Development Goals www.undp.org/mdg).

Marine ornamental fish do present an opportunity for community-based, conservation-focused aquaculture initiatives in developing countries. Community-based aquaculture that has the effect of reducing exploitation of wild populations of marine ornamental fish has the potential to provide a number of direct conservation benefits (Job, 2005). Challenges in achieving this relate to a) selecting species that are suitable for culture; b) economically viablity; c) participation of local fishers in aquaculture ventures and d) regional restructuring of the aquarium fish trade to ensure the equitable distribution of benefits derived from culturing (Job, 2005). In terms of seahorse aquaculture, this would encourage operations to focus on the culture of local species. Any culturing of seahorse species in non-source countries should actively seek to ensure that fishing communities within the source countries benefit equitably from these endeavours. Unless fishing communities derive equitable benefit from their biological resources (e.g. seahorses), there will be no reason for them to protect and manage these resources in a sustainable manner. Furthermore, setting up hatcheries in source countries would also reduce the risk associated with escapes and, by extension, the risk of introducing exotic species (Vincent and Koldewey, 2006; Wabnitz et al., 2003).

From the questionnaire responses, most viable seahorse aquaculture operations (11/13) were found to be supplying the live aquarium market domestically, with only 6/13 supplying the international market. Developing country operations tend to have smaller domestic markets for the ornamental trade and may be more dependent on the international market. The lower costs of production may therefore be balanced with the additional costs of transport, paperwork to ship seahorses internationally in order for these developing country facilities to be competitive. There is evidence that at least two facilities in developing countries (Sri Lanka and Viet Nam) are regularly supplying international markets for the ornamental trade. Developing country seahorse aquaculture operations reported technical problems as their major challenges, rather than economic factors.

Culturing will only be of conservation benefit if it reduces pressures of exploitation on wild populations. As developing countries are the major exporters of wild seahorses (Brazil, India, Indonesia, Malaysia, Mexico, Philippines, Thailand, Viet Nam), well-planned, sustainable aquaculture in these countries has the greatest potential to ensure the benefits for seahorse fishing communities and alleviate the pressure on wild seahorse populations. Trade data (Fig. 3a) indicate cultured animals have become an increasing percentage of the live trade since 2002. Production from culture facilities may have the potential to meet the demand of the live trade if reported figures are accurate: The questionnaire respondents currently report a median adult production of 12,000 seahorses yr^{-1} for temperate species and 13,425 seahorses yr^{-1} for tropical species (Table 4), while trade data reported a mean of 35,400–52,700 (±32,700–62,800 sd) live seahorses yr^{-1} traded by 46 exporting countries (Fig. 3a). However, Vincent (1996) estimated global demand for live seahorses to be an order of magnitude higher than this, implying that aquaculture could not meet demand at historical levels. It seems clear that a first step in assessing the impact of live seahorse aquaculture on global trade would be to validate the current levels of demand.

Aquaculture has not, to date, proven to be able to produce sufficient volumes of seahorses cost effectively to reduce the demands of the TCM trade on wild populations. The majority of the trade in seahorses is for TCM, which is estimated to involve over 20 million animals from 20 species moving among nearly 80 countries in 2000 (Vincent, 1996; McPherson and Vincent, 2004; Baum and Vincent, 2005; Giles et al., 2006). Recorded exports of dried seahorses were lower, ranging from 1 to more than 10 million yr^{-1} (Fig. 3b), although this is likely to be a result of under-reporting, perhaps as much an order of magnitude (Vincent, 1996). Unvalidated and/or poor quality trade data have and will continue to hamper efforts to determine the effects of seahorse aquaculture on exploitation of wild populations. It appears that there are still significant technical and economic hurdles to overcome to enable the large-scale culture of seahorses for the TCM market.

The encouraging technical advances in seahorse aquaculture should now enable current and future seahorse aquaculture operations to review their practices, increase their sustainability–through codes of practice or certification–and consider the conservation costs and benefits of their activities. At present, the consequences of seahorse aquaculture operations on wild seahorse populations and seahorse fishing communities are unknown. While seahorse aquaculture is often promoted to alleviate the pressure on wild populations, further research is required to know whether this has occurred.

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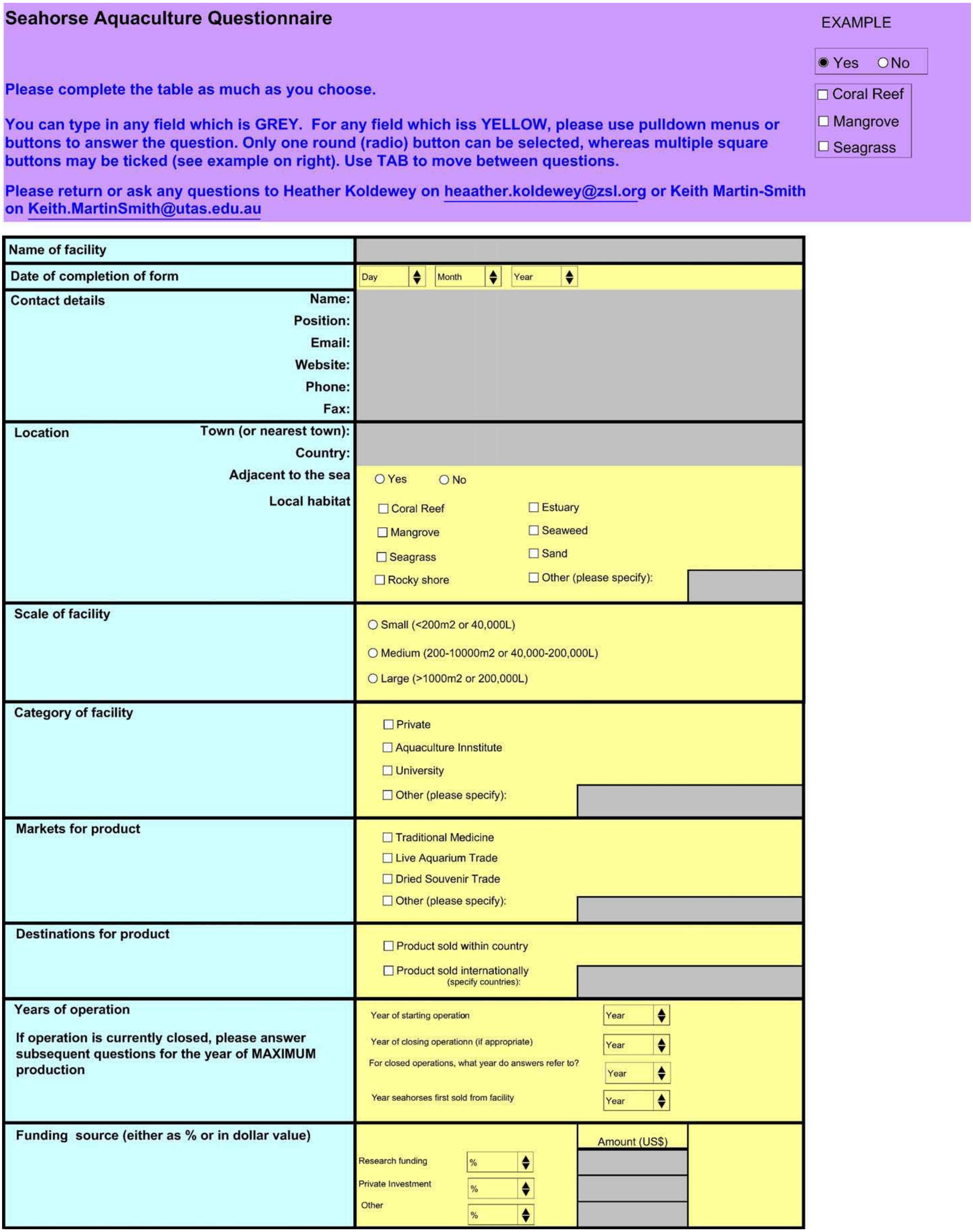
Appendix A. Example of initial questionnaire sent to aquaculture operations



Seahorse Aquaculture Questionnaire

EXAMPLE

● Yes ○ No

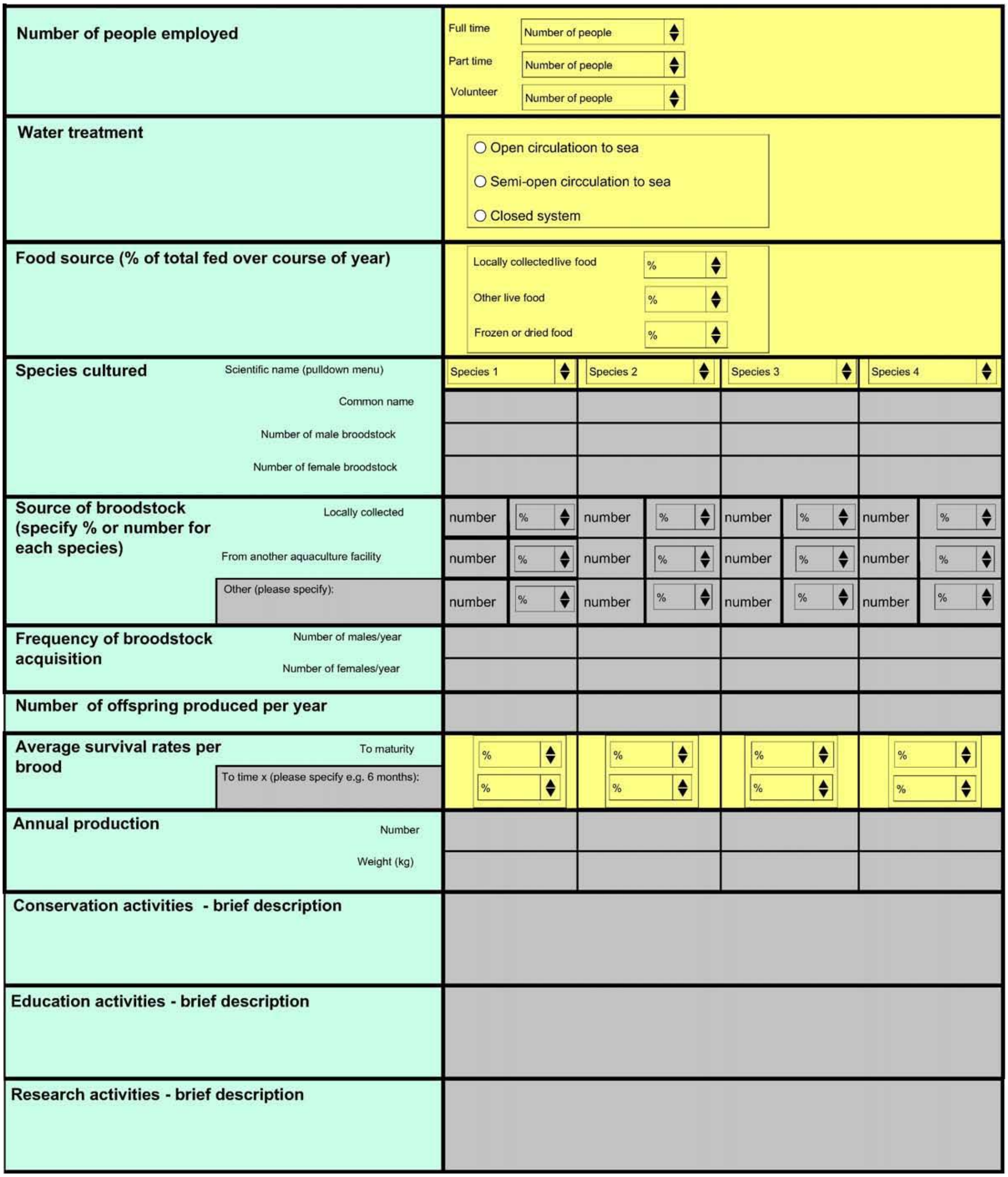
☐ Coral Reef
☐ Mangrove
☐ Seagrass

Please complete the table as much as you choose.

You can type in any field which is GREY. For any field which iss YELLOW, please use pulldown menus or buttons to answer the question. Only one round (radio) button can be selected, whereas multiple square buttons may be ticked (see example on right). Use TAB to move between questions.

Please return or ask any questions to Heather Koldewey on heaather.koldewey@zsl.org or Keith Martin-Smith on Keith.MartinSmith@utas.edu.au

Name of facility		
Date of completion of form		Day ▲▼ Month ▲▼ Year ▲▼
Contact details	**Name:** **Position:** **Email:** **Website:** **Phone:** **Fax:**	
Location	**Town (or nearest town):** **Country:**	
	Adjacent to the sea	○ Yes ○ No
	Local habitat	☐ Coral Reef ☐ Mangrove ☐ Seagrass ☐ Rocky shore ☐ Estuary ☐ Seaweed ☐ Sand ☐ Other (please specify):
Scale of facility		○ Small (<200m2 or 40,000L) ○ Medium (200-10000m2 or 40,000-200,000L) ○ Large (>1000m2 or 200,000L)
Category of facility		☐ Private ☐ Aquaculture Innstitute ☐ University ☐ Other (please specify):
Markets for product		☐ Traditional Medicine ☐ Live Aquarium Trade ☐ Dried Souvenir Trade ☐ Other (please specify):
Destinations for product		☐ Product sold within country ☐ Product sold internationally (specify countries):
Years of operation **If operation is currently closed, please answer subsequent questions for the year of MAXIMUM production**		Year of starting operation Year ▲▼ Year of closing operationn (if appropriate) Year ▲▼ For closed operations, what year do answers refer to? Year ▲▼ Year seahorses first sold from facility Year ▲▼
Funding source (either as % or in dollar value)		Amount (US$) Research funding % ▲▼ Private Investment % ▲▼ Other % ▲▼



Number of people employed

Full time: Number of people
Part time: Number of people
Volunteer: Number of people

Water treatment

○ Open circulatioon to sea
○ Semi-open circculation to sea
○ Closed system

Food source (% of total fed over course of year)

Locally collectedlive food: %
Other live food: %
Frozen or dried food: %

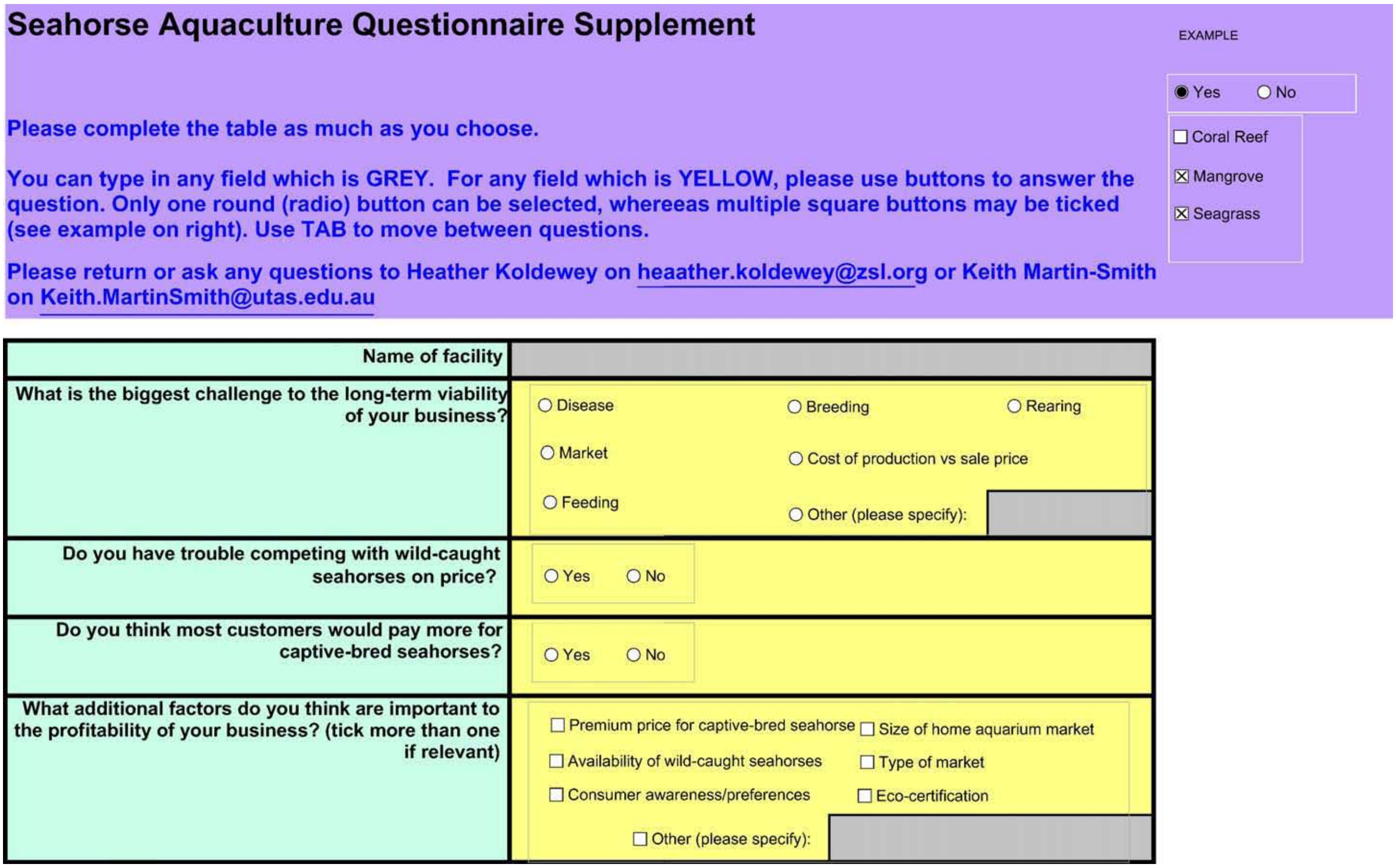
Species cultured	Scientific name (pulldown menu)	Species 1	Species 2	Species 3	Species 4
	Common name				
	Number of male broodstock				
	Number of female broodstock				
Source of broodstock (specify % or number for each species)	Locally collected	number %	number %	number %	number %
	From another aquaculture facility	number %	number %	number %	number %
	Other (please specify):	number %	number %	number %	number %
Frequency of broodstock acquisition	Number of males/year				
	Number of females/year				
Number of offspring produced per year					
Average survival rates per brood	To maturity	%	%	%	%
	To time x (please specify e.g. 6 months):	%	%	%	%
Annual production	Number				
	Weight (kg)				

Conservation activities - brief description

Education activities - brief description

Research activities - brief description

Appendix B. Example of follow-up questionnaire sent to commercial aquaculture operations



Seahorse Aquaculture Questionnaire Supplement

EXAMPLE

● Yes ○ No

☐ Coral Reef
☒ Mangrove
☒ Seagrass

Please complete the table as much as you choose.

You can type in any field which is GREY. For any field which is YELLOW, please use buttons to answer the question. Only one round (radio) button can be selected, whereeas multiple square buttons may be ticked (see example on right). Use TAB to move between questions.

Please return or ask any questions to Heather Koldewey on heaather.koldewey@zsl.org or Keith Martin-Smith on Keith.MartinSmith@utas.edu.au

Name of facility	
What is the biggest challenge to the long-term viability of your business?	○ Disease ○ Breeding ○ Rearing ○ Market ○ Cost of production vs sale price ○ Feeding ○ Other (please specify):
Do you have trouble competing with wild-caught seahorses on price?	○ Yes ○ No
Do you think most customers would pay more for captive-bred seahorses?	○ Yes ○ No
What additional factors do you think are important to the profitability of your business? (tick more than one if relevant)	☐ Premium price for captive-bred seahorse ☐ Size of home aquarium market ☐ Availability of wild-caught seahorses ☐ Type of market ☐ Consumer awareness/preferences ☐ Eco-certification ☐ Other (please specify):

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