Mud Crab Aquaculture.
Chapter 4, Recent Advances and New Species in Aquaculture

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- Paterson, B. D. and Mann, D. L. (2011) Mud Crab Aquaculture, in Recent Advances and New Species in Aquaculture (eds R. K. Fotedar and B. F. Phillips), pages 115-135, Wiley-Blackwell, Oxford, UK.

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4.1 Introduction

Portunid crabs emerged as a new aquaculture species because of their high value and the then ready availability of wild-caught “seed” crabs. They also fit into existing coastal mariculture infrastructure- an important feature in areas where shrimp farming had been hit with viruses. However, the different marketing options available and the biological quirks of crabs make them a different prospect for farming from shrimp. Portunid crabs, particularly mud crabs, have a heavy calcified exoskeleton and robust, strong claws. They are built to dismember and crush other crabs and molluscs - habits that are obviously not a good fit with high density mariculture!

The biggest crab tends to win all the fights- so it is no surprise that portunid crabs are amongst the fastest growing crustaceans on Earth. In the fishery, portunids take 2 years to reach commercial size (300-800g depending on species)- but in aquaculture this can be reduced to within one year (Christensen, Macintosh, Phuong, 2004; Trino, Millamena, Keenan, 1999; Ut, Le Vay, Nghia, Walton, 2007). Juvenile portunid crabs typically double their weight each time they moult, but this weight change is tempered as maturation sets in by redirecting energy into sexual development (Hill, 1976). While the weight change is massive upon moulting, the crabs are soft and helpless for about an hour or so but even when their cuticle have hardened up on the outside, days and weeks may elapse before they have filled their impressive carapace with meat. For significant periods after moulting the crabs can be “empty.”

Scylla and other portunids are usually marketed live. Mud crabs are well suited to live marketing which is an advantage for countries with limited infrastructure for seafood processing and distribution. Because of their heavy shell and lack of abdomen, edible recovery in crabs is lower than it is for tailed decapods like shrimp or lobster – but in mud crabs, the gonads of mature females provide an added premium (Chiou, Huang, 2003).

Portunid crabs are “farmed” in a variety of ways. The simplest forms of this are arguably not aquaculture at all. Firstly, soft empty post-moult crabs are harvested from the fishery, individually contained and fed with trash fish to “fatten” them for market. In one of Nature’s ironies, the opposite practice, soft-shell crab production, is increasingly becoming favoured, catching hard-shell crabs, feeding them individually until they moult and double their weight and then marketing them while they are soft. Competition for a limited resource of wild crabs has inevitably seen these live-holding practices evolve a longer term focus. Here, farmers purchase small juveniles or “seed” crabs from the wild and rear them extensively in earthen ponds for on-growing to commercial size on a diet of trash fish. Marketing the crop as hard-shell is still the

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doi: 10.1002/9781444341775.ch4

most common but regional improvements in transport and processing infrastructure means that production of soft-shell product for export is becoming increasingly common.

Inevitably, demand for crab “seed” soon became so intense that coastal mud crab stocks diminished and supply of juveniles to crab farming became a significant bottleneck to industry growth, (Shelley 2008). In response to this, mud crab hatchery methods have now been development, following an international collaborative effort, putting crab farming on a more sustainable footing. In this chapter we describe the current status of mud crab farming in Asia, the suitability of the mud crab biology and lifecycle to aquaculture; an update on recent developments in research before examining a number of significant areas requiring further development.

4.2 Portunid crab aquaculture

Crab farming is largely a practice centred on Asia, and marine farming of portunid crabs (primarily mud crabs *Scylla spp.*) accounts for only a third of global farmed crab production (about 660,000 tonnes), the remainder involves freshwater farming of the Chinese mitten crab *Eriocheir japonica sinensis* (FAO, 2008). The high value of the later means that portunid crabs only account for a 5th of the total value of farmed crab production, which is USD $2.8 billion, (FAO, 2008).

Aquaculture of mud crabs *Scylla spp.* and more recently swimming crabs *Portunus spp.* was originally based on collection and extensive on-growing of juvenile or “seed” crabs in earthen ponds. Farming occurs in coastal areas of southern Asia and South-East Asia and in southern China. While all crabs are generally harvested for the hard-shell live market, an emphasis on production of soft-shell crabs is also emerging. Mud crab females with mature ovaries also attract a price premium, presenting an opportunity for mono-sex culture(Khatun, Kamal, Yi, 2009; Trino, Millamena, Keenan, 1999). The relatively high prices and ready live transportability and marketability of *Scylla spp.* added to the fact that they did not initially fall victim to significant pathogens like WSSV (Lavilla-Pitogo, de la Pena, Catedral, 2007) also meant that crab farming was for many years an attractive alternative in areas where viral outbreaks prevented penaeid shrimp farming.

However, this explosion of interest quickly threatened the sustainability of coastal crab populations and the subsequent recruitment difficulties was at best a tight brake upon industry expansion and at worst, stopped crab farming altogether in some regions. Wild juveniles also presented some practical problems. As demand forced harvesting at smaller and smaller sizes it became more and more difficult to identify them accurately to species, meaning that in some areas farmers may inadvertently buy less desireable varieties (such as *S. olivacea*) in the mix of juveniles on offer (Christensen, Macintosh, Phuong, 2004; Walton, Le Vay, Lebata, Binas, Primavera, 2006a).

Fortunately, the recent development of hatchery and nursery techniques for mud crabs and other species promises to set the industry on a more sustainable footing, and pave the way for and expansion of production (Christensen, Macintosh, Phuong, 2004; Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Rodriguez, Parado-Estepa, Quinitio, 2007; Walton, Le Vay, Lebata, Binas, Primavera, 2006a).

4.2.1 Growout

Scylla spp. are apparently the fastest growing of all commercially-farmed crustaceans. Average weekly gain for mud crabs *Scylla spp.* grown to harvest size in ponds is calculated to around 10 g/wk compared to values of only about 2g/wk for both the so-called "giant" tiger shrimp *Penaeus monodon* and the freshwater prawn *Macrobrachium rosenbergii* (Wickens, Lee, 2002). Apparent growth rates for *Scylla serrata* and *S. paramamosain* calculated from production figures (Christensen, Macintosh, Phuong, 2004; Trino, Millamena, Keenan, 1999) give incredible average weekly gains of 14 to 28 g/wk!

It is easy to understand why evolution would favour mud crabs that grow fast- giving them protection from other crabs and predators. However, it's also possible that at least some of the commercial growth is illusory. For example, if large crabs kill off smaller crabs, or if farmers don't harvest any residue of unmarketable small individuals in the pond then the observed average size can easily become inflated.

The downside for crab farmers is that the production from mud crab ponds is about one tenth of what is possible from a well managed intensive penaeid shrimp pond (up to 2 tonnes/ha compared to up to 20 tonnes for shrimp, (Wickens, Lee, 2002). The prices for mud crabs would need to be high indeed to make up for that low productivity. Yields for mud crabs in ponds are in fact similar to those for other commercial decapods with claws; freshwater prawns and crayfish (Wickens, Lee, 2002). Like the latter, *Scylla* species and other swimming crabs have to be stocked at low densities (<1 crab/m^2) to boost survival.

Mud crabs are grown in earthen ponds- with perimeter fences to prevent the crabs from walking out (Figure 4.1). They are known to burrow in the wild, but this behaviour doesn't seem to become commonly expressed when crabs are reared in ponds. Soon after stocking, the "natural" levels of food in the pond environment are sufficient to satisfy the early stage crablets. The crab's diet is eventually supplemented with low cost, local fishery products and wastes (Christensen, Macintosh, Phuong, 2004). The crop is initially trapped out for sale or finally gathered by drain harvesting. Obviously, the crabs must be tied (restraining their claws) immediately to allow for efficient bulk shipment.

Fig.4.1 Fences serve an important purpose in this crab farm in Vietnam, they keep the crabs in the pond.

Polyculture is possible with mud crabs and other portunids under certain circumstances. For example, it is feasible to grow mud crabs as a “house-keeping” crop underneath floating pens or cages holding fish. Generally however, free polyculture of fish and crabs together is not recommended. Depending upon the timing of the introduction of each crop and the relative size and growth rate of the fry, the fish could eat the juvenile crabs- or vice versa (particularly when rearing a swimming portunid like *P. pelagicus*).

4.2.2 Softshell crabs

Large mud crab juveniles up to 60g in size are induced to moult using multiple limb autotomy (removing all claws and legs, leaving only the paddles) and stocked at high density and fed in small earthen ponds (Dat, 1999). After about one and half weeks the pond is drain harvested and the pre-moult crabs with well developed limb-buds are transferred in small groups into floating baskets so that they can be regularly checked and harvested immediately that they moult.

Confining crabs in this manner allows them to be stored and checked efficiently at much higher densities than is typical for crab culture. For this reason, greater care is required in feed management and control of pond water quality to avoid stressing the crabs, particularly as they undergo moulting (Dat, 1999).

4.2.3 Crab fattening

A broad category that spans several short-term culture practices, “fattening” is primarily a value-adding process, like soft-shell crab production. For example, taking low-value “lean” market-sized mud crab and feeding it for a short period to harden the shell and restore the flesh content (Dat, 1999). But taken more loosely, “fattening” also encompasses other practices such as maturation of females for sale, as well as a kind of proto-aquaculture- the growth of sub-commercial sized mud crabs through a single moult to improve their marketability (Trino, Rodriguez, 2001). As such, fattening practices can vary in their intensity, from labour intensive housing and maintenance of crabs in baskets or enclosures through to pond practices similar to longer term pond culture, (Khatun, Kamal, Yi, 2009; Shelley, 2008). Crabs are housed and fed intensively in bamboo cages up to 25 kg crabs/m^2, so management of fresh feed to the ponds is crucial to avoid deterioration in water quality,(Dat, 1999).

4.3 Biology and Life-cycle

Mud crabs possess almost all of the key characteristics required of a viable candidate for aquaculture (high market price; rapid growth; simple feed and abiotic requirements; ready availability/production of juveniles and no disease hurdles) (Wickens, Lee, 2002) but they fail in one dramatic area. Their aggressive appearance and behaviour, probably a major reason for their premium market value, is a profound biological obstacle to intensive communal culture.

4.3.1 Habits

Mud crabs (*Scylla spp.*) are amongst the largest of the Portunidae, the swimming crabs, a group including a number of other commercially important fishery species in the Indo-Pacific (*Portunus spp.*) and in the Americas (*Callinectes spp.*). Four species of *Scylla* are recognised, of which the largest, *Scylla serrata* is the most widespread, ranging from the coast of southern Africa around the coast of Southern Asia through to the oceanic Western Pacific (Keenan, 1999; Keenan, Davie, Mann, 1998; Macintosh, Overton, Thu, 2002). While all species are to varying degrees estuarine in habit, (they are all quite literally “mangrove crabs”) spawning *Scylla serrata* migrate the furthest from the mangal, and spawn in the open sea. The other *Scylla* species are largely restricted to South East Asia, and their life-histories are more closely tied to estuaries. They were only distinguished relatively recently from amongst the existing diversity of local *Scylla serrata* stocks.

Despite the large size of these crabs as adults (300g or more), the fifth leg is a typical swimming paddle. While not pelagic by preference, the crabs are able to swim, even as adults. Typically, they have a cryptic benthic habit, and are readily found on intertidal flats and mangrove fringes (Hill, Williams, Dutton, 1982; Le Vay, Ut, Jones, 2001; Walton, Le Vay, Truong, Ut, 2006b). To survive in this habitat, *Scylla* species possess a thick exoskeleton, robust claws and a capacity for prolonged survival out of water (Varley, Greenaway, 1992). As adults, they are nocturnal predators of molluscs and other crabs (Hill, 1976; Hill, 1979). While foraging, their singular morphology and sheer size probably protect them from all but the largest and most determined of predators. While they dig burrows in mangroves as adults, as juveniles they hide during daylight under rocks, amongst marine plants such as sea grasses or by burying into the sedment. As they grow, their habitat preferences change, for example juvenile *Scylla serrata* is readily found at high densities on complex intertidal mudflats while the adults forage subtidally at much lower densities (Hill, Williams, Dutton, 1982; Walton, Le Vay, Truong, Ut, 2006b). Growing best under tropical conditions of temperature, their estuarine lifestyle means that juvenile and adult mud crabs tolerate a wide range of salinity (Chen, Chia, 1997; Davenport, Wong, 1987; Nurdiani, Zeng, 2007).

4.3.2 Growth

The widely occurring *Scylla serrata* is the fastest and largest growing of the four scylla species, exceeding 1 kg as an adult (Williams and Primavera 2001). In contrast, tropical *Scylla paramamosain*, the species the most commonly farmed, matures at a slightly smaller size, and is marketed at only 200-250g. *S. serrata* moults 15-17 times after metamorphosis, over 2 or 3 years under natural conditions (Williams, Primavera, 2001). Juvenile and sub-adult mud crabs, like other portunids, double their weight at each moult by inflating a greatly expanded new cuticle through imbibing large amounts of seawater (Neufeld, Cameron, 1994) (Figure 4.2). As expected, the moult increments of portunids decrease below 100% of pre-moult weight with the onset of sexual maturation (Josileen, Menon, 2005; Paterson, Mann, Kelly, Barchiesi, 2007). Immediately after moulting, the crabs are soft and vulnerable to predation. The large moult increment also means that recently-moulted crabs extracted from the fishery (when they harden and first resume feeding) are more or less “empty” of edible meat. The crabs take some time to “grow into” their newly expanded shell.

4.3.3 Reproduction and life history

Scylla, like other portunids, display mate-guarding behaviour. Hard-shelled males compete for mature pre-moult females, and the successful male shelters the female with his body, protecting the female during ecdysis and mating immediately afterwards (Jivoff, Hines, 1998). This strategy is expressed through a familiar form of sexual growth dimorphism. The males ultimately grow to a larger total weight and invest proportionally more of their body mass into their claws. In contrast, the cost of gonadal development and spawning reduces total somatic growth amongst females, and they show no exaggeration of claw size (Heasman, 1980) (Figure 3).

Fig.4.2 Juvenile mud crabs double their weight when they moult. In this example, the post-moult crab has also substantially regenerated a claw (missing from the exuvia on the right).

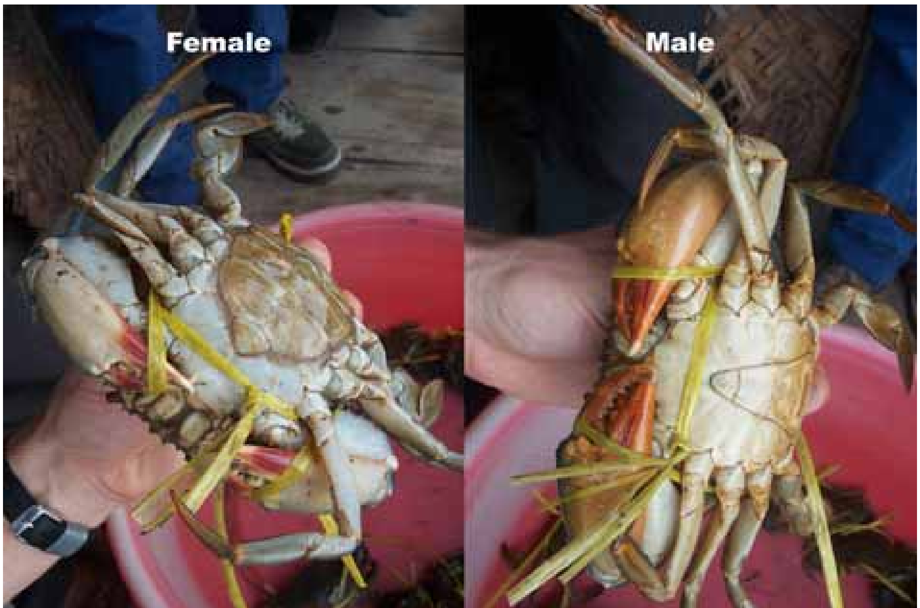

Fig.4.3 Female mud-crabs (in this case *Scylla paramamosain*) are readily distinguished from males by their proportionally smaller claws and wider abdominal flap.

After mating and hardening, the female retains the spermatophore internally and uses it later to fertilise the extruded eggs she attaches to the ovigerous pleopods within her abdominal flap. Mature *S. serrata* females can extrude egg sponges totalling around 3 million eggs! Mud crabs spawn all year, especially in the tropics, and can fertilise several batches of eggs using sperm from just one mating. The spermatophore serum contains potent antimicrobial compounds to ensure longevity of the spermatozoa, (Jayasankar, Subramoniam, 1999). The ovigerous females then migrate so that the eggs hatch offshore. There the newly hatched larvae feed on zooplankton, growing through 5 zoeal moults, before metamorphosing into the "lobster-like" megalops stage. This recruits into the estuary and it settles amongst the tidal flats or mangrove fringe areas and undergoes a further metamorphic moult to the first crab stage or "crablet."

4.3.4 Mud crabs as candidates for aquaculture

Decapods with large chelae are often difficult to farm because of aggression and territorial behaviour (Wickens, Lee, 2002)- and locked in an "arms race" of their own, *Scylla* species probably take the concept of "difficult" to an entirely new level.
It is likely that in terms of evolution, the need to win fights above all other factors drives the phenomenal growth rate achieved by mud crabs and other portunids. The biology of mud crabs is story of rapid somatic growth rate, extraordinary levels of fecundity and dispersal. As seen in the next section (4.3), this fecundity meant that an industry could rapidly develop, based upon a ready supply of wild juveniles. However, their prolific life strategy didn't always support the huge fishing pressure that resulted. Thus the primary focus of technology development (section 4.4) has been to develop sustainable methods of larval rearing.

4.4 Technology development

Practical hatchery methods are no longer a bottleneck preventing sustainable farm production of mud crabs (Marichamy, Rajapackiam, 2001; Quinitio, Parado-Estepa, Millamena, Rodriguez, 2001; Wang, Li, Zeng, Lin, Kong, Ai, Lin, 2005). Variations on these methods applied to mud crabs and other portunid species has enabled routine production of crablets for fishery enhancement/ re-stocking purposes (Lebata, Le Vay, Walton, Binas, Quinitio, Rodriguez, Primavera, 2009; Obata, Imai, Kitakado, Hamasaki, Kitada, 2006; Zmora, Findiesen, Stubblefield, Frenkel, Zohar, 2005) as well as evaluation of other species as candidates for aquaculture, (Marshall, Warburton, Paterson, Mann, 2005; Nicholson, Mann, Fotedar, Paterson, 2008; Parado-Estepa, Quinitio, Rodriguez, 2007).

4.4.1 Hatchery

Where spawning occurs year-round in the tropics, hatchery production can rely upon collection of egg-bearing females. Because female *Scylla* store viable spermatophores for months after mating (Jayasankar, Subramoniam, 1999), mature female mud crabs can also be brought into maturation tanks and allowed to spawn naturally, though spawning can be accelerated by eyestalk ablation, (Millamena, Quinitio, 2000; Zeng, 2007). During maturation, broodstock can be fed either on fresh diets or fresh diets supplemented with formulated ingredients (Alava, Quinitio, de Pedro, Orosco, Wille, 2007a; Millamena, Quinitio, 2000). While HUFA lipids are recognised to be an important component of the maturation diets, further research in this area is required (Alava, Quinitio, de Pedro, Priolo, Orozco, Wille, 2007b; Parado-Estepa, Quinitio, Rodriguez, 2007).

Larval rearing methods for mud crabs have been readily adopted by shrimp hatcheries, where perhaps the only departure from conventional shrimp practices involves the feeding live rotifers to the first larval stage (Davis, Wille, Hecht, Sorgeloos, 2005; Ruscoe, Williams, Shelley, 2004), a practice more common with finfish larval rearing. Where *Artemia* of appropriate nutritional quality are available, then feeding early “teardrop” or “umbrella” stage *Artemia* to the Z1s is also possible (Nghia, Wille, Binh, Thanh, Van Danh, Sorgeloos, 2007), the important thing being to not overwhelm the small crab larvae with large prey items. An example of a rotifer/*Artemia* feeding table for *Scylla serrata* is presented in Table 4.1.

Table 1. An example of a feeding schedule for Scylla serrata larvae culture.

	zoea1	zoea2	zoea3	zoea4	zoea5	megalop	crab 1
Rotifers, L strain	10 to 15 per ml						
Artemia nauplii		1.0 to 1.5 per ml					
Artemia juveniles						0.2 to 0.3 per ml	
Artemia adults						0.1 per ml	
Particulate diet	1.0 to 2.0 g per tonne						

Batch tank culture is typically practiced, with periodic exchanges to control microbial and chemical quality of the water, (Seneriches-Abiera, Parado-Estepa, Gonzales, 2007). Temperatures are kept as high as practical to facilitate rapid development (28-30°C). Because larval development of *Scylla* species proceeds in or near estuaries, salinities close to full marine salinity are not obligatory even for *Scylla serrata* (Nurdiani, Zeng, 2007). Though its also true that the salinity in estuaries can fall dangerously low during rain events, For this reason, it is always prudent for hatcheries in or near estuaries to have ample seawater storage capacity.

Larval rearing of *Scylla* species can involve relatively high mortality. Of course, the easiest way to increase percentage survival is to dramatically reduce larval densities. But in the end, high survival in this case would either reduce the hatchery output or would require construction of a huge inefficient hatchery! In fact, the large egg masses produced by *Scylla* spp. mean that there is usually a gross excess of zoea. At a typical growout density of say 0.5 crab/m^2, a single spawner hatching 3 million eggs could theoretically stock 600 hectares of ponds if all larvae survived! Enough to satisfy the requirements of an entire country! So what does it matter if survival through the hatchery is only 5 to 10%?

Crab zoeas are predators and rely on their feeding appendages to fragment and render their food, (Lumasag, Quinitio, Aguilar, Baldevarona, Saclauso, 2007). A recent study recommended that tanks have darker backgrounds to aid feeding efficiency and reduce stress (Rabbani, Zeng, 2005), though feeding efficiency will also be influenced by prey density. Rotifers and *Artemia* are of course used for convenience in aquaculture (Holme, Zeng, Southgate, 2006a), and rotifers are likely to be considerably easier to catch than the larvae’s natural food, (Lumasag, Quinitio, Aguilar, Baldevarona, Saclauso, 2007).

Nutritional problems may cause some reported difficulties in survival and growth. Cannibalism can be a problem, ironically, when survival is high at high densities, when zoea moult through to the next stage and prey upon smaller larvae remaining in the previous instar. This can become particularly acute when development in larval populations becomes very asynchronous- larvae begin moulting through to the clawed, lobster-like megalops while there is still a large residue of Z4's and Z5s in the tank. "Moult-death syndrome" (or MDS) is also sometimes reported. This occurs when larvae "hang-up" or are unable to free themselves from their old exoskeleton, and die when moulting, The exact cause of this syndrome is not fully understood, but inadequate nutrition is often suspected, (Holme, Zeng, Southgate, 2006b; Holme, Southgate, Zeng, 2007b).

Larval nutrition studies have benefited from development of particulate larval diets, but more research is needed (Holme, Zeng, Southgate, 2009). Live feeds are not nutritionally complete and are routinely fortified either with algae or commerical booster formulations (Genodepa, Zeng, Southgate, 2007). Fully manufactured larval diets are attractive because of the expense and labour involved in growing live feed and algae cultures, (Holme, Zeng, Southgate, 2006a). Initial trials using micro-bound diets are promising, htough there is still a way to go before they can be used commercially, (Holme, Zeng, Southgate, 2006a). Current test diets are well accepted by the zoea, which is already an achievement given that the larvae must manipulate the diet particles within them disintegrating and fouling the water, (Genodepa, Zeng, Southgate, 2007; Lumasag, Quinitio, Aguilar, Baldevarona, Saclauso, 2007). Studies already show that dietary HUFA levels can improve survival (Nghia, Wille, Binh, Thanh, Van Danh, Sorgeloos, 2007) but practical demonstration of this can be complicated by other uncontrolled factors impinging upon hatchery outcomes.

Bacterial problems are largely blamed for the "crashes" in hatchery tanks, leading in some cases to near total mortality. For this reason, there has been too much reliance upon antibiotics such as OTC in hatcheries to manage the risks of batch failure (Nghia, Wille, Binh, Thanh, Van Danh, Sorgeloos, 2007). Though, fungi have also caused issues in crab hatcheries, requiring a different solution (de Pedro, Quinitio, Parado-Estepa, 2007). Widespread use of antibiotics in this manner is not recommended (and it is often illegal in some countries). The biggest problem here is not the tiny residues of antibiotics that might persisting in the larvae beyond the hatchery phase and any uncertain food safety risk to humans. The greatest threat from unregulated use of antibiotics is the build up of resistance to those antibiotics amongst environmental microbes- which can not only recoil back on the hatchery operators but also lead to transfer to resistance to other animal (and human) pathogens (Akinbowale, Peng, Barton, 2006; Akinbowale, Peng, Barton, 2007).

4.4.2 Nursery

High-density nursery production has emerged as an important intermediate practice between hatchery production of megalops and first crablets (Crab 1) on the one hand and the routine grow-out to harvest size at low density on the other. The megalops is readily transported in water (Quinitio, 2000), but ongrowing a couple of instars post-settlement has a practical benefit in that the more robust crablets can be shipped to farms in damp packing material, without water. Nursery conditioning is also beneficial in cases where juveniles are reared for re-stocking into the wild (Davis, Wille, Hecht, Sorgeloos, 2005; Lebata, Le Vay, Walton, Binas, Quinitio, Rodriguez, Primavera, 2009).

Farmers are understandably reluctant to take on the increased risk of on-growing small hatchery-reared juveniles, at least until they are confident in the consistency and quality of the product. While on the face of it these high density nursery methods make more efficient use of space during early growth stages, the work in this area is also providing us with our first insights into the growth and survival of mud crabs and other portunids at high densities.

Mortality of 50% or more during the nursery phase of *S. serrata* and *S. paramamosain* is still reported (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Rodriguez, Parado-Estepa, Quinitio, 2007; Ut, Le Vay, Nghia, Hong Hanh, 2007). Cannibalism is believed to be a major cause of this mortality, but inter-batch variation is also reported, implying differences in the "condition" of megalopa leaving the hatchery (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007). Reducing stocking density reduces but does not eliminate the percentage mortality (Ut, Le Vay, Nghia, Hong Hanh, 2007). As crablets grow, one crab occupies more area and the acceptable stocking density declines. Cannibalism and aggression amongst crablets leaves its mark. Within weeks of stocking a pond with post-settlement *P. pelagicus*, the stable isotopic profile of the largest juveniles in a pond indicated a mixed diet of pellets and other crabs (Møller, Lee, Paterson, Mann, 2008). The survivors from even a brief period of nursery growout already show a relatively wide divergence in size (as many as four or five instars may be present at harvest!), and a high proportion of crablets are missing one or both chelae, presumably because of agonistic encounters with other individuals (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007). Repeated loss and regeneration of claws by some individuals may explain the wide divergence in size (Paterson, Mann, Kelly, Barchiesi, 2007).
Mortality is reduced by including shelter or artificial habitats in nursery systems (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Ut, Le Vay, Nghia, Hong Hanh, 2007). Increased environmental complexity, even objects as simple as paving stones apparently confer a benefit by expanding the available surface area or reducing the encounters between inidividuals, (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Marshall, Warburton, Paterson, Mann, 2005; Ut, Le Vay, Nghia, Hong Hanh, 2007).

4.4.3 Growout and feeding

Recent mud crab growout research has examined practical issues such as stocking density and diet supplementation in extensive pond or mangrove-enclosure systems. To reduce the costs of aggression and cannibalism on survival during grow-out, crabs must be stocked at 0.5 crab m^{-2} – anything more than that and mortality becomes unacceptable, (Trino, Millamena, Keenan, 1999). Stocking density is so low that in the first few months there is enough biota in the pond environment to sustain the crablets. "Supplemental" feeding is only required once the crabs outgrow the natural productivity (Christensen, Macintosh, Phuong, 2004).

The crabs are fed using fresh feeds, such as fish and molluscs and fishery by-products, since Scylla species are understood to be predators, at least as adults, (Hill 1979). Development of formulated diets is under way, (Trino et al 2001), and for experimental work, mud crabs and *Portunus spp.* can be grown on high quality fish-meal based penaeid shrimp diets (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Paterson, Mann, Kelly, Barchiesi, 2007) though these are too expensive for commercial adoption.

Amongst mud crabs, males grow significantly heavier than females, while "roed-up" females achieve a market premium (Trino, Rodriguez, 2001). Monosex culture also apparently alleviates cannibalism when fattening "lean" male and female Scylla serrata (Cholik, Hanafi, 1992; Trino, Rodriguez, 2001). This finding deserves closer attention as it apparently contradicts the outcome expected from normal male "mate guarding" behaviour- crucially, the survival of each sex in the mixed-sex treatment was not reported. Trials of monosex male and female production of *S. serrata* show that males and females show similar levels of survival when not mixed together but there are different economic outcomes; depending upon the respective growth rates of males or females (Trino, Millamena, Keenan, 1999; Trino, Millamena, Keenan, 2001) . Interestingly, monosex culture did not improve survival of *S. olivacea* during fattening in bamboo pens, though this is consistent with the presence of natural mangrove habitat and with the sexes being of similar average weight (Khatun, Kamal, Yi, 2009).

4.5 Future development

Improvements in productivity that address cannibalism loom large as areas of improvement for mud crab farming. This involves two broad areas- improving survival in the ponds and investigating the feasibility of containerised production. That later research area emerges from experienced gained from individual rearing of crabs for feed research. Development of alternatives to “trash fish” is also emerging as a priority because low-cost feed is emerging as the next bottleneck to industry expansion. Of course, while sustainable hatchery production is now common, some effort remains to minimise industry reliance upon antibiotics.

4.5.1 Questions about growth

Grow-out feed research has been expedited by the ready supply of hatchery-reared juveniles. Of course, the cannibalistic nature of the crabs has also meant that these experiments involve distribution of feeds to large numbers of isolated crablets- using individuals as true replicates. Unlike growth trials involving fish or shrimp, where growth is continuous or relatively so, growth trials with rapidly growing juvenile portunids involve large amounts of individual variation. The juveniles basically double their weight each time they moult. Added to this, at any given time, treatments might contain individuals of three different instars, and so differ up to four-fold in wet weight. Fortunately, using initial weight as a covariate accounts for much of the variation in size in any given instar- an interesting point for future selective breeding programs.

Compared in terms of SGR, wild and hatchery reared seed crabs achieve similar growth rates and survival in ponds (Ut, Le Vay, Nghia, Walton, 2007). However, SGR is unlikely to be a suitable growth model for crabs- for example, the graphs in one recent study show that growth is not exponential- it only departs slightly from linear, (Christensen, Macintosh, Phuong, 2004). Daily Growth Coefficient (DGC) may be a more widely applicable, but as it calculates a change in a single dimension from a change of weight or volume- the efficacy of this “width” needs to be judged against simply measuring the growth of carapace width.

Issues of measuring growth aside, published growth rates for mud crabs in nursery and growout ponds should be treated with caution because of the bias inherent in sampling and harvesting. Calculating growth to harvest as average weekly gain or AWG (g/wk) shows that crops of *S. serrata, S. paramamosain* and *S. olivacea* after 120-160 days all achieve impressive AWGs of 13-27 g/wk (Christensen, Macintosh, Phuong, 2004; Trino, Rodriguez, 2002; Trino, Millamena, Keenan, 1999). However, crabs measured/harvested following indoor feed trials or nursery trials, show much lower AWG values (0.05 to 5 g/wk) ((Catacutan, 2002; Sheen, 2000; Sheen, Wu, 1999; Ut, Le Vay, Nghia, Walton, 2007)), even crabs reared in nursery ponds (AWG of 0.7 to 3.6 g/wk) (Rodriguez, Parado-Estepa, Quinitio, 2007). The highest of these values (2-5 g/wk) may be consistent with the slower weekly gains expected at early instars. But the reports of growth rates for extended periods as slow as or even slower than that typical of slower growing aquaculture species such as the giant tiger shrimp *Penaeus monodon* ought to ring alarm bells. The recorded growth of less than 0.1g/wk for early instar juveniles for several weeks (Sheen, 2000; Sheen, Wu, 1999) is a concern since this is around half of the typical farm grow-out period. *Scylla* would normally be close to 100g in weight after 60-80 days.

Animals will grow poorly in suboptimal conditions. But what is “sub-optimal” for mud crabs? Factors possibly explaining slower growth by crabs from laboratory feeding trials include lower ambient temperatures, disturbance during regular cleaning/maintenance, inadequate nutrition, or even social isolation. But this doesn’t explain why crablets confined in net enclosures would grow more slowly but survive better than crabs at the same density free in the pond (Rodriguez, Parado-Estepa, Quinitio, 2007). Its more tedious to find absolutely all of the smallest pond individuals hidden in the mud and algal slime (Rodriguez, Parado-Estepa, Quinitio, 2007) however this doesn’t seem to account for the wide differences in average weight observed (4-6g, rather than 10-16g). While certain physico-chemical parameters may also differ between enclosures (eg. fouled with epiphytes) and open ponds, a “social” dimension to growth should also be considered. By analogy with freshwater crayfish, perhaps individuals in an enclosure can become stuck in a social hierarchy if they continually encounter the same individuals (Hemsworth, Villareal, Patullo, Macmillan, 2006).

4.5.2 Feed development

The digestive enzyme profiles of *Scylla serrata* and *Portunus pelagicus* are typical of carnivores (Figueiredo, Anderson, 2009). Reports of digestive cellulases in predatory *Scylla serrata* may seem to be a paradox, however it may simply indicate that juvenile *Scylla* have a more omnivorous diet than adults (Pavasovic, Richardson, Anderson, Mann, Mather, 2004), or that the enzymes are produced by endosymbionts (Figueiredo, Anderson, 2009). Whatever the origin of the cellulases, the net result is that *Scylla serrata* can readily digest a wide range of plant meals (Catacutan, Eusebio, Teshima, 2003; Truong, Anderson, Mather, Paterson, Richardson, 2008; Tuan, Anderson, Luong-van, Shelley, Allan, 2006) and these observations are being extended to *S. paramamosain*, with some evidence emerging of differences between the *Scylla* species (Truong, Anderson, Mather, Paterson, Richardson, 2009). The crucial question is the extent to which fish meal can be replaced with these plant meals in manufactured diets without compromising growth, (Truong, Anderson, Mather, Paterson, Richardson, 2009).

Scylla serrata is reported to require a diet of 32-40% crude protein and 6-12% crude lipid, along with certain nutrients such as cholesterol (Catacutan, 2002; Sheen, 2000). Interestingly, the usual caution about elevated dietary lipid for crustaceans does not appear to hold for *Scylla serrata*, where levels as high as 13.8% lipid did not impair growth or lead to abnormal accumulation of lipid (Sheen, Wu, 1999). Even, the megalops stage of *S. serrata* tolerates relatively high dietary lipid levels, (Holme, Southgate, Zeng, 2007a), an outcome raising the prospect that protein in mud crab diets can be spared using lipid (Holme, Zeng, Southgate, 2009).

4.5.3 Addressing aggression and cannibalism

Cannibalism remains a major obstacle to improving the productivity of portunid crab grow-out. The factors contributing to cannibalism are poorly understood except at the most superficial level, however if these factors could be addressed on farm, then this would improve the profitability of pond production (Figure 4.4). Research using with nursery-sized animals has shown that mortality from cannibalism is reduced by lowering stocking density and adding artificial habitat, both strategies that reduce encounters between individuals (Mann, Asakawa, Kelly, Lindsay, Paterson, 2007; Ut, Le Vay, Nghia, Hong Hanh, 2007). The cannibals are the larger individuals present (Marshall, Warburton, Paterson, Mann, 2005; Møller, Lee, Paterson, Mann, 2008) and the victims tend to be pre- or post-moult animals (Marshall, Warburton, Paterson, Mann, 2005).

Fig.4.4 Injury and size variation are significant issues for nursery production of mud crab juveniles.

Artificial habitat, which apparently works by spreading the population out and "reducing" the local population density, is a strategy also relevant to farming other clawed decapods (Baird, Patullo, Macmillan, 2006). A distinction should probably be drawn in future studies between "habitat" and "shelter," in that "habitat" refers to enhancing the general landscape within the pond, while a "shelter," like a pot, is a resource, and potentially a focus of aggression between individuals. Complicating the pond floor terrain with "habitat" however raises practical issues for pond management.

Grading appears to be a promising strategy to adopt- if practical issues can be overcome (Marshall, Warburton, Paterson, Mann, 2005). Left to themselves, even a graded sample of crablets rapidly spreads across several instars(Mann, Asakawa, Kelly, Lindsay, Paterson, 2007). Regular harvesting and grading of crabs is out of the question. Partial harvesting is a simple "high-end" approach to grading, targeting "shooters" as they moult through to harvest size (Trino, Rodriguez, 2001). This regular "fishing mortality" has the double advantage of removing dominant individuals and steadily reduces the population density. Another passive approach from the low-end could be drawn by analogy with ecological studies of crab nurseries in the wild (Hovel, Lipcius, 2002; Hovel, Fonseca, 2005). Distribute a nursery "habitat" in areas of the pond, for example a bundled net with a mesh size only suited to small individuals. While this "nursery" would initially protect them, the crabs would eventually have to abandon that nursery as they grow.

Understanding the social behaviour of crabs in ponds is probably the key to mitigating cannibalism. What we know about the role of body size, sex or moult stage (Marshall, Warburton, Paterson, Mann, 2005; Trino, Rodriguez, 2001), must be weighed against the recognition that observations in clear water laboratory conditions are unusual- vision can play no role in the real night-time encounters between crabs in the depths of a turbid pond.

There is as yet no evidence that distance chemoreception plays a role in targeting of moulting individuals, but this cannot be ruled out due to the sophisticated chemical awareness of crabs, (Wall, Paterson, Mohan, 2009). That last study however demonstrated that size determined a communally-reared crab's response to the odour of crushed conspecific- an outcome consistent with observations that larger individuals are cannibals. We need to establish how this behaviour is acquired and reinforced. It remains to be demonstrated whether active cannibals become larger or whether large crabs are simply opportunistic cannibals. Ordinarily, the odour of "blood in the water" or the presence of a carcass in a trap is repellent to crabs (Diaz, Orihuela, Forward Jr, Rittschof, 2003; Moore, Howarth, 1996).

4.5.4 Containerised production

Individual rearing of crabs is an obvious solution to the mortality and injury that occurs when crabs are reared "socially." Experience shows that crabs show almost no mortality when raised in a properly maintained system, albeit with a slower growth rate than the break-neck rates of growth achieved in ponds.

However, indoor containerised rearing of crustaceans is not yet common, presumably because of the extra start-up costs and the higher risks (Figure 4.5). Containerised growth of crabs and other crustaceans adds an extra dimension to the already technically intense set up and running costs of a recirculation aquaculture system (RAS)- fish won't climb out of the tank! Judging by accounts in the literature, (Barki, Karplus, Manor, Parnes, Aflalo, Sagi, 2006; Nicosia, Lavalli, 1999) the technology for homarid lobsters and freshwater crayfish is further advanced than that for mud crabs. However, the long but largely unrealised, to date, interest in containerised production of homarid lobsters is a sobering reminder that technological solutions in aquaculture are not always cost-effective (Kazmierczak, Caffey, 1996).

While a million mud crabs under a large pavilion sounds like a lot, biologically it is not large scale at all for a species that produces millions of eggs per spawner. And a RAS crab farmer would potentially operate all year round, moving small cohorts (tens of thousands say) through each stage of the farm. In this context, a mud crab hatchery supporting a RAS system and operating a modest genetic selection program would find itself tipping most of its larval production down the drain. One such hatchery could supply many farms! Distributed to farms, one million seed crabs would require 200 hectares of water at 0.5 crabs/m^2. But safe in 25x25cm containers they take up just 6.25 hectares of water. The implied efficiency of land use is compelling- but can the numbers stack up? It is worth considering briefly what issues to consider when running an indoor crab farm as a RAS system.

RAS economics are improved by either reducing capital and operating costs and/ or increasing revenue (eg. sale price) (De Ionno, Wines, Jones, Collins, 2006). It is generally recommended that RAS systems concentrate upon exotic and/or high-value species because they generally cannot compete against well established competition from pond aquaculture or wild fisheries, (Funge-Smith, Phillips, 2001; Zohar, Tal, Schreier, Steven, Stubblefield, Place, 2005). It could argued that pond-production of mud crabs is already so well established in SE Asia as to push RAS mud crab production out of contention on the international stage. Certainly, any proponents would have to carefully weigh up the market before proceeding. Production of higher value "soft-shell" crabs looks to be a better candidate for RAS production, but even this market may not prove resilient to cheaper pond-reared competition. Still, it's hard to believe you can't make money selling something that doubles its weight before harvest simply by drinking seawater!

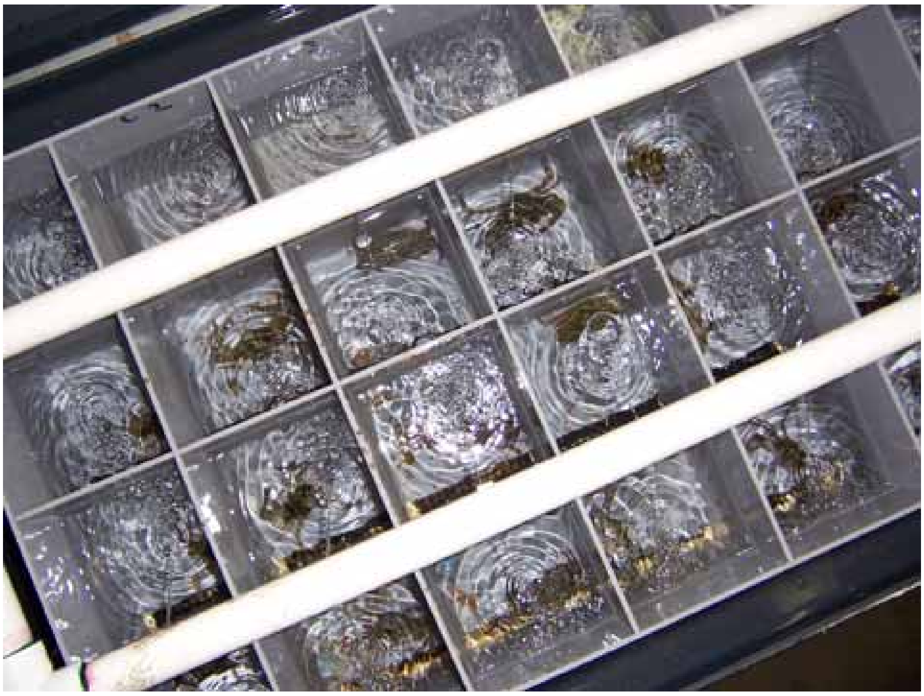

Fig.4.5 High production densities can be achieved at an experimental scale by growing crabs in containers (such as for this stable isotope feeding trial), but what are the consequences for growth rate and the economics of a scaled up commercial system?

RAS systems ideally spread their fixed costs by operating at a large economy of scale (Dunning, Losordo, Hobbs, 1998). For fish, large scale generally means bigger tanks. For crabs, it means deciding how small the compartments can be. A corollary of having a large economy of scale is that each part of the facility must be stocked as fully as possible (Dunning, Losordo, Hobbs, 1998), hence the importance of working out the minimum practical size for compartments (Nicholson, Mann, Fotedar, Paterson, 2008).
RAS systems also have some practical advantages for complete closure of the species' life-cycle (Zohar, Tal, Schreier, Steven, Stubblefield, Place, 2005) but intensification needs to be practiced all the way through the cycle. For crabs, juveniles could be grown intensively in a succession of appropriately sized nursery containers and then distributed from there into the growout containers (Nicholson, Mann, Fotedar, Paterson, 2008). Even with finfish, regular stock handling comes at a cost, (Dunning, Losordo, Hobbs, 1998), so imagine how onerous handling a million individual crabs would be. In well designed infrastructure, the containers could be handled robotically but of course this adds further to the set up and running costs of the enterprise.

Operating the RAS system at maximum efficiency means there is little margin for error (Zohar, Tal, Schreier, Steven, Stubblefield, Place, 2005). To begin with the recirculation and remediation systems in place must be rated realistically to the designed output of the plant, (Dunning, Losordo, Hobbs, 1998). Much also hinges upon the skills and expertise of RAS farm operators and the decisions they make (Kazmierczak, Caffey, 1996)- even before you take into account the "newness" of operating a containerised system. On the face of it, a large RAS crab farm requires huge numbers of individual containers which need to be cleaned and maintained plus a more expensive and complicated water reticulation system. While hygienically challenging, a containerised system can be automatically fed and uneaten feed recorded (crabs will change their feed intake during the moult cycle). To avoid disturbance, crabs and feed can be photographed using infra-red cameras in the otherwise shadowy confines of their containers (Figure 4.6).

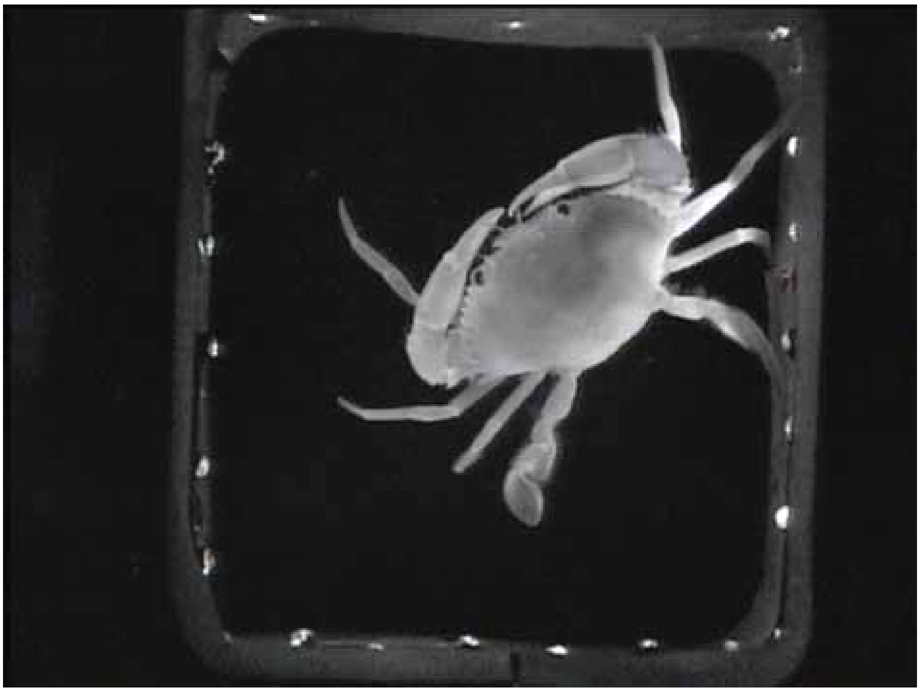

Fig.4.6 Containers may suit cryptic species like mud crabs – and yet individuals can be examined with minimal disturbance using infra-red LEDs and cameras to reveal the animal within.

4.5.5 Improving hatchery efficiency

Finding alternatives to use of antibiotics in hatcheries is a major priority. While acceptable levels of survival to metamorphosis occur in hatcheries, bolstering these figures using antibiotics to control the bacterial flora is not acceptable. More work needs to be done to encourage adoption of alternatives such as ozonation or use of specific probiotics, (Nghia, Wille, Binh, Thanh, Van Danh, Sorgeloos, 2007). Development of artificial larval diets for mud crabs, a worthy aim in its own right in terms of refining hatchery management practices, also promises to remove a major vector of microbial contamination – via the growout and enrichment of live feeds (Holme, Zeng, Southgate, 2009).

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