

Overview of recent research and development in temperate culture of the freshwater prawn (*Macrobrachium rosenbergii* De Man) in the South Central United States

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Abstract

Research and development efforts concerning freshwater prawn farming have in the past been principally conducted in tropical regions. However, activities in temperate regions also date back several decades. Culture of *Macrobrachium* in temperate zones offers positive opportunities, despite the inability to culture year-round. Unique problems imposed by a restricted growing season must be addressed, and opportunities capitalized on, to attain commercially viable production in these regions. Much recent research in the South and Central USA has been directed towards intensifying production (kg ha^{-1}) without decreasing average harvest sizes or deteriorating water quality. Particular areas of research include evaluating and maximizing the relative contributions of natural foods, effects of artificial substrates on growth and prawn population structure and grading of animals before pond stocking to reduce heterogeneous individual growth and aggressive interactions. Recent studies have concentrated on combining these factors into a 'best management practices' (BMPs) production model. With these factors combined, production has increased from an average of 1000 kg ha^{-1} of 30 g animals to almost 3000 kg ha^{-1} of 40 g animals produced in research ponds in 110 days of culture. In commercial ponds, $1500\text{--}2000 \text{ kg ha}^{-1}$ has been achieved in a similar period using BMPs.

Keywords: freshwater prawn, *Macrobrachium*, temperate culture

Unique problems of temperate culture

Compared with tropical environments where culture throughout the year is possible, the growing season for prawns in temperate zones is limited to 100–150 days. This growing period is defined by low and eventually lethal water temperatures during the period before stocking and after harvest. This condition creates at least a potential for crop loss, because of an unanticipated temperature decrease during the period soon after stocking or just before harvest. However, such losses are rare, and experienced producers can normally achieve maximum growth without incurring undue risks. Production in temperate climates is generally limited to the practice of batch culture, i.e. a single stocking and a complete harvest before reaching lethally low water temperature.

Successful culture in temperate climates requires special considerations at both stocking and harvest. At stocking, juveniles of the proper size and number must all be available at the same time so that the maximum number of days in the production (grow-out) ponds can be realized. Also, the fewer the number of available production days, the greater the importance of stocking nursed juveniles of appropriate size (weight) rather than new postlarvae. In the central USA, pond water temperatures are suitable for approximately 120–140 days of culture in production ponds. To achieve marketable sizes of $>30\text{--}60 \text{ g}$ within that period of time, a sufficient supply of juveniles of approximately $0.3\text{--}0.5 \text{ g}$ mean individual weight are required to stock production ponds at $25\text{--}100\,000$ juveniles ha^{-1} . This recommended

stocking size/weight imposes a requirement of 45–60 days of a nursery culture phase after the post-larval stage. This need for a local nursery facility can potentially impair the growth of a regional industry.

Seasonal availability of the final marketable product is another potential problem imposed by production in temperate regions. Marketable-sized prawns can only be harvested during a 4- to 8-week period, depending on growth. Also, the water temperature-imposed need to harvest ponds completely in the autumn can 'flood' markets with fresh or live product over a relatively short period of time.

Opportunities

The greatest advantage of freshwater prawn culture in the USA is proximity of market. The USA is one of the largest and most lucrative markets for almost all major aquaculture products. The USA imports seafood products valued at US\$10 billion annually and is exporting only US\$3 billion, equating to a trade deficit of approximately US\$7 billion annually. In addition, shrimp is now the number one seafood product consumed in the USA.

Macrobrachium rosenbergii (De Man) inhabits freshwater for most of its life cycle. Hence, production can occur much farther inland than is normally feasible with penaeid species (marine shrimp). Production in temperate regions offers the opportunity for prawns to be produced in close proximity to large inland urban markets and for producers to supply these markets with unique product forms, such as fresh or live product. These product forms are especially important for fulfilling the demand of special niche markets, such as the large ethnic communities found in many of these urban areas.

Temperate conditions also create unique production options. For example, in the Midwest region of the USA, prawn producers raise rainbow trout (*Oncorhynchus mykiss* Walbaum) during the winter in prawn ponds as part of a seasonal rotation (Tidwell, Webster & Knaub 1991). Prawns have also been successfully intercropped with another crustacean species, the red swamp crayfish, *Procambarus clarkii* (D'Abramo, Daniels, Sullivan & Ohs 1997). Researchers at Kentucky State University are currently evaluating the polyculture of tilapia (*Oreochromis niloticus*) in cages suspended in prawn ponds.

Current challenges in freshwater prawn production in the USA

Research on the culture of the freshwater prawn, *M. rosenbergii*, in the USA was conducted in Hawaii in

the 1960s, South Carolina in the 1970s, and Mississippi in the 1980s and 1990s. Despite these efforts, substantial concentrated commercial-scale production of this species did not develop. Large-scale production was hindered by relatively low production, a wide size variation at harvest, and the unavailability and high cost of seed stock.

During the past 5 years, interest in prawn production in the USA has again increased considerably and pond production area has reached an estimated 1000 ha. This is primarily because of an increased demand for shrimp products, reduced supplies of shrimp (especially large sizes) because of disease problems in marine shrimp production, and increases in production of prawns based on new management and production practices. Other factors that have led to increased interest include identified markets for live fresh prawns in inland locations, the discovery of the ability to culture prawns further north than previously thought, and strong promotion by private companies that have created a 'boom' in production.

Current constraints to an emerging industry are very similar to those encountered in the past. Production at a commercial level of farming is approximately 50% (1000 kg ha⁻¹) of what has been reported in research trials (> 2000 kg ha⁻¹) (Tidwell, Coyle, Weibel & Evans 1999). The inconsistency appears to be primarily related to poor survival (50–60%) in commercial operations when compared with that in research ponds (85–90%). Fresh on ice and pond bank prices range from US\$15 to 20 kg⁻¹ for whole animals. Although these niche markets do exist, they can quickly become saturated in localized production areas. Wholesale buyers have paid US\$7–12 kg⁻¹, a price currently at or below production costs for most operations and not likely to increase in the frozen markets because of competition from foreign imports. The major operational expense for farmers continues to be the high cost of seed stock. Recent establishment of new hatcheries has increased availability and may over time decrease the costs of stocking. Also, the inaccurate counting methods used by seed stock producers may result in unintentional shortages to grow-out farmers. This lack of accuracy is likely because of large-size variability within nursed juvenile populations, which makes stocking by weight problematic. This unintentional shortage could account for unexplained poor survival that translates into reduced production in commercial operations.

Current challenges appear to be achieving accuracy in counting methods for pond stocking to increase survival and production in ponds, and

identification and expansion of markets that are compatible with projected breakeven costs. Future research should focus on the scaling up of research results, development of technologies for live distribution and reduction of operational costs for hatcheries. Infrastructure needs lie in transport, marketing, processing and distribution. A summary of recent research conducted at Kentucky State University and Mississippi State University follows to help support the emerging freshwater prawn industry.

Temperate production cycle

Broodstock holding

Under tropical conditions, ovigerous 'berried' females are available year-round from production ponds or wild populations, and no special broodstock holding systems are required. In temperate climates, freshwater prawn broodstock are normally collected during the autumn harvest and overwintered indoors in temperature-controlled tanks. The largest males and females are typically selected from pond-reared populations because of higher egg-yield in females and the greater mating success of larger males. If newly hatched larvae are needed after March, then males representing the orange claw morphotype should be stocked at three to four males per 10 females to reduce the mortality rate of males over the relatively long holding period (Daniels, D'Abramo & Parseval 1992). In temperate regions where it is necessary to hold broodstock for up to 6 months before hatchery operations, broodstock should be stocked at approximately 1 g L^{-1} of holding tank volume. Even at these relatively low densities, typical survival at the end of this period is 50–60% for females and 20–30% for males. Only approximately 5% of females will be carrying eggs ready to hatch at any given time and this asynchrony of egg development among females requires that large numbers of broodstock be maintained over long periods of time (4–6 months) in temperate climates. This need for broodstock holding results in high-operational costs and high-mortality of broodstock. Additional research is needed to develop techniques to improve survival and fecundity of prawn broodstock during over wintering in tanks.

Effect of holding temperature on broodstock survival and oviposition

Adult prawns are tolerant of a wide range of water temperature (18–34 °C) but temperatures ranging

from 27 to 32 °C are believed to be optimal. In wild populations of *M. rosenbergii*, peak spawning occurs between 29 and 30.5 °C (Rao 1991). D'Abramo, Daniels, Fondren and Brunson (1995) reported that maturation, mating and spawning occur if water temperatures are maintained above 22 °C. Daniels and colleagues (1992) suggested that as water temperature decreases, the number of eggs decreases, the time for egg development increases and fungal growth on eggs occurs. However, in transport studies, Chen and Kou (1996) reported that lower temperatures (19–20 °C) lower metabolic rates, increase survival and reduce activity, oxygen consumption and nitrogenous excretion. If optimal temperatures for survival for holding adult prawns were different (potentially colder) from that found to be optimum for spawning (e.g. oviposition), then broodstock survival could be readily improved.

A recent unpublished study was conducted to determine the effect of temperature (20, 26 and 32 °C) on growth, survival and oviposition of freshwater prawn broodstock maintained in temperature-controlled tanks. Adult freshwater prawns were evaluated under controlled temperature conditions in tanks for 10 weeks to determine the effect of temperature on survival and sexual morphology. Pond-harvested prawns were purged in clean water, and then classified into either one of three female morphotypes: berried (egg carrying; berried females (BF)), open (previously egg carrying; open females (OP)) and virgin females (VF), or one of three male morphotypes: blue claw (BC), orange-claw (OC), and small males (< 20 g; SM) as described by Cohen, Raanan and Brody (1981) and modified by D'Abramo, Heinen, Robinette and Collins (1989). Only OC males and ovigerous females were used in the study. The mean stocking weight was determined from a sample of 100 prawns from each population (OC males and BF) that were blotted free of surface water and individually weighed. The average weight for OC males was 78.6 ± 7.6 g, and the average weight for BF was 44.7 ± 5.6 g. One hundred prawns were hand counted into each of nine 3610 L cone-bottomed polyethylene tanks with three replicate tanks per temperature treatment (20, 26 and 32 °C) at a ratio of four females/one male in two rotations of 40 females/10 males. Each tank contained 9.811 m² of artificial substrate in the form of 120 cm wide panels of polyethylene 'construction/safety fence' with a mesh opening (length × width) of 7.0 cm × 3.5 cm supported by a 1.875 cm PVC frame with a 5 cm separation between layers. The surface area contributed by

the artificial substrate was calculated to increase the available surface area by 150% compared with the combined area of the sides and bottom of tanks without substrate. The surface area of the substrate was calculated based on dimensions of one side of the mesh (length \times width). Prawns were fed a commercial penaeid diet (42% crude protein) two times daily at 2.0% initial body weight per day.

After 70 days, survival was significantly higher ($P < 0.05$) in the 26 °C treatment (91%) compared with that of the 32 °C treatment (73%), which was significantly higher than that of the 20 °C treatment (24%). The percentage of males reaching sexual maturity (BC males) in the 20 °C treatment (7%) was significantly lower ($P < 0.05$) than the 26 °C treatment (53%), and 32 °C treatment (68%). The percentage of sexually mature females carrying eggs (BF) was significantly lower ($P < 0.05$) in the 20 °C treatment (5.1%), than the 26 °C treatment (48.1%), and the 32 °C treatment (58%). These data indicate that temperature plays a significant role in survival, and the sexual morphology of broodstock being overwintered in a temperate climate. Holding temperatures of 26–28 °C may be optimal to maximize survival and oviposition when maintaining freshwater prawn broodstock.

Hatchery phase

In temperate climates, the hatchery phase usually begins approximately 4 months before the planned stocking of juveniles into production ponds. The duration of a hatchery (or larval) cycle, from the hatching of eggs to the harvest of postlarvae, usually occurs within a 28–30-day period. The restricted pond grow-out period in temperate regions presents some unique challenges for larval culture because only a 'window' of 3 or 4 weeks is available for the production of postlarvae. Therefore, the need to stock grow-out ponds as early as possible, and an imposed 45–60 day nursery period, require planning and success during the hatchery phase and are especially critical in temperate regions. There is no second opportunity to recover if problems, which cannot be readily resolved, occur because of seasonal constraints. Special attention, therefore, needs to be focused on the quality of the broodstock and the cleanliness of the system.

Another special consideration for larval culture, dictated by the restricted growing season, is light. Some researchers have suggested that larvae actively feed by sight rather than by passive encounter; therefore, larvae must be cultured in indirect light of suffi-

cient intensity to allow prey to be readily seen. During the hatchery season (late winter) the number of days with sufficient intensity are relatively few, requiring that natural light be supplemented with artificial light to achieve appropriate light conditions for culture. Larval tanks should be stocked with larvae hatched during a 1–4-day interval. Longer periods of larval collection will increase size variation within the culture tank, promoting the incidence of cannibalism and increasing the length of the larval cycle.

Complete replacement of *Artemia* with a microparticulate diet

The absolute need for live food is considered a limiting factor in commercial hatchery operations. Although *Artemia* has proven to be successful for raising the larvae of many species, including *Macrobrachium*, inherent problems persist. Problems include the year-to-year variation in nutrient composition and availability, potential introduction of pathogens into the culture system and the high costs of labour and infrastructure required for preparation. Also, the nutritional quality of *Artemia* can vary considerably depending on the source and time of harvest of the cysts. Numerous attempts have been made to develop formulated diets that effectively replace live food, but most have not been successful as exclusive diets. A recent study by Kovalenko, D'Abramo, Ohs and Budington (2002) was designed in response to the results of several preliminary investigations devoted to the preparation and evaluation of larval diets and the challenges identified. The overall goal is to produce a comparatively inexpensive, easily prepared, microbound diet that will completely replace live food for the larval culture of the freshwater prawn.

A high moisture (63–71%), semi-purified microbound diet containing alginate was compared with newly hatched live *Artemia* nauplii as an exclusive diet for the culture of larval *M. rosenbergii* from 5th stage (weighted mean) through metamorphosis to postlarvae (Kovalenko *et al.* 2002). Two independent trials, representing larvae from different hatches, were conducted. Larvae were stocked at 50 L⁻¹ into cone-shaped vessels that contained 2 L of 12 gL⁻¹ seawater and were part of a temperature-controlled (28 °C) recirculating culture system. Larvae were manually fed either the live *Artemia* diet or the microbound diet exclusively, several times daily.

After 14 days [23 days posthatch (dph)], growth of larvae fed the microbound diet was 90% of that achieved for larvae fed newly hatched nauplii of *Arte-*

mia. Survival of larvae fed the microbound diet was 77.3%, and was not significantly different from that of *Artemia*-fed larvae. Composed of readily available ingredients, the diet contained 46.2% crude protein and 37.4% crude lipid, was easy to prepare and had good water stability. The diet has the potential to serve as an economically practical alternative to the fluctuating cost, nutrient uncertainty and labour associated with the use of *Artemia* nauplii hatched from cysts. The characteristics of the diet suggest high potential for successful application to the larviculture of other fish and crustacean species, in either the existing or a modified state.

Effect of tank colour on hatchery survival

Colour has been shown to affect the feeding behaviour, growth and survival of some aquatic invertebrates. If a colour affects either growth or survival in *Macrobrachium* larvae, then rearing tanks used in the hatchery phase could be easily modified to the appropriate colour.

A recent study (Yasharian, Coyle, Tidwell and Stilwell III, this issue) evaluated the effect of tank colouration on survival, metamorphosis rate, weight and time required to reach the postlarval (PL) stage during larval culture of freshwater prawns. Newly hatched prawn larvae were stocked into eighteen 16 L plastic rearing tanks at a density of 30 L⁻¹. Tank colours (entire tank) were red, black, white, blue, green and yellow, with three replicate tanks per treatment. Larval prawns were fed brine shrimp (*Artemia franciscana*) nauplii and egg custard.

On day 25, all larvae had metamorphosed into PL and were harvested. Data indicated that the colour of the tank used for larviculture did not significantly impact ($P > 0.05$) final PL size or rate of metamorphosis. However, survival was significantly higher ($P < 0.05$) in red and green tanks (84% and 78% respectively) compared with that observed for the white and blue tanks (56% and 44% respectively). Survival in the yellow and black tanks was intermediate (71% and 71% respectively). If these results are applicable to larger volumes, then a positive impact on production can be realized because most tanks currently used in commercial larviculture in the USA are either blue or black.

Nursery phase

Achieving average harvest weights of > 30 g in the 100–140-day growing period requires that PL be cul-

tured in temperature-controlled nursery tanks to achieve larger sizes, for pond stocking. In the nursery phase of production, PL (average weight < 0.01 g) grow to an average weight ≥ 0.3 g in 30–60 days depending on initial stocking density and water temperature. Nursed juveniles are less likely to be subject to predation and fluctuating environmental conditions in grow-out ponds. In addition, larger average harvest sizes will result. Although the nursery period is vital to prawn culture in temperate climates, relatively little research has been conducted on the effects of different management practices or environmental factors on juvenile prawn growth and survival during the nursery phase.

Effects of stocking density on nursery production and economics

Survival at the end of the nursery phase can vary substantially and may be related to the territorial and cannibalistic nature of prawn PL when cultured at high densities. Several authors have suggested use of artificial substrates to increase the amount of two-dimensional space available to prawns and thereby yielding an increase in survival and production (Juarez, Holtschmit, Salmeron & Smith 1987; Tidwell, Coyle & Schulmeister 1998; D'Abramo, Daniels, Gerard, Jun & Summerlin 2000). With the addition of artificial substrate, PL utilize the full three-dimensional volume of the tank, rather than only the walls and bottom. A wide range of stocking densities have been used in experimental nursery systems, ranging from < 200 to > 6000 PL m⁻² of bottom area. However, optimum stocking densities have not been determined for the longer nursery periods required under temperate conditions (40–60 days). Nurseries in temperate climates usually rely on recirculating or water exchange systems with pumps and heaters, thereby requiring relatively high-energy costs. Seed cost is a dominant variable cost in prawn production (Dasgupta & Tidwell 2004). Thereby, cost efficiency of nurseries significantly impacts the prices of stocker size juveniles, which in turn has a dramatic influence on the profitability of prawn grow-out.

Coyle, Dasgupta, Tidwell, VanArnum and Bright (2003a) evaluated the effect of stocking density, relative to the provision of artificial substrate (number of prawns m⁻² of substrate), on growth, survival and economic variables for freshwater prawn juveniles during nursery production. PL (0.01 g, $n = 300$) were stocked into nine 1900 L tanks, each provided

with 20.5 m² of artificial substrate in the form of horizontal layers of black plastic mesh (10 mm) spaced 5 cm apart. Tanks were randomly assigned one of three prawn densities (215, 430 or 860 postlarvae m⁻² of substrate), which were equivalent to 2.3, 4.6 and 9.2 prawn L⁻¹ respectively. Juvenile prawns were fed a commercial trout diet (42% protein) according to a feed table (D'Abramo *et al.* 1995). Water quality in each tank was maintained using a flow rate of 8 L min⁻¹ from a reservoir pond. Temperature was maintained at approximately 28 °C using heat pumps.

After 56 days, there was no significant difference ($P > 0.05$) in the average weight of juvenile prawns stocked at the three densities (overall = 0.58 g). Survival of prawns stocked at 860 m⁻² (62%) was significantly lower ($P < 0.05$) than that of those stocked at 430 m⁻² (78%) and 215 m⁻² (94%), which were not statistically different ($P > 0.05$). Even with reduced survival, the highest stocking density produced the greatest number of nursed juveniles based on both tank volume (5.5 L⁻¹) and surface area (530 m⁻²), at the lowest average cost.

Effect of photoperiod on nursery production

Photoperiod has been shown to affect food consumption, moulting frequency, the incidence of cannibalism and growth performance of crustaceans (Roubichaud Martin & Waddy 1983, Minagawa & Murano 1993; Minagawa 1994; Constanon-Cervantes, Lugo, Aguilar, Gonzalez-Moran & Fanjul-Moles 1995; Gardner & Maguire 1998; Aiken). However, the actual effects of photoperiod are highly variable among different genera. Conflicting results on the effects of photoperiod on juvenile freshwater prawns have been reported. Withyachumnarnkul, Poolsanguan and Poolsanguan (1990) reported that freshwater prawn juveniles grown for 110 days under total darkness (L0:D24) had higher weight gains than those grown under other light regimes at (L12:D12, L16:D8, or L20:D4). In contrast, Lin (1991) reported that the growth and survival of freshwater prawn larvae increased as the period of light increased.

Since the nursery phase of temperate prawn production occurs indoors, the light cycle can be readily controlled if a particular light regime could be determined to be significantly beneficial. Therefore, a study was conducted to compare the effect of different light regimes on growth and survival of juvenile freshwater prawns under typical nursery conditions

(Tidwell, Coyle, VanArnum, Bright & McCathy 2001). Four hundred PL prawns (0.025 ± 0.04 g) were stocked into nine 170 L nursery tanks at a density of 2.3 postlarvae L⁻¹ and 430 postlarvae m⁻² of artificial substrate. Tanks were randomly assigned to one of the following light (L):dark (D) conditions: 24 h darkness (L0:D24), 12 h light:12 h darkness (L12:D12) or 24 h light (L24:D0) with three replicate tanks per treatment.

After 60 days, there was no significant difference in average individual weight of prawns exposed to the different light regimes (overall mean 0.86 g). Survival was significantly greater ($P < 0.05$) in prawns reared under continuous light L24:D0 (72%) than those raised under L12:D12 (59%) or L0:D24 (58%), which did not differ significantly ($P > 0.05$) from each other. This study indicates that continuous light conditions have a positive impact on survival of freshwater prawn juveniles during the nursery phase, possibly by reducing activity and therefore the incidence of encounter.

Evaluation of interim size-grading and substrate orientation

Higher survival during the nursery phase is known to be related to the provision of artificial substrate (Coyle *et al.* 2003a). Substrate has been installed in both horizontal and vertical orientations. Vertical orientation may be preferred because it may allow increase in inclusion rates and potentially improve water flow and solids collection in nursery tanks. Also, as the duration of the nursery phase increases, size variation increases because of differential growth rates and may contribute to poor survival because of cannibalism by larger individuals. Therefore, size-grading juveniles at some time during the nursery period may decrease size variation and increase survival.

A recent unpublished study was designed to evaluate the effect of substrate orientation (horizontal vs. vertical) and size grading at the midpoint of the duration of the nursery phase on growth and survival of freshwater prawn juveniles. For the substrate study, PL (average weight = 0.01 g) were stocked into eight 189 L polyethylene tanks, each provided with 1.7 m² of artificial substrate in the form of a black plastic mesh (12.7 mm) supported by PVC pipe. Tanks were randomly assigned to a treatment and stocked with 828 PL per tank or 500 PL m⁻² of substrate provided. Each of a group of four tanks was provided

with either vertical substrate or horizontal substrate. Juvenile prawns were fed a commercial penaeid shrimp diet (42% crude protein), as a percentage of body weight. After 30 days, the average weight of prawns (0.27 g) and survival (92%) were not significantly different between the vertical and horizontal substrate treatments. After 60 days, there was no significant difference in the average weight or survival between ungraded populations in the horizontal (0.57 g; 81%) and vertical treatments (0.56 g; 84%), indicating that substrate orientation has no significant impact on prawn nursery survival or average weight.

For the grading study, ungraded prawns were cultured under conditions described previously for the substrate study (horizontal) for the first 30 days. At 30 days, eight tanks were harvested, pooled, size graded using an #8 grader bar into two size classes and subsequently restocked at the same density, but into three tanks per treatment (either high or low grade). After 60 days, average weights of the high-grade prawn and ungraded prawn were significantly higher than that of the low-grade fraction. High and ungraded treatments were not significantly different. Survival of prawns for the low-grade fraction (89%) was significantly higher than that for prawns from either ungraded (81%) or the high-grade fraction (76%). These data suggest that larger individuals within nursery populations negatively impact survival. To maximize survival in the nursery phase, it may be beneficial to remove them or stock them first. In addition, survival at 30 days (92%) was significantly higher than survival at 60 days (82%), indicating that nursery duration does have a significant effect on survival.

Pond grow-out

In temperate climates, prawns are usually stocked into grow-out ponds at the lower densities that are characteristic of semi-intensive culture. A high stocking density is not practical with a growing season of approximately 4.5–5 months. Growth is density-dependent and hence, a marketable product cannot be realized within the time-limited grow-out period. The density-dependent reduction in growth rates occurs in response to achieving a particular biomass. Therefore, this density-dependent factor becomes operative earlier in high-density ponds where the population has a smaller mean weight. As a result, with equivalent survival, the mean harvest size is reduced at comparatively higher densities. D'Abra-

mo and colleagues (1989) showed that average harvest weight decreased 23.2%, from 26.0 to 19.3 g, when stocking densities were increased from 39 536 to 79 072 ha⁻¹.

The short-duration and single-crop culture of prawns in temperate climates warrants low stocking densities. This management practice has an additional benefit because the incidence of water quality problems arising from oxygen depletions is reduced when stocking densities are lower. Nevertheless, at high water temperatures, vigilance is necessary and management practices should call for either constant aeration or the initiation of emergency aeration procedures when dissolved oxygen concentrations are at, or are anticipated to fall below, 3 ppm.

Lower stocking densities also permit a greater contribution of natural productivity for growth. At low stocking densities farmers can use the natural productivity of the pond to sustain maximum growth rates of juvenile prawns until biomass reaches approximately 200–250 kg ha⁻¹. At that point, feeding must be initiated. A commercially available sinking catfish feed, manufactured by pelleting or extrusion, works well, especially during the early stages of culture. This diet may serve to enhance natural productivity as much or more than serving as a direct source of nutrients. Nevertheless, some means to increase the overall energy flow is required. A fertilization regime may either substitute or complement feeding (Tidwell, Coyle, Webster, Sedlacek, Weston, Knight, Hill, D'Abramo, Daniels & Fuller 1997). Careful attention must be directed towards the quantity, the frequency of application and the time of day when fertilizers are applied, to avoid the possible depletion of oxygen, which may occur as the material is decomposed.

Effects of reduced temperatures on population structure

Macrobrachium rosenbergii is a tropical species and is therefore believed to require water temperatures of 26–31 °C for good growth, with 28–31 °C being considered optimal (Sandifer & Smith 1985). However, Tidwell, Webster, Goodgame-Tiu and D'Abramo (1994) reported rapid growth rates for prawns raised at a mean water temperature of 25 °C during the pond grow-out phase. At this culture temperature, harvested prawns exhibited a population structure markedly different from those reported for populations in regions with higher mean water temperatures during the grow-out season. The primary

differences associated with the cooler temperature were a reduced number of stunted males and a corresponding increase in the number of larger, faster-growing OC males.

These water temperature effects on pond populations were conclusively documented using standardized management practices for experimental production ponds located at different latitudes (Tidwell, D'Abramo, Webster, Coyle & Daniels 1996). Stocking rate, stocking date, source of juveniles, diet and feeding rates were identical at both locations. This approach was designed to permit direct comparisons of production and population structure of prawns raised under different water temperature regimes. At the more northerly (cooler) latitude, fewer prawns reached sexual maturity and those that did were larger, indicating a delayed onset of maturation. This delay in attaining sexual maturity of prawns raised at lower temperatures translated into more energy being directed to somatic growth and correspondingly less to maintenance and reproductive demands. Both total yield and growth rates were significantly greater at the higher latitude (cooler) site.

Size grading

Size grading of nursed juveniles before pond stocking has been found to increase both mean harvest size and total pond production in temperate climates, thereby enhancing economical viability. Size grading is essentially a husbandry technique designed to separate the largest, fastest-growing prawns from others in the nursery population. Fast-growing individuals are able to retard the growth of other individuals in the population, although, the mechanism of growth retardation in *Macrobrachium rosenbergii* is not currently known (Karplus, Hulata, Wohlfarth & Halevy 1986). Removal or separation of these fast-growing individuals improves the prospects that other individuals will achieve their growth potential. The smaller individuals in the prawn population, generally males, respond by increasing growth rates to compensate for their small size that is a product of the retarded growth that was initially experienced. Essentially, size grading succeeds in disrupting the continuation of the socially induced, differential growth rates, which results in a wide variation in size within the population over time. D'Abramo, Malecha, Fuller, Daniels and Heinen (1991) stocked ungraded and graded populations of juvenile prawns with a mean weight of 0.33 and 0.30 g, respectively, in earthen experimental ponds at a density of 29 652 ha⁻¹. At

the end of a 5-month grow-out season, the mean harvest size and mean yield of the graded populations exceeded those of the ungraded populations by 37.3% and 45.6% respectively. The mean food conversion ratios were also improved: 2.4 (graded) vs. 3.2 (ungraded).

Size grading can be accomplished by using finfish bar graders. The desired separation is achieved through knowledge of the size distribution of the population, combined with selection of the appropriate bar width. A 50–50% (upper-lower) or 40–60% (upper-lower) size grade is advised because this approach allows the use of both post-graded populations for stocking. Having higher percentages of the upper class reduces the overall effect of size grading on production characteristics in ponds. Daniels and D'Abramo (1994) evaluated the production characteristics of graded and ungraded populations stocked and grown in earthen ponds for a period ranging from 125 to 138 days. The graded populations were numerically divided into 70% upper and 30% lower, and 30% upper and 70% lower groups, according to size. The average yields of the 30% upper (1106 kg ha⁻¹) and 70% upper (884 kg ha⁻¹) populations were significantly greater than that of the ungraded treatment (775 kg ha⁻¹) and corresponded to similar significant differences in mean harvest weight. These significant differences in production characteristics were a reflection of changes in the percent distribution of different groups of individuals comprising the populations, a product of the size grading. Most importantly, based upon the size distributions of the harvested populations, the calculated gross revenues in graded populations were 6–73% greater than those realized for the ungraded populations.

Daniels, D'Abramo, Fondren and Durant (1995) stocked the upper group of a size graded population of juveniles into earthen experimental ponds at densities of 39 540, 59 300 and 79 100 ha⁻¹. After a grow-out of 131–134 days, the mean harvest weight was significantly higher for prawns stocked at the lowest density. Total yield, survival and feed conversion were not significantly different. The relationship of an increase in the proportion of small males at harvest as stocking density increases, a characteristic of ungraded stocked populations, was not observed in their study. The significant differences in mean harvest weight were the result of an increase in the mean harvest weights of certain morphotypes rather than changes in the proportional distributions of the morphotypes. The higher mean harvest weight of po-

pulations harvested from the lower stocking density translated into higher revenue, based upon the proportions of tail count categories.

Effects of stocking different fractions of size-graded juvenile prawns

Grading of juvenile prawns before pond stocking is used to disrupt social interactions that adversely affect growth. Animals graded off the upper end of the size range outperform ungraded animals by 20–50%, but reportedly differ on the performance of the lower grade fraction. Some studies indicate that yields from lower grade animals may equal or surpass those from ungraded animals if the growing season is sufficiently long. However, because the growing season in the temperate region is limited to 110–130 days, it is essential that the performance of the lower grade fraction be evaluated under these conditions.

Tidwell, Coyle and Dasgupta (2004) evaluated the effects of stocking different fractions of size-graded juvenile prawns on production and population structure. Juveniles harvested after a 60-day nursery period were separated into three groups using a #13 bar grader (0.5 cm spacing): ungraded controls, upper grade and lower grade. Ponds (0.04 ha) were randomly assigned to one of three treatments with three replicates per treatment. Artificial substrate consisting of 120 cm wide panels of polyethylene 'construction/safety fence' was added to ponds to increase available surface area by 50%.

After 105 days of grow-out in ponds, survivals of prawns from the ungraded, low-grade, or high-grade fractions were not significantly different. The overall survival was 88%. Total production and average individual weight of prawns were significantly greater ($P < 0.05$) from the high-grade fraction (3310 kg ha⁻¹; 43 g) while feed conversion ratio was significantly lower (2.0). Total production and average weight of prawns stocked from the ungraded (2888 kg ha⁻¹; 36 g) and low graded fractions (2560 kg ha⁻¹; 35 g) were not significantly different. Marketable production (kg ha⁻¹) was significantly higher ($P < 0.05$) in the high-grade treatment based on minimum marketable weights of both 20 and 30 g.

Impacts of grading procedures on population structures were much more pronounced in females than in males. Within females, high-graded populations had a percentage of sexually mature reproductive females (85%) that was significantly higher

($P < 0.05$) than that of the ungraded and low graded populations. In summary, stocking of the upper graded group increased total production, average weights and marketable production. There was no difference in low graded and ungraded animals in the above variables.

Artificial substrate

As noted earlier, in temperate regions it is important to increase total production without decreasing average individual weights. Cohen, Raanan and Brody (1983) reported that total production and average weight increased 14% and 13%, respectively, when artificial substrate was added to ponds in Israel. Tidwell and colleagues (1998) reported that production and average harvest size of prawns stocked at relatively low densities (59 280 ha⁻¹), and grown under temperate conditions, increased 20% and 23%, respectively, when grow-out ponds contained added substrate. Raanan, Cohen, Rappaport and Zohar (1984) reported that added substrate was more effective in intensively stocked production ponds. However, Tidwell and colleagues (1999) found no significant interaction between the addition of substrate and increased stocking density, although substrate did increase the total production by 18%, the average harvest size by 13% and marketable (> 20 g) production by 25%. An unexpected benefit of added substrate was a 17% improvement in feed efficiency. The increased surface area provided by the substrate in the ponds most probably contributes to an increase in the supply of natural foods through enhanced periphyton production. Substrate provision on a commercial scale has resulted in production and mean harvest size exceeding 1800 kg ha⁻¹ and 35 g respectively. Substrate orientation (vertical vs. horizontal) did not affect substrate efficacy. When addition of substrate was combined with higher stocking rates (64 500 ha⁻¹), and increased feeding rates, production exceeding 2500 kg ha⁻¹, with average weights > 40 g, was consistently achieved in experimental ponds (Tidwell *et al.* 2004a).

Compared with finfish species, which utilize the three-dimensional space provided in a pond environment, freshwater prawns are benthic animals and distribution is therefore limited by the two-dimensional surface area of the pond bottom. The concept of adding substrate is to provide for use of the three-dimensional volume, by increasing the amount of two-dimensional surface available in the pond. This

management approach may allow for successful production of prawns in smaller, deeper ponds, which were previously considered unsuitable. This possibility is advantageous in hilly inland regions where suitable sites for large shallow ponds are very limited.

Added substrate can be permanently installed in ponds equipped with catch basins located at the drain end for collection of prawns. As the water is drained, prawns will leave the substrate and follow the flow of water to the catch basin. This approach eliminates the labour required for removal of substrate at harvest. In addition, the materials needed and labour involved in installing substrate can be amortised over several production cycles (years).

Impact of different management technologies on production, economics and population structure

In freshwater prawn production, several management practices (grading, added substrate, etc.) have proven effective in increasing production without decreasing average sizes. These techniques have been developed over several years of experimentation (investigation), appear to be additive and can be combined into a best management practices (BMPs) approach. However, because of the increased investment required, BMPs have not been widely adopted in commercial culture.

A recent study evaluated production levels and cost-and-returns of three prawn production technologies (Tidwell, Coyle, Dasgupta, Bright and Yasharian 2004). A previously recommended technology (39 500 ha⁻¹; no substrate) (low input), an intensified version of that technology (54 500 ha⁻¹; no substrate) (medium input) and a currently recommended BMP package (68 500 ha⁻¹; with substrate) (high input-BMP) were evaluated under standardized conditions. Nine 0.04 ha ponds were randomly assigned to each of the low input, medium input or the high input-BMP treatment. Juvenile prawns were stocked at the previously stated treatment-dependent densities. High Input-BMP ponds received 'high-grade' juveniles that were retained by a #13 grader bar and had an average weight of 0.89 g while the low input and medium input treatments received ungraded juveniles (0.58 g). Artificial substrate was added to the high input-BMP ponds, at a rate sufficient to increase available surface area by 50%. Low and medium input treatments were fed a 32% crude protein-sinking pellet according to a feeding table.

High input-BMP ponds were Phase-Fed at rates of 20% above the feed table recommendations.

After 104 days, survival for the high input-BMP treatment (92%) was higher than that for the medium input treatment (83%) with low input ponds having an intermediate survival (88%). Compared with the previously recommended Low Input Technology, the change to Medium Input Technology significantly increased production (18%) and reduced average weight (9%) and feed conversion ratio (14%). There was no significant difference between Low and Medium Input technologies in per unit production of marketable size animals (> 20 g) or premium size animals (> 30 g). Compared with the original Low Input Technology, the High Input-BMP treatment significantly increased production (92%), average weight (6%), Production size index (PSI) (102%), marketable production (> 20 g) (140%) and production of premium sizes (> 30 g) (130%) while improving feed efficiency (32%). Use of the BMP technology reduced the break-even price for prawns by 22% and 19% compared with that of the Low Input and Medium Input treatments respectively. In summary, adoption of the High Input-BMP technology appears to be biologically and economically justified if similar results can be realized in commercial-scale ponds.

Harvest and post-harvest

Harvesting

In temperate regions, the harvesting of the total pond population of prawns must occur before water temperatures drop below approximately 17 °C. However, some animals may attain marketable sizes 4–6 weeks before final harvest. In tropical regions where year-round culture is possible, selective harvests have been implemented to improve total production by focusing on the removal of larger aggressive morphotypes. This procedure appears to disturb an established behavioural hierarchy and allows less dominant animals to respond to the absence through higher compensatory growth rates. In most temperate regions, the time between the initiation of selective harvest and the temperature-imposed final harvest does not appear to favour this management practice. However, a partial or selective harvest may be a beneficial practice if it succeeds in lengthening the marketing season.

Harvest of prawns by seine in temperate zone prawn culture ponds is relatively inefficient. Seining

without reduced water depth may still leave as much as 25% of the crop in the pond. Total harvest of batch production in ponds may be efficiently achieved through the addition of a catch basin within a drainable pond. When the water is drained, prawns are concentrated in the basin. Sufficient aeration must be provided to this basin to avoid any oxygen deficiencies. If a pond is properly designed and constructed, then very few prawns will become trapped on the pond bottom during draining. In ponds with added substrate, the substrate can be left in place because prawns will move out of the substrate as the water level drops and follow the flow of water to the catch basin.

Handling of prawns during and after harvest is partially determined by the type of market being addressed. In temperate areas where fresh, and especially live, markets are important, harvesting methods that reduce the incidence of handling stress as much as possible must be followed to ensure long-term, post-harvest survival. These methods include aeration of the harvest basin, purging in clean, aerated, holding tanks and harvesting and holding at lower water temperatures (20–22 °C).

Marketing strategies

Successful commercial culture of freshwater prawns in temperate regions offers the opportunity to raise prawns in close proximity to inland urban markets where product forms such as head-on, live or even fresh product are usually unavailable. In these regions, prawns may be considered in a pricing structure that is separate from frozen shrimp. In Kentucky, USA, for example, farm-gate prices for live freshwater prawns of mixed sizes generally achieve US\$13.2–22.0 kg⁻¹. Higher selling prices should compensate for the lower annual yields in temperate regions as imposed by seasonal production.

The higher selling prices that prawns need to command for the economic viability of such an enterprise, when compared with frozen shrimp tails, may also be justified relative to size and quality. Current financial pressures originating from the frequent incidence of disease in marine shrimp (Chamberlain 1994) are causing marine shrimp to be harvested at comparatively small sizes, resulting in an overabundance of small to medium sizes, but an insufficient supply of larger sizes. In fact, many of the larger size and higher priced deheaded 'shrimp' currently being sold in markets in the USA are actually imported de-

headed freshwater prawns. Prawn producers who have established a goal of harvesting large average sizes are readily locating markets for prawns (heads on) that weigh more than 35 g.

Currently, consumers have demonstrated a desire to know something about the conditions under which food is raised. Consumer acceptance of a crop and its purchase may be enhanced by knowledge of the sustainability or responsibility of the associated production methodology. This consumer 'awareness' provides an opportunity for producers in temperate regions who are close to potential markets to demonstrate their rearing techniques to the public. The development of regional 'festivals', based on the harvest and consumption of fresh product, could further satisfy the consumer demand for product information.

Effect of substrate and temperature on transport survival of market-size freshwater prawns

Following the harvesting of live adult prawns in the USA, they have sometimes been transported by truck to urban Asian markets. Hauling stress has been implicated as a potential problem because poor survival during transport and in post-transport live holding tanks has been reported. If techniques could be developed that would enable market-size prawns to be successfully transported live at relatively high densities (1 kg live prawn 10 L⁻¹) then a relatively large market for live product could be found. Methodologies to reduce stress and subsequently increase survival could contribute to industry viability.

A recent unpublished study evaluated the effects of added substrate and water temperature on post-harvest transport survival of pond-harvested adult prawns (38 g). The experimental design was a 2 × 2 factorial consisting of two temperatures (20 and 26 °C), with and without substrate. There were three replicate 100 L insulated plastic containers per treatment, each containing 10 kg of adult market size prawn. The substrate consisted of 2 mm plastic mesh supported by a PVC frame. After 24 h, a water quality sample was collected for analysis, all prawns were removed, determined to be alive or dead, weighed and counted.

The presence of substrate had no significant ($P < 0.05$) impact on prawn survival. However, temperature had a dramatic effect on survival ($P < 0.01$). At 20 °C, prawn survival averaged 96% compared with 24% at 26 °C. Water temperature also signifi-

cantly impacted mean total nitrite-nitrogen concentrations at 20 °C (0.58 mg L⁻¹) and 26 °C (0.93 mg L⁻¹) within transport containers. These data indicate that while reduced water temperature positively impacts prawn survival and water quality in the transport of freshwater prawns, added substrate appears to provide no benefit.

Efficacy of general anaesthetics on freshwater prawns

Two major constraints in the establishment of commercial culture of the freshwater prawn in the USA are poor survival during live transportation of seed stock to grow-out ponds, and live transportation of pond harvested prawns to distant live markets because of their territorial and cannibalistic nature. The use of anaesthetics could greatly improve transport survival; however, currently little is known about the effect of the use of anaesthetic agents with prawns.

A recent study by Coyle, Tidwell, Yasharian and Bright (2003b) compared the effect of five anaesthetics commonly used in finfish (Tricaine (MS-222), 2-phenoxyethanol, quinaldine, clove oil and Aqui-STM) on prawns. Anaesthetics were applied at concentrations of 100, 200 and 300 mg L⁻¹ in three replicate 6 L glass containers containing five juvenile prawns (0.7 g). Times to induction of and recovery from, anaesthesia were measured and compared among treatments.

Tricaine and 2-phenoxyethanol were determined to be ineffective at all levels tested. Clove oil generally induced anaesthesia faster and at lower concentrations than Aqui-STM or quinaldine. Aqui-STM generally induced anaesthesia faster and at lower concentrations than quinaldine. At the highest concentration rate (300 mg L⁻¹) prawns suffered 60% mortality in the Aqui-STM treatment, 20% mortality in the quinaldine treatment, and 0% mortality in the clove oil treatment. Additional research to determine optimal time and dose relationships to minimize stress during transport is currently being carried out.

Summary of the potential

The data presented and discussed in this paper indicate that economically viable culture of *M. rosenbergii* can be extended to cooler latitudes than previously considered possible, not only in the US but also globally. Critical to the success of farming in temperate climates is the implementation of three

management practices: stocking of advanced juveniles, size grading of juveniles and substrate provision in grow-out ponds. These management practices are designed to minimize the major limiting factors of seasonal culture, the limited duration of the growing season and the growth impacting social interactions that are a biological characteristic of this species. The economic benefits derived from each of these management procedures appear to outweigh the increase in operational costs, especially when these management techniques are used collectively in what we term 'BMP' for temperate climate culture. Stocking advanced juveniles, between 0.3 and 0.5 g, typically results in production of 1000 kg ha⁻¹ with a mean harvest weight that exceeds 30 g. With the addition of artificial substrate, in higher production rates, 1800 kg ha⁻¹ have been achieved in < 140 days, while maintaining mean harvest weights of > 35 g. Size grading of juveniles before stocking increases mean annual production even further. When these management practices are combined, production near or above 2000 kg ha⁻¹, with a mean harvest size of > 30 g, has been achieved in commercial operations in less than 140 grow-out days. These production levels, combined with the unique marketing opportunities associated with inland production, are a strong foundation for achieving economically practical production of freshwater prawns in temperate regions of the world.

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