An evaluation of potential diets for the culture of postpueruli spiny lobsters *Panulirus argus* (Palinuridae)

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Abstract

Provision of a suitable feed is paramount for the ongoing success of spiny lobster culture. This study compared and evaluated the performance of seven diets for first instar juvenile spiny lobster *Panulirus argus* [5–6 mm carapace length (CL)] based on growth rates, survival, and feed conversion ratio. Results demonstrated that a seafood-based juvenile formulation produced the fastest growth rate (3.49% weight gain day^{-1} and 0.90% CL increase day^{-1} over a 28-day period). These growth rates were also reflected by a low feed conversion rate (3.04) for this formulated feed. Similar results were also obtained for juveniles fed a frozen seafood diet, however, frozen brine shrimp, *Artemia salina* (both enriched and un-enriched), frozen enriched mysis shrimp, a dry pellet, and a meal-based juvenile formulation did not produce consistent growth rates. Survival rates ranged between 38% and 85% and demonstrate that juvenile lobsters have better likelihoods of survival in captive culture environments compared to the wild. Although further nutritional refinement is recommended, the results from this research have significant implication for the possible expansion of juvenile spiny lobster growout to a larger scale.

KEY WORDS: feed conversion efficiency, formulated feed, juvenile, *Panulirus argus*, specific growth rate

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Introduction

The spiny lobster, *Panulirus argus*, has generated significant interest in the Caribbean region, both as a natural fishery resource and its potential for aquaculture. This species offers more favourable prospects for commercial farming compared with temperate species because of the greater availability of wild seed lobsters and more rapid growth rates (Jeffs & Davis 2003; Cox & Davis 2006). In addition, much is known about this lobster species including its extensive distribution (Lellis 1991), growth rates both in the wild and captivity (Lellis & Russell 1990; Forcucci *et al*. 1994; Sharp *et al*. 2000) and husbandry and collection techniques (Witham *et al*. 1968; Ryther *et al*. 1988; Lellis 1991; Briones-Fourzán & Lozano-Álvarez 1994; Field & Butler 1994).

However, the provision of a suitable feed remains a significant impediment in the transition from experimental scale to commercial scale grow out of juveniles. The diet must be cost-effective, easily produced and modified to suit developmental characteristics of this species, can be stored and handled easily, and reduces the risk of bacterial contamination (Cox & Johnston 2003; Cox 2004). At this stage, the provision of a cost-effective feed for juvenile *P. argus* is probably the single most important obstacle to large-scale commercial aquaculture development of this species (Jeffs & Davis 2003).

Grow out studies have indicated that commercial diets currently available in the USA are less than optimum for both adult and juvenile *P. argus* culture (Booth & Kittaka 2000; Jeffs & Davis 2003). However, research has indicated significant interest in the rapid development of cost-effective feeds for commercial-scale aquaculture of spiny lobsters (Lellis 1990, 1992; Sjoken 2000; Pardee & Foster 1992; S. Cox, unpubl. observ.). Considerably more research is required to better understand the nutritional requirements and feeding behaviors particular to juvenile *P. argus*, enabling successful formulation of a diet for this important first instar [5–15 mm carapace length (CL)] juvenile phase (Cox & Davis 2006).

Dietary studies with juvenile *P. argus* to date have revealed adequate performance when provided a diet of natural marine foods, particularly live invertebrates (Sweat 1968; Witham *et al*. 1968; Ting 1973), amphipods, isopods, *A. salina* (Lellis

1990; Lellis & Russell 1990; Pardee 1992) and other seafood material such as fish and prawn byproducts (Diáz-Iglesia *et al*. 1991; Assad *et al*. 1996; Lozano-Alvarez 1996; Sjoken 2000; Cox & Davis 2006). General conclusions were that high mortality rates, bacterial introduction and financial costs associated with these feed items were too great to warrant further expansion of the use of these items. Typically, *A. salina* (i.e. live or frozen) have been used for the culture of juvenile *P. argus* (Lellis 1990; Lellis & Russell 1990; Pardee 1992); however, this has proven expensive, labor intensive and a vector for bacterial contamination (Cox & Johnston 2003). Natural feeds have been trialed with juveniles of several spiny lobster species including *Panulirus* spp. and *Jasus* spp. (Booth & Kittaka 2000). Although fresh natural food sources, such as clams, mussels, squid, worms and various crustacea have proven excellent for growth, they are not a practical alternative for commercial juvenile growout (Sjoken 2000). They are typically expensive and a consistent supply may not be readily available. In addition, storage and handling may be difficult, and these natural feeds may introduce disease or bacteria to the system (Cox & Johnston 2003).

Spirulina and n-3 fatty acid enriched *A. salina* have been trialed as a food source for juvenile *Homarus americanus* with great success, demonstrating that enriched feedstuffs may be beneficial during the hatchery rearing stage and yield animals with better condition and survival (Tlusty *et al*. 2005a,b). Additionally, enriched products also have an increased nutritional value, are economical, and free of bacteria (Tlusty *et al*. 2005a,b). However, no trials to date have evaluated the use of enriched *A. salina* or mysis shrimp for the culture of juvenile (algal-phase) *P. argus*.

Sjoken (2000) evaluated three artificial diets including a commercial Homarid lobster feed for growth, survival, and biomass on subadult (34–64 mm CL) *P. argus* and found that none of the feeds performed as well as natural food. Similar results were obtained by Lellis (1992) using two crustacean reference diets developed for the American lobster, *H. americanus*, for early-juvenile (6.4 mm CL) *P. argus* and found that neither was suitable because of poor growth and high mortality. Soybean-based artificial diets have also been trialed with juvenile lobsters (Brown *et al*. 1995, 1999), and although good growth rates were reported, the effectiveness of the diet was difficult to assess as mortalities and a control diet were not reported. A commercial fry feed, BioKyowa Fry Feed-C, in combination with *A. salina* was also trialed on juvenile *P. argus*; however, extremely poor growth rates were reported highlighting the importance of formulating diets specifically for this species (Ryther *et al*. 1988). Research which evaluated the suitability of clam, squid, chiton and fish-meal in formulated feeds for late-juvenile (120 g wet weight) *P. argus* indicated growth-enhancing effects of these supplementary high quality protein sources (Perera *et al*. 2005). However, further growout trials were recommended to decide whether the growth rate increase was sufficient to warrant using these protein sources.

The objective of this research was to thoroughly assess the suitability of a range of natural prey items, including enriched products, in comparison with artificial diets formulated specifically to address the requirements of first instar juvenile spiny lobsters. To date, no studies have focused on the dietary requirements of this important developmental phase. The suitability of seven potential diets was evaluated on the basis of two main criteria: (i) optimal performance in terms of growth rates and survival during the first instar phase, (ii) best feed conversion ratio (FCR).

Materials and methods

Animal collection and husbandry

Panulirus argus pueruli (5–6 mm CL) were collected from the Florida Keys, following the new moon recruitment phase in June 2005. Transparent pueruli were collected from 10 modified witham collectors (Witham *et al*. 1968), moored in surface waters within close proximity to shore. Once collected, they were transported to Harbor Branch Oceanographic Institution, Fort Pierce, Florida and subsequently placed into experimental tanks to acclimate for 1 week prior to the start of the experiment. During this time, they were provided refuge in a macroalgal mat (*Caulerpa* sp.) and provided a diet of frozen *A. salina* and wild prey (i.e. worms, amphipods, various crustaceans, frozen seafood items) to ensure food was available at the time of first feeding. Pueruli were not used in the experiments until they had pigmented and had functioning mouthparts (i.e. moulted into first instar juveniles). Lobsters were held at a 14 : 10 light dark cycle, at 28 °C (±1 °C) in a flow-through tank system. Salinity was maintained at 30 g L^{-1} (±2 g L^{-1}) and individual refuges (polyvinylchloride pipes) were provided to the lobsters once the experiment commenced. Water quality parameters (pH, dissolved oxygen, ammonia, nitrate and nitrite) were measured twice weekly and water was sterilized using UV to control for potential pathogens.

Experimental design

A total of 280 first instar juveniles (6–7 mm CL ± 0.35 mm standard deviation) were randomly assigned to experimental

tanks at a density of 10 individuals per experimental tank (250 mm length × 150 mm width × 100 mm depth), with four replicate tanks per diet treatment (i.e. 40 lobsters in total per diet treatment). Treatments consisted of seven diet types: frozen *A. salina*, frozen seafood (including clams, shrimp, fish, squid), enriched frozen *A. salina*, enriched frozen mysis shrimp (both enriched with bioencapsulated vitamins, minerals and spirulina), seafood-based formulated diet (juvenile formulation 1), fish meal-based formulated diet (juvenile formulation 2), and a dry pelleted feed (Table 1). Lobsters were fed to excess (100% wet body weight, BW) once per day at 1700 h, as recommended by Cox & Davis (2006). Quantity of diet fed was calculated on a dry weight basis to account for moisture differences between feeds. Uneaten feed was removed daily at 0800 h and reweighed. The trial ran for 28 days with survival and CL (mm), total length TL (mm), wet weight (g), and specific growth rate (SGR) recorded at the start of the experiment (week 0) and weekly thereafter. Specific growth rate, and food conversion efficiency (FCE) and ratio (FCR) were calculated using the following equations:

$$\mathrm{SGR_{wt}} = \frac{(\mathrm{LNWt_{28}} - \mathrm{LNWt_0}) \times 100}{D}$$

$$SGR_{CL} = (LNCL_{28} - LNCL_0) \times 100/D,$$

where LN = natural log, Wt_{28} = average weight at day 28 (g), Wt_0 = average weight at day 0 (g), D = number of days, CL_{28} = mean carapace length at day 28 (mm), CL_0 = mean carapace length at day 0 (mm);

FCR = (W_{tD}/Wt_w), where Wt_D = dry weight of diet fed (g), Wt_W = wet weight of animal (g)

$$\mathrm{FCE} = \frac{1}{\mathrm{FCR}} \times 100$$

To calculate FCR (a measure of weight gain, combined with the measure of the amount of food used to produce that weight gain), the weights of daily food rations were recorded and converted to dry weight values by correcting for moisture content. Conversion factors to correct for moisture content were determined using 1 g representative feed samples oven-dried at 80 °C for 24 h and calculating ratios of dry weight per initial wet weight. FCE or food efficiency is the reciprocal of the FCR converted to a percentage value. Carapace length and total length were measured as the distances along the dorsal line from between the base of the rostral horns to the posterior margin of the CL, or the posterior margin of the sixth abdominal segment (TL). FCR and FCE were also calculated based on a feeding level of 100% BW day^{-1} and corrected for moisture content. Feed ration was recalculated and adjusted accordingly at the end of a sample week to account for growth and loss of biomass because of mortalities. Mortalities which occurred during the trial were not replaced. The cost analyses of the diets were calculated using current retail purchase price at the time of experiment.

Table 1 Ingredient composition of the three formulated diets used in the feed trial

Ingredient	Quantity (g)	Cost/kg (US$)	Cost/batch (US$)	Total cost of diet/kg (US$)
Seafood-based formulation				
Frozen *Artemia salina*[1]	200	3.14	0.63	11.68
Frozen seafood	200	15.40	3.08	
Gelatin[2]	40	11.00	0.44	
Activa RM[3]	8	50.00	0.40	
Lyo-P-Gold[4]	4	135.55	0.54	
Vitamin/mineral premix[5]	5	48.40	0.24	
Meal-based formulation				
Krill meal[6]	200	10.12	2.02	9.14
Fish meal[6]	200	2.62	0.52	
Gelatin[2]	40	11.00	0.44	
Activa RM[3]	8	50.00	0.40	
Lyo-P-Gold[4]	4	135.55	0.54	
Vitamin/mineral premix[5]	5	48.40	0.24	
Dry pelleted feed				
Krill meal[6]	1100	2.62	2.88	6.51
Fish meal[6]	700	10.12	7.08	
Wheat flour[7]	1600	0.57	0.91	
Starch[8]	300	2.20	0.66	
Gelatin[2]	300	11.00	3.30	
Vitamin C[5]	45	19.03	0.86	
Vitamin/mineral premix[5]	30	48.40	1.45	
Cholesterol[6]	43	176.00	7.57	
Naturose [9]	50	26.20	1.31	
Hex phosphate[5]	50	33.00	1.65	
Shark oil (with paprika)[6]	295	5.75	1.70	
Lecithin 25%[5]	18	4.40	0.08	
Santiquin[10]	1	26.40	0.03	

Note: Frozen seafood used in formulation 1 consisted of chopped clams, shrimp, fish and squid in approximately 1 : 1 : 1 : 1 ratio.
[1] Seacritters, Key Largo, FL, USA.
[2] Florida Aqua Farms, FL, USA.
[3] Ajinomoto Food Ingredients, IL, USA.
[4] Seabait Ltd., England, UK.
[5] Ziegler Bros, Inc, PA, USA.
[6] Aqua-In-Tech, WA, USA.
[7] Sams Club Wholesalers, FL, USA.
[8] ICN Biomedical, OH, USA.
[9] Cyanotech, HI, USA.
[10] Novus International, Inc., MO, USA.

Statistical analysis

Analysis of variance (two-way ANOVA) was used to identify statistical differences between treatment means with respect

to growth parameters (weight and CL) and differences in survival. Factors included in the test were week, diet and the interaction between week and diet. When differences were detected, Tukey's test was used for means separation. Percentage data for survival were normalized using arc sine square root transformation before analysis. Initial weight of lobsters in each treatment group was not significantly different (df = 6, $t = 1.632$, $P < 0.911$). Significance was accepted at $\alpha = 0.05$. Data analysis and statistical testing was performed using SigmaStat® Version 3.0 software for personal computers (SPSS, Chicago, IL, USA).

Results

There was a significant improvement in growth (measured in terms of increased weight gain and CL) of juvenile lobsters fed juvenile diet formulation 1 at the end of the trial period compared with the other diet treatments tested, although this was not significantly different than frozen seafood ($P < 0.001$) (Fig. 1a,b). There was no significant difference in total weight gain in lobsters fed frozen *A. salina*, enriched *A. salina*, enriched mysis, juvenile formulation 2 or the dry pellet. Lobsters fed seafood produced significantly ($P < 0.001$) higher CL increases than those fed frozen *A. salina*, enriched *A. salina*, enriched mysis, juvenile formulation 2 or the dry pellet, which were not significantly different from each other.

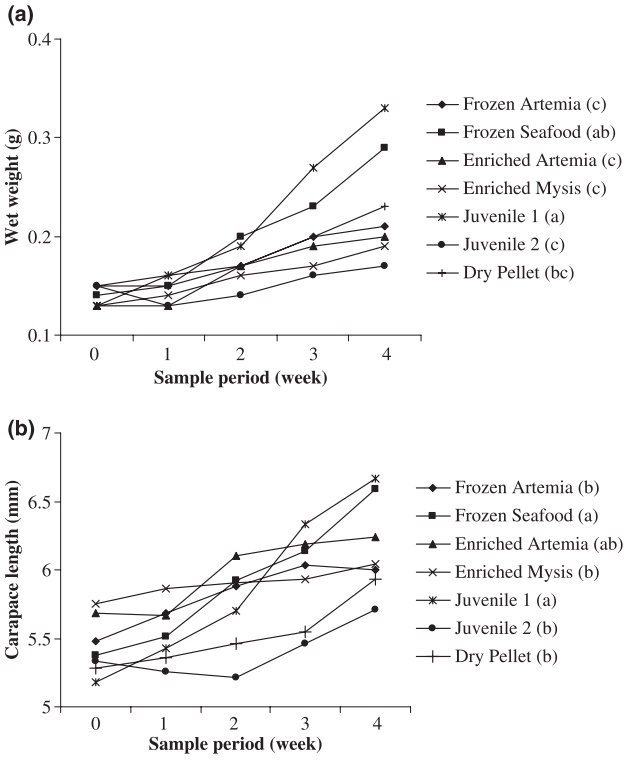

Figure 1 (a) Mean wet weight gain (g) and (b) mean carapace length increase (mm) of juvenile *P. argus* over a 4-week period fed 100% BW day^{-1} of one of seven dietary treatments. Error bars have been omitted for clarity. Means that were significantly different ($P < 0.05$) have different superscripts.

The percentage weight gain (62.3%) and CL increase (22.4%) during the 28-day period was higher in juveniles fed formulation 1 (Table 2). Similarly, frozen seafood resulted in a 49.8% weight gain and a 18.4% CL increase. Weight gains and CL increases for frozen *A. salina*, enriched *A. salina*, enriched mysis, juvenile formulation 2 and the dry pellet were low and ranged from 11.7 to 36.7% and 4.8% to 11.1%, respectively.

Similar trends were reflected in SGR values for weight gain and CL for each of the dietary treatments (Fig. 2a,b). Significantly faster growth rates were achieved in lobsters fed juvenile formulation 1, at 3.49% weight gain day^{-1} and 0.90% CL increase day^{-1}. Frozen seafood also produced comparable SGR values with 2.46% weight gain day^{-1} and 0.73% CL increase day^{-1}.

While there were large differences in survivorship between dietary treatments, survival was generally high for all groups of lobsters except those fed juvenile formulation 2 and the dry pelleted feed (Table 3). Survival ranged from 38% to 85% by week 4 of the trial; however, survivorship decreased significantly on a week by week basis for each diet ($P < 0.01$). It was noted that cannibalism occurred almost exclusively during the post-molt period in all treatments.

Feed conversion ratio and efficiency for each of the seven diet treatments are also shown in Table 3. Juvenile formulation 1 proved to be the most efficiently converted diet, with a ratio of 3.04:1 and efficiency of 32.95%. Frozen *A. salina*, frozen seafood, enriched *A. salina* and frozen enriched mysis

Table 2 Mean percentage increase of weight and carapace length in juvenile *P. argus* after a 4-week trial period when fed one of seven experimental diets

	% Increase	
Diet treatment	Weight gain	Carapace length
Frozen *Artemia salina*	28.9 (b)	8.8 (c)
Frozen seafood	49.8 (a)	18.4 (ab)
Frozen enriched *Artemia salina*	37.2 (ab)	9 (c)
Frozen enriched mysis	29.3 (b)	4.8 (c)
Juvenile formulation 1	62.3 (a)	22.4 (a)
Juvenile formulation 2	11.7 (b)	6.8 (c)
Dry pelleted feed	36.7 (b)	11.1 (bc)

Means that were significantly different ($P < 0.05$) have different letters.

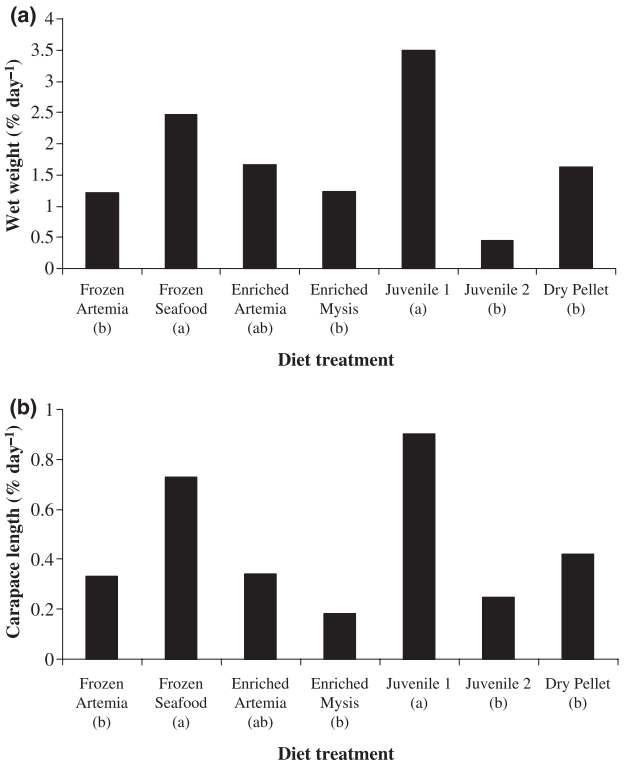

Figure 2 (a) Specific growth rate for weight and (b) Specific growth rate for carapace length in juvenile *P. argus* fed one of seven dietary treatments over a 4-week period. Means that were significantly different ($P < 0.05$) have different superscripts.

shrimp also indicated good potential for juvenile culture, with similarly low ratios and high percentage efficiencies. Feed conversion efficiency was markedly lower for juvenile formulation 2 and the dry pelleted feed at 1.33% and 2.77% respectively.

Discussion

Specific growth rates reported here for the seven diets tested demonstrated that juvenile formulation 1, a seafood-based gelatin bound diet, produced faster growth rates during the 28-day trial at 3.49% weight gain day^{-1} and 0.90% CL increase day^{-1}. These values highlight the success of this formulated feed over other dietary items such as frozen and live *A. salina*, which have been primarily used in the past (Lellis 1990; Lellis & Russell 1990; Pardee 1992). Other studies evaluating live or frozen *A. salina* have reported SGR values between 0.22% and 0.70% CL increase day^{-1} (Ryther *et al.* 1988; Lellis & Russell 1990; Pardee 1992). Previously published results are comparable with SGR for both frozen *A. salina* and enriched *A. salina* reported here at 0.33% day^{-1} and 0.34% day^{-1}, respectively.

The recent advent and mass production of enriched *A. salina* products provides cost-effective and nutritionally complete food sources for many species. Excellent results have been obtained for juvenile American lobsters, *H. americanus* fed *A. salina* enriched with either n-3 fatty acids or spirulina (Tlusty *et al.* 2005a). However, it appears the enriched *A. salina*, and also the enriched mysis shrimp used in the current study did not produce comparably good growth or survival, and resulted in the lowest overall CL and weight increases. The enrichments for both the *A. salina* and mysis shrimp consisted of bioencapsulated vitamins and minerals and spirulina (Hikari Sales, Hayward, CA, USA), however, the exact composition does not appear to be specific for juvenile *P. argus*.

Poor results were obtained in lobsters fed juvenile formulation 2, a fish meal-based gel diet, indicating that juvenile lobsters are not receiving sufficient nutrition from these formulations for growth or survival. Similar results have been reported in juveniles fed BioKyowa Fry Feed-C and HFX CRD-84 and BML-81S, two crustacean reference diets (Ryther *et al.* 1988; Castell *et al.* 1989; Lellis 1992), the latter not being eaten at all. It has been demonstrated that diets composed primarily of fish or fish-meal result in a high frequency of molt death syndrome (Lellis 1990, 1992). Juvenile formulation 2 consisted of approximately 50% fish meal,

Table 3 Comparison of weekly survival (%) and efficiency of feed utilization for juvenile *P. argus* lobsters fed one of seven experimental diets, fed one of seven experimental diets

	Survival (%)						
Diet treatment	Week 0	Week 1	Week 2	Week 3	Week 4	FCR	FCE
Frozen *Artemia salina*	100	93	85	73	70	4.8	21
Frozen seafood	100	98	95	93	85	5.4	19
Frozen enriched *Artemia salina*	100	98	73	53	53	5.0	20
Frozen enriched mysis	100	93	83	68	60	5.8	17
Juvenile formulation 1	100	100	85	60	60	3.0	33
Juvenile formulation 2	100	98	70	60	35	75.4	1
Dry pelleted feed	100	98	88	55	38	36.1	3
	a	a	b	c	c		

Survivorship which was significantly different between weeks ($P < 0.05$) have different subscripts. FCR, feed conversion ratio; FCE, feed conversion efficiency.

which may explain the high mortality rate (possibly attributable to molt death syndrome) and low growth rates attributed to juveniles fed this diet.

The dry pellet resulted in good growth (SGR 0.42 mm day^{-1} and 1.63 g day^{-1}); however, survival was poorest with only 38% of the individuals surviving through the 28-day trial. This diet contained a range of dietary nutrients; however, based on growth and survival, it does not appear they were not readily absorbed. Therefore, it appears the true nutritive value of a formulated feed is ultimately dependent on the digestibility of its nutrients and not simply its composition (Sjoken 2000). Wild caught *P. argus* pueruli do not possess sufficiently developed mouthparts or foreguts to consume a variety of food items, and may require an adaptive weaning period (once feeding has commenced) during the conversion from live feed to dry feed (Lellis 1992). In addition, early instar juveniles do not appear to possess the mouthpart structures or ability to effectively manipulate and ingest harder, dry feeds (Wolfe & Felgenhauer 1991; Matsuda *et al*. 2001; S. Cox, unpubl. observ.).

Survival rates reported in juveniles fed these seven diets were variable and did not accurately reflect the SGR or percentage weight or CL increases achieved for each diet. Variable survival rates were not caused by lack of food, as the lobsters were fed 100% BW once daily, as recommended by Cox & Davis (2006), nor does it appear to be a density dependant effect (these observations were confirmed visually as lobsters fed and engaged with the diets immediately upon feeding, and secondly, there were more pellets/pieces of food in the tanks than there were lobsters, indicating that lobster density was not influencing food availability). Lobsters were cultured at approximately 267 individuals m^2, which is the level suggested for culture of young juveniles in a nursery (Lee & Wickins 1992). Early benthic *P. argus* juveniles (<15–18 mm CL) are generally asocial, however, has been documented that they undergo an ontogenetic shift at approximately this stage, becoming social and seeking shelter with conspecifics (Marx & Herrnkind 1985a,b; Childress & Herrnkind 1994). This behavioural pattern may explain the cannibalism observed between juveniles and account for the differences between survival and growth rates. However, it has been documented that communally reared *P. argus* juveniles are cannibalistic (Ting 1973) and it was suggested that availability and type of cover may be a contributing factor to frequency of cannibalism (Sweat 1968). The results of this study show that the design and management of systems which prevent cannibalism via suitable habitats and hides will be one important component in achieving successful culture of *P. argus*. Provision of a nutritionally inadequate diet may also lead to an increase in cannibalism, particularly during the postmolt phase when lobsters are soft and vulnerable to predation (Crear *et al*. 2000). It appears that diets used in this study which resulted in poor growth (i.e. frozen *A. salina*, frozen mysis, juvenile formulation 2 and the dry pellet) may also have resulted in inadequate nutrition, and subsequently cannibalism.

It is valid to note, however, that PaV1, a pathogenic virus was observed in the recirculation system at the conclusion of the trial (as confirmed by histological examination of additional juvenile lobsters held in the same recirculation system). This virus has been documented to infect sub-legal sized individuals (Behringer *et al*. 2001). Infected individuals display marked behavioural characteristics, such as lethargy, lack of appetite and anti-social habits, and milky hemolymph which does not clot (Shields & Behringer 2004). None of the lobsters used in this trial exhibited those characteristics and histological examination of dead juveniles removed during the trial did not reveal the presence of this virus in these individuals. Therefore, it is not believed that the survival of juveniles used in this trial was compromised by viral infection.

The large variation between FCR for the seven diets, suggests there are differences in assimilation efficiency between the diets. FCRs have been reported for juvenile spiny lobster, *Jasus edwardsii*, with results indicating that mussels (1.26–1.29), a commercial prawn diet (2.24–2.57) and a formulated moist pellet (3.57–3.78) were effectively assimilated (Crear *et al*. 2000). Even though FCR for *J. edwardsii* fed moist pellets and *P. argus* fed juvenile formulation 1 are higher than that of mussels, it is equivalent to that of many other crustaceans (i.e. Penaeid prawns, fed similar formulated diets (Sarac *et al*. 1993; Baillet *et al*. 1997). This result indicates that the use of juvenile formulation 1 should be feasible for the culture of juvenile *P. argus* once the diet is further refined to meet specific nutritional requirements.

Utilization efficiency of diets can be affected by temperature, specifically, decreasing at high culture temperatures (Crear *et al*. 2000). FCRs previously obtained for adult *P. argus* in culture were constant over a wide temperature range and only decreased at a high temperature (Lellis & Russell 1990). Culture temperature was fairly constant (28 °C ± 1 °C) throughout the duration of this trial and is not expected to have influenced the efficiency of nutrient utilization between diet treatments.

A cost analysis based on current purchase price of ingredients indicated that juvenile formulation 1 was slightly more expensive ($11.68 kg^{-1} wet weight) than juvenile formulation 2 ($9.41 kg^{-1} wet weight) and the dry pellet ($6.51 kg^{-1} wet

weight), both of which were meal-based formulations. The three diets developed for this trial were costly to develop and produce, however, the costs could be dramatically reduced with further refinement of the formulation. Purchasing ingredients from wholesalers in larger quantities (particularly the frozen seafood), manufacturing larger batches, and substituting expensive sources of protein and chemoattractants would contribute to an overall cost decrease for each of the diet formulations. Consistency in batch quality and control of the introduction of potential disease pathogens via the seafood could be addressed through purchasing from reputable suppliers, appropriate food handling and manufacturing procedures and the careful application of antibiotics to the culture system. Diet costs for most cultures of larvae and juveniles are high (Cox 2004), but *P. argus* reaches sexual maturity in as little as 12 months (Lellis & Russell 1990; Lellis 1991) so weaning onto a possibly less expensive adult formulation is an option.

Live *A. salina* are expensive (approximately \$7.65 US kg^{-1}) and laborious to maintain or grow (Pardee & Foster 1992). Similarly, specialty diets for rearing crustacean larvae or juveniles, or broodstock diets are also very costly as these life stages require high quality protein sources and appropriate minerals and vitamins. For example, maturation diets for shrimp may cost \$2–4 US kg^{-1}, with special formulations for disease control, immunity boosters, colour enhancers or broodstock formulas fetching even higher prices (R. Laramore, pers. comm.).

Formulated feeds have been identified as the best way to meet the nutritional requirements of spiny lobsters and would be more cost-effective to supply compared with fresh natural diets (Crossland 1988). The problems associated with the current alternatives for *P. argus* culture (i.e. live and frozen *A. salina* and frozen seafood) have highlighted the importance and relative urgency of developing these formulated diets for the commercial success and expansion of juvenile *P. argus* culture. These results confirm other findings which strongly suggest that the specific dietary requirements of spiny lobsters are quite unique compared with other groups of crustaceans and will require specific development (Crossland 1988). The impetus for this research was to develop a suitable diet for first instar *P. argus* lobsters which could be used for the first 1–2 months, and based on the results it is recommended that a soft gelatin-bound seafood formulation be used in experimental-scale culture systems. The authors recommend further dietary trials to determine the optimum feed formulation to accommodate ontogenetic changes in feeding requirements.

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