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Assessment of Five Shelter Types in the Production of Redclaw Crayfish *Cherax quadricarinatus* (Decapoda: Parastacidae) Under Earthen Pond Conditions

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Abstract

An experiment was designed to assess the relative performance of several shelter types on the production of redclaw crayfish *Cherax quadricarinatus* under earthen pond conditions. Juvenile crayfish with a mean stocking weight of 12.76 g were cultured in 24 net pens at 12.5 m ^{2} within a 0.2 ha earthen pond, and were provided with one of five shelter types or no shelter over 162 d. The various shelter types assessed were: mesh bundles, pipe stacks, car tires, elevated cement/fiber-board sheets, and cement/fiber-board sheets laid flat on the substrate. Crayfish in each pen were fed a formulated pellet diet three times each week. Treatments were assessed on the basis of crayfish growth, survival, harvest biomass and berry rate among females at harvest. There was no significant effect ($P > 0.05$) of shelter type on growth; however, there was a highly significant effect ($P < 0.001$) on survival with mesh bundles (75.1%), tires (51.4%), and pipe stacks (43.25%) performing significantly better than the no shelter control (15%). The consequence of equal growth and differing survival among treatments produced significant differences in harvest biomass ($P < 0.01$). There were also significant differences in berry rate for the different treatments ($P = 0.002$), and a significant negative correlation of berry rate on survival for those treatments where shelter was provided. This experiment showed that the shelter types provided during pond culture had a significant effect on harvested biomass, primarily through its effect on survival. The efficacy of the mesh bundle shelters may be attributable to the variability in the size of the spaces provided, and the ability of the mesh to separate many individuals relative to the overall volume of the shelter.

Aquaculture of redclaw crayfish *Cherax quadricarinatus* is a relatively new industry to northeastern Australia and is poised for substantial expansion. Redclaw production in the State of Queensland has risen from 32 tons in 1993–1994 to 77 tons in 1998–1999. Average yield from those farms that produce in excess of 1,000 kg/yr was 1,796 kg/ha (Lobegeiger 2000). The approach taken by farmers varies considerably, ranging from simple harvesting of unmanaged farm dam populations of crayfish to semi-intensively managed aquaculture ponds. Well managed redclaw farms are now achieving yields in excess of 4,000 kg/ha per yr (Lobegeiger 2000) and are characterized by consistencies in the approach taken and the pond environment provided. One factor in particular that appears to be of fundamental importance in maximizing yields of redclaw is the provision of shelter.

The natural habitat of redclaw generally consists of permanent water-holes in the upper reaches of rivers, with static or slow water flow. Where crayfish are relatively abundant, there are usually considerable amounts of fallen timber in the water. In addition or alternatively, dense beds of macrophytes may occur where redclaw abundance is high. The correlation of redclaw abundance and the physically complex environment afforded by the fallen timber or macrophytes suggests that redclaw may benefit from shelter.

It is clear that the bulk of freshwater crayfish species do require some form of shelter (Hogger 1988). Many species satisfy this demand by burrowing into the soil substrate where they live, sometimes forming very intricate burrows (Horwitz and Richardson 1986; Hogger 1988) from which they rarely, or only seasonally emerge. Other non-burrowing species will utilize rocks, gravel or vegetation to obtain shelter (Mason 1978; Hogger 1988; Eversole and Foltz 1993; Foster 1993). It has been suggested that these habitat preferences provide shelter for the crayfish during periods of vulnerability when moulting, protect against predation, and minimize aggressive interactions.

Previous studies of redclaw have indicated the importance of shelter for early stage juveniles (Du Boulay et al. 1993; Jones 1995a, 1995b; Karplus et al. 1995). These studies demonstrated that redclaw are able to discriminate between different shelter types and display clear preferences.

Most redclaw farmers provide some form of shelter in their ponds; however, there is no consensus as to the amount or type of shelter that is most effective. Greatest consideration is given to the cost, and this explains the widespread popularity of discarded car tires as a redclaw shelter. Increasingly strict environmental regulations for the disposal of tires are likely to disallow this usage or to demand their removal, and consequently redclaw farmers may be faced with a significant financial liability. Moreover, the adequacy of tires as a redclaw shelter has not been formally assessed.

It is also common for redclaw farmers to use bundles of onion bags or similar mesh material as crayfish shelters, particularly for juveniles (Fielder and Thorne 1990; Jones 1990). For such shelters, material is bunched together and weighted to the bottom. Less common shelter types include off-cuts of pipe, corrugated fiber-board sheet, plastic sheeting, discarded fishing nets, bamboo pieces, or mounds of fallen timber.

As the redclaw aquaculture industry develops, it will be important to adequately define suitable shelter specifications. Ultimately, it should be possible to design an artificial shelter with characteristics that maximize its use by redclaw.

To assist in defining the ideal shelter, and with a view to providing specifications that a manufacturer could use for mass-production, an experiment was designed to assess the relative performance of several shelter types under conditions typically used for the pond production of redclaw.

Materials and Methods

The experiment was conducted in pen enclosures within a 0.2-ha earthen pond at the Freshwater Fisheries and Aquaculture Research Centre, Walkamin in Northern Australia (17.1°S, 145.5°E) over 162 d from 22 June to 1 December (i.e., winter–late spring).

Pens were fabricated from 9-mm extruded plastic mesh. Each pen was 4 m × 4 m × 1.8 m high with no top or bottom. Pens were secured to the pond floor by burying the bottom margin of the pen approximately 300 mm into the pond soil. The four corners of the pens were secured to steel poles, placed inside the corners and driven deeply into the pond bottom. PVC pipe (90-mm) was attached to the top inside margin of each pen to prevent crayfish escape.

The pond was prepared with applications of dolomite at the rate of 1,000 kg/ha, diammonium phosphate at 250 kg/ha, and mulching hay at 1,000 kg/ha. Additional applications of fertilizers were used throughout the experiment to maintain a plankton bloom. Water was maintained at a constant depth of between 1.3 m and 1.8 m for all pens. New water was added only to match losses due to evaporation and seepage. Dissolved oxygen, pH, secchi depth, and maximum and minimum temperatures at the pond bottom were measured twice per week at 0830.

Each pen was furnished with a single 100-mm diameter PVC airlift pump (Jones and Curtis 1994) to provide aeration and water circulation. Air was injected at 0.435 kPa through a perforated 12-mm polythene pipe at a depth of 1 m within the 100-mm

TABLE 1. *Description of shelter types as assessed for redclaw.*

Shelter type	Description	Quantity
1 Control	no shelter	
2 Tires	14-inch diameter car tires, arranged in rows of three. The first tire lay flat on the substrate with the remaining two propped up on an angle of about 30°. A hole (minimum diameter 50 mm) was cut in both walls of each tire, diametrically opposed, to facilitate drainage of water when draining the pond, and to prevent the capture of air when the pond was filled	Four rows of three tires were provided per pen equivalent to three tires per four square meters
3 Mesh Bundles	Made from strips of oyster shade material (Southcorp Industrial Textiles Pty Ltd.), a light-weight open weave mesh similar to that used for onion bags. Each bundle was attached to a rope which was weighted at one end, with a float at the other. All bundles were of an equivalent size and were made from 12 strips of material (1 m × 10 cm lengths) tied on their longitudinal centers to the main rope. Because of the buoyant nature of the material used, this shelter simulated a large rooted macrophyte and provided an abundance of edges, the benefits of which have previously been suggested (Smith and Sandifer 1979; Jones 1995a).	Eight mesh bundles were provided per pen, equivalent to one shelter per two square meters
4 Elevated Sheets	Each consisted of two flat sheets of synthetic cement/fibre board, 300 mm × 300 mm × 5 mm attached together to two pairs of 300-mm length, 50-mm polythene pipe. Similar structures have been shown to provide shelter for the spiny lobster *Panulirus argus* (Eggleston et al. 1990).	Sixteen shelters were placed equidistant from each other on the pond floor (per pen), equivalent to one per square meter.
5 Flat Sheets	A single sheet of synthetic cement/fibre board, 300 mm × 300 mm × 5 mm, was placed directly on the substrate.	Sixteen shelters were placed equidistant from each other on the pond floor (per pen), equivalent to one per square meter.
6 Pipe stacks	A fixed structure consisting of 24 250-mm lengths of 80-mm diameter corrugated polythene pipe, placed in a stack 3 high by 8 wide. Steel fencing clips were used to secure each pipe to adjacent pipes. A 240 mm × 640 mm piece of rigid plastic mesh was attached to one side of the structure so that crayfish access was from one end only. One pipe on the bottom row was filled with concrete to facilitate sinking and to ensure that the habitat remained upright throughout the experiment.	Eight shelters were provided per pen, equivalent to one unit per two square meters.

pipe. Airlift pumps were operated continuously throughout the experiment.

Twenty-four pens were used to accommodate six treatments with four replicates, arranged in a randomized block design. The treatments consisted of a control for which no shelter was provided and five artificial shelter types (Table 1). Juvenile redclaw stock for this experiment was harvested with a flow trap (Jones and Curtis 1994)

FIGURE 1. *Photograph of tires as used for shelter.*

from ponds that had been stocked 4 mo previously with Flinders River broodstock. Each pen was stocked with a random selection of 200 size-graded juvenile redclaw (12.5 crayfish/m^2) with a mean weight ($\pm$ SE) of 12.76 $\pm$ 1.19 g. A sample of 50 crayfish allocated to each cage were individually weighed at the start of the experiment.

Shelters used for this experiment were chosen on the basis of those commonly used by redclaw farmers, and to maximize the variability in specifications and characteristics of the shelter. Having chosen five shelter types, consideration was given to their volume, surface area and how they may be used by redclaw, in determining the appropriate number of each shelter per cage. The quantity used was considered surplus to the minimum requirements of the stocking density applied. Shelter types are described in Table 1. Photographs of each shelter type are presented in Figs. 1–5.

A commercial crayfish diet (Athmaize™), previously established as a good supplementary food, was provided 3 times per week at dusk. Feeding was based on a percentage of biomass, initially calculated at 5% per day. Feeding rate during the experiment was then adjusted according to observations for under or excess feeding.

Because individual crayfish were not identifiable, analysis of specific growth rate (SGR, %/d) (Evans and Jussila 1997) used pen means of individual weight at harvest, minus the mean weight of redclaw in that pen when stocked. Survival was expressed as the percentage of crayfish alive at harvest. Biomass represented the total weight of crayfish harvested for each pen (16 m^2). The percentage of berried females found at harvest was calculated by dividing the number of berried females found in each pen by the total number of females from that pen. As the structure of the harvest population is an important parameter in crayfish aquaculture, a comparison of the frequency distributions was carried out.

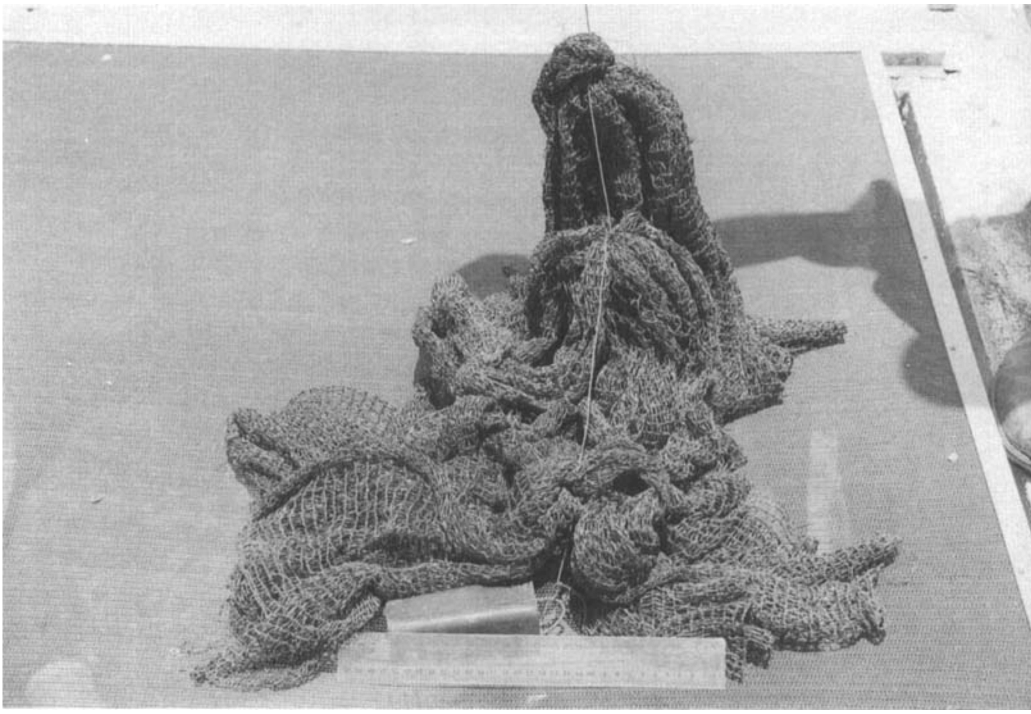

FIGURE 2. *Photograph of mesh shelter.*

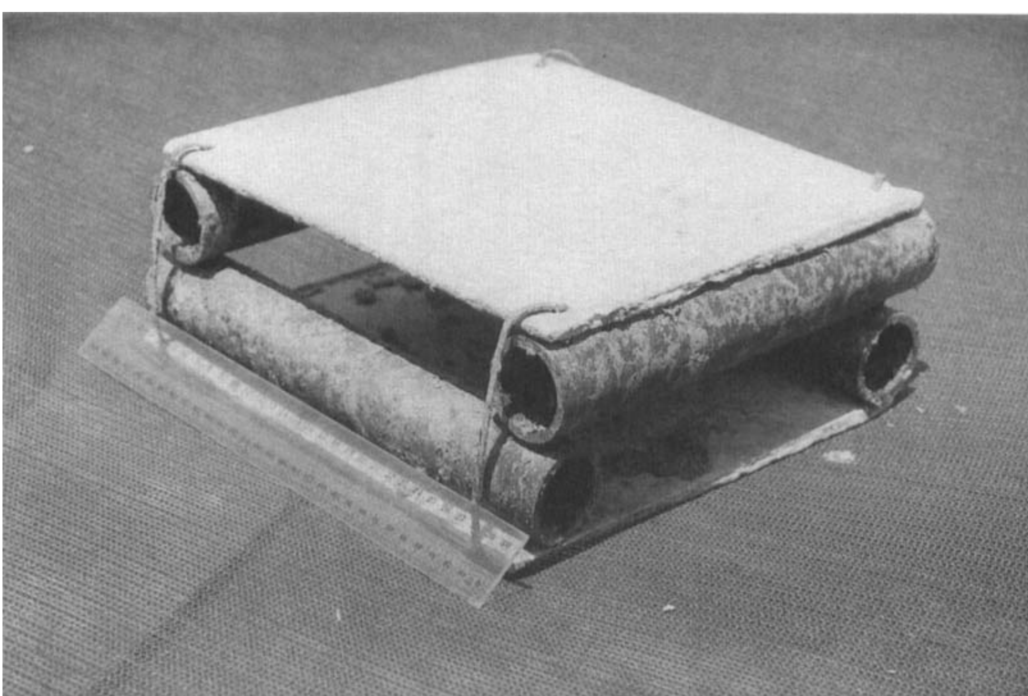

FIGURE 3. *Photograph of elevated sheets (casitas) shelter.*

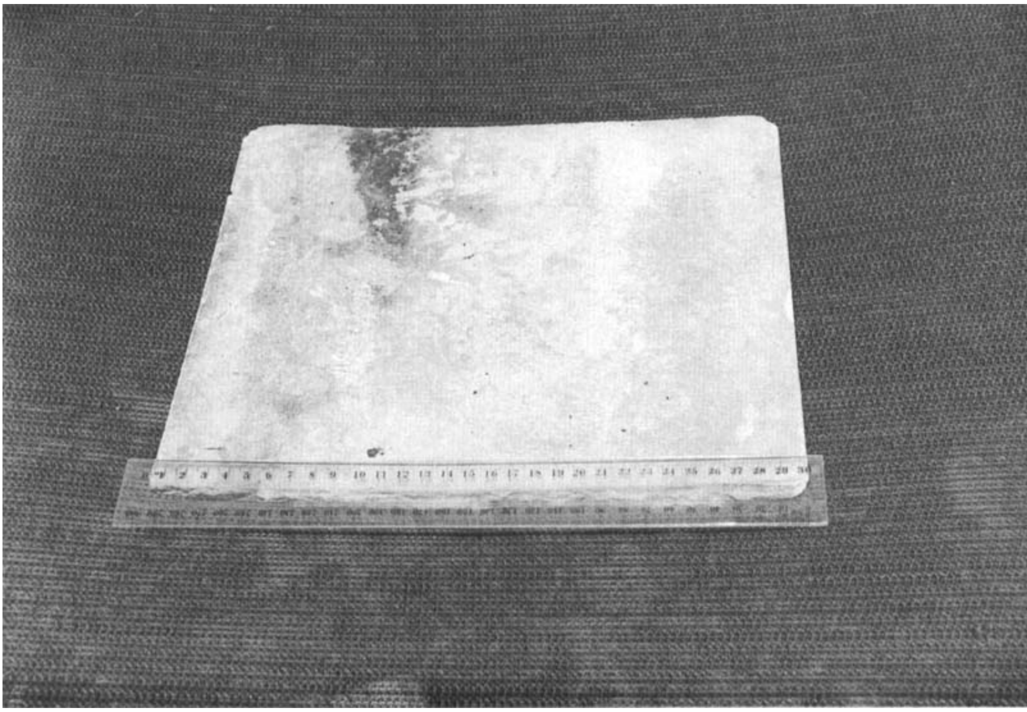

FIGURE 4. *Photograph of flat sheet shelter.*

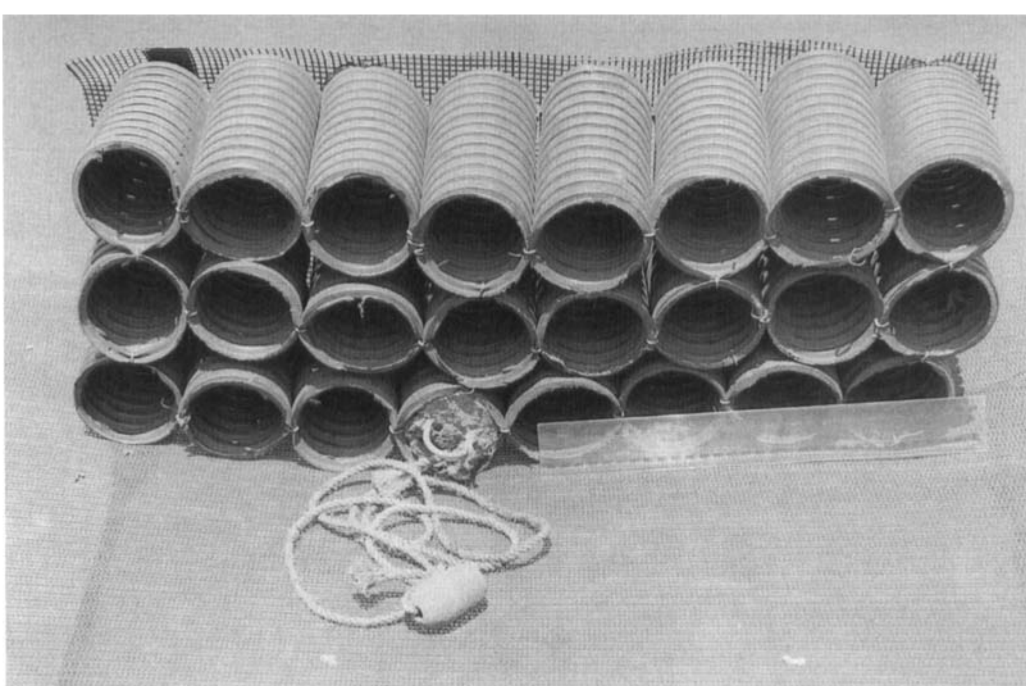

FIGURE 5. *Photograph of pipe stack shelter.*

This was achieved by comparing the relative position (mean weight) of, and the amount of variation (standard deviation) in the distributions.

All statistical computations were performed at the 0.05 probability level. Data for initial weight, harvest weight, standard deviation of harvest weight, SGR, survival, biomass, and the proportion of berried females in each cage for the six treatments were analyzed with analysis of variance, and where significance was established, was followed by pairwise comparisons of means with the Least Significant Difference test. A simple linear regression analysis was performed on berry rate versus survival for those habitats where artificial shelter was provided. Residuals of all parameters were examined to determine a requirement for data transformations. Analyses were performed using Genstat 5 for Windows and Microsoft Excel 97.

Results

Conditions in the pond remained relatively stable and suitable for the cultivation of redclaw throughout the experimental period. At the beginning of the experiment the diel temperature was in the range 20–24 C but steadily increased to peak between 27–32 C in the week of harvest. Secchi disk depth remained between 90 and 100 cm, dissolved oxygen was between 3.4 and 8.5 ppm with an average of 6.4 ppm, and pH between 7.0 and 9.5 with an average of 8.4, throughout the experiment.

Means and standard errors for initial weight, harvest weight, standard deviation of harvest weight, survival, SGR, harvest biomass, and the percentage of berried females are presented in Table 2.

While harvest weight and SGR of crayfish were not significantly different ($P > 0.05$) among the shelter types, survival was ($P < 0.001$). As a consequence, biomass was also significantly different between shelter types ($P < 0.01$).

Means (± SE) for survival for each shelter type are presented in Table 2, showing a clear variability between treatments, and a significant advantage conferred by the mesh bundle shelter. Tires and pipe stacks were moderately successful as shelters, but elevated sheets and flat sheets were clearly deficient.

A comparison of the population structure at harvest for each shelter type is illustrated in Fig. 6. Frequency of each 10-g size class is shown as a percentage of the total number (four replicates pooled) harvested. Note that the total number for each shelter type varied significantly as indicated by the N value appended to each size frequency distribution. No significant differences were found in the position of, or amount of variation in, the distributions between treatments.

Analysis of variance of harvest weight for each gender, (all treatments combined), indicated that males were significantly ($P < 0.01$) heavier than females at harvest. Mean harvest weight for males was 35.98 ± 1.62 g while that of females was 29.18 ± 0.90g.

A significant difference ($P = 0.002$) in female berry rate between treatments was found (Table 2). For those treatments where artificial shelter was provided, a weak but significant negative correlation ($P = 0.044$, $R^2 = 0.16$) was found for berry rate versus survival (Fig. 7).

Discussion

Provision and type of shelter had a significant influence on the production of redclaw under earthen pond conditions. Results showed that when no shelter was provided, production was limited, primarily because of decreased survival. Differences between shelter types were also significant with regard to survival. Mean individual growth for each treatment did not vary significantly. However, the product of growth and survival resulted in clear differences in biomass at harvest.

The dependence of survival and independence of growth rate in relation to shelter availability and specification appears to be common to many benthic crustaceans (Van

TABLE 2. *Means (±SE) for initial and final weights, standard deviation of final weight, specific growth rate, survival, harvest biomass, and frequency of berried females among surviving females for the shelter experiment held over 162 d. Where superscripts are not present, P > 0.05. Means within columns with the same superscript are not significantly different at the 0.05 probability level.*

Shelter type	Initial weight (g)	Final weight (g)	Standard deviation of harvest weight (g)	SGR (%/d)
No shelter	12.11 ± 3.06	32.54 ± 7.51	14.99 ± 0.31	0.62 ± 0.08
Tires	13.47 ± 2.73	35.08 ± 8.32	17.09 ± 1.73	0.59 ± 0.04
Mesh bundles	12.63 ± 2.99	29.99 ± 7.02	14.03 ± 0.41	0.54 ± 0.04
Elevated sheets	13.01 ± 2.86	35.14 ± 8.11	15.83 ± 1.47	0.61 ± 0.05
Flat sheets	13.08 ± 2.83	31.12 ± 7.98	15.50 ± 1.26	0.54 ± 0.01
Pipe stacks	12.28 ± 2.96	33.76 ± 8.5	17.14 ± 0.95	0.63 ± 0.04

Olst et al. 1975; Mason 1978; Eggleston and Lipcius 1992; Geddes et al. 1993; Ingerson 1995). However, exceptions have been reported. Tidwell et al. (1999) found that in *Macrobrachium rosenbergii* there was no significant difference in survival or growth between a no added shelter control and an added shelter treatment. The resulting total yield was, however, significantly greater (18%) for the added shelter treatment. Karplus et al. (1995) found shelter impacted heavily on growth but not survival for newly released juvenile redclaw. Those authors suggested that the similarity in size at hatching reduced cannibalism and promoted survival.

The reasons why crayfish require shelter have not been well investigated. Some investigators (Lowery 1988; Fielder and Thorne 1990; Smallridge 1994) have suggested that shelters may play an important role in providing refuge during ecdysis when vulnerability to predation is very high. While this is a logical argument, the authors observations of redclaw over many years suggest the opposite. Exuviae are commonly found in the shallows of ponds, well removed from available shelters. Furthermore, during periods when redclaw have been held in tanks furnished with shelters, exuviae are often found on the tops of shelters provided, suggesting pre-molt crayfish will seek out areas away from normal shelter. Given the propensity of intermolt crayfish to cannibalize their post-molt conspecifics, there is adaptive advantage in molting in areas remote from those where abundance of intermolt animals is greatest, that is, in and near shelter. Presumably, the predation risk from other species is lower than that from their own kind. Observations of crayfish actively leaving shelters to molt have been documented for *Astacus astacus* (Westin and Gydemo 1988) and for *Pacifastacus leniusculus* (Westman 1973).

Van Olst et al. (1975) suggested survival of the marine lobster *Homarus americanus* in captivity was primarily reduced by cannibalism (presumably during molting) and this may be independent of food availability. A similar mechanism may be at play for redclaw, and therefore, shelter design and placement should primarily aim to mitigate molt-related cannibalism by providing suitable shelter for both molting and intermolt crayfish.

Redclaw would appear to seek out and occupy shelter as general protection against predation, although not during molting episodes. Sheltering behavior may provide a mechanism for concentrating individuals which facilitates reproduction. This hypothesis was supported by the increased incidence of berried females from the shelter treatments in contrast to the control. The elevated cement/fiberboard sheets also yielded significantly more berried females than the other shelter types. The capacity of this shelter type to facilitate interaction between animals, as opposed to the separating

TABLE 2. *Extended.*

Survival (%)	Harvest biomass (kg/pen)	Berried females (%)
15.12 ± 3.38[c]	0.96 ± 0.19[c]	18.03 ± 4.79[c]
51.38 ± 8.11[b]	3.54 ± 0.44[ab]	33.57 ± 3.10[b]
75.13 ± 1.88[a]	4.50 ± 0.18[a]	29.42 ± 3.11[b]
20.75 ± 6.11[c]	1.44 ± 0.42[c]	49.7 ± 6.98[a]
17.50 ± 1.54[c]	1.10 ± 0.14[c]	38.25 ± 5.19[ab]
43.25 ± 6.61[b]	2.90 ± 0.40[b]	36.95 ± 2.53[ab]

nature of the other shelter types, may have brought about the increased incidence of berry rate. The significant negative correlation between berry rate and survival, for treatments where shelter was provided, would appear to indicate a density-dependent regulation of reproduction. As harvest weight did not differ significantly between treatments, size or nutritional condition were probably not controlling factors. Regression analysis confirmed that there was no significant correlation between female harvest weight and berry rate (P = 0.219, R^2 = 0.03).

While this experiment did not specifically investigate why redclaw use shelter, it clearly demonstrated that shelter is important. Of the shelter types assessed, mesh bundles were significantly more effective than the others. Mean survival with mesh bundles (75%) was 46% higher than the next best shelter which was tires. Tires and pipe stacks were equivalent in their suitability. The two shelter types based on flat fiber-board sheets were ineffective. Despite the perceived suitability of the elevated sheet type shelter for enhancing the physical environment for the rock lobster *Panulirus argus* (Eggleston et al. 1990), they appear not to be suitable at all for redclaw.

Uniform growth among the treatments including the no shelter control suggests all crayfish were able to achieve the maximum intrinsic growth rate possible under the experimental conditions. That is, given the

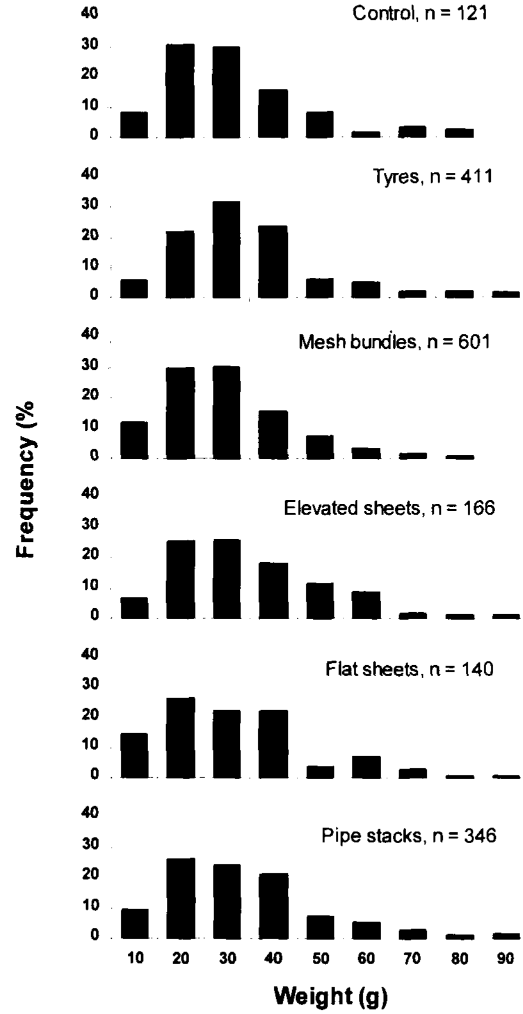

FIGURE 6. *Size (weight) frequency (%) distribution of redclaw crayfish at harvest after 162 d of culture with different shelter types. N indicates total number (replicates pooled) of animals harvested for that treatment.*

uniform and suitable environmental conditions, abundance of food and initially uniform density, growth was not limited by the shelter available. Widely disparate survival, however, indicates that the shelter types were different in their capacity to accommodate the behavioral preferences of redclaw. From a commercial production perspective, this is clearly as significant as an influence on growth would have been, in that the biomass generated was significantly

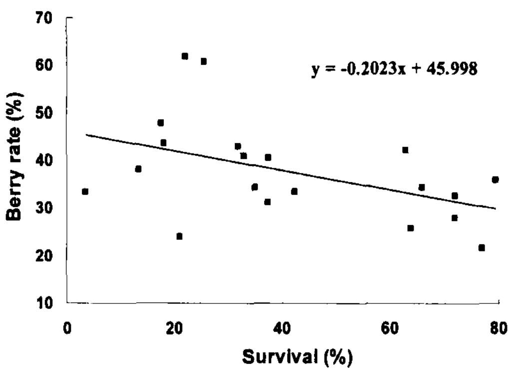

FIGURE 7. *Regression of berry rate on survival for those treatments where artificial shelter was provided.*

influenced by shelter type. Mean biomass for the mesh bundle treatment (equal to 2.81 t/ha per 162 d) was 27% higher than the next most effective shelter (tires) and over 370% higher than no shelter at all. Clearly, from an economic perspective, these differences are extremely significant. It must be noted that under the experimental conditions, the 'no shelter' treatment was contained within a pen which is a form of substrate in itself. Pond production of redclaw with no shelters or pens may be even lower than the 'no shelter' treatment in the experiment would suggest.

The uniformity of growth was mirrored in uniformity of population structure as illustrated in Fig. 6. This figure, based on percentage frequency shows that the distribution of sizes for each shelter treatment was very similar. The lack of significant differences in mean harvest weight and standard deviation between treatments suggests that there is no difference between population structures. It seems that this skewed population structure is intrinsically programmed in redclaw and will develop regardless of whether artificial habitat is provided or not and regardless of the type of artificial habitat provided. It also seems that redclaw density does not impact on population structure.

The different shelter types provide different physical environments to the crayfish. The superiority of the mesh bundle, despite its lack of firm structure, may be attributable to its capacity to separate many individuals. It has been demonstrated that many shelter-seeking crustaceans are sensitive to spaces and edges, quite independent of shelter volume (Sheehy 1976; Smith and Sandifer 1979). In addition, some researchers have found a strong relationship between refuge size and animal size in relation to the suitability of a particular shelter for occupation (Eggleston et al. 1990; Wahle 1992; Foster 1993). The mesh bundle shelter superiority may be attributable to its plasticity in regard to the size of spaces it can provide. While the pipe stack also provided the capacity to separate individuals, its rigid structure limits the number of crayfish it can hold. The edge effect as described by Smith and Sandifer (1979) may also explain the advantage of the mesh bundle. The mesh bundle provides many edges while the pipe stack provides considerably fewer.

However, the efficacy of the tires negates these arguments to some extent in that the tire provides little physical separation of individuals and possesses few edges. The advantage of the tire may be minimization of light penetration, which is likely to be another influential factor. Alberstadt et al. (1995) and Fielder and Thorne (1990) have both demonstrated that opaque structures were preferred to translucent ones for crayfish. Both the pipe stack and tire shelter were opaque and provided an abundance of dark space. The mesh bundle, however, would provide an even greater abundance of dark spaces well hidden from incident light.

Attributing reasons for the poor performance of the cement/fiber-board sheet shelters is uncertain, particularly given the effectiveness of this shelter type for marine rock lobsters (Eggleston et al. 1990). Observation of both sheet type shelters during harvesting of the experiment indicated that some excavation of the soil beneath the shelters had occured, but that the resultant 'burrow' was only ever occupied by one or two crayfish. Further, the soil beneath these shelters was often anoxic, a characteristic not seen under any of the other shelter types. Their inferiority as a redclaw shelter may be attributed to their lack of structure and the poor environmental conditions they confer.

In assessing shelters from a commercial perspective, consideration must be given to the cost of manufacture. From a purely economic standpoint, second-hand car tires are likely to be the most cost-effective, given their zero material cost. However, Australian government regulations concerning use of tires are tightening. Considering the labor necessary to cut holes in each tire and to place them in the pond, the difficulty of moving or removing them from the pond at harvest and the possibility of a financial liability for disposal if environmental authorities deem the practice unacceptable, their economic superiority is not likely to be sustainable.

Material costs for mesh bundles were not particularly high, however, they require considerable labor to fabricate and the nature of their design does not lend itself to automated production. On the basis of manual construction, the pipe stack shelter had the highest material cost and a substantial labor component. The costs of the cement/fiber-board shelters were quite low, however, since they performed so poorly their further consideration is not warranted.

As the optimal specifications for a redclaw shelter are further defined, consideration of size specific requirements may also be necessary. This experiment covered the mean size range of around 12 g to 30–40 g. In Australia, redclaw are generally marketed at a minimum size of 30 g up to 150 g and above. It is possible that the superiority of the mesh bundle in this experiment reflected juvenile shelter requirements (Jones 1995a, 1995b), and that larger crayfish above 30 g may prefer different shelter characteristics and specifications.

Another factor that was not specifically investigated in this experiment, but that has important economic implications, is the quantity of shelter necessary for a given pond area or density of crayfish. While every attempt was made to provide equivalent quantities of the various shelter types in this experiment, their widely variable design characteristics made this difficult.

Having established the effectiveness of the mesh bundle shelter relative to the other four shelters assessed, improvements on its design should now be sought. Pursuing the theme of multiple spaces with separation and minimal light penetration, modifications of the mesh bundle can be conceptualized, which would be worthy of further assessment. A disadvantage of the mesh bundle design as used in this experiment is that it does not easily lend itself to mass production. A more rigid structure that could be moulded or extruded in plastic would provide greater opportunity for automated manufacture and lower unit cost.

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