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Growth of Stygobitic (*Orconectes australis packardi*) and Epigean (*Orconectes cristavarius*) Crayfishes Maintained in Laboratory Conditions

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ABSTRACT

This study reports on maintenance and growth of the cave crayfish, *Orconectes australis packardi,* and the epigean crayfish, *Orconectes cristavarius,* within laboratory conditions for 1 and 2 years. The *O. a. packardi* survived well compared to the *O. cristavarius* in captivity. The poor survival of the epigean species was probably due to unsuitable conditions. The epigean as well as the cave crayfish molted and grew in captivity, but without any significant difference in molt frequency between species. In the first year, total body length was obtained to assay growth, whereas in the second year the more accurate measure of post-orbital carapace length was used. The ability of *O. a. packardi* to adjust to captivity is likely due to their lower metabolic rate and ability to handle hypoxic stress better than epigean species.

INTRODUCTION

The growth and maintenance of cave crayfishes in laboratory conditions is not well documented but advantageous to know for several reasons. Although field studies may inform us of those aspects of growth that occur in nature, they are complicated by many variables that cannot be controlled. For instance, with respect to crustaceans as well as mammals, periodic climate changes over a yearly cycle or over several years can bias data obtained during a brief period of time. This is also relevant for cave crustaceans that are influenced by surface streams varying seasonally in temperature. Resources, such as food and shelter, also may impact one subset of the population but not another (e.g., location dependent), as is known to occur in sand crabs (Siegel and Wenner 1985). Standardization of such variables in controlled laboratory studies allows them to be assessed and tested for integration in field studies. In addition, knowledge of how well stygobitic (i.e., aquatic cave obligate) animals survive in a holding facility is of use in case of a need to temporarily circumvent species eradication by acute environmental impacts. Such disturbances occur with land development, producing a high sedimentation and anthropogenic pollutants known to be lethal to crustaceans in general (Fingerman 1985).

Growth measurements of stygobitic crayfishes in the field have proven to be a difficult task, and this is likely the reason for the scarcity of quantitative data. Problems of marking and recapture of cave crayfish species over the molt cycle have been addressed by Cooper (1975), Cooper and Cooper (1976), Hobbs III (1978), and Weingartner (1977). Using various marking approaches, individuals have been recaptured and identified for 5 years in one study (Cooper 1975), 3.5 years by Weingartner (1977), and 2 years in another study (Hobbs III 1973). Recapture studies of troglophilic crayfish (*Cambarus laevis* Faxon) over a year and ones maintained in jars held within surface and cave streams were conducted by Weingartner (1977).

Field monitoring of crustacean development in a variety of karsts with wide-ranging dynamics is necessary since water temperature, environmental space, and food resources are not constant within all karst systems. Surface stream runoff from summer to winter alters water temperature in caves. For example, karst waters in an Indiana cave varied from 11.6 to 8.0°C after a rain on a snow-laden surface (Poulson 1964). In the second longest cave in Kentucky (Coral Cave, 38.46 km of passages) and the third longest (Sloans Valley Cave, 37.70 km of passages), both in Pulaski County, stygobitic crayfish (*Orconectes australis packardii* Rhoades, 1944), occur within a short distance of a karst window (30 m in Coral Cave) and are exposed to fluctuating water temperatures. In contrast, the longest cave

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in Kentucky (Mammoth Cave, Edmonson County, 580 km of passages) contains deep bodies of water with little variation in temperature as well as regions more directly influenced by surface stream temperatures (Barr and Kuehne 1971; Packard 1888; Poulson 1992). Since water temperature is the major environmental trigger for inducing molting in cave crayfishes (Jegla 1966, 1969), one would expect crayfish populations within caves to have varied molt cycles. Thus, growth rates of crayfishes may vary depending on the region of a cave in which the animals are being monitored. Estimates of age and developmental rates of cave crayfishes suggest that they develop very slowly and that some can live for long periods (~30 years) (Cooper 1975; Cooper and Cooper 1978; Weingartner 1977), but direct measurements over this long have not been made. In addition, since temperature is a regulating environmental factor in crustacean development, generalizations for all cave crayfishes are impractical since the animals inhabit various physiomorphic regions of caves.

Here we report on a preliminary study to monitor the growth and laboratory maintenance of a stygobitic species (*Orconectes australis packardi* Rhoades, 1944) and an epigean (surface-dwelling) species (*Orconectes cristavarius* Taylor, 2000). We used both juvenile and mature crayfish so we could determine if various age groups would survive in controlled conditions. In this preliminary study, we report on the laboratory conditions used and the growth of these species maintained over a 1-year and in some cases a 2-year period in a defined laboratory setting.

MATERIALS AND METHODS

Orconectes a. packardi were collected in the Sloans Valley Cave System at the "Appalachian Trail" in a pool of water measuring 3 m wide, 6 m long, and at most 0.3 m deep. *Orconectes cristavarius* were obtained from a relatively fast-moving surface stream (Fourmile Creek) by Fourmile Road in Clark County, KY. Species identification was confirmed by Dr. Gunther Schuster of Eastern Kentucky University for *O. cristavarius* and by the taxonomic key provided in Hobbs Jr. et al. (1977) for *O. a. packardi.*

The crayfishes were transported to the laboratory in Lexington, KY, in water obtained from their environment. They were then transferred to individual aquaria (33 × 28 × 23 cm; water depth 10–15 cm) and held as isolates throughout the study. Some individuals were housed successfully for a year. Containers were cleaned biweekly and animals were fed with commercial fish food pellets (Aquadine), which is marketed as "shrimp and plankton sticks: sinking mini sticks." Since this consists of ground-up fish it would appear to be a suitable and nutritious diet for crayfishes. Fragments of cleaned chicken egg shell also were placed in the containers as a source of calcium. The chloramines Lexington uses for water purification were removed by carbon-based filters for the aquaria water. The carbon-filtered water was held in a 190 liter (50 gallon) plastic tank and aerated for several days before utilization. Bacteria and algae were allowed to grow in the tank in order to detoxify any NH_4^+ and convert it to nitrite and nitrate, since NH_4^+ is known to be toxic to crustaceans (McRae 1999). Cave animals were maintained in total darkness except for feeding, cleaning, and measuring. Epigean animals were exposed to a low light level with a light cycle of 16:8 (light:dark) produced by full spectra lights (General Electric). When the aquaria were cleaned or when measurements were obtained, observations were made if the animals had molted by the appearance of the animal and by the presence, in the holding tank, of the chelae from the old exoskeleton. Neither species would fully consume the chelae after they consumed the rest of the old exoskeleton. The temperature was maintained at 16 to 17°C throughout the year; this was the temperature of the laboratory. At one period the laboratory temperature was uncontrolled as mentioned in the results during the second year of this study. Aquaria for both the surface and cave species were stored in the same room over the same period of time, and the tanks containing the cave species were covered with black plastic to block light. Aquaria were marked with numbers so that individuals could be monitored.

Total body length (tip of rostrum to the end of telson) was measured to an accuracy of 1 millimeter with a flexible plastic ruler. Measurements were obtained four times during the first year. After the first year we learned that the total body length measure is likely in-accurate because of the flexibility of the jointed abdomen. So for a subsequent year of holding some of the same crayfishes in captivity, along with the addition of new individuals, the postorbital carapace length (from the posterior, dorsal surface of the orbital cup to the end of the carapace directly posterior to the eye cup) was used. These measures were made with calipers (Swiss Precision, Switzerland, 0.1 mm). As for the first-year study, four different time points were used throughout the year. A similar periodic sampling had previously been used by Weingartner (1977). The percent growth was determined by: [(postmolt length − premolt length)/(premolt length)] × 100.

RESULTS

The epigean and stygobitic species grew and molted in captivity, but the survival rate over the first and second years was lower for the epigean species than for the stygobite. The highest mortality for the epigean species occurred after 7 months, although two of them died after 4 months. The stygobitic species demonstrated a better survival rate, with only one dying after 4 months and another after 9 months. The one that died at 4 months appeared to do so during ecdysis since the exuvium was still attached to the body. The individuals that died are represented in Figure 1 as line plots that do not fully extend to the end of 1 or 2 years. The lines terminate at the period when measurements were last obtained.

The frequency of molting was substantially higher (9 of 12 animals) for the epigean species within the first few months of containment. A second molt was noted for only one of the epigean species within the first 12 months (Figure 1B, note two asterisks). Of the four surface crayfish that progressed to the second year of study only the largest one died. Three of the 13 stygobites molted during the same first few months and two of them after 9 months. The individuals that molted are indicated with asterisks within the period of time a molt was noted (Figure 1). Only in the stygobitic species was it observed that some individuals actually had a reduction, instead of an increase, in their body length after a molt. This phenomenon has also been reported for *O. a. australis* by Cooper (1975), and in an earlier report Creaser (1934) stated that in the crayfish *O. propinquus* (Creaser used the name *Faxonius propinquus*) growth was not always associated with a molt when the male changed in sexual form. We are fairly confident in the recorded dates of molts for each animal; however, there were a few animals, in both species, that indicated a growth in body length without a molt being observed. This lack in changes of length we account to not being able to fully stretch the abdomen of the animal consistently during all measures. Perhaps the muscles between the segments of the abdomen were relaxed more during some

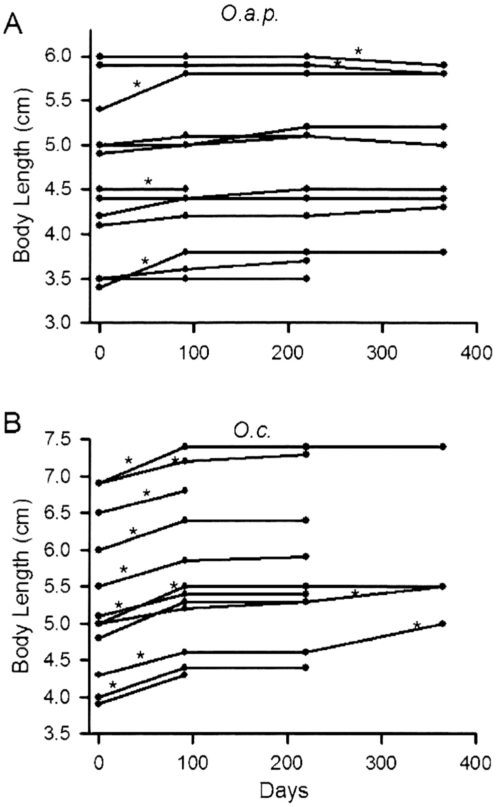

Figure 1. Growth of stygobitic (*Orconectes australis packardi*) and epigean (*Orconectes cristavarius*) crayfishes in laboratory conditions. Growth curves were obtained by measures of total body length of the animals maintained as isolates (A) *Orconectes australis packardi* (*O.a.p.*) and (B) *Orconectes cristavarius* (*O.c.*) for a 1-year period in captivity. Asterisks denote that a molt occurred in that time period. Individuals that died have their growth plot terminated at the last date a measurement was taken. There was substantial mortality for the epigean *O.c.* species after 7 months of containment. Initially N = 13 for *O.a.p.* and N = 12 for *O.c.*

measures than others. This problem was avoided during the second year of this study in which the postorbital carapace length was measured.

Four freshly caught stygobites were added to the study for the second year because we released a few from the first-year study back in the cave since we clipped one pair of antennules from some individuals at the end of the first-year study to aid in another study in antennule growth within a molt cycle. Figure 2A contains the data obtained during the second year of the study of the stygobites. The ones in the graph depicted with circles were from the first-year study and the ones represented by triangles were crayfish newly added to the study. The results obtained in the second year indicate that the animals did increase in length during a molt although a minor amount in some cases. For the stygobites, three out of the four added to the study in the second year molted within the first 2 months. Six out of the eight molted within the last 150 days, which was likely a result of the laboratory having environmental temperature swings for a period of about 2 weeks with temperatures reaching as high as 28°C.

The few epigean crayfish appeared to increase in size to a greater degree than the stygobitic species. As in Figure 2A, the lines in Figure 2B depicted with circles were ones from the first-year study, and the crayfish represented by triangles were newly added epigean species. Only three animals were carried over from the first-year study. One died within 1 month, another within 3 months, and the last one within 7 months of the second study in which postorbital carapace length was measured. As in the first-year study, the newly added epigean crayfish also showed a low resistance to laboratory rearing since a good number had died before the year was completed.

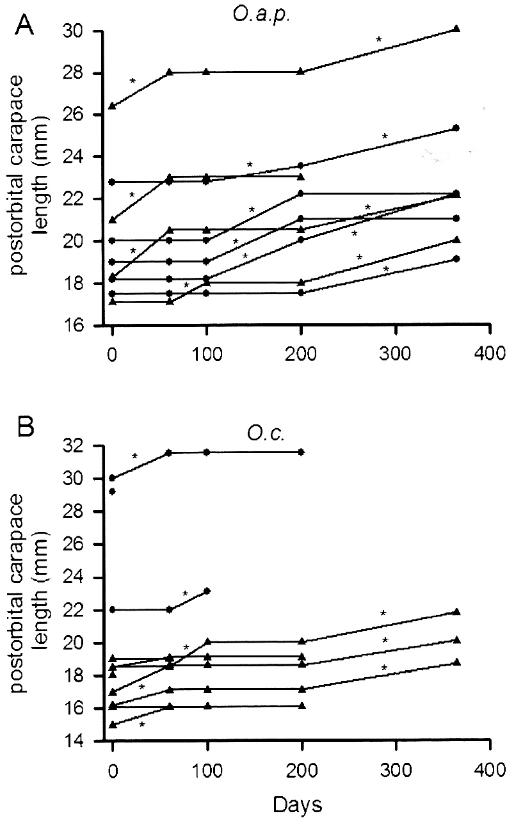

Figure 2. Growth curves of stygobitic (*Orconectes australis packardi*) and epigean (*Orconectes cristavarius*) crayfishes as measured by postorbital carapace length. Plots for *Orconectes australis packardi* (*O.a.p.*) (A) and *Orconectes cristavarius* (*O.c.*) (B) are shown. Animals held throughout a second year in captivity (solid circles) as compared to 1 year (solid triangles) are indicated. Asterisks denote that a molt occurred in that time period. The individuals that died have their growth plot terminated at the last date a measurement was taken. As in the first year of study, there was again high mortality for *O.c.* No *O.c.* survived for 2 years in captivity. Initially N = 13 for *O.a.p.* and N = 12 for *O.c.*

To determine the extent of the difference in growth between the two species during the first year of the study, a percent change for each individual was determined and the means of the percent differences were compared between species (Figure 3A_1). Since so many animals died in the epigean population in the period between 220 days and 365 days, the 220-day measurement session was used to calculate the percent difference in growth for this species during the first year. Most of the growth for the epigean species occurred earlier than that for the stygobitic species. As mentioned earlier, the total body length was likely subject to error, but since such measures of surface crayfish species are rapidly made for aquaculture purposes, we retained these data since they can be of use. The growth measures during the second year for the stygobitic and epigean crayfishes of the postorbital carapace were also compared as a mean of a percent change (Figure 3B).

One group of stygobite crayfish was used for comparison of postorbital carapace length to total body length (Table 1). The postorbital carapace length accounts for about 40% of the total body length. The percent in the increase of growth, as measured by postorbital carapace length, is ca. 9% (Table 2). There did not appear to be a correlation with size of the animal and the percent increase in growth within a single molt.

DISCUSSION

The results of this study demonstrate that *O. a. packardi* can be maintained well in captivity under defined conditions for up to 2 years. This was the case for both small and large crayfish. However, *O. cristavarius* initially showed a good survival rate, which declined rapidly the longer they were housed, particularly after 7 months. Since small and large epigean crayfish died, the failure to survive was probably due to unsuitable conditions for this species within the laboratory rather than to senescence. This study also demonstrated that the epigean as well as the cave crayfish molted and grew in captivity. One approach to measure growth rates in crustaceans is to measure the time from one molt to the next in addition to size increases resulting from each molt. Only some of the crayfish we held molted a second time (Table 3). Based on the molt frequency, there is little or no difference in growth rate between the two species, with *O. a. packardi* having slightly more second molts. In some cases where a molt was documented the cave animals did not show more than a few millimeters increase in body length as assessed during the first year of study by total body length. With measures of postorbital carapace length, as used in the second year of study, an approximate increase in length with each molt is 9%, but there is considerable individual variation (Table 2).

Preliminary growth studies with the stygobitic crayfish *Orconectes inermis inermis* Cope 1872, in Pless Cave, Indiana, using a mark-and-recapture approach, indicated that juveniles showed larger increments of growth at ecdysis than mature animals (Hobbs III 1976). Using repetitive recaptures of hundreds of marked individuals of three species of stygobitic crayfish in Shelta Cave, Alabama, Cooper (1975) predicted that one of the species, *Orconectes australis australis* (Rhoades 1941), might live for 30 years or more. This was based on known minimum size at recruitment, maximum size, and growth increments observed following molts (Cooper and Cooper 1978, 1979; Culver 1982, p. 51). Detailed growth studies over a 1-year period of *Cambarus laevis* from epigean groups as well as groups that lived within the cave were conducted with recapture techniques. From such measures, growth curves were established (Weingartner 1977). In Weingartner's study a

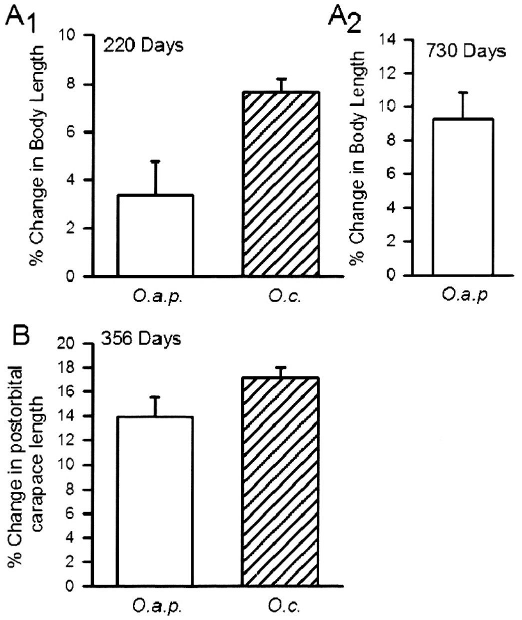

Figure 3. Comparisons in the growth between stygobitic (*Orconectes australis packardi*) and epigean (*Orconectes cristavarius*) crayfishes. (A_1) During the first year of study in which the total body lengths were used, a comparison in percent of growth between *Orconectes cristavarius* (*O.c.*) and *Orconectes australis packardi* (*O.a.p.*) is shown (N = 13 for *O.a.p.* and N = 10 for *O.c.*). Since so many *O.c.* died, the values obtained after 220 days were used for both species. The error bars represent the ± of the standard error of the mean. (A_2) The percent of growth for *O.a.p.* based on total body length, is shown after a 2-year period in captivity. Since no *O.c.* survived for 2-years a comparison could not be made. (B) In the second year of study the postorbital carapace length was used as an index of growth (N = 8 for *O.a.p.* and N = 3 for *O.c.*). The sample size is smaller for *O.c.* because of the lack in survival of this species.

Table 1. Comparison of total body length to postorbital carapace length for *Orconectes australis packardi.* Two additional animals not used in the growth studies were used for these morphometric measures.

Total body length (mm)	Postorbital carapace length (POL) (mm)	Ratio body/POL
43	16	0.37
44	18	0.41
47	17.5	0.37
50	20	0.40
51	20	0.39
55	22.5	0.41
58	19	0.33
60	23	0.38
60	23.5	0.39
71	29	0.41
71	28	0.39
Mean		0.39
SEM		0.024

Table 2. The percent change in POL within a molt for *Orconectes australis packardi.*

Premolt (mm)	Postmolt (mm)	% change
17.1	18.0	5.26
17.5	19.1	9.14
18.0	20.0	11.1
18.2	20.0	9.89
18.3	20.5	12.02
19.0	21.0	10.53
20.0	22.2	11.0
20.5	22.1	7.8
21.0	23.0	9.52
22.8	23.5	3.07
23.5	25.3	7.66
26.4	28.0	3.06
27.0	29.0	7.41
28.0	30.0	7.14
Mean		8.4
SEM		0.7

few animals were recaptured after 3 years and the growth curves were extended for that length of time; however with only a few animals the variability was not able to be assessed for differences in the age of the animals.

Poor survivorship for *O. cristavarius* in our studies is likely a species-dependent phenomenon, since another epigean crayfish, *Procambarus clarkii* (Girard 1852), from Raceland, Louisiana, survived well in the same laboratory conditions for 2 years or more. The reason for the difference in survival between these two epigean species may be a result of environmental adaptation, since *O. cristavarius* is predominantly found in fast-moving, highly oxygenated streams, and *P. clarkii* comes from swamps. It might be that the *P. clarkii* and *O. a. packardi* can survive well in water that is not highly oxygenated, such as that used in our laboratory, while *O. cristavarius* cannot. It is known that *P. clarkii* is very hardy and can tolerate all but the severest cases of hypoxia (McClain 1999). There might also be dietary factors that we did not investigate to account for the survival differences. All crayfishes held in captivity were fed the same diet at the same time. In addition, larger animals had a greater quantity of food provided to them.

Stygobitic crayfishes also show an amazing resistance to experimentally induced fluctuations in temperature, from freezing in blocks of ice to rapid exposure of high temperature (32.5°C) (Park et al. 1941). In addition, they are known to be starvation resistant, possibly due to a lower metabolic rate (Dickson and Franz 1980; Dickson and Giesy 1982). Burbanck et al. (1948) and Jegla (1964) both reported that cave crayfish have a lower metabolic rate as compared to epigean species. Comparable studies on *O. cristavarius* are lacking, so it remains unknown if this species can tolerate general stress as well as *P. clarkii* and *O. a. packardi.*

The differential in the initial growth rate between *O. cristavarius* and O. *a. packardi* is interesting. It is possible that the handling, transport, and exposure to a new environment are factors, although care was taken not to allow the animals to heat up in transport or be exposed to fluctuating temperature. However, a change in temperature from a surface stream or cave could have an impact on the initial molting frequency. Temperature is con-

Table 3. Comparison of growth rates by frequency of molts within the first and second years of captivity for *Orconectes australis packardi* and *Orconectes cristavarius* crayfishes.

	1st molt	2nd molt
1st year		
O.a.p.	5 of 12 animals	none
O.c.	10 of 12 animals	1 of 4
2nd year		
O.a.p.	14 of 8 animals	5 of 8 animals
O.c.	10 of 9 animals	3 of 3 animals

sidered to be one of the most significant factors in regulating crustacean growth (Conan 1985): not only an increase in water temperature but a reduction as well can induce molting. Other small crustaceans, such as copepods (Vidal 1980) and amphipods (Dagg 1976), reduce their molt frequency in cold temperatures, but when this occurs the animals grow larger after each molt than when they molt more frequently. In contrast, an increase in temperature can inhibit some crustaceans from molting (Haefner and van Engle 1975). The shrimp *Crangon crangon* Linnaeus is known to have varied longevity depending on environmental temperature (Labat 1977; Llyod and Yonge 1947; Oh 1999). For a review of factors regulating growth in crustaceans see Wenner (1985).

The increase in initial growth of *O. cristavarius* is not likely due to 'catch-up' growth, common in crustaceans when they are exposed to sufficient food after being deprived of food (Bostworth and Wolters 1995), since the habitat from which they were obtained was abundant in crayfish, fish, and snails as dietary resources. On the other hand, the lack of growth for *O. a. packardi* even after a molt might be expected since it has been reported that an *O. a. australis* measuring 35.2 mm in total carapace length did not alter its length after two molts (Cooper 1975). It would be of value to know if stygobitic crayfish do show 'catch-up' growth depending on resources, or if the growth attained for a molt is temperature regulated. If such growth does occur it would make it difficult to determine the correct age of adult animals without knowing their complete life history and environmental conditions. This is particularly relevant since Weingartner (1977) showed differential rates of growth within various regions in a single cave system. It was concluded that the environmental differences in water temperature and food resources likely accounted for the regional differences.

It is our hope that one will consider the possibility of long-term rearing of crayfishes in suitable laboratory conditions to gain insight into environmental factors regulating the developmental issues and to further refine laboratory conditions that promote survival.

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