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# Effects of Cadmium on the Predator-Prey Interaction Between the Turbellarian *Dendrocoelum lacteum* (Müller, 1774) and the Isopod Crustacean *Asellus aquaticus* (L.)

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**Abstract.** The toxicity of cadmium to the freshwater triclad turbellarian Dendrocoelum lacteum and the isopod crustacean Asellus aquaticus was determined for each species when maintained individually (96 h LC50 for D. lacteum, 23.22 mg Cd/L, and for A. aquaticus, 0.16 mg Cd/L) and when kept together. When exposed together over a concentration range of 20–100 μg Cd/L, the effect of this predator-prey system was, as expected, *i.e.*, direct toxicity to A. aquaticus, but there was also a reduction in the predation rate by D. lacteum. Both responses increased with increasing toxicant concentration. The possible causes of these observed effects, including the diet of A. aquaticus, cannibalism by A. aquaticus, and speed of the predator, are discussed. The possible ecological consequences of removing either predator or prey from a freshwater ecosystem as a result of a pollution incident are also considered.

The effects of pollutants on freshwater ecosystems have normally been predicted from the results of acute (and sometimes chronic) toxicity tests carried out with single species (Pascoe and Edwards 1989). However, it is evident that such tests cannot provide information about the way in which food chains, interspecific interactions, nutrient cycling, and other higher order processes and mechanisms may be modified by the presence of pollutants, and there is a clear need for studies to be carried out at higher levels of organization than that of a single species (Cairns 1983, 1986). Consequently, a great variety of multispecies test procedures and systems, including microcosms and mesocosms with defined species assemblages, have been developed and tested (Cairns 1985). While such systems can provide valuable additional information about the toxicity of test chemicals, they are invariably complex and expensive and difficult to operate. The current study forms part of a series of investigations into the development of relatively simple toxicity tests involving two species (*e.g.*, a predator and its prey) which may provide more information than single species tests without the disadvantages inherent in using more complex multispecies systems. The effects of cadmium, as a model toxicant, on the predator-prey interaction between the triclad turbellarian Dendrocoelum lacteum (Müller 1774) and the isopod crustacean Asellus aquaticus (L.) were examined. D. lacteum uses A. aquaticus as a food refuge, its distribution and abundance being directly related to the occurrence of the prey species (Herrmann 1984a), which is related to the nutrient quality of the water. In the absence of A. aquaticus, D. lacteum will consume other prey species such as Gammarus pulex and Chironomus sp. larvae; however, its ability to catch these species is less than that of its competitors; if A. aquaticus is removed (*e.g.*, by a pollutant), this would be reflected in the success of D. lacteum.

The basic biology of these two species has been well documented, both individually (Steel 1961; Herrmann 1985) and as an interacting pair (Reynoldson and Young 1965; de Silva 1976a, 1976b; Macan and de Silva 1979; Hermann 1984a, 1984b). Although information is available on pollutant toxicity to A. aquaticus (Green *et al.* 1986; Martin and Holdich 1986; McCahon *et al.* 1990), little is known about the effect of different chemicals on D. lacteum (Brown and Pascoe 1988), and nothing is known about toxicant effects on the interaction between the two species; this investigation was intended to remedy this shortfall.

## Materials and Methods

### *Collection and Maintenance of Animals*

D. lacteum were collected from Roath Stream, Cardiff, UK (Grid Reference: ST 193 783). The animals were removed from the underside of stones using a soft brush and transported to the laboratory in stream water, which was then aerated and gradually mixed with increasing quantities of dechlorinated mains water. A. aquaticus (6–8 mm) were provided as food (to excess) at regular twice weekly intervals, and the animals were kept at 11°C (±1°C).

A. aquaticus were collected by netting from beds of Elodea canadensis in the Brecon and Monmouthshire Canal (Grid Reference: SO 307

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**Table 1.** Statistical analysis of predation of *A. aquaticus* by *D. lacteum* under control conditions to show variation in the time required to reduce the prey number from one value to another

| Number of *A. aquaticus* consumed | Mean time (h) | Standard deviation | Standard error | Coefficient of variation % |
|---|---|---|---|---|
| 30 to 5 (25) | 317.0 | 70.2 | 28.7 | 22.1 |
| 30 to 10 (20) | 239.3 | 58.1 | 23.7 | 24.3 |
| 30 to 15 (15) | 180.3 | 49.3 | 20.1 | 27.4 |
| 30 to 20 (10) | 124.3 | 48.2 | 19.7 | 38.8 |
| 25 to 5 (20) | 272.8 | 67.1 | 27.4 | 24.6 |
| 25 to 10 (15) | 190.5 | 50.1 | 22.4 | 26.3 |
| 25 to 15 (10) | 131.5 | 44.8 | 18.3 | 34.1 |
| 20 to 10 (10) | 110.8 | 13.0 | 5.3 | 11.7 |
| 20 to 15 (5) | 52.2 | 4.7 | 1.9 | 8.9 |
| 15 to 5 (10) | 136.9 | 23.8 | 9.7 | 17.4 |
| 15 to 10 (5) | 60.4 | 14.5 | 5.9 | 23.9 |

042) and were kept in dechlorinated water in the laboratory at 11°C (±1°C) and fed on conditioned (Bird and Kaushik 1985) horse-chestnut leaves (Aesculus hippocastanum).

### *Standardization of Conditions for Studying Predation of* A. aquaticus *by* D. lacteum

Preliminary experiments had shown that predation rate was low, and it was therefore necessary to optimize experimental conditions for maintaining the predator-prey system so that predation could be easily quantified. Several pilot studies were carried out and as a result of these and the recommendations of de Silva (1976a), the following experimental conditions and design were adopted.

D. lacteum greater than 14 mm in length were used, together with A. aquaticus of 4–6 mm, since this is the size that gives the greatest energy return for mature D. lacteum (de Silva 1976a). The animals were maintained at 16°C with a 12:12 h light:dark photoperiod in tanks of dechlorinated water (3 cm depth, 4,700 $mm^2$ surface area) changed completely each day. Plastic mesh (0.25 mm) was provided as cover for both species, and leaf discs were provided as food for A. aquaticus. Each tank contained a single D. lacteum (starved for 48 h before the experiment) and 30 Asellus. The number of prey remaining was recorded daily and the experiment continued for 18 days. The study was replicated six times. Coefficients of variation were calculated for the time taken to consume particular numbers of prey, *e.g.*, from an initial 30 to 5 remaining prey or from an initial 25 to 15 remaining prey (Table 1). Using this coefficient of variation, the number of replicates required to detect a significant difference in predation rate between toxicant-treated and control populations was calculated, using a FORTRAN computer program (NESTI—developed at the University of Wales College of Cardiff) based on the methods of Sokal and Rohlf (1981).

### *Toxicity of Cadmium to* A. aquaticus *and* D. lacteum

In order to select the appropriate cadmium concentrations for the predator-prey-toxicant interaction study, preliminary acute lethal toxicity tests were carried out with both species. Ten A. aquaticus (4–6 mm) were placed in each of the following test concentrations: 70, 140, 180, 240, 320, and 450 μg/L Cd (recorded cadmium concentration) and in control dilution water. For D. lacteum, seven animals were used in each of the six test concentrations: 3.2, 10, 18, 32, 56, and 100 mg/L Cd and control dilution water. Mortality was recorded and dead animals removed at 24-h intervals, together with any cocoons laid by the D. lacteum, which were also counted. Death was determined when there was no reaction to gentle probing with a seeker. Solutions were changed daily and samples of the water fixed with 1% AristaR nitric acid for cadmium analysis. For each species, the Median Lethal Concentration (LC50) at 96 h was determined by a computerized form of the method recommended by Litchfield and Wilcoxon (1949).

### *The Effects of Cadmium on Predation Rate*

Experiments were carried out using the protocol described above (2) and based upon preliminary single species tests to determine the effects of cadmium on predation rate. Studies involved prey that were (a) starved or (b) fed. In each case, tanks without a predator were also set up at each cadmium concentration to measure only the effects of toxicant on A. aquaticus. The range and number of cadmium concentrations were extended in (b) in order to increase the opportunity to detect predation effects.

(a) *Effects of cadmium on predation of starved* A. aquaticus *by* D. lacteum. Cadmium concentrations used: 20 and 40 μg/L; 7 replicates for each concentration and control water; initial prey density, 30; no food provided for prey; duration of experiment 21 days. A similar set of experiments but without the predator was also set up.

(b) *Effects of cadmium on predation of fed* A. aquaticus *by* D. lacteum. Cadmium concentration used: 20, 60, and 100 μg/L; 3 replicates for each concentration and control (not 7 due to shortage of animals); initial prey density 25 (not 30 due to shortage of animals); prey fed on leaf discs presoaked for 30 min in the respective cadmium solution; duration of experiment 29 days. A similar set of experiments but without the predator was also set up.

Three additional studies were made to help explain the results obtained in this investigation.

### *The Toxicity of Cadmium to Starved and Fed* A. aquaticus

The effect of feeding or starvation of A. aquaticus on the toxicity of cadmium was investigated at 20, 30, 40, 60, 80, and 100 μg/L and in control water. Sixty A. aquaticus were used at each concentration: 30 fed and 30 starved. The fed animals were given conditioned horse-chestnut leaf discs pre-treated for 30 minutes in the appropriate test solution. Solutions and leaf discs were changed each day; the number of prey remaining was noted and any dead animals were removed. Samples of water were taken for cadmium analysis and the test was concluded after 40 days.

### *Extent to which Cannibalism Occurs Among* A. aquaticus

In tanks where predators were absent, it was noted that dead prey disappeared. This could only have been due to cannibalism and was investigated as follows.

Three replicates of 20 A. aquaticus were exposed in the same size containers as used for the predation experiments, at 20 and 100 μg/L Cd and in control dilution water, and cannibalism was allowed to take place. A. aquaticus were also placed individually in separate compartments at the same concentrations to measure the toxic effect but precluding cannibalism. The number of liver and dead Asellus present was

**Table 2.** The consumption of live (L) and/or dead (D) *A. aquaticus* by *D. lacteum* when offered a choice. Data are means of three replicates

| Choice offered | | Predator present | First prey taken | Mean Number of prey items remaining: after 24 h | | after 48 h | |
|---|---|---|---|---|---|---|---|
| L | D | | | L | D | L | D |
| 0 | 10 | Yes | D | — | 9.7 | — | 9.7 |
| 5 | 5 | Yes | L | 4 | 0 | 3.7 | 0 |
| 10 | 0 | Yes | L | 7 | — | 6.3 | — |
| 5 | 5 | No | — | 5 | 0[a] | 5 | 0[a] |
| 10 | 0 | No | — | 10 | — | 10 | — |

[a]Removal of these dead *A. aquaticus* in the absence of *D. lacteum* was due to cannibalism

noted daily, and the solutions were sampled and changed at 48 h intervals for a period of 29 days.

### *The Preference of* D. lacteum *For Live/Dead Prey*

After a starvation period of 48 h, large healthy D. lacteum (>14 mm) were offered live and dead A. aquaticus (4–6 mm). Dead animals were obtained by freezing and allowing then to thaw at 16°C for two days. The ratio of live to dead prey offered to the predator was varied (Table 2) and where live prey were present, the experiment was repeated in the absence of a predator to provide a measure of cannibalism by the A. aquaticus. The number of animals remaining, both live and dead, was noted over a 48-h period. Three replicates were used for each of five experiments (Table 2).

### *Cadmium and Water Quality Analysis*

All cadmium solutions for toxicity studies were prepared by dilution of a stock solution of cadmium chloride. Filtered samples from all test tanks were fixed for later cadmium analysis using AristaR nitric acid at a final concentration of 1%. Analysis was performed using an IL457 Atomic Absorption Spectrophotometer at a wavelength of 228.8 nm. The flame system was used for concentrations of > 60 μg/L, dilutions being made where necessary. For the lower concentrations, the furnace was used and calibration curves constructed.

Water hardness was derived from the individual analyses of magnesium and calcium using the Atomic Absorption Spectrophotometer. Conductivity, dissolved oxygen, temperature, and pH were measured by the appropriate meters.

### *Statistical Analysis*

Data were compared by ANOVA, following tests for normality and homogeneity of variance. Any non-conforming data were transformed or a non-parametric test (Games and Howell 1976) was used.

## Results

Dendrocoelum lacteum was successfully maintained in the laboratory under the described conditions. During the autumn and early winter months, the animals were predominantly immature and were kept until maturity prior to use. Larger D. lacteum (>14 mm) were collected in late winter and spring and some produced cocoons, after which they died. Each fertile cocoon produced 2–10 young, which were then fed on crushed A. aquaticus until large enough to take live prey. A. aquaticus was also kept successfully under the described conditions. Animals of the required sizes (4–6 mm as prey and 6–8 mm as a general food supply) were generally most readily available from the field in the autumn and early winter, however, laboratory cultures provided a limited number of animals throughout the year.

**Table 3.** Acute toxicity of cadmium to *A. aquaticus* and *D. lacteum*—96-h LC50 (mg/L) and slope function (S) with 95% confidence levels

| | *A. aquaticus* | *D. lacteum* |
|---|---|---|
| LC50 | 0.16 | 23.22 |
| 95% confidence limits | 0.10–0.26 | 13.50–39.8 |
| S | 3.5 | 2.07 |
| 95% confidence limits | 1.3–9.6 | 1.40–3.0 |

Recorded concentrations of cadmium were very close to nominal values, which were therefore used throughout the text. However, in the case of the acute toxicity test carried out to determine the 96-h LC50 for A. aquaticus, concentrations were lower than nominal and actual recorded values were used in determining the LC50. Water quality parameters recorded throughout the study were: hardness, 87 ± 14.1 mg/L as $CaCO_3$; temperature, 16.0 ± 1.0°C; dissolved oxygen >80% ASV; conductivity, 332.5 μS/cm; pH, 6.9.

### *Standardization of Conditions for Studying Predation of* A. aquaticus *by* D. lacteum

Initial predation of A. aquaticus by D. lacteum was relatively rapid until the predators became satiated (after 1.5 to 2 h) and from this point, predation continued at a steady but slower rate. The mean time to consume 50% of prey was 181.2 h (standard error ±20.2). Coefficients of variation were calculated for different time periods (Table 1), and it was seen that the time taken to reduce the number of prey from 20 to 15 and from 20 to 10 gave the lowest and second-lowest values, respectively. The data obtained from the time taken to reduce the number of prey from 20 to 10 were used in the NESTI program, and from this it was decided to use seven replicates in future experiments (when numbers permitted). This would provide an 80% chance of detecting a 20% difference between 3 populations, *i.e.*, two toxicant concentrations and a control. The 20 to 15 data were not used, since it was felt that the consumption of 5 animals did not adequately reflect the duration of the experiment.

### *Toxicity of Cadmium to* A. aquaticus *and* D. lacteum

A. aquaticus was significantly more sensitive to cadmium (96-h LC50 = 0.16 mg/L Cd) than D. lacteum (96-h LC50 = 23.22 mg/L Cd) (Table 3). Cocoons laid by D. lacteum during the test period were spherical, approximately 3 mm in diameter, and attached to the sides of the container by mucus.

### *The Effects of Cadmium on Predation Rate*

(a) *Effects of cadmium on predation of starved* A. aquaticus *by* D. lacteum: No significant difference was found after 240 h

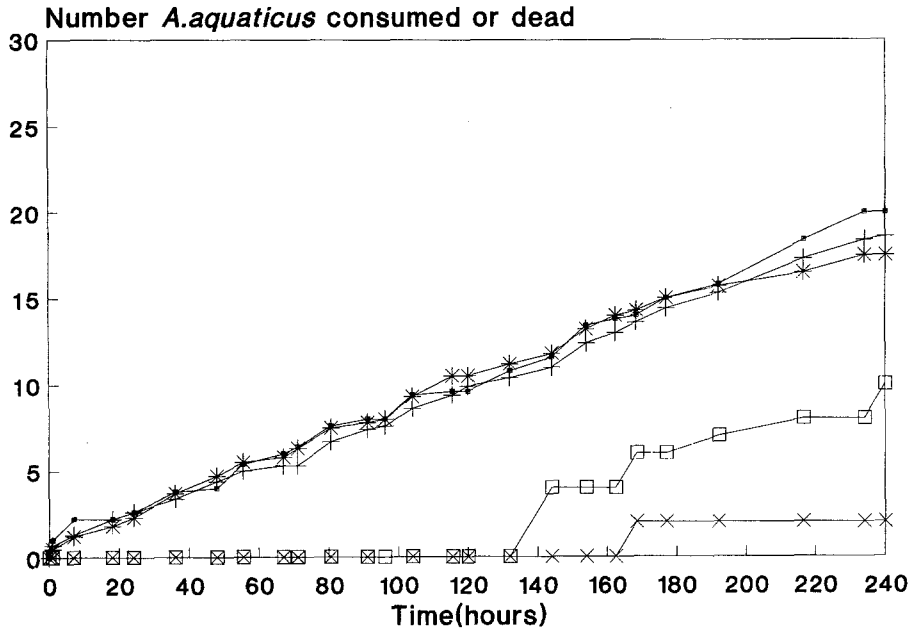


**Fig. 1.** Effects of cadmium and/or predation by 1 *D. lacteum* on 30 starved *A. aquaticus*. Control dilution water, *D. lacteum* present ⊡, 20 μg Cd/L, *D. lacteum* present *, 40 μg Cd/L, *D. lacteum* present +, 20 μg Cd/L, *D. lacteum* absent X, 40 μg Cd/L, *D. lacteum* absent □

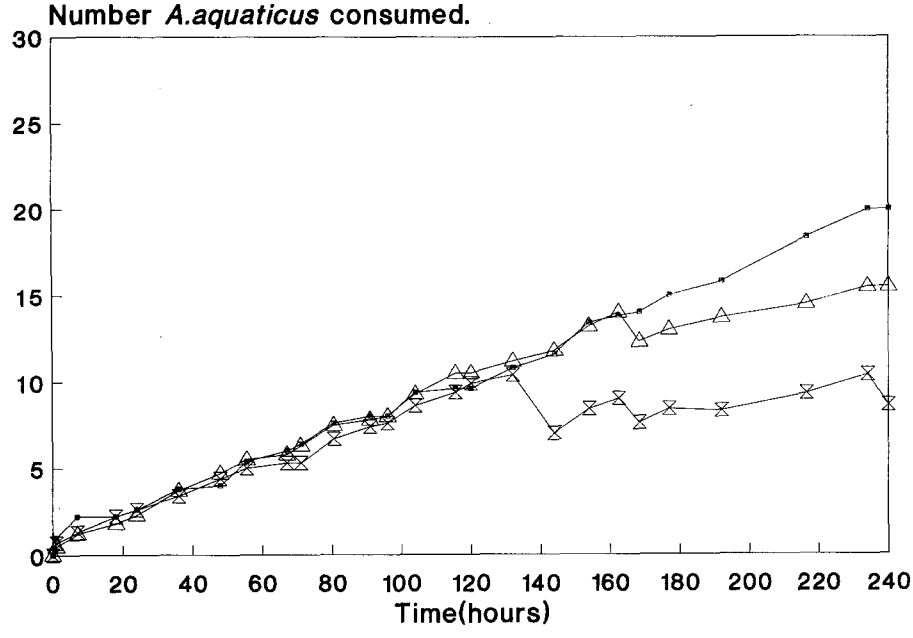


**Fig. 2.** Effect of cadmium on the predation of starved *A. aquaticus* by *D. lacteum*, taking into account the mortality due to cadmium alone. Control dilution water ⊡, 20 μg Cd/L △, 40 μg Cd/L ⧖

between the number of A. aquaticus consumed by the D. lacteum in test (20 and 40 μg Cd/L) and control waters (Figure 1), and one-way analysis of variance (MINITAB: ANOVA) performed on each sampling occasion showed no significant differences ($P > 0.05$) between treatments. However, a reduction in number of A. aquaticus was evident (Figure 1) in the absence of D. lacteum at 20 and 40 μg Cd/L. Presumably, animals killed by the toxicant were then cannibalized. When this reduction was taken into account (Figure 2), predation in the 40 μg/L test solution was significantly lower ($P < 0.05$) than in both the control and 20 μg/L solutions after 144 h. A significant difference ($P < 0.05$ level) was detected between the control and the 20 μg/L test solution after 192 h, with an apparent decrease in the number of A. aquaticus being consumed with increasing cadmium concentration. Statistical analysis (ANOVA) of the time taken to reduce from 20 prey to 10 showed no significant differences ($P > 0.05$) between control and treated animals when death due to toxicant was not taken into account. If such deaths were taken into consideration, in many instances the number of animals remaining did not reduce to 10 during the experiment, and so such analysis was not possible.

(b) *Effects of cadmium on predation of fed* A. aquaticus *by* D. lacteum: There was no significant difference (ANOVA) between the number of A. aquaticus remaining in exposed and unexposed populations with the predator present (Figure 3). However, taking into account the data from the non-predator controls where death was due to toxicant activity and subsequent cannibalism, significant differences

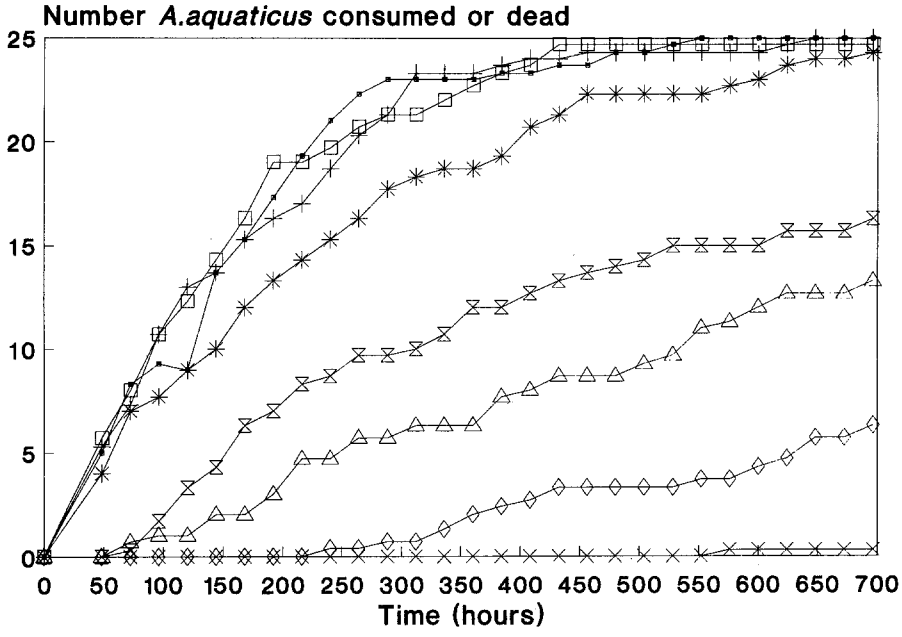


**Fig. 3.** Effects of cadmium and/or predation by 1 *D. lacteum* on 25 fed *A. aquaticus*. Control dilution water, *D. lacteum* present ⊡, 20 μg Cd/L, *D. lacteum* present +, 60 μg Cd/L, *D. lacteum* present *, 100 μg Cd/L, *D. lacteum* present □, control dilution water, *D. lacteum* absent X, 20 μg Cd/L, *D. lacteum* absent ◇, 60 μg Cd/L, *D. lacteum* absent △, 100 μg Cd/L, *D. lacteum* absent ⧖

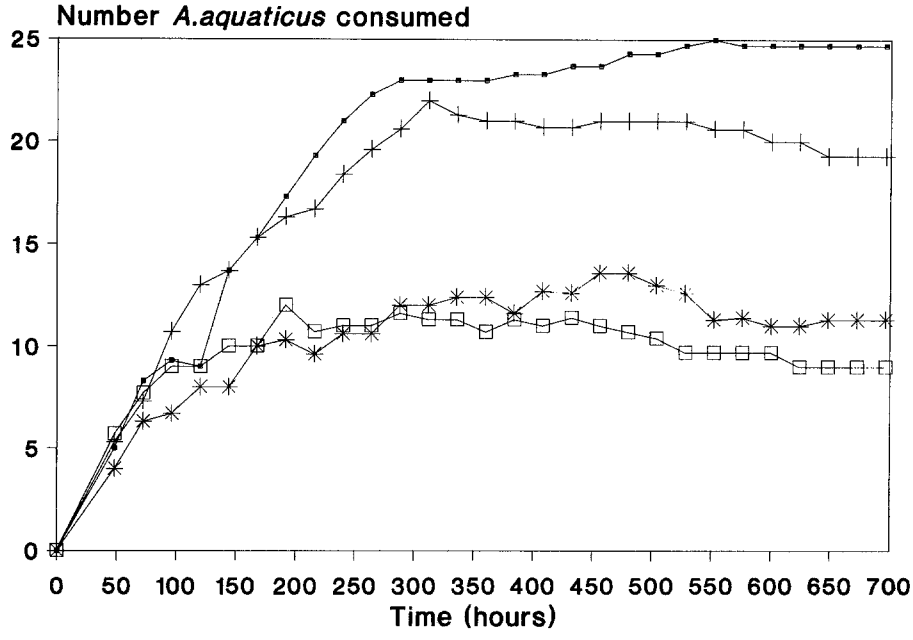


**Fig. 4.** Effect of cadmium on the predation of fed *A. aquaticus* by *D. lacteum*, taking into account the mortality due to cadmium alone. Control dilution water □, 20 μg Cd/L +, 60 μg Cd/L *, 100 μg Cd/L □

were found ($p < 0.05$, Figure 4). For example, after 240 h at 60 and 100 μg/L Cd, predation was less than that seen at both 20 μg Cd/L and in control water.

### *The Toxicity of Cadmium to Starved and Fed* A. aquaticus

There was a concentration-related response to cadmium for both the starved and fed A. aquaticus, but no significant difference ($P > 0.05$) in mortality between fed and starved animals at any concentration. LC50 and slope function values were calculated for day 6 (when 50% mortality first occurred), day 10, and at 5-day intervals until day 40 (Table 4). Again, no

**Table 4.** Median Lethal Concentrations (LC50's) with 95% confidence intervals for cadmium, recorded at different times for fed and starved *A. aquaticus*

| Day | LC50 for fed *A. aquaticus* | LC50 for starved *A. aquaticus* |
|---|---|---|
| 6 | 96.8 (72.5–129.2) | 87.8 (53.0–145.5) |
| 10 | 75.8 (53.3–107.9) | 53.8 (38.4–75.5) |
| 15 | 61.0 (43.6–85.2) | 46.4 (33.9–63.8) |
| 20 | 49.0 (36.2–66.4) | 38.7 (27.0–55.5) |
| 25 | 42.0 (32.8–53.8) | 36.9 (26.0–52.3) |
| 30 | 40.0 (32.0–50.1) | 33.0 (24.8–44.0) |
| 35 | 38.6 (31.0–47.9) | 32.4 (24.4–43.0) |
| 40 | 33.2 (26.8–41.2) | 28.7 (22.6–36.6) |

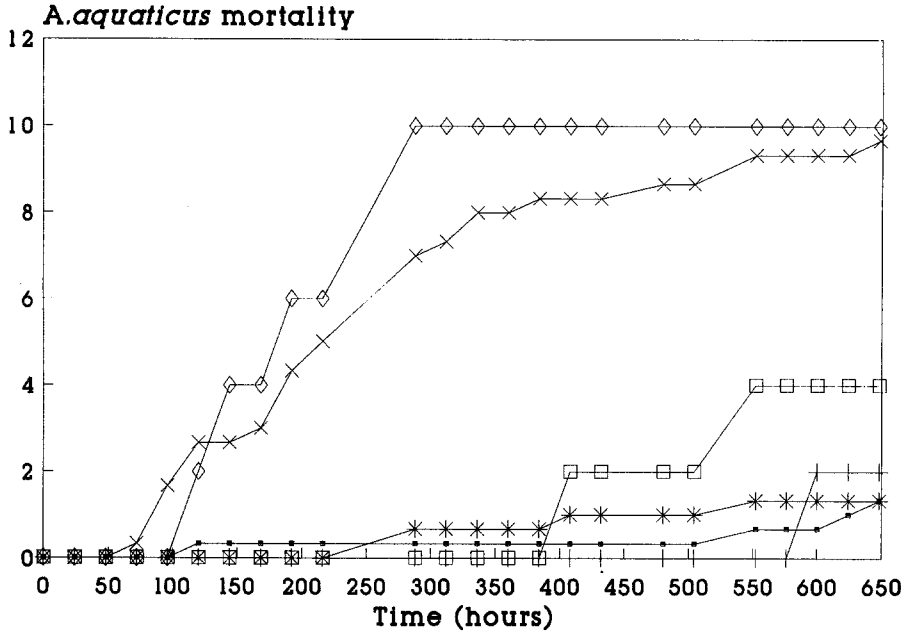


**Fig. 5.** Mortality of *A. aquaticus* due to cadmium when cannibalism was and was not possible (data are means of 3 replicates). Control dilution water, cannibalism possible ⊡, 20 μg Cd/L, cannibalism possible *, 100 μg Cd/L, cannibalism possible X, control dilution water, cannibalism not possible +, 20 μg Cd/L, cannibalism not possible □, 100 μg Cd/L, cannibalism not possible ◇

significant differences ($P > 0.05$) were found, although in all cases, starved animals appeared to be more sensitive than fed animals.

### *The Extent to which Cannibalism Occurs Among* A. aquaticus

Cannibalism occurred among A. aquaticus in both toxicant solutions and in control water. However, there was no significant difference ($P > 0.05$) in mortality rate where cannibalism was and was not permitted (Figure 5), but mortality was significantly greater in the 100 μg/L concentration when compared to the control and 20 μg/L cadmium solution. Observations suggested that early in the investigation (at 100 μg/L Cd) when an animal died, it was left by the others as they consumed the leaf disc provided. However, by 192 h, dead animals were cannibalized immediately. This suggests that in a long-term test, even when fed, prey animals will be removed by cannibalism in preference to the food provided and thus be unavailable to the predator.

### *The Preference of* D. lacteum *for Live/Dead Prey*

When D. lacteum were offered dead A. aquaticus, although initial interest was shown by movement towards the prey, in all but one instance the predator quickly disengaged itself. When a mixture of live and dead prey was offered, it appeared that the number of dead prey remaining decreased faster than that of live prey (Table 2). This, however, was probably due to cannibalism of the dead A. aquaticus, as seen (Table 2) when a predator was not present. This suggests that the predator is only consuming the live prey and that any decrease in the number of dead prey is entirely due to cannibalism (Table 2). Where the predators were offered only live food, they ate at a similar rate to that seen in previous experiments. When live prey were kept in the absence of a predator, no cannibalism occurred.

## Discussion

The single species acute toxicity tests revealed a marked difference in sensitivity to cadmium between the two species, with A. aquaticus approximately 140 times more sensitive (96 h LC50) than D. lacteum (0.16 and 23.2 mg Cd/L, respectively) in accordance with previously reported values for these species (Brown and Pascoe 1988; Green *et al.* 1986). Consequently, the concentrations of cadmium used in the study of the two species together were determined by the tolerance of A. aquaticus, the most sensitive species, since at higher concentrations, prey mortality would have been too high to sustain the required test duration. On the basis of this differential sensitivity, it might be predicted that the prey would initially be affected more readily than the predator, which could then either suffer from a lack of food and/or accumulate an increased cadmium body burden from consumption of contaminated prey.

The establishment of a standard experimental protocol for studying the predator-prey system was necessary in order to minimize variability, and for this reason, the system that gave a low coefficient of variation was used in preference to that with the highest number of prey consumed. A standard regime of feeding to excess followed by a starvation period ensured that all predators were of the same status prior to testing, *i.e.*, healthy with an empty gut. The predation rate recorded was consistent with that recorded by de Silva (1976a), and was clearly appropriate for medium and long-term studies in which sufficient numbers of prey would be consumed to allow comparisons between treatments.

The interaction between D. lacteum and A. aquaticus as reflected in the predation rate did not initially appear to be modified by the presence of cadmium in the water as compared to that recorded for animals maintained in control dilution water. This was the case for interactions involving both starved or fed prey. However, if prey mortality due to cadmium alone is taken into account, there is a significant difference in predation for all cadmium concentrations tested, both with fed and starved prey, compared to that for control animals. In all cases,

the number of prey consumed by the predator decreased with increasing cadmium concentrations. The validity of taking toxicant-induced mortality into account when calculating the true predation is dependent upon two assumptions.

The first assumption is that no additional A. aquaticus were actually dying other than those killed by the toxicant or those killed *and* eaten by the predator. Another possible cause of death would be "wasteful killing" in that D. lacteum would attack and kill a prey item, but not consume it. Although this is possible, it is unlikely due to the nature of the attack and consumption of the prey. D. lacteum covers its prey, everts its proboscis (penetrating the exoskeleton), produces hydrolytic enzymes which begin the digestion process, and the food material is then sucked into the gut (Herrmann 1984a). Up to the point of penetration, the attack may cease without ill effects to A. aquaticus. After this point, some degree of feeding has taken place, and so the prey may be considered as having been consumed. Therefore, the number of A. aquaticus killed by the toxicant in the prey-only controls is likely to be equal to the mortality due to toxicant in the presence of predator. Secondly, the assumption is made that upon death due to toxicant, A. aquaticus is not consumed by D. lacteum but is cannibalized by those prey remaining alive. It was shown that A. aquaticus did cannibalize any moribund prey in preference to the offered food of horse-chestnut leaf discs in the absence of predation. It is likely that such cannibalism was also occurring in the predation experiments. Triclads will feed on dead and dying prey (Reynoldson and Young 1963), and so there was a strong possibility that such feeding was occurring here. In the study where a choice of live and dead prey was offered to the predator, the number of dead prey decreased faster than the live prey. However, as a similar rate of dead prey disappearance was recorded in the absence of predator, it is probable that all dead prey were removed by cannibalism. Therefore, the second assumption holds; that is, prey killed by the toxicant are likely to be removed by cannibalism and not by the predator.

Toxicity is dependent upon a number of physiological factors (Pascoe 1987), including diet (Mehrle *et al.* 1977). As the same prey species was used throughout both the laboratory maintenance of D. lacteum and toxicity testing, the quality of food provided for the predator was consistent. In the case of the prey, the effect of feeding regime on the toxicity of cadmium was investigated. Although there was an increase in mortality for the starved A. aquaticus when compared to those fed, in terms of calculated LC50 values, this was not significant. An increase might have been expected in view of the added stress of starvation (Pascoe and Woodworth 1980). A possible explanation for a lack of difference is that the fed animals may also have been subject to a stress, *i.e.*, increased cadmium uptake via contaminated food, to which the starved animals were not subject. The similar response of fed and starved prey to cadmium explains why the effect of cadmium on the predation rate in the species interaction study was the same whether the prey were fed or starved.

The overall effect of cadmium on this predator-prey system therefore is direct toxicity to the prey and a reduction in the predation rate by D. lacteum, with both effects increasing in relation to the toxicant concentration. The reason for the reduction of the number of prey consumed by the predator could be either that the predator was less able to function in its predatory role or that it was less hungry. It was not feasible to examine the latter possibility, but studies carried out in this laboratory have examined effects of chronic cadmium exposure on the speed of movement of the predator. No significant difference was seen in the speed of movement of D. lacteum with regard to toxicant concentration. However, the speeds recorded were approximately half those recorded by de Silva (1976a), possibly due to stress caused by daily handling. In other experiments, A. aquaticus appeared to be less affected by mucus from untreated D. lacteum than from cadmium-exposed animals. This could suggest that the cadmium was affecting the production of mucus, either causing an increase or changing the protein content in some way. However, differences in time to capture were not significant.

Although the experiments relate to chronic discharges where low levels of toxicant are present in a body of water for a long period of time, there will also be certain instances where episodic incidents result in the presence of high concentrations of pollutant for a short period. In these instances, it is possible that the predator but not the prey will survive due to the different sensitivities. If this were to occur, then the predator would have two possible survival strategies: either to enter a prolonged period of starvation until the A. aquaticus population became re-established by recolonization, or to compete with other species for a different prey source. Triclads are well able to survive for a long time without food by utilizing reserve materials and shrinking in size (Reynoldson 1968). However, the ability of D. lacteum, a relatively short-lived triclad, to shrink and regenerate is much less than its potential planarian competitors, and it is also more prone to senescence (Reynoldson and Young 1965). Its ability to survive until the A. aquaticus returned to the habitat would be dependent on the size of the D. lacteum at the time of the pollution incident.

D. lacteum uses A. aquaticus as a "food refuge" in a combination of preference and opportunistic feeding behaviour involving competition. Other workers have found that the second prey of choice, in terms of number consumed, is Gammarus, a faster moving amphipod, and the third is an oligochaete (Reynoldson 1975). Gammarus pulex is more sensitive to cadmium than Asellus, having a 96-h LC50 of 0.03 mg Cd/L (Williams *et al.* 1985), and will also be removed from the habitat, while Limnodrilus hoffmeisteri, an oligochaete, is more tolerant, with a 96-h LC50 of 2.9 mg Cd/L (Williams *et al.* 1985), and in certain circumstances may remain. D. lacteum will be in competition for these species (particularly Oligochaeta) with other triclads, although it cannot obtain as much energy from oligochaetes (Herrmann 1984a) as from Asellus. The ability of D. lacteum to pursue its prey and react to a fast-moving animal will be critically important for catching food. At concentrations of 5 and 10 mg Cd/L, the movement of the predator has been shown in this laboratory to be severely impaired and the time to capture greatly extended, and so it is reasonable to conclude that the competitive ability of the animal will be reduced. However, other triclads in the habitat will also be exposed to the toxicant and their sub-lethal reactions are not known. 96-h LC50 values have been recorded for Polycelis felina, 29 mg Cd/L (Brown and Pascoe 1988) and for Polycelis tenuis, 80 mg Cd/L (Williams *et al.* 1985). It is likely that Polycelis felina will be affected at similar levels to D. lacteum; however, being more tolerant, Polycelis tenuis may survive longer than D. lacteum, particularly because the main "food refuge" of P. tenuis is oligochaetes, the third choice of D. lacteum. In laboratory ecosystems when only damaged A. aquaticus were available, P. tenuis eliminated D. lacteum (Reynoldson and Bellamy

1973). the reduced quantity and quality of the food available to D. lacteum would affect the ability of the animal to reproduce and could increase its susceptibility to the toxicant. Survival of D. lacteum would be in doubt. Removal of D. lacteum from the ecosystem may not have a large direct effect on the food chain as it does not have many predators and as a food source is not vital, but the increase in A. aquaticus numbers that could follow would have major consequences. However, it is likely that the mucous it produces aids prey capture by other organisms living in the same habitat (Greene 1974).

The overall effect of cadmium on this interaction therefore depends on the exposure involved. D. lacteum would be affected at lower concentrations than inferred from single species tests since it would be affected by the removal of its main food source at comparatively low concentrations. Similary, it may not be able to compete successfully for the prey species that are still available.

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