Technical Memorandum 25

Element concentrations in the freshwater mussel, Velesunio angasi, in the Alligator Rivers Region

H.E. Allison and R.D. Simpson

Supervising Scientist for
the Alligator Rivers Region

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ABSTRACT

Allison, H.E. & Simpson, R.D. (1989). Element concentrations in the freshwater mussel, *Velesunio angasi*, in the Alligator Rivers Region. Technical Memorandum 25, Supervising Scientist for the Alligator Rivers Region.

The freshwater mussel, *Velesunio angasi*, was investigated as a possible biological monitor for the waterbodies around the uranium mining ventures in the Alligator Rivers region of the Northern Territory. The majority of the study centred around the Magela Creek system with comparative work on Nourlangie and Cooper creeks, and on the Finniss River. The mussel accumulates biologically available pollutants over time. Concentrations of fourteen elements (Al, As, Ba, Ca, Cd, Cu, Hg, Mg, Mn, Pb, S, Se, U, Zn) were determined in the soft parts of mussels collected from the field. Most of the elements were chosen because they are considered to be potential pollutants. In addition Ca and Mg were chosen for possible synergistic or antagonistic chemical relationships with other elements. The sampling strategy for these analyses was designed to (1) determine baseline data before mining operations commenced - i.e. natural levels of the elements in the soft parts of mussels; (2) identify differences in these levels in the mussel soft parts with differences in (a) location and time, (b) environmental conditions and (c) the biology of the mussels; (3) provide an estimate of the dietary intake by Aboriginal people of elements from mussels. Experiments were also undertaken to evaluate uptake and loss of some elements by mussel organs under field conditions.

1 INTRODUCTION

1.1 Use of mussels as bioaccumulating monitors of water quality

There are a number of methods for the biological monitoring of water quality pollution and these have been extensively reviewed (Bayly & Lake 1979; Cairns 1979; Cairns & Van der Schalie 1980; Davey 1980; Phillips 1980; Williams 1980; Campbell 1982; Herricks & Cairns 1982; Matthews et al. 1982; Simpson 1982, 1983). The term 'bioaccumulating' monitor has been used here to distinguish between ecological or pollution indicators, that is the presence or absence of a particular species which gives an indication of water quality. Bioaccumulation is the general term describing a process by which chemical substances are accumulated by aquatic organisms from the water directly or through the consumption of food containing the chemicals (Rand & Petrocelli 1985).

One method of biological monitoring is the use of organisms which accumulate chemicals from their surroundings or from food, sequestering them in their bodies, so that when the tissues are analysed an indirect estimate of prevailing environmental concentrations of these substances may be made. The main advantages of such a method are that the organisms: (a) accumulate biologically available chemicals to levels where direct analysis may be feasible, whereas the ambient water concentration may be at the limits of analytical detection, and (b) are potentially continuously exposed to concentrations of chemicals, which may be intermittent and hence may be missed in water sampling regimes.

Bivalve molluscs such as oysters and mussels have been selected to act in monitoring studies because many features of their general biology and ecology closely match the identified requirements for organisms to be used as monitors. Such requirements have been expounded upon and listed by Butler et al. (1971) with additions to this list being made by other authors such as Haug et al. (1974), Phillips (1977) and Forester (1980). The desirable attributes for a bioaccumulating monitor are:

- taxonomically distinct and easily identified in order to be sure that one species is being collected;
- established body of knowledge on biology and ecology;
- wide distribution locally and geographically (if relevant) in order to facilitate comparison between study areas;
- not restricted to specialised habitat;
- abundant and easy to sample;
- robust - in terms of tolerance to environmental stress, survival in the laboratory and use in relocation experiments in the field;
- sessile or relatively immobile to ensure that findings are related to the area studied;
- of sufficient size to provide adequate sized samples for analysis, especially when studies are to be made on specific organs;
- long-lived, to enable samples to be taken over several year-classes and provide evidence of long-term effects; and
- high concentration factor for the chemicals of concern.

In reality, organisms having all these attributes are unknown, however, some meet one or more of the criteria.

One feature that has sometimes been cited as a requirement for a bioaccumulator is that individuals, both within and between populations, should exhibit the same correlations between their chemical contents and ambient chemical levels, at all locations and under all conditions. This is extremely unlikely to be met. There will be variation in the sampling of animals from the field and the sources of that variation need to be identified to enable a

sampling strategy that will reduce the variation and thus enhance both spatial and temporal comparisons. One suggestion to avoid the problem of variation across field animals has been to use mussels from the one population, which are transplanted to appropriate sites (Ritz et al. 1982).

Most bivalves, including the freshwater unionaceans, have another attribute that is advantageous to their use as a bioaccumulating monitor of water quality: as filter-feeders of phytoplankton they are at a low position on the food chain and are exposed to chemicals both from large volumes of water passing over their gill surface and from algae and particulates which have readily absorbed/adsorbed metals; hence they reflect environmental levels of pollutants more directly and with little interaction with other trophic levels. When comparing organisms it is important that they are in the same trophic levels, e.g. phytoplankton filtering molluscs should not be compared with carnivorous fish.

The ideas and problems in using mussels as biological monitors have received considerable attention in the marine environment (Goldberg 1975; Goldberg et al. 1978; National Academy of Sciences 1980; Hammond 1982; Klump & Burdon-Jones 1982; Ritz et al. 1982). Freshwater mussels live in a more variable aquatic environment than their marine counterparts. It is therefore very important to establish the variation in element concentrations caused by changes in the animals' biology and ecology (the background noise) in order to be able to distinguish an increase in concentrations in tissues caused by increased levels in the environment (the signal).

The role of organisms in pollution monitoring needs to be clearly understood. The main objective here is to determine levels of chemicals in the bodies (usually soft parts) of the organisms and to then use those determinations to differentiate between non-polluted and polluted circumstances. This is achieved by sampling and analysing organisms both before and after input of pollutants into a site or in existing polluted sites, often along a gradient of pollution. It follows from this characterisation that a natural 'baseline' can be established - i.e. expected levels of potential pollutants for a non-polluted environment.

This baseline must take into account the natural variation in levels of the chemical in the monitoring organism. Some of this variation may be reduced by selective sampling (see later). The question then is: what degree of change from these levels constitutes contamination? Generally, differences of at least ten-fold are necessary to identify that any change has gone beyond the wide, natural variability encountered in levels of potential pollutants across individual organisms (Goldberg et al. 1978; Lobel & Wright 1982*a, b, c*). Improvements in techniques in the use of organisms will reduce the degree of difference required to discriminate between natural and polluted environments.

The ultimate concern is: what are the biological effects of pollution on the environment and on man. The response of organisms to toxic chemicals can be manifested at four levels of biological organisation: (1) biochemical and cellular; (2) organismal, including the physiological, biochemical and behavioural responses; (3) population, including alterations in population dynamics; and (4) community, resulting in changes to community structure and dynamics (Cappuzzo et al. 1988). If man eats the bioaccumulating organism, as occurs for *Velesunio angasi*, and contamination exceeds levels identified as constituting a health risk, then the problem is a tangible one and remedial action can be invoked. The equating of detection of pollution to adverse impact upon nature is a much more difficult task. Wider studies need to be undertaken in order to gauge the extent of the effects on the ecosystem from any pollution which has been quantitatively detected by the bioaccumulating organism. Some workers have suggested that bioaccumulating monitors (particularly bivalve molluscs) could also provide indications of biological effects through determination of changes in their physiology and biochemistry - in addition to their role of providing a convenient measure of changes in levels of the pollutants (Bayne 1978; National Academy of Sciences 1980; Phelps et al. 1981; Simkiss et al. 1982).

1.2 Strategy of investigation of *Velesunio angasi* as a potential bioaccumulating monitor

The initial objective of this project was the identification of sources of variation in the natural levels of elements in the soft parts of mussels. Such knowledge is a pre-requisite to using the mussels for any comparisons between pre-mining and mining or post-mining conditions. Consequently, studies have been undertaken on the biology and ecology of *Velesunio angasi* in Magela Creek (Humphrey & Simpson in press). At the same time, concentrations of fourteen elements[1] have been determined in the soft parts of mussels from thirteen locations in the Magela Creek catchment, one billabong on Nourlangie Creek and one billabong on Cooper Creek (Figs 1 and 2). Mussels from around the abandoned Rum Jungle mine site on the Finniss River (see Fig. 9) were also sampled for the same elements. Most of the elements measured were chosen because of their known toxicity and/or because they have been identified as potential pollutants from the orebody or the mining process. Calcium and magnesium have been measured because of studies on their antagonistic action in the metabolism of Ra-226 in the mussels (Jeffree & Simpson 1986).

The strategy for sampling the mussels was designed to provide the following: (1) identification of variations in concentrations of potential pollutants in the soft parts of the mussel with differences in location, environmental conditions, and the biology of the mussels; (2) baseline data before mining operations commenced; and (3) an estimate of the dietary intake by Aboriginal people of elements from mussels. Evaluation of uptake and loss of elements in the soft parts of the mussel was made by transferring mussels between selected billabongs as well as placing them in retention ponds at the Ranger uranium mine site (see section 2.3).

1.3 Consequences of analytical variability

Other studies assessing the use of mussels as bioaccumulating monitors, both marine and freshwater, have reported wide ranges for the levels of various elements in the tissues (Ayling 1974; Manly & George 1977; Jones & Walker 1979; Gordon et al. 1980; Orren et al. 1980; Lobel et al. 1982; Millington & Walker pers. comm.).

As previously mentioned, it was a prime aim of the investigation into the use of *V. angasi* as a potential biological monitor of pollution, to identify sources of biological variation in the natural levels of elements in the soft parts of the mussels - so that such variation could be reduced by an appropriate sampling strategy. This would then allow detection of reasonably small unnatural changes in these levels.

A severe impediment to this aim has been the wide variation in the results of the chemical analyses of samples - i.e. a wider variation than was expected from existing chemical techniques (Allison & Simpson 1983). Common sources of possible analytical variability have been identified by Sill (1976) as: incomplete initial decomposition of the sample, evaporating solutions to dryness, contamination, and standardisations carried out in a careless and inaccurate manner. The fundamental problem was that the project was dependent on the use of external laboratory resources for the analyses of samples. During the course of the project, various problems were encountered in the execution of these analyses and, in all, three analytical laboratories were used at different stages of the work. Unfortunately, assessment of the variation in determinations of the elements in the study samples showed that analytical performance did not match expectations for two of the laboratories. The wide variation inherent in the analyses meant that the chance of discerning subtle differences between chosen study situations was severely curtailed. The determination of trends with time were made difficult when samples within the series were analysed at

[1] aluminium, arsenic, barium, calcium, cadmium, copper, mercury, magnesium, manganese, lead, acid soluble forms of sulphur, selenium, uranium, and zinc

different times (= different batches - see Allison & Simpson 1983). Changes in element concentration could be correlated with time of analyses (such instances are identified in the current report).

However, with the analytical variability clearly identified, positive evaluation of the mussel as a biological monitor was then possible in many parts of the study. It is anticipated that future checks on doubtful results will be undertaken on replicate samples, which are presently stored (at -20°C).

2 MATERIALS AND METHODS

2.1 Baseline study - collecting of mussels and analytical companies used

Collecting of mussels - baseline study

Mussels were collected over a two-year period from one location in Cooper Creek, one location in Nourlangie Creek and 13 locations in the Magela Creek catchment (Figs 1 and 2 and Table A1). Mussels from 11 locations in Magela Creek were collected every two months while mussels from Cooper and Nourlangie creeks were taken approximately every three months. In addition, mussels were sampled on one occasion from Murganella Billabong on Cooper Creek (Fig. 1). (Hereafter particular billabongs will be referred to by name without the use of the term 'billabong' after the name.)

The mussels were collected by hand with or without the aid of compressed air (supplied by a hookah) depending on the depth of water. In the creek locations, the mussels were embedded in the banks of the creek, particularly at the base of *Pandanus*. In billabongs where visibility was low, mussels were located by feeling for them by hand in the substrate. They were collected in a net bag then taken to the shore or boat for sorting on the basis of length. Mussels used in this study had in general a length in the range of 61-65 mm, however, in those billabongs where population densities were low, a wider size range was sampled. Those not selected were returned to the billabong as closely as possible to the place where they had been found. In Island and the floodplain billabongs (Jabiluka and Leichhardt), the size range taken was 66-70 mm as this was the size range in which mussels were most abundant. The mussels to be used for analyses were placed in plastic barrels containing water from the billabong from which they had been collected, and transported to the laboratory.

Initially, samples of 20 mussels were grouped for analyses. Also, analyses were undertaken on individual mussels to obtain an estimate of the variance in the samples in order to calculate the optimum sample size.

The formula used to calculate the optimum sample size (given in Elliot [1979]) was:

$$n = t^2 s^2 / D^2 \bar{x}^2$$

where: n = optimum sample size
D = index of precision (the ratio of the standard error to the mean)
t = Student's t-distribution (1.96 for 95% probability level of D)
s^2 = variance
$\bar{x}$ = mean of the initial sample

This initial sampling strategy was used to reduce the number of analyses, and hence cost, and because the availability of large numbers of mussels was undetermined. (Work in the ecological studies showed that, for most sites, mussel numbers were high.) Subsequently,

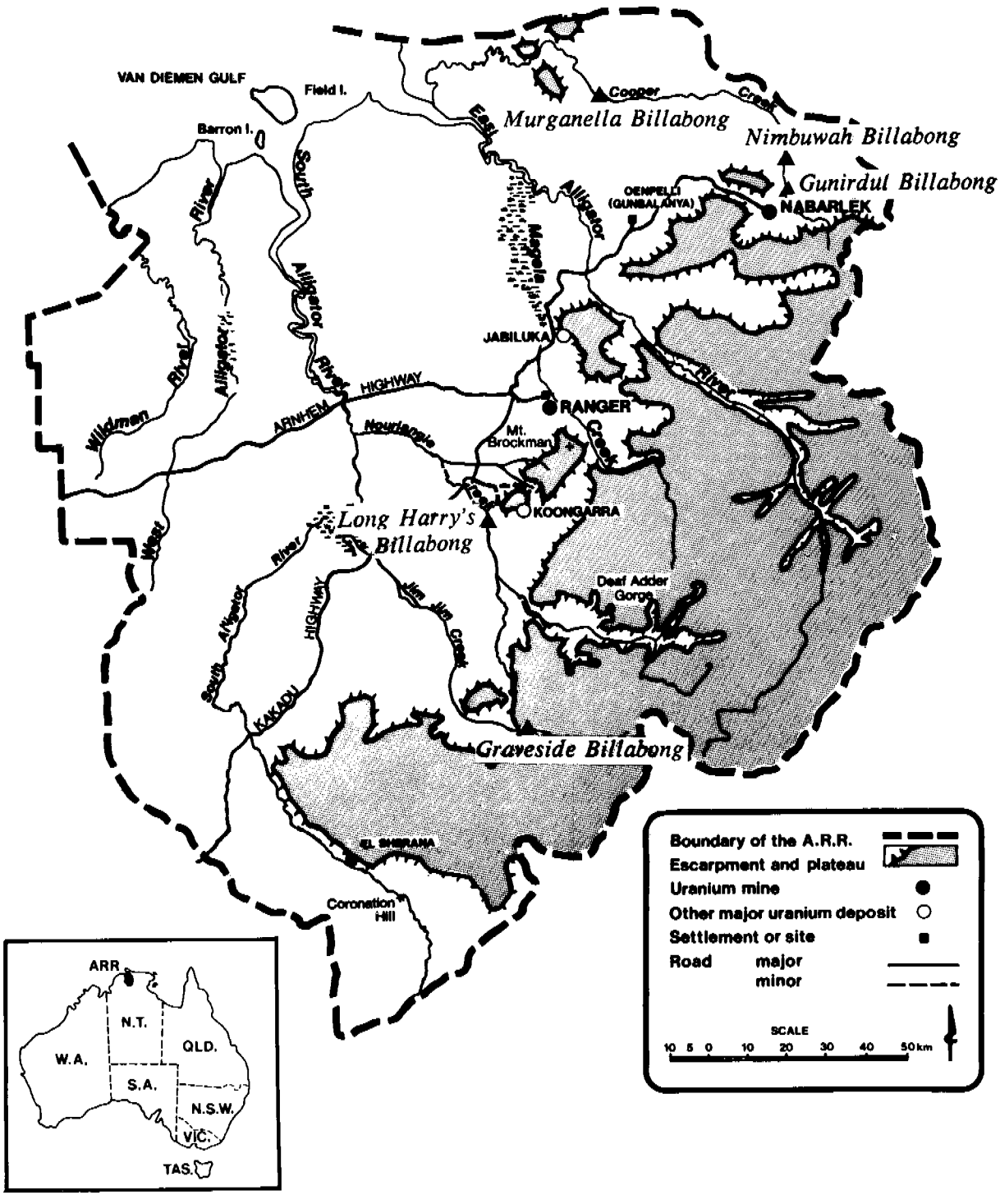


Figure 1. Location of the Alligator Rivers Region[2] and of the billabongs sampled on Cooper and Jim Jim creeks

[2] Outline of the Region is shown as it was at the time of the study. It has since been extended. [ed.]

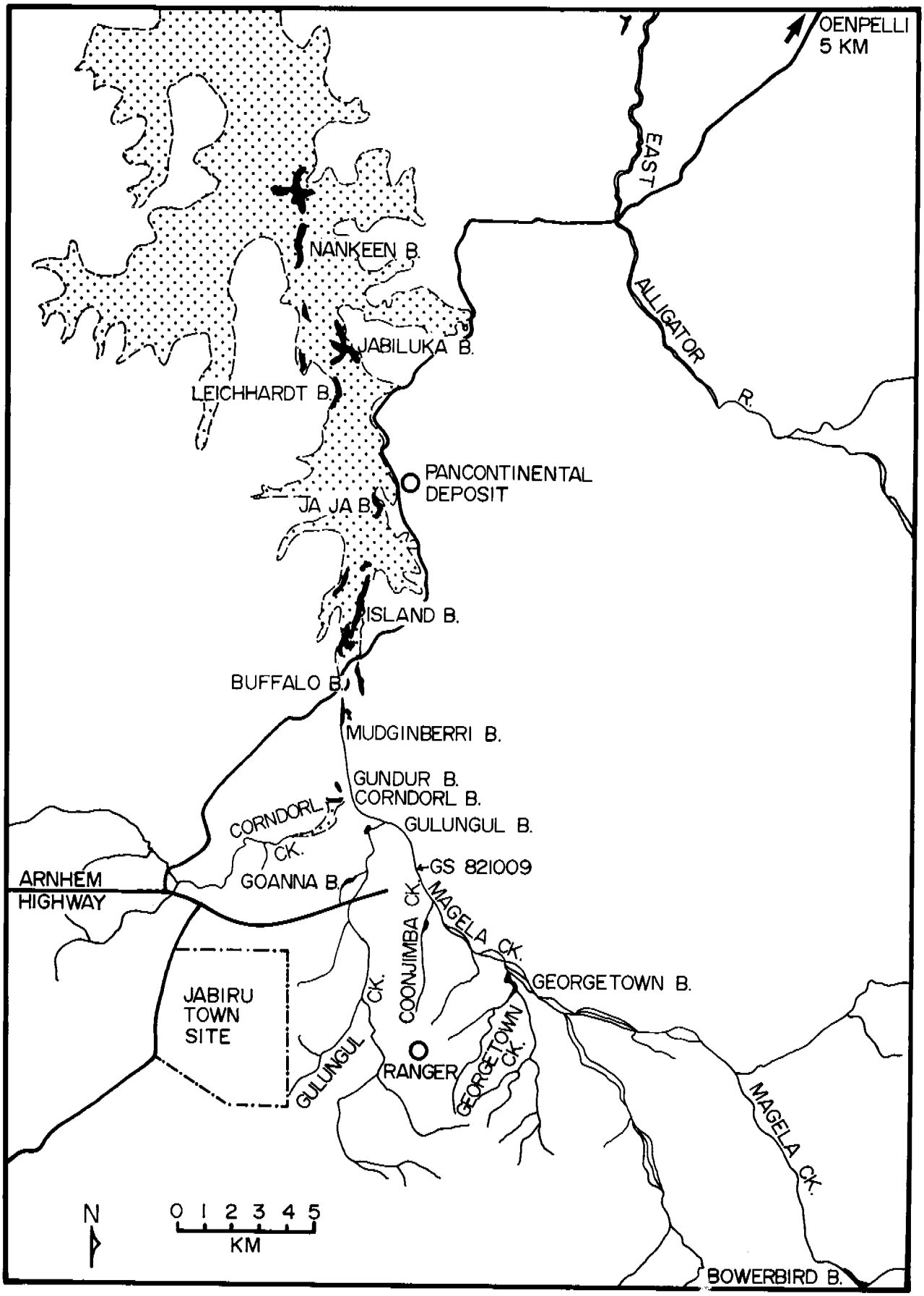


Figure 2. Location of the billabongs sampled on Magela Creek

sufficient numbers of mussels were collected to enable a selection of twenty male mussels within a particular size class. (One sex was chosen to eliminate any possible sexual difference in metal concentrations in the animals throughout the study period.) These twenty mussels were divided into five groups of four so that estimates of variance at all sampling occasions could be obtained.

Results for concentrations of elements in individual males and females of one age (seven-year-olds) were analysed to estimate the minimum sample size required to obtain any nominated percentage difference between means. These tests were undertaken subsequent to the findings that concentrations of some elements were age dependent. Therefore the hypothesis was that restriction to one age would reduce variability, resulting in the determination of smaller minimum sample sizes than found in the same tests performed on mussels of the same size class but of different ages.

At the beginning of the study (in March, April and June 1980) one composite sample for each billabong was made up from 20 mussels (male and female). In August 1980, 20 mussels from each billabong were divided into five samples of four, each group of four being of the same sex as far as possible. In October 1980 and beyond, 20 male mussels were randomly allocated into five samples of four each.

Analyses of samples were carried out by AMDEL, SGS and OSS, as described in section 2.7. The March to October 1980 samples were analysed by AMDEL (Australian Mineral Development Laboratories). The samples taken from December 1980 until February 1982 were analysed by SGS (Societe Generale de Surveillance). Fresh (wet) samples were analysed here to avoid volatilisation of As, Se and Hg. A small subsample was dried to calculate the wet/dry weight ratio. All results are expressed on a dry weight basis unless stated otherwise.

A test on ten pairs of samples was conducted by AMDEL to measure the degree of element volatilisation, due to their drying process, which may have occurred in the samples analysed by them. One of each pair of wet samples was dried at 60°C in an oven before analysis and the other sample was processed without being dried.

2.2 Preparation of the soft parts of mussels for chemical analysis

Purging

On arrival at the laboratory the mussels and water from each billabong were placed in separate 50-litre white polyethylene containers, lined with disposable polythene bags. Any large items of vegetation were removed from the water before it was filtered (1 μm filter) and circulated. This removed any material which mussels might filter. (Mussels are known to filter particles to a minimum size of 1 μm [Boyle 1981; Brönmark & Malmqvist 1982; Ward 1982].) Any excreted solid matter or psuedofaeces were siphoned from the bottom of the tanks each day. Where mussels were to be purged of their gut contents they were maintained in the filtered water for 48 hours. Where mussels were to be analysed without being purged, they were put in polythene bags and placed on ice until processed (within 24 hours).

Dissection and preparation of samples

At all times when soft parts were handled, only stainless steel instruments which had been cleaned prior to use with diluted HNO_3 and then with de-ionised water were used. Mussels were opened by cutting both the adductor muscles with a high quality 'Feather' scalpel blade. Before use each new blade was run through a piece of expanded polystyrene to remove the feather edge, dipped in dilute (5%) HNO_3 and rinsed three times with de-ionised water. Polyethylene containers for sample storage were soaked for at least 24 hours in dilute HNO_3 and rinsed three times with de-ionised water prior to use.

Once the mussels were opened, free water was drained off quickly and discarded. The soft parts were then scraped out, using a glass knife, into a polyethylene container prior to homogenisation. Care was taken during the removal of the soft parts from the shell to collect tissue fluids, which may contain some elements (Ch'ng-Tan 1968; George et al. 1982). Where analysis of the individual organs was required (mussels from Georgetown, Mudginberri and Leichhardt) organs were dissected out using a pair of high quality stainless steel scissors. The organs were separated into six groups: (1) mantle, (2) gills and palps, (3) visceral mass, (4) adductor muscles, (5) heart, and (6) kidney. The hearts and kidneys from 20 mussels were grouped according to the organ type to provide sufficient material for analysis. During dissection care was taken to avoid contamination between tissues, in particular from kidney tissue adhering to the visceral mass.

Preparation of fresh samples. The soft parts of mussels were homogenised using an Ultra-Turrax T45 homogeniser fitted with an 18N shaft. The time taken to homogenise each sample was dependent on the sample size. Certain organs e.g. the outer edge of the mantle, were difficult to homogenise and care had to be taken to ensure that no lumps of material remained in the sample. Once the mussel soft parts appeared homogeneous by visual inspection, samples of the homogenate were placed in polyethylene vials. If sufficient material was available two or three replicates of the homogenate were taken. The samples were frozen at -20°C until required for analysis.

Preparation of dry samples. Mussel soft parts were sampled as described previously and placed in polyethylene vials. The samples were then dried to constant weight in an oven at 60°C. Once dry, the samples were ground in an automatic agate mortar and pestle until a fine powder was formed. The powder was then divided into one to three replicates. Between grinding each sample, the mortar and pestle were cleaned with dilute HNO_3 and rinsed with de-ionised water.

Recording of biological information

The length and height of the shells were measured to the nearest millimetre and width to the nearest 0.5 millimetre. Once opened the mussels were sexed either by looking for embryos in the gills of females or by piercing the gonads within the visceral mass. Eggs or sperm could then be identified.

Figure 3 shows a male mussel which has been cut through both the anterior and posterior adductor muscles and the valves splayed out. The visceral mass has been pulled over into the left valve (on the right hand side of the Figure) and partly covers the left gill. Inorganic granules are identifiable as a brown colouration which may be present in all organs except the adductor muscles. The overlay shows the areas covered by granules.

Figure 4 shows a female mussel with glochidia in the marsupia of the inner flaps of the gills. The brown colour caused by the presence of the glochidia should not be confused with the presence of granules. Although the photographs have been developed differently, there are differences in the degree of colour of granules ranging from very light brown (Fig. 4), through mid-brown (Fig. 3), to a deep orange. The mantle, gills, palps, and visceral mass were given a score on a scale of 1 to 6 on the basis of area covered by granules. These granules are known to contain high concentrations of some elements (Ch'ng-Tan 1968; George et al. 1982); therefore the amount of granular material present was recorded in order to try to correlate it with the concentrations of certain metals in the tissues.

The mussel in Fig. 3 had a granule score of: mantle - 4, gills - 2, palps - 6 and visceral mass - 2; and the mussel in Fig. 4 had a granule score of: mantle - 3, gills - 1, palps - 5 and visceral mass - 1. Figure 5 shows the possible areas covered by the granules and the appropriate scores.

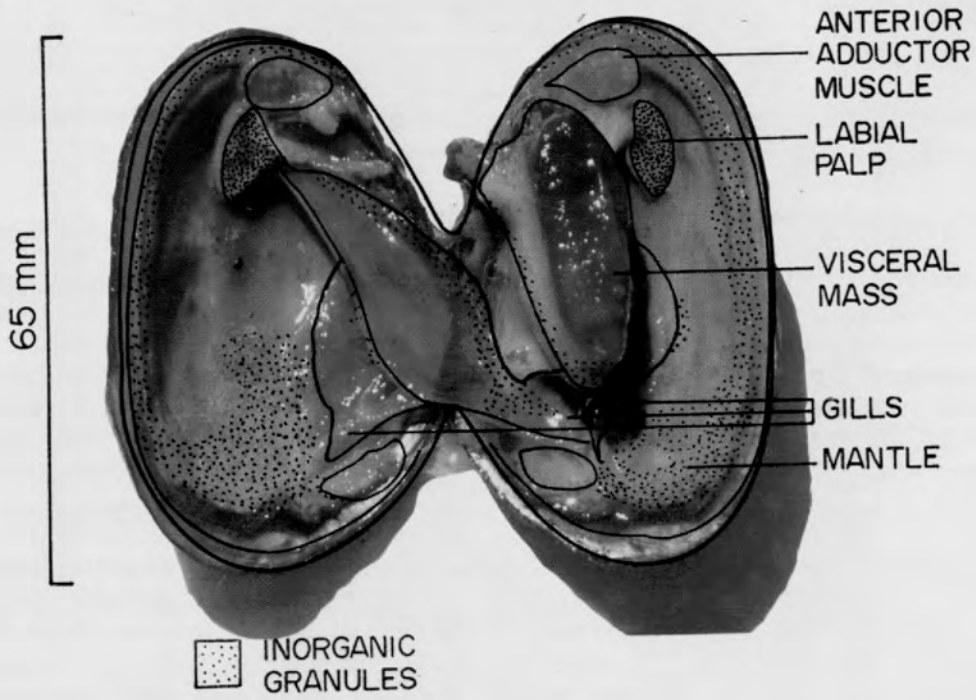


Figure 3. The internal organs of a male mussel
The position of granular material is shown on the overlay

Figure 4. The internal organs of a female mussel
The brown colouration is the result of glochidia in the marsupia of the gills. The black specks on the mantle are parasitic mites.

The wet weight of the mussel soft parts in the samples was weighed to 0.1 g. After the sample was homogenised, a subsample was taken and weighed to 0.001g. This subsample was dried to constant weight in an oven at 60°C and reweighed to 0.001 g to calculate the wet/dry weight ratio for each sample.

The age of each mussel was determined by directing a strong light through the shell and counting the yearly growth rings (Humphrey & Simpson in press).

Test for contamination during sample preparation

Two replicates of each of two National Bureau of Standards standard reference materials (Orchard leaves SRM 1571 and Bovine liver SRM 1577), as well as two replicates of a fish meal standard (obtained from Dr B. Noller, OSS) were prepared. De-ionised water was added to the dry powder in the ratio 1:8, powder to water, to simulate the consistency of the mussel samples. One replicate was homogenised for five minutes. Both replicates were then dried at 60°C in an oven and ground in an agate mortar and pestle in the usual manner.

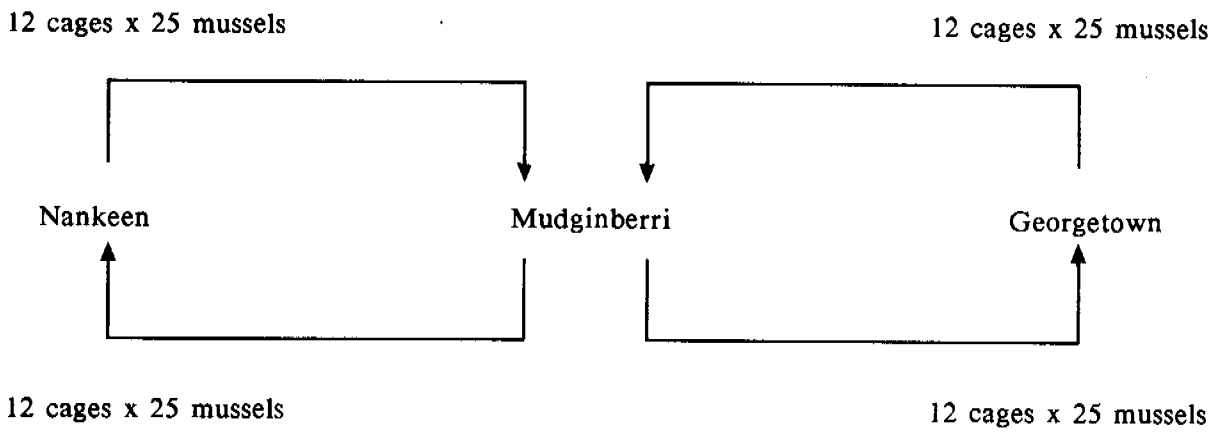
The two replicates of the three standard reference materials were analysed by AMDEL and the results are shown in Table A2. The second determinations were undertaken by AMDEL upon request when the values of the first determinations were found to vary widely from the certified values. These results showed possible contamination by Cr, the source being the stainless steel homogeniser shaft. This was of no concern because Cr (and V) were dropped from the elements selected for study because of their low concentrations (below limits of detection) in mussel samples.

2.3 Experimental methods

Transplants between billabongs

Three hundred mussels were collected from each of Georgetown (backflow billabong) and Nankeen (floodplain billabong) and 600 mussels from Mudginberri (channel billabong). The mussels were transported back to the laboratory in black polyethylene containers, in water from the billabong from which they had been collected. The mussels (61-70 mm in length) were divided into groups of 25. Each group was placed in a cage made from plastic mesh. To prevent heat stress and desiccation of the mussels, the cages were covered with wet tarpaulins while they were transported, as quickly as possible, to the receiving billabong.

The mussels were transplanted according to the following scheme:



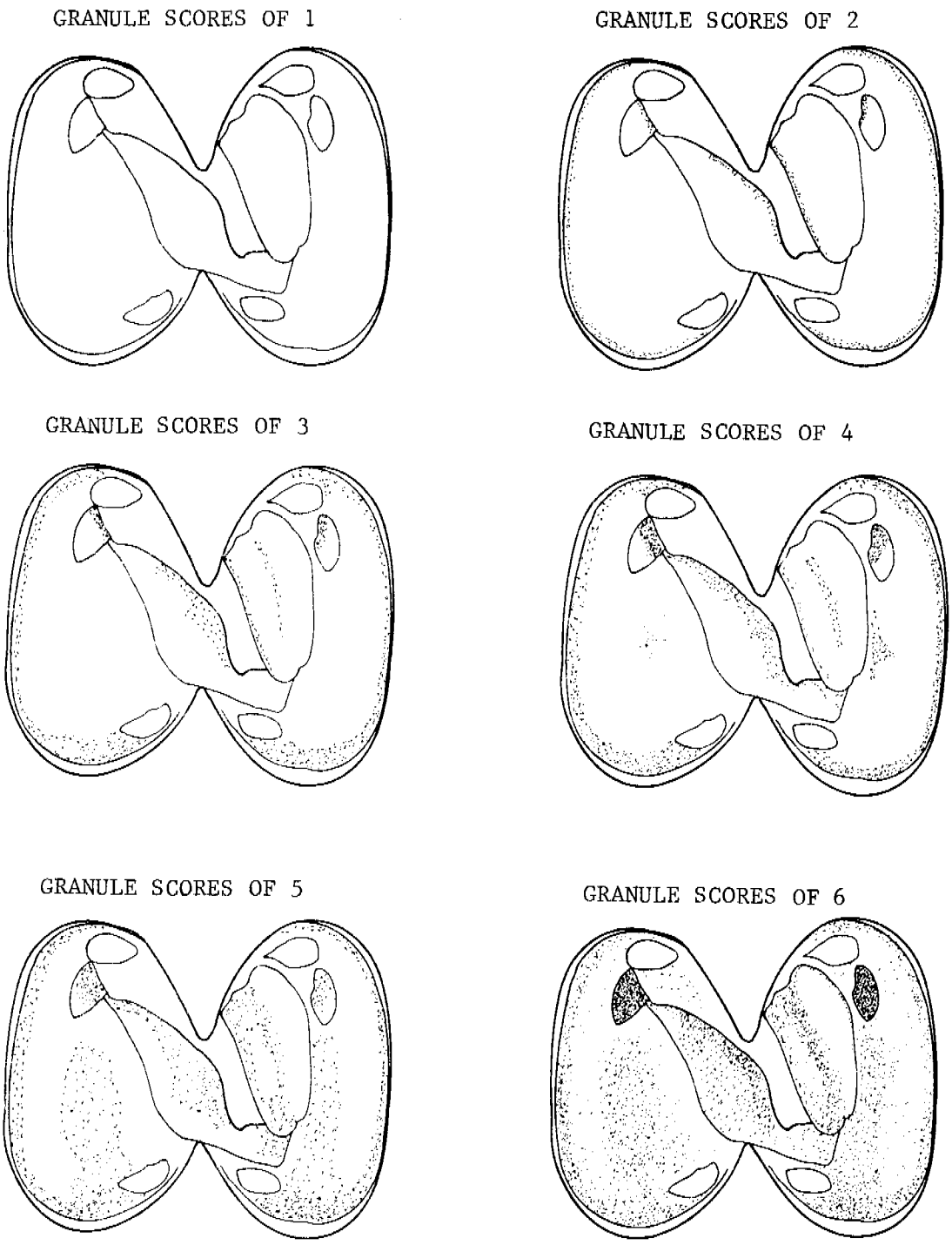


Figure 5. Diagrams of opened mussels showing the extent of coverage by granules for scores of 1 to 6

Each month for 12 months one cage from each transplant scheme was recovered and twenty mussels were randomly chosen for analysis. There are no data for some of the later months owing to vandalism of the cages.

The mussels sampled each month were transported to the laboratory and held in filtered billabong water for 48 hours to purge themselves of their gut contents. The mussels were then opened, sexed, and allocated into five groups of four mussels. Groupings were made of the same sex and, in the case of females, of the same stage of maturity in the reproductive cycle (because these factors were concurrently being investigated as possible sources of variation in element levels in the mussels). They were then processed in the usual way.

The samples taken in June to October were dried at 60°C in an oven and the analyses conducted on the dried samples. Samples taken after this time were analysed in the wet form and a small subsample taken to calculate the wet to dry weight ratio.

Uptake and loss studies

Retention ponds - short-term. Mussels were collected from Mudginberri and sorted on site into three age classes as closely as was possible with live mussels: (1) less than one year, (2) three years, and (3) four-seven years. Initially, the mussels were separated into age classes using the growth rings visible on the external shell surface. (Later, on dissection, precise ages were determined by the usual method - see section 2.2.) The mussels were held in cages in Mudginberri until transferred to Retention Pond Nos 1, 2 and 4. The cages were made of 1 cm square nylon 'Nylex' mesh secured with plastic clips. Three cages, each holding mussels of one age class, were placed in the Retention Ponds and sampled 11 times according to the following sequence: 0, 12 hours, 24 hours, 2 days, 4 days, 7 days, 2 weeks, 3 weeks, 4 weeks, 5 weeks and 6 weeks. The remaining mussels were then returned to Mudginberri and again sampled on the above schedule with additional samples taken at 9, 12 and 16 weeks.

On each sampling occasion five mussels were selected from each age group. The five less than one-year-old mussels were grouped on each occasion to provide sufficient material for analysis. The mussels from the other age classes were analysed individually where sufficient material was available or 2-3 mussels were grouped. The mussels were not purged (to avoid loss of elements with short biological half-lives), and were processed as described in section 2.2.

Retention ponds - long-term. Six hundred mussels, length 61-70 mm, were collected from Mudginberri and held in billabong water in the laboratory in cages (as described above) until placed in Retention Pond Nos 2 and 4. The mussels were sampled at one-monthly intervals. On each occasion one cage was retrieved and 20 mussels were randomly selected. The mussels were returned to the laboratory and opened immediately without being purged. They were processed as stated in section 2.2.

Over the 12-month period some cages of mussels were lost, therefore only 10 months data exist for mussels in Retention Pond No. 2. After 12 months the mussels remaining in Retention Pond No. 4 were transferred to Mudginberrri and sampled as follows: 12 hours, 24 hours, 2 days, 4 days, 7 days, 2 weeks, 3 weeks, 4 weeks and 5 weeks, to allow the possible loss of elements from the soft parts.

Gulungul Billabong enclosures. In co-operation with Dr B. Hart (Chisholm Institute of Technology) mussels (in plastic mesh cages) were placed in an enclosure located in Gulungul and in Gulungul itself (as a control). The enclosure isolated a small section of the billabong using a 1 m x 1 m x 1.3 m (depth) plastic frame enclosure (Fig. 6). Copper (8.1 mg in an acidified solution) was added to raise the Cu concentration within the enclosure to approximately 11 μg/L. The water column was sampled at regular intervals over a 2.5 day period by Dr Hart. Full details of this experiment may be found in Hart et al. (1982).

Gulungul has a very small population of mussels, therefore to avoid depleting this population 40 mussels (length 61-65 mm) were collected from Mudginberri for this experiment. These were placed in the enclosure or the billabong according to the following scheme: cage no. 1, billabong control; cage no. 2, enclosure; cage no. 3, enclosure; cage no. 4, Mudginberri for 3 days. After 2.5 days the mussels were removed. In order to determine the contribution by the gut contents to element concentrations the mussels from cage no. 2 were purged of their gut contents for 48 hours in filtered (1 μm) Gulungul enclosure water. All mussels were processed individually in the usual manner.

Island Billabong enclosures. This experiment was conducted in co-operation with Dr B. Hart. Three 5-m diameter cylindrical polyethylene enclosures were installed in a line down the billabong on 8.9.81. The enclosures had an inflatable ring at the top and the walls were sealed into the bottom sediments (Fig. 7).

Thirty mussels (length 61-67 mm) were collected from Island. Five mussels were processed immediately without purging and the remaining 25 were put in five plastic-mesh cages, five mussels per cage, and placed in the enclosures (see Table A3). The mussels were placed in the enclosures on 8.9.81, 34 days prior to the addition of the metals and sampled on 12.10.81 before the enclosures were spiked with the metal solutions and also on the final day (28.11.81). This avoided disturbances of the sediment which would have affected the sedimentation study results.

Copper chloride, ZnCl and MnCl (in the free ionic form) were added (on 12.10.81) to produce trace metal concentrations approximately ten times greater than those occurring naturally - Cu into enclosure 1, and Zn and Mn into enclosure 2 and no additions to a third control enclosure (see Table A3). The water column was sampled at regular intervals in all three enclosures and the billabong between 12.10.81 and 28.10.81 by Dr B. Hart. Full details of this experiment can be found in Hart et al. (1983).

When the mussels were removed from the enclosures they were not purged of their gut contents before they were processed in the usual manner. The mussels were not purged of their gut contents because the total metal content (as ingested by a person eating the soft parts of the mussels) was to be determined. At the end of the study, only one mussel remained in the cage in the enclosure containing copper (the other four mussels were accidentally lost).

2.4 Studies related to Aboriginal activities

Comparison of concentrations of elements in uncooked and cooked mussels from Mudginberri (August 1981)

Twenty mussels (length 61-65 mm, sex ratio unknown) were collected in August 1981. These were cooked by the method used by local Aboriginals (the mussels were boiled in water, with a teaspoonful of salt added, in an aluminium billy until the shells opened [approx. 15 minutes]). (The billy was taken from an abandoned Aboriginal camp site.) The mussel soft parts were then removed from each shell and placed in individual polyethylene vials. These were taken back to the laboratory, homogenised (see section 2.2) and frozen prior to analysis. The results for these cooked mussels were compared with the results for the mussels collected at same time in the baseline study.

Estimation of mussel consumption by local Aboriginals

Collections were made of mussel shells which had been recently left behind by Aboriginals (Fig. 8) in order to estimate the dietary intake of elements through the consumption of mussel soft parts. Searches along the creek banks were made between the north end of Mudginberri and the south end of Georgetown over the Dry seasons of 1980 and 1981. All

Figure 6. The enclosure used in the Gulungul Billabong uptake study

Figure 7. One of the enclosures used in the Island Billabong uptake study

Figure 8. A campfire site and mussel midden left by Aboriginals

the shells from all deposits were taken. (Except from Gundur, 27.11.81, because they were so numerous. On this occasion all the shell valves were counted and the total number was divided by two to calculate the number of mussels.) Length frequencies were calculated on a collection of 1% of the mussels shells counted. The left valves were selected from the shells which had been collected, and their lengths were measured to the nearest millimetre.

2.5 Leichhardt Billabong mussel kill

Mussels were observed floating on the surface of Leichhardt on 11.1.82. On the 12.1.82, 40 mussels were collected and four mussels were analysed individually (the soft parts of the remaining 36 mussels were largely decomposed).

2.6 Finniss River study

Four billabong locations and one river location on the Finniss/East Finniss rivers were sampled over the period 23-25 August 1981. Thirty mussels were collected from locations 1, 2, 3 and 5, and 25 mussels from location 4 (Fig. 9 and Table A4) there being fewer mussels at the last location. The mussels were maintained for up to four days in 40 litres of water taken from the respective locations. At the laboratory the water was filtered for 48 hours and the mussels were allowed to purge themselves of their gut contents before being processed individually in the usual way (section 2.2).

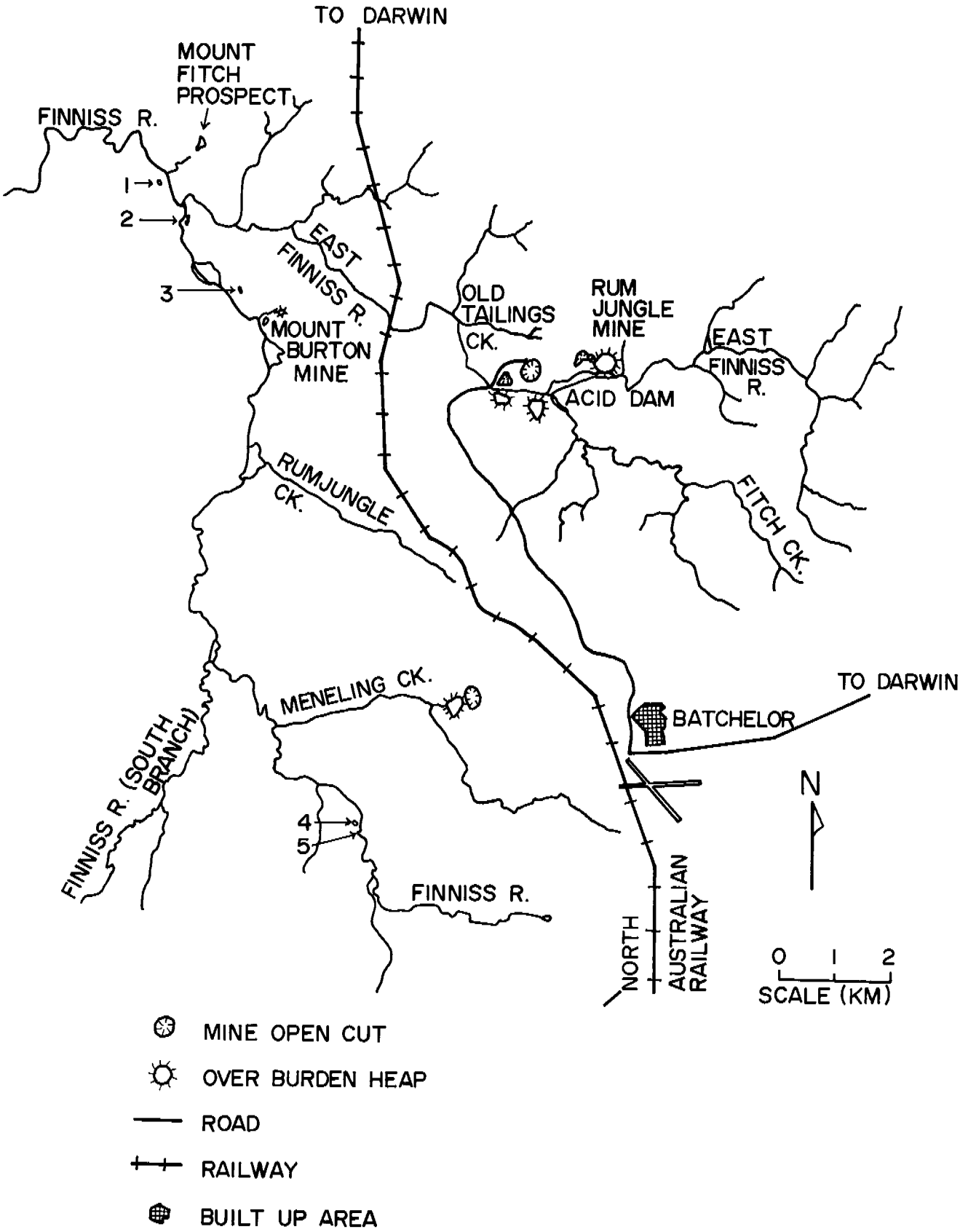


Figure 9. Location of the sampling sites on the Finniss and East Finniss rivers

2.7 Digestion and chemical analysis

Societe Generale de Surveillance (SGS)

SGS undertook the analysis of the major portion of the samples in this study. The elements determined were aluminium, arsenic, barium, calcium, cadmium, copper, mercury, magnesium, manganese, lead, acid soluble forms of sulphur, selenium, uranium and zinc by the methods outlined below.

Digestion. The frozen homogenised samples were allowed to thaw, then stirred with a spatula. Up to 0.5 g of each sample was then placed in a 50 mL beaker with 20 mL HNO_3 + 2 mL $HClO_4$ mixture and left overnight for cold digestion. The digestion was completed by hot digestion and evaporated to dryness. The residue was then dissolved in 25 mL HCl (2 N), to make a stock solution 'A' for analysis.

Uranium. To a 5 mL aliquot of stock solution 'A', was added 25 mL saturated calcium nitrate solution ($Ca(NO_3)_2.4H_2O$ + 1.2% di-sodium EDTA. Uranium was then extracted using 5 mL methyl isobutyl ketone for two minutes, the aqueous phase discarded and 0.2 mL of the organic extract pipetted on to each of two pellets (98% NaF + 2% LiF) in a petri dish. The organic phase was 'flashed off' before measuring the fluorescence on a Galvanek-Morrison Mark V fluorimeter.

Acid soluble forms of sulphur. The method used determined all acid soluble forms of sulphur (organic, pyritic and sulphate). The following were added to a 1 mL aliquot of the stock solution 'A': 4 mL distilled water, 1 mL conditioning reagent (50 mL glycerol + 50 mL solution containing 30 mL HCl (conc) + 300 mL H_2O + 100 mL ethanol + 75g NaCl), a few crystals of ascorbic acid, a spatula tip of $BaCl_2.2H_2O$ crystals. The solution was stirred for one minute then the turbidity immediately measured (within the next minute) at a wavelength of 420 nm.

Cadmium, copper, zinc, manganese, calcium, magnesium, aluminium. All these elements were determined by flame atomic absorption spectrophotometry (AAS) using the most sensitive lines.

Barium. Barium was determined by flame emission.

Lead. Lead was determined by hydride generation analysis.

Arsenic and selenium. After analysis of the flame elements, a small spatula tip of EDTA was added to each sample, mixed thoroughly and allowed to stand for a few minutes to complex the Se. Selenium was then determined by using hydride generation followed by AAS using a Varian spectrophotometer.

To determine As, the samples were chemically reduced by adding a small spatula tip of KI then an equal amount of ascorbic acid and allowed to stand for a minimum of one hour. Arsenic was then determined by AAS following hydride generation as for Se.

Mercury. Mercury was determined by direct combustion of the sample and AAS cold vapour analysis.

To check the accuracy of their results, SGS used National Bureau of Standards Standard Reference Materials (NBS SRM). In the case of the majority of individual batches of samples analysed by SGS, samples of both NBS SRM 1566 (Oyster tissue) and NBS SRM 1575 (Pine needles) were analysed concurrently. Towards the end of the analyses NBS SRM 1577 (Bovine liver) was also used. Hereafter the term 'batch' is used to describe a number of samples analysed together at a specific time along with either one or more NBS SRMs. In all, 55 batches were analysed.

As an internal check for precision, one out of every group of ten samples was subjected to repeat analysis. Assessment of the precision and accuracy of the analytical results of SGS is outlined in Allison & Simpson (1983).

Concealed precision controls. Replicates of an OSS mussel reference material (wet) were included periodically along with the wet samples from the study (29 in all). These were similar in color and consistency to the study samples. They were used as a check on precision by concealing their identity from SGS. At the end of the initial period of analysis ten of these samples were analysed (within one batch) as a precision check. As a check on homogeneity, a quantity of the wet OSS mussel reference material was reprocessed using the homogeniser for 1 hour, and ten replicates taken. Replicates of a dry OSS mussel reference material were included periodically among the dry samples from this study (5 in all). Their identity was concealed.

Office of the Supervising Scientist (OSS)

Analyses for Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn were performed by OSS on 601 dry samples. (Al, As, Hg, S, Se and U in the same 601 samples were analysed by SGS.) A summary of the analytical methods of OSS is shown schematically in Fig. 10. A more detailed account of the analytical methods is given by Noller (1983).

Analytical variation. An analytical program to measure Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn in the biota of the region, initially mussels, was developed at OSS, Alligator Rivers Region Research Institute (ARRRI). A full account of this is given in Noller (1983). The following results have been extracted from that paper.

Precision and accuracy of analysis were established using NBS SRM 1566 (Oyster tissue), SRM 1577 (Bovine liver) and SRM 1571 (Orchard leaves). The precision (i.e. relative variability) is expressed by the standard deviation as a percentage of the mean and in Noller (1983) is termed the relative standard deviation (% RSD). In the present report the term 'coefficient of variation' (CV), the more commonly used statistical terminology is used. Accuracy refers to the degree of agreement between the concentration measured by the test method and the certified value given by NBS. It is expressed as the relative error, and is the difference between the measured and the certified value expressed as a percentage of the certified value.

Four bulk samples (consisting of the soft parts of mussels, dried then ground) were used as reference materials (OSS mussel reference material, dry) and were analysed concurrently with the NBS SRMs (Table A5) to establish 'within-batch' control data (Table A6). Subsamples of this reference material were subsequently analysed in rotation with each batch of samples analysed, to calculate the 'between-batch' precision (Table A7).

The precision for the 'between-batch' analyses (Table A7) was lower than the 'within-batch' precision (Table A6). This loss of precision was attributed to day-to-day errors in analytical preparation, differences in standards, instrumental changes and different operators.

Following investigations into different techniques for digestion and AAS measurements, the wide variation in the Ba data (CV [%RSD] 6.5-15.2%, Table A6) was attributed by Noller (1983) to non-homogeneity of the control freshwater mussel samples. By comparison, the precision for Ba determinations in NBS 1571 Orchard leaves remained low (CV 7%). However, it was shown by SGS that where the S concentration was high, as it was in mussels (10 mg/g), then $BaSO_4$ precipitated from the digest solution with time. If, therefore, different periods of time elapsed between digestion and analyses results would be highly variable. The concentration of S in NBS SRM 1571 was 1.9 mg/g (uncertified value) and $BaSO_4$ would not therefore be formed to the same extent, resulting in less variable results. In conclusion Noller (1983) suggested that to identify a real change in element concentration

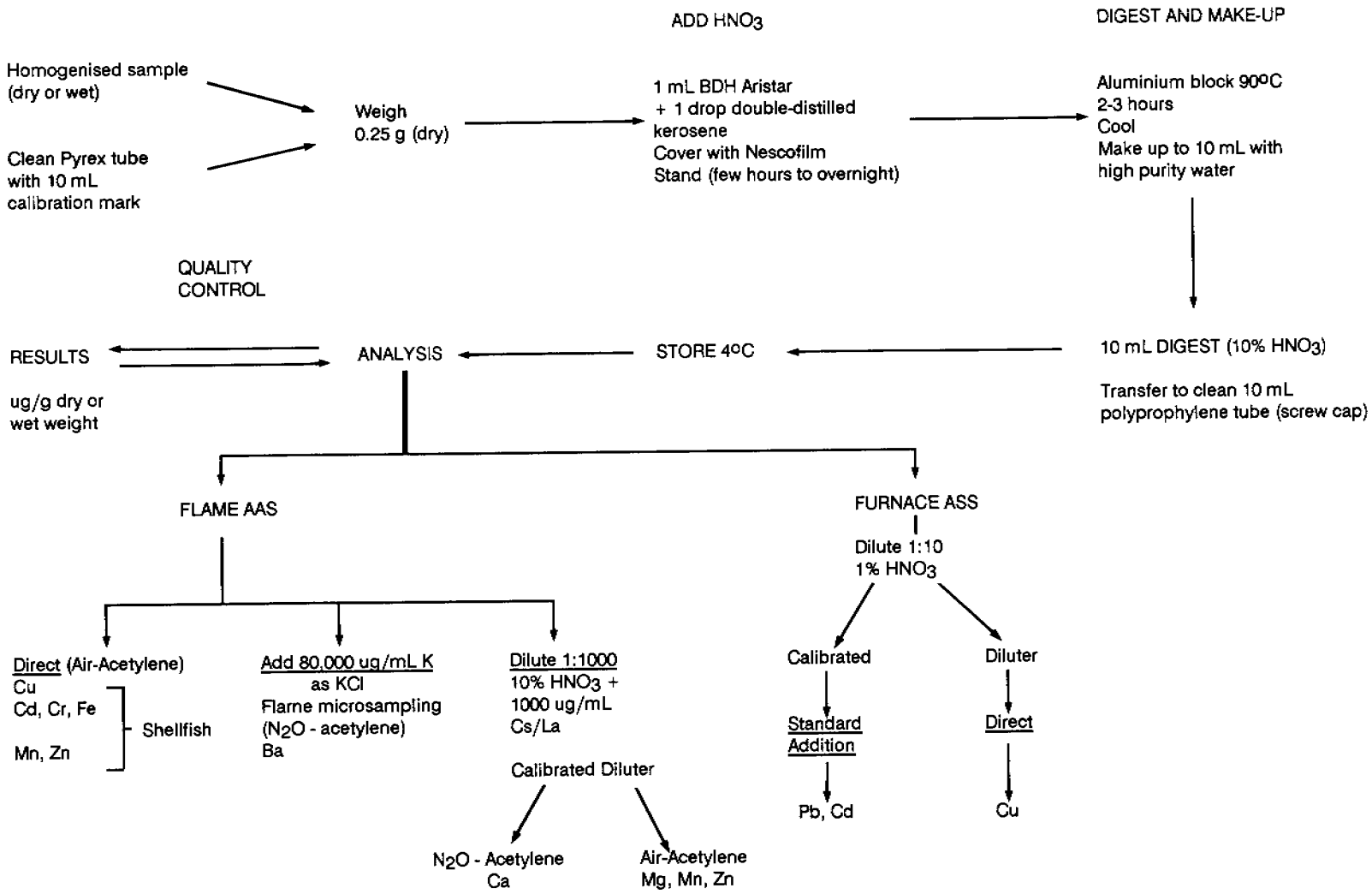


FIGURE 10. OSS - ANALYTICAL FLOWCHART FOR ANALYSIS OF HEAVY METALS IN BIOTA

(when analyses were performed by OSS) in mussel soft parts, the observed change in concentrations must exceed three times the per cent relative error of the accuracy derived from analyses of NBS SRMs.

Australian Mineral Development Laboratories (AMDEL)

AMDEL undertook the initial analyses of 131 dry samples from the baseline study from March-October 1980. Initially, the elements As, Ca, Cd, Cr, Cu, Hg, Mg, Mn, Pb, S, V, U and Zn were determined and the following methods of sample analysis used: As - addition of sodium borohydride to an aliquot and measurement by vapour AAS; Cd - filament in furnace atomisation; Hg - addition of stannous chloride to an aliquot and measurement by vapour AAS; Cu, ZN, and Mn by AAS; U - fluorimetry; and Ca, Mg and S - inductively coupled plasma atomic emission spectrophotometry (ICPAES). Al and Se were also determined in samples collected in October 1980. Chromium and V were subsequently withdrawn from the elements to be determined because they were below the levels of detection of the methods being used. Once the ranges of concentrations had been established it was suggested that the elements As, Cd, Cu, Zn and Mn as well as Ca, Mg and S should be analysed by ICPAES as the concentrations of all of them were well in excess of the lowest limits of detection of that method. Hg was analysed by vapour AAS and U by fluorimetry. Appropriate standards such as NBS SRM Bovine liver and plant material were used as controls to check the accuracy of the analyses.

Analytical variation. As a check for contamination when homogenising the samples, duplicate samples of NBS SRM 1577 (Bovine liver), SRM 1571 (Orchard leaves) and a fish meal standard (prepared by Dr B. Noller, OSS) were included (see section 2.2). The results of the analyses are reported in Table A2, as determination No. 1. The discrepancies in the results of the first determination from the certified values of the NBS SRMs for Cu, Mg and Pb necessitated that they be determined for a second time, determination No. 2. The accuracies of those determinations are recorded in Table A8, based on the one analysis for each of the determinations of the elements.

The accuracies of the determinations vary between the two NBS SRMs analysed. Discrepancies may have occurred for some elements because the concentrations in the NBS SRMs were of different magnitudes to concentrations in the study samples (for which the instrumentation had been set). For example, the determinations for Cu and Hg in Orchard leaves had an accuracy of 33% and 15% compared with 72% and 119% for the determination of those elements respectively in Bovine liver. However, the opposite trend was found for the results of Cd and Zn in which the lower accuracy was reported for the NBS SRM in which the concentration was closer to that of the test sample concentrations i.e. the accuracy for Cd in Bovine liver was 530% whereas the accuracy of Cd in Orchard leaves was 15%.

When repeat analyses were requested on the test materials the company was informed the materials were NBS SRMs. The second determinations of the elements were more accurate than the first determinations. AMDEL suggested that the discrepancies may have been caused by different methods of analysis. The initial samples were determined by ICP and were the first samples of this type run on the instrument, whereas the repeat samples were determined by atomic absorption. Unfortunately there were no repeat analyses on a number of control samples to calculate the precision of AMDEL's methodology.

Because accuracy was poor, it can be implied from the accuracy results that large fluctuations from the mean concentrations would have to occur before the change could be attributed to any external influence and not to analytical variation. A comparison of Tables A5 and A8 shows that the accuracy of AMDEL was poor compared with that of OSS. A similar difference was found between SGS and OSS (Allison & Simpson 1983). It was found that the accuracy and precision of results produced by the two commercial analytical laboratories were well below the standard achieved by OSS (ARRRI).

Comparison between AMDEL and SGS

One of two replicates of each of five samples were analysed by both AMDEL and SGS. The concentrations of As, Ca, Cd, Cu, Mg, Mn, Pb, S, Se, U and Zn were determined and the values are given in Table A9. The results of an analysis of variance (Table A10) showed that, between companies, there were very significant differences ($P < 0.01$) between the means for determinations of As, Ca, Mg, Mn, Pb, Se and Zn; significant differences ($P < 0.05$) for Cd, Cu and S and a non-significant difference ($P > 0.05$) between companies for U.

The two companies used different methods of analyses, which may have given rise to differences in determinations for some elements. However, both companies standardised their determinations by analysing NBS SRMs and each reported good accuracy. The baseline samples were analysed by these two companies (see section 3.5); from March to October 1980 by AMDEL and after that time by SGS. Also, in the long-term uptake study, the initial sample was analysed by AMDEL and the subsequent samples by SGS. The above differences shown in the results from the two companies make any comparisons across these time periods extremely difficult.

3 RESULTS

3.1 Comparisons of concentrations of elements in the soft parts of mussels from Georgetown, Mudginberri and Leichhardt billabongs (March 1980)

Statistically significant sample sizes. Seven-year-old male and female mussels from Geogetown, Mudginberri and Leichhardt were used to estimate the relationship between sample size and percentage differences which can be detected for the means of each of the elements analysed (Figs A1 and A2). Tables A11-A13 show the calculated values of the sample sizes required to estimate a 10% and a 20% difference between means ($P < 0.05$) for the 14 elements.

Concentrations of elements in the soft parts of mussels in relation to age

All concentrations are given on a dry weight basis unless stated otherwise. A diagramatic representation of the results of multiple comparisons tests using the least significant difference (LSD) is shown in Fig. 11 for Georgetown, Mudginberri and Leichhardt. Males and females have been grouped together into five age classes: (1) < 1 year; (2) 1-1.9 years; (3) 2.0-3.9 years; (4) 4-6.9 years and (5) ≥ 7 years. The means are arrayed in order of increasing magnitude from left to right. The lines beneath the numbers represent a non-significant difference ($P > 0.05$) of mean concentration. For example, in mussels from Georgetown the concentration of Mg in age classes 1 and 2 are not significantly different from each other but are significantly different from age classes 3, 4 and 5. However, age class 2 is not significantly different from age class 3.

Inorganic granules occurred in the mantle, gills, palps, and visceral mass (see section 2.2). In Fig. 12 the mean scores for the individual organs have been grouped to give a score for the whole body versus age for male and female mussels from Leichhardt.

The mussels in the younger age classes from Georgetown and Mudginberri were small in weight and had to be grouped. For ease of statistical analysis the number of samples in each age group had to be equal, reducing the number of repeat samples to three for Mudginberri and five for Georgetown.

Not all the elements determined in the soft parts of the mussels were measured in the water of the billabongs by Water Division, Department of Transport and Works (Leichhardt was one of the locations not sampled). The minimum, maximum, mean and SD of the concentrations of Cu, Pb, Zn, Cd, Mn, U, Mg (total and residue) and the pH and turbidity in the water of Georgetown and Mudginberri for the period November 1978 to August 1981 are shown in Table A14.

Concentrations of elements in the soft parts of mussels in relation to sex

A diagramatic representation of the results of the means ± 95% CL of the 14 elements and the age for male and female mussels from Georgetown, Mudginberri and Leichhardt is shown in Fig. 13.

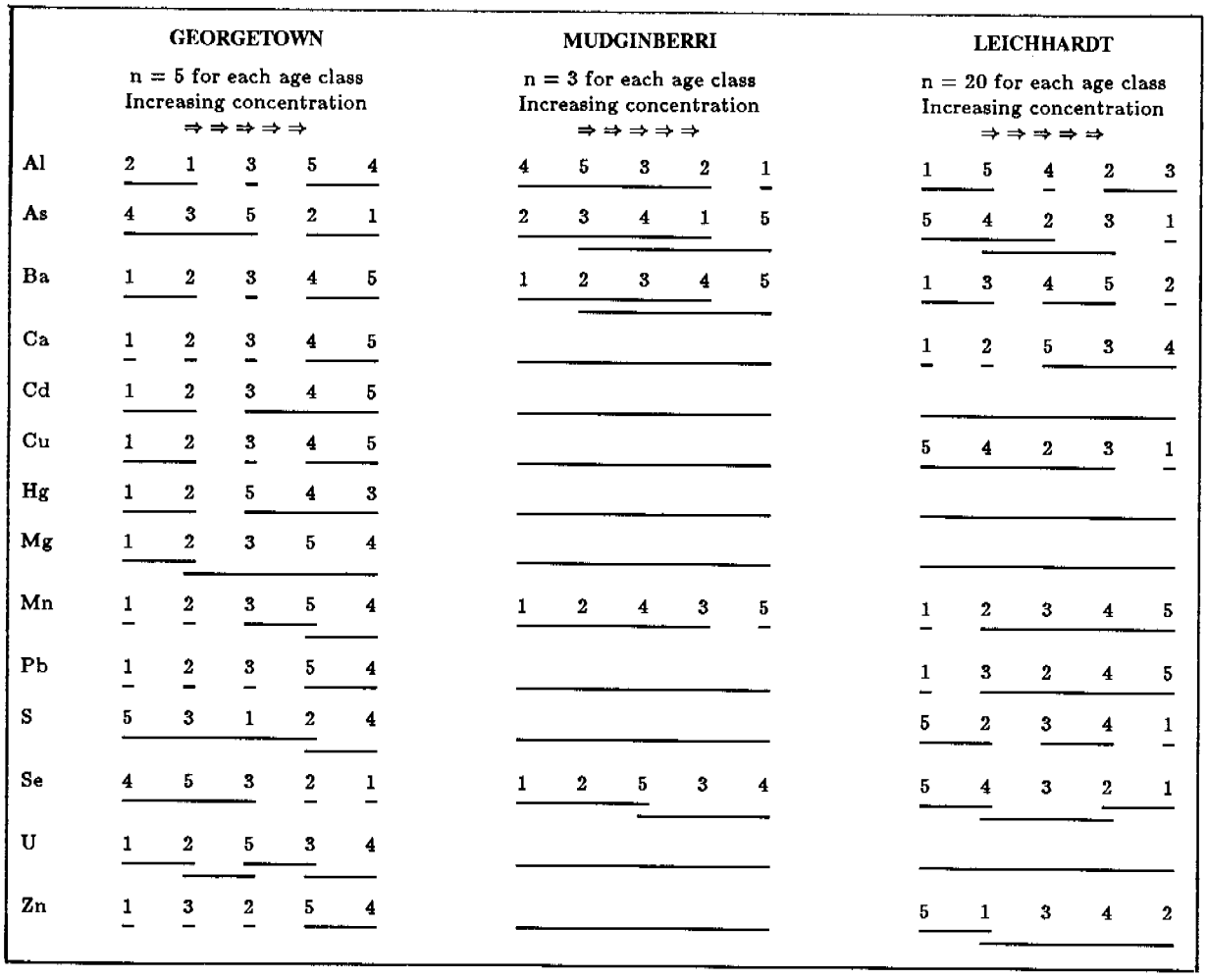


Figure 11. A ranked representation using LSD ($P < 0.05$) of elements with age in the soft parts of mussels (males and females) from Georgetown, Mudginberri and Leichhardt billabongs, March 1980
Age classes: 1, < 1 year; 2, 1-2 years; 3, 2.1-3.9 years; 4, 4-6.9 years.

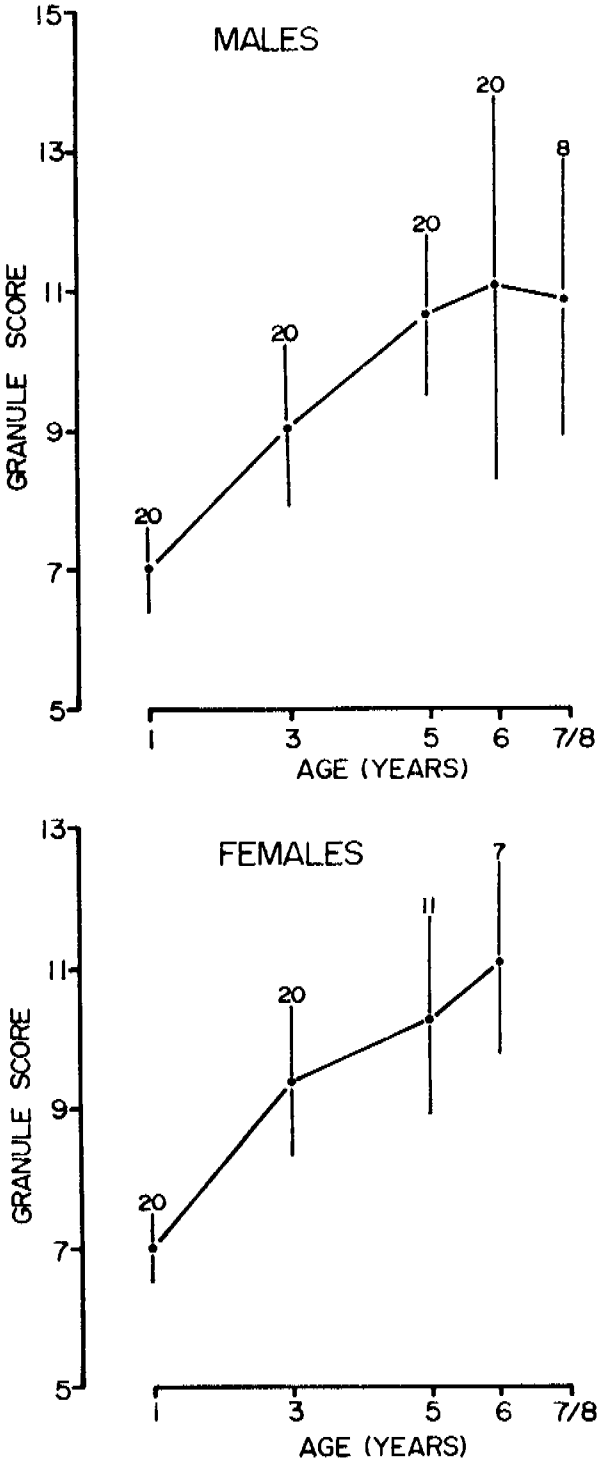


Figure 12. Mean ± 95% C.L. of the granule score for the whole body versus age in male and female mussels from Leichhardt Billabong

The samples sizes used to calculate the 95% CL were:

	Females	Males
Georgetown	44	53
Mudginberri	118	132
Leichhardt	99	132

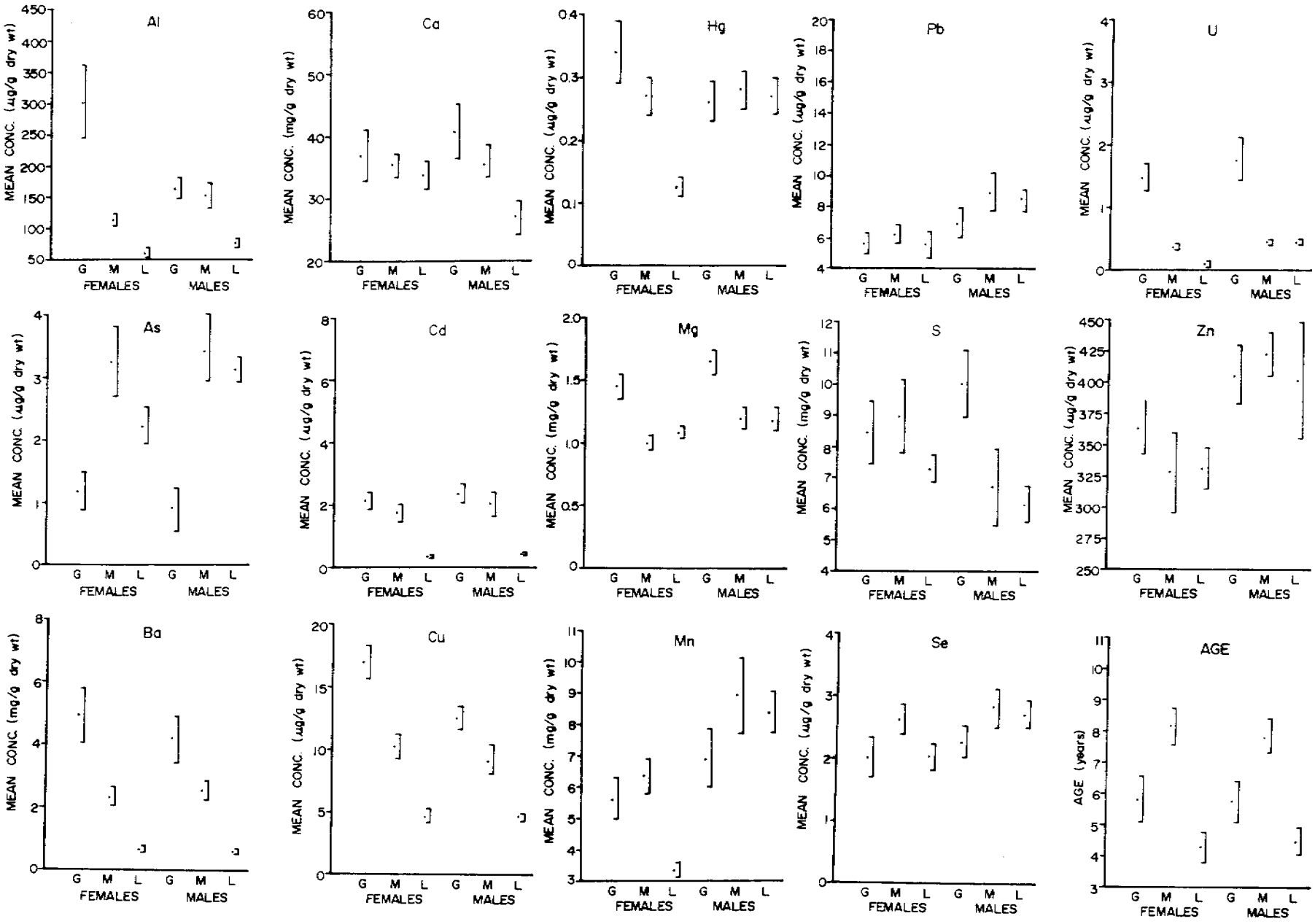
Males and females in Georgetown, Mudginberri and Leichhardt were used to test for differences in element concentrations between the sexes. A summary of the F-ratio test is shown in Table A15.

Concentrations of elements in the soft parts of mussels in relation to sex and age

Figures A3-A16 show the concentrations of 14 elements in the soft parts of male and female mussels from Georgetown, Mudginberri and Leichhardt plotted against age; Tables A17-A19 show the regression equations, r^2 and levels of significance of element concentrations with age. Table A20 gives a summary for the levels of significance and sign of the slopes of the regression equations of the concentrations of the elements shown in the above three tables. The significant differences between the mean concentrations in the soft parts of male and female mussels in five age classes from Georgetown, Mudginberri and Leichhardt are shown in Table A21.

Concentrations of elements in the soft parts of mussels in relation to the reproductive cycle of females

The female mussels collected from Georgetown, Mudginberri and Leichhardt in March 1980 were classified according to stage of maturity of the eggs and embryos. Females at three of the most distinctly separate stages were chosen (out of the six stages recognised in the accompanying biological studies): stage 2 - eggs in the gonads only; stage 3 - embryos in the gills, eggs also present in the gonads; stage 5 - glochidia present in the gills, eggs also present in the gonads. The mean concentration of each element for each stage of maturity is shown in Tables A22-A24 for Georgetown, Mudginberri and Leichhardt respectively and as bar graphs in Fig. 14.


Al
MEAN CONC. (µg/g dry wt)
450
400
350
300
250
200
150
100
50
G M L G M L
FEMALES MALES
Ca
MEAN CONC. (mg/g dry wt)
60
50
40
30
20
G M L G M L
FEMALES MALES
Hg
MEAN CONC. (µg/g dry wt)
0.4
0.3
0.2
0.1
0
G M L G M L
FEMALES MALES
Pb
MEAN CONC. (µg/g dry wt)
20
18
16
14
12
10
8
6
4
G M L G M L
FEMALES MALES
U
MEAN CONC. (µg/g dry wt)
4
3
2
1
0
G M L G M L
FEMALES MALES
As
MEAN CONC. (µg/g dry wt)
4
3
2
1
0
G M L G M L
FEMALES MALES
Cd
MEAN CONC. (µg/g dry wt)
8
6
4
2
0
G M L G M L
FEMALES MALES
Mg
MEAN CONC. (mg/g dry wt)
2.0
1.5
1.0
0.5
0
G M L G M L
FEMALES MALES
S
MEAN CONC. (mg/g dry wt)
12
11
10
9
8
7
6
5
4
G M L G M L
FEMALES MALES
Zn
MEAN CONC. (µg/g dry wt)
450
425
400
375
350
325
300
275
250
G M L G M L
FEMALES MALES
Ba
MEAN CONC. (mg/g dry wt)
8
6
4
2
0
G M L G M L
FEMALES MALES
Cu
MEAN CONC. (µg/g dry wt)
20
15
10
5
0
G M L G M L
FEMALES MALES
Mn
MEAN CONC. (mg/g dry wt)
11
10
9
8
7
6
5
4
3
G M L G M L
FEMALES MALES
Se
MEAN CONC. (µg/g dry wt)
4
3
2
1
0
G M L G M L
FEMALES MALES
AGE
AGE (years)
11
10
9
8
7
6
5
4
3
G M L G M L
FEMALES MALES

Concentrations of elements in the individual organs of mussels from Mudginberri Billabong (March 1980)

Mantle, gills and palps, visceral mass, adductor muscles, heart and kidney from 20 male and female mussels collected in March 1980 from Mudginberri were analysed for the 14 elements. The very small organs (heart, kidney and adductor muscles) were grouped (according to organ type) into two samples, one each for males and females. The larger organs (mantle, gills and palps and visceral mass) were divided into five groups of four mussels. The results are shown in Fig. 15. (The means, SD, CV and 95% CL for these figures are given in Tables A25-A28.) The mean dry weights (for mantles, gills and palps, and visceral mass) ± 95% CL, variance (s^2) and F-ratio significance are shown in Table A29.

3.2 Comparison of element concentrations in non-purged and purged mussels

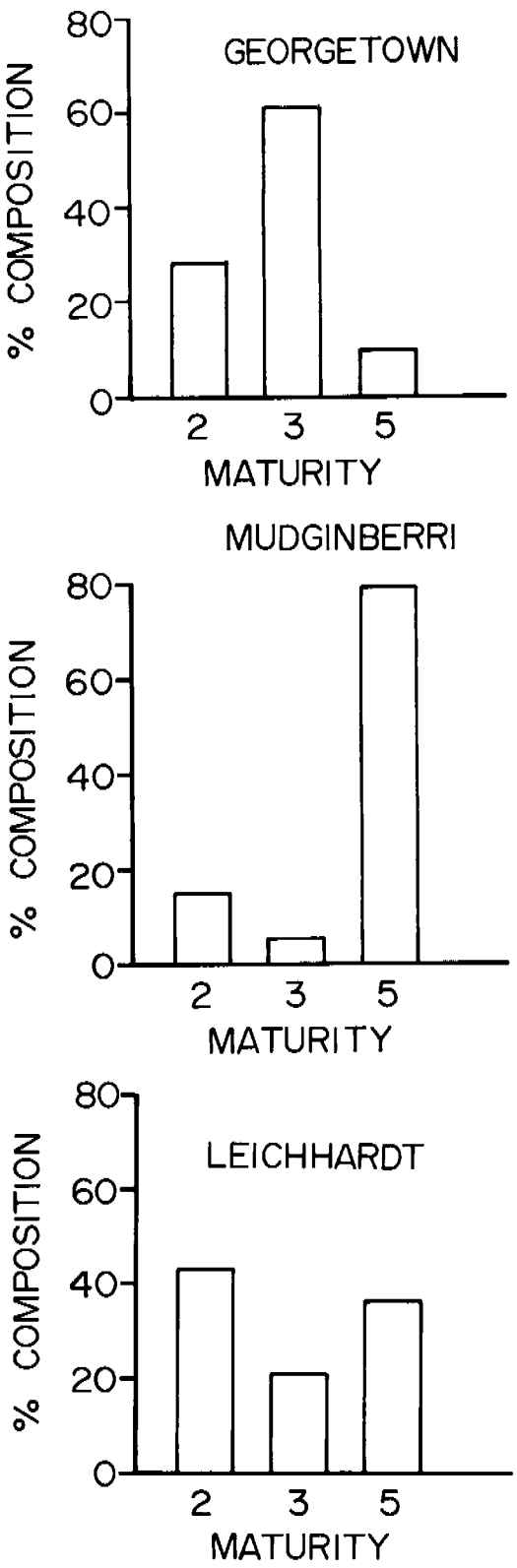
The mean concentration, SD, CV and 95% CL in the soft parts of non-purged and purged mussels from Mudginberri are shown in Tables A30 & A31 respectively. Concentrations of elements in mussels from the long-term uptake study in Retention Pond Nos 2 and 4 were also used in a similar comparison (Tables A32-A35). The results of a significance ratio test of the element concentrations in the soft parts of purged and non-purged mussels from Mudginberri and Retention Pond Nos 2 and 4 are shown in Table A36.

3.3 Comparison of the element concentrations in mussels collected from a sandy and a detrital substrate in Mudginberri Billabong (February 1982)

The means, SD, CV and 95% CL for age and concentrations of elements in the soft parts of mussels collected from sandy and detrital substrates are shown in Tables A37 & A38 respectively.

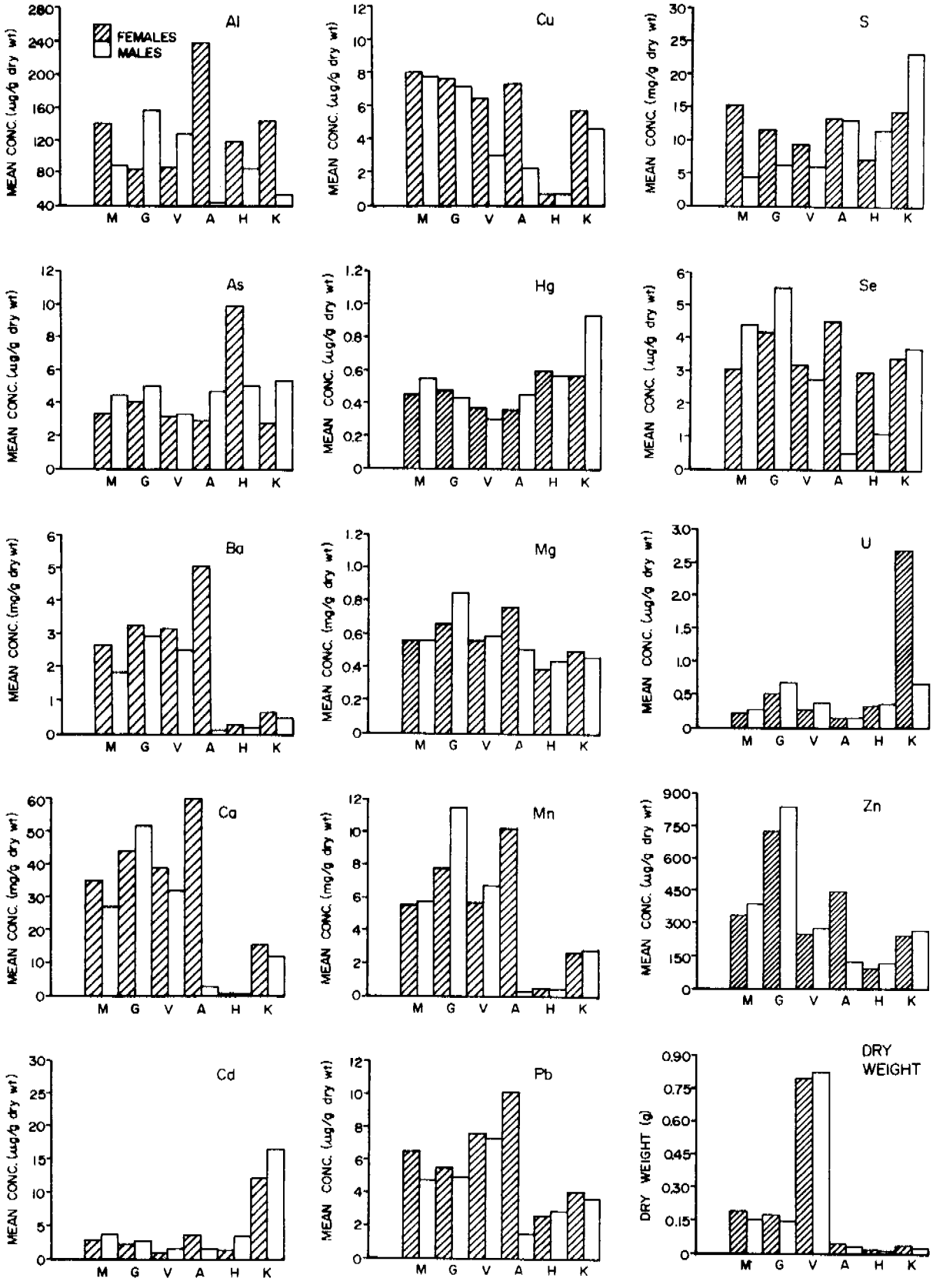
Figure 13. *(Opposite)*. The mean ± 95% CL of the concentration of the fourteen elements in mussels for Gulungul, Mudginberri and Leichhardt billabongs

The mean (± 95% CL) age of the mussels is also shown.



2 - Eggs in gonads
3 - Embryos in the gills
5 - Glochidia in the gills

Figure 14. Bar graphs showing the percentage composition of maturity stages for the reproductive cycle of females from Georgetown, Mudgingerri and Leichhardt (March 1981)


FEMALES
MALES
Al
Cu
S
As
Hg
Se
Ba
Mg
U
Ca
Mn
Zn
Cd
Pb
DRY WEIGHT
MEAN CONC. (µg/g dry wt)
MEAN CONC. (mg/g dry wt)
DRY WEIGHT (g)
M G V A H K

3.4 Studies related to Aboriginal activities

Comparisons of concentrations of elements in the soft parts of uncooked and cooked mussels from Mudginberri Billabong (August 1981)

The results of element concentrations in the soft parts of uncooked and cooked mussels are shown in Tables A39 and A40 respectively. The tables show the mean, standard deviation, CV and the 95% CL for age and concentrations of all 14 elements.

Estimation of the consumption of mussels by the local Aboriginals

The frequency of mussel shells (in ten length classes, ranging from 31 mm to 80 mm) disposed of by Aboriginals over the two years 1980 and 1981 from Corndorl, Mudginberri, Gundur, Mudginberri Crossing, Georgetown and Magela Creek between Mudginberri and Gulungul are shown in Fig. 16. The total numbers of mussels collected at these locations in the two years are shown separately in Table A41.

In 1981 no shells were found around Corndorl. In comparison, 7610 mussels were found around Gundur, a small billabong approximately 500 metres downstream from Corndorl. The shell morphologies of the mussels from these two billabongs are quite distinct, and this was used to substantiate that the mussels were not taken from one billabong and cooked and eaten at the other site.

In 1981 most of the shells were found on the sand-bank at the southern end of Mudginberri whereas in the previous year no mussel shells were found there but were located along the eastern bank.

The numbers of Aboriginals based at Mudginberri include 16 adults and 28 children in 11 family units (information supplied by the Department of Aboriginal Affairs). This information, together with data from the collection of discarded shells, was used to estimate the numbers of mussels and weight of mussel soft parts consumed per person per year (Table A42). From this the yearly intake of elements was estimated (Table A43). Three main assumptions have been made in these calculations:

1. The mussel shells collected represent the total intake of mussel soft parts. This may be untrue as some mussels may be returned to the Aboriginals' camp to be eaten. Such shells could not be collected and no attempt has been made to estimate their numbers.

2. All Aboriginals eat mussels. However, some have a particular liking or disliking for mussels.

3. One child consumes half as much as one adult.

To put the concentration of elements in the mussels into perspective, Table A43 also includes the weights of some elements found in one average mineral supplement tablet. Table A44 shows the National Health and Medical Research Council standards for the maximum permitted concentrations of some of the elements in food.

Figure 15. *(Opposite).* Bar graphs showing the concentrations of the fourteen elements in the mantle (M), gills and palps (G), visceral mass (V), adductor muscles (A), heart (H) and kidney (K) of mussels from Mudginberri Billabong (March 1980)

The dry weight of the various organs is also shown.

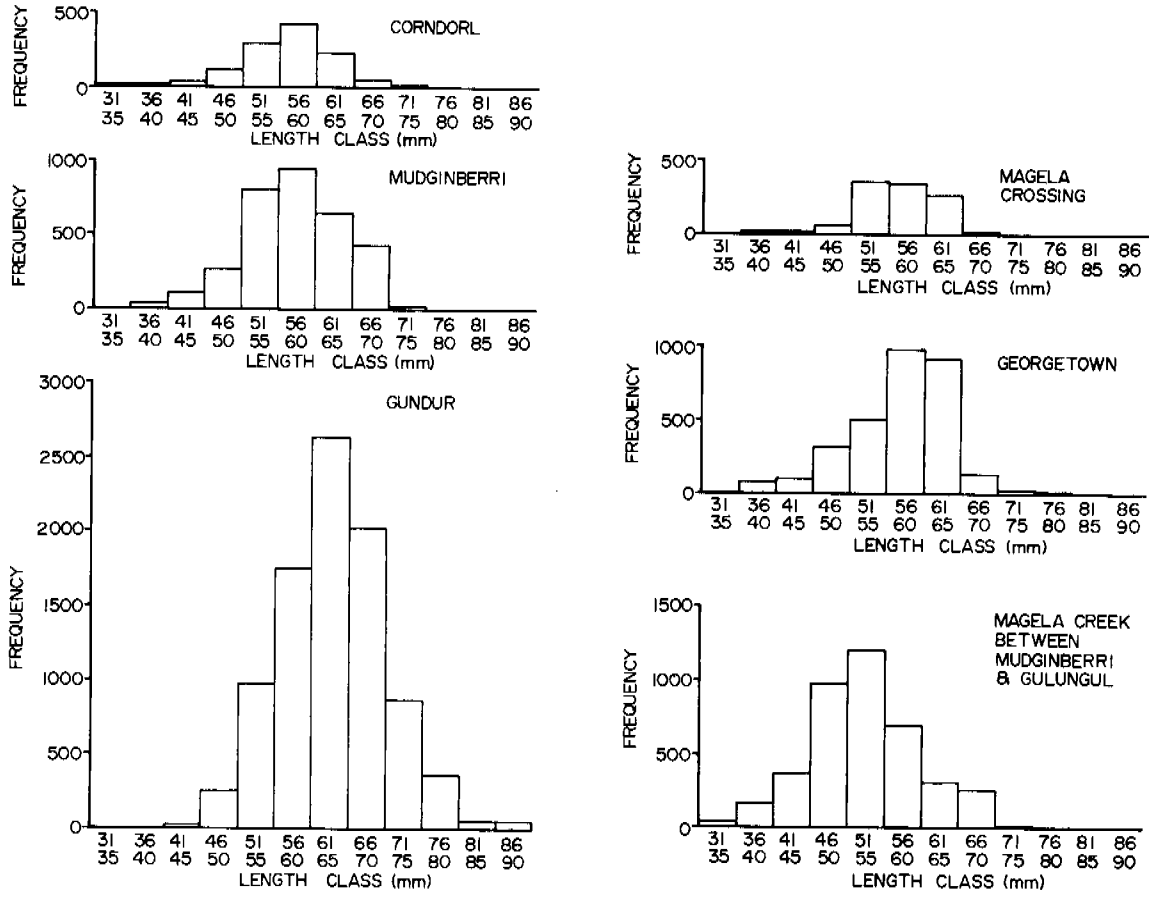


Figure 16. The frequency of mussel lenghts collected from middens around Corndorl, Mudginberri, Gundur, Magela Crossing, Georgetown and Magela Creek between Mudginberri and Gulungul during the 1980 and 1981 Dry seasons

3.5 Baseline concentrations

Magela Creek

The results of the baseline study are presented as a series of figures (Figs A17-A30). Twelve locations were sampled and are shown in two sets of six locations for each of the 14 elements determined. The locations are displayed from the most upstream escarpment billabong, Bowerbird, to the most downstream floodplain billabong, Nankeen. Each cross represents the determination of the concentration of an element in one sample, the means of which are connected by a solid line. The dashed line joins the mean load per mussel of the element on each sampling occasion. The mean load represents the absolute amount of the element for the mean weight of the mussels on each sampling occasion (load = concentration × mean weight). Comparisons of the load may be made only among sampling occasions when the standard length mussels (61-65 mm) were analysed. However, it was not always possible to select from the size range of 61-65 mm in Bowerbird, Island, Ja Ja North Extension (NE), Leichhardt and Jabiluka (see Table A48). The mussels from Bowerbird were of a smaller size and those from Island, Ja Ja (NE), Leichhardt and Jabiluka on some occasions were of a larger size (Table A48). In the latter four billabongs the mussels which were collected throughout the two years varied in size although every effort was made to collect the 'standard mussel'. However, because numbers in 61-65 mm size range were low, the time taken to collect mussels in these four billabongs was greater than the time taken in others. The mean concentrations of elements in the soft parts of the mussels per billabong

over the total study are shown in Table A45. All concentrations are on a dry weight basis unless stated otherwise. The way in which the dry weight of the soft parts varies with the seasons is shown for mussels from Georgetown, Mudginberri and Nankeen in Fig. A31.

Table A46 shows the mean concentrations of Ca, Cd, Cu, Mg, Mn, Pb, S, U and Zn and the pH and turbidity in the water of Bowerbird, Georgetown, Goanna, Gulungul, Corndorl, Mudginberri, Island, Ja Ja (NE), Jabiluka and Nankeen during the period November 1978 to August 1982.

The analyses on the soft parts of the mussels for the baseline concentrations were undertaken by two analytical companies, AMDEL and SGS, the former undertaking those samples collected from March-October 1980. Analyses of variance on 11 elements determined in two sets of five samples are shown in Table A9 in which only U was found to be not significantly different ($P > 0.05$) between the two companies (Table A10).

The dates on which billabongs were sampled and on which the water first entered at the commencement of the Wet seasons of 1980-1981 and 1981-1982 are shown in Table A27 to look at cause and effect relationships. When trying to assess the results of the baseline study over a two-year period, the influence of the seasons on the mussels' biology must be investigated and taken into account when discussing any trends in the concentrations and loads of the elements in the in the soft parts of the mussels. Times of particular significance are the commencement of the Wet season and the flushing of the system with fresh water (Table A47). This is further discussed in the report on the biology and ecology of the mussels (Humphrey & Simpson in press).

An intensive study was made of the variability of results of analyses by SGS and of the implications of interpreting those results in the light of the large variability in those results (Allison & Simpson 1983). Such a comprehensive study was not made on the precision of AMDEL because it was not realised at the beginning of the study that there was a need for such stringent checks. However, there are some results showing the determinations by AMDEL when sent NBS SRMs (unidentified as such) as a check for contamination from equipment used to homogenise the samples (Table A2). From the results based on the 'not homogenised' material only, to avoid confounding the effects of homogenisation, the accuracy of the determinations of As, Ca, Cd, Cr, Cu, Hg, Mg, Pb, S, Se and Zn were calculated (Table A8). Of 19 determinations only 5 had an accuracy of under 20 per cent.

The results of the concentrations of Al in samples collected between April and October 1980 were very high in comparison with the results after these dates. The y-axis scales of the concentration on Fig. A17 have been set to give more effect to the results with lower concentrations between December 1980 and February 1982. The determinations in the former time period were made by AMDEL and the latter by SGS. The determinations of Al in samples collected in March 1980 from Georgetown, Leichhardt and Nankeen were analysed by SGS. The actual values for the mean concentrations which are greater than the maximum value on the graphs are printed above each figure.

The following locations were not sampled continuously for various reasons:

Bowerbird - mussels were first discovered to be in the creek above and below Bowerbird in November 1980, after which access was only possible from June 1981 in the Dry season. The mussels collected in November 1980 and June 1981 were from the creek downstream and in August 1981 upstream of the billabong. The mussels collected from upstream of Bowerbird had a lower dry weight per unit length than those downstream because those downstream fed on the algae carried downstream from the billabong.

Gulungul - only low numbers of mussels are present in this billabong and mussels were first found here in October 1981.

Goanna - this billabong had very few mussels. As a result, collection from here was discontinued but a final sample was taken in January 1982 for comparative purposes.

Gundur - this small billabong became important as a site for mussel collection by Aboriginals from Mudginberri in the Dry season of 1981. A sample was taken in December 1982 at the very end of the Dry season, before the first flush entered it.

Island - collection from this billabong started in December 1980.

Ja Ja (NE) - sampling from this billabong commenced in April 1981 to compensate for the cessation of sampling in Jabiluka (see below).

Jabiluka - mussels were low in numbers, necessitating the searching of extensive areas to find the required number of mussels of any length. Therefore, collection from this 'high risk' crocodile populated billabong was stopped after April 1981, with Ja Ja (NE) replacing it because of the higher density of mussels.

Nouglangie Creek, Cooper Creek and Jim Jim Creek

The dates of sampling and flow events in Nourlangie and Cooper creeks during the 1980-81 and 1981-82 early Wet seasons are shown in Table A50. The results for the element concentrations in the soft parts of mussels in Long Harry's Billabong on Nourlangie Creek and in Gunirdul on Cooper Creek are shown in Figs A32-A36 for the 14 elements determined during 1980 and 1981. The mean concentrations of elements are given in Table A51. On one occasion mussels were collected from a billabong on Cooper Creek by the Murganella road crossing (Murganella Billabong) and the element concentrations in the soft parts are shown in Table A51.

The results for element concentrations in the soft parts of mussels collected in the escarpment reaches of Jim Jim Creek above Graveside Billabong are shown in Table A52. For comparative purposes the concentrations of elements in the soft parts of mussels from the escarpment reaches of Magela Creek above Bowerbird are shown in Table A53.

3.6 Transplants between billabongs

Mussels were transplanted from Georgetown to Mudginberri and vice versa, and from Nankeen to Mudginberri and vice versa in March 1980. The results for the concentrations of the 14 elements in the mussel soft parts are shown in Figs A37-A50. During the course of the experiment a number of cages with mussels disappeared or were washed away in the Wet season of 1980-1981. As a result the mussels were sampled monthly for the first six months followed by intermittent sampling, which was determined by the number of mussels remaining.

3.7 Uptake and loss studies

Retention ponds

Short-term uptake and loss. The results for the short-term uptake and loss are shown in Figs A51-A106. These results were grouped by age: < 1 year, 1 to 2.9 years, 3 to 5.9 years and ≥ 6 years. Each figure shows the concentrations of one of the elements determined in the soft parts of mussels from Retention Pond Nos 1, 2 and 4. The individual determinations are shown by the symbols, the solid lines join the mean of each set of determinations and the dashed line shows the mean load of the element per mussel. The set numbers refer to the number of occasions on which samples were taken (see Table A54). This table also shows that the first flow of the creek in the 1981-1982 Wet season entered Mudginberri on

27 November 1981 (between set numbers 18 and 19 for age class 1 and between set numbers 19 and 20 for age classes 2 to 4).

Table A57 shows the concentrations of Cu, Pb, Mn, Zn and U in water in Mudginberri before mussels were collected and when the mussels were replaced into Mudginberri, and also shows the concentrations of those elements in Retention Pond Nos 2 and 4 during the course of the experiment. The concentrations of Mg, Ca and SO_4, and the pH and turbidity for the same locations and time periods are shown in Table A56. The determinations of the elements in the OSS mussel reference material (wet) analysed at the same time as experimental samples in set numbers 2, 8, 12, 16 and 18 are shown in Table A57. These have been included to compare the trends in the concentrations of the reference materials with the trends in the experimental samples. The regression equations and the r^2 values for the uptake and loss of U from mussels in age classes 1, 2, 3 and 4 placed in Retention Pond Nos 2 and 4 are shown in Table A58.

The mean maturity scores for the reproductive cycle of females placed in Retention Pond Nos 1, 2 and 4 are shown in bar graphs in Fig. 17. Figures 18 and 19 are photographs of the cages of mussels after four weeks duration in Retention Pond Nos 2 and 4 respectively.

Long-term uptake and loss study. The results of element concentrations in the soft parts of mussels during the long-term uptake and loss study are shown in Figs A107-A120. The batch numbers show the way in which samples were grouped for analysis by SGS and are shown below each diagram. These show how element concentrations were related to the batch in which they were analysed rather than related to any possible biological or ecological cause. The batches without numbers for the elements Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn determined in the soft parts of mussels from Retention Pond No. 4 were analysed by OSS. The mean load per mussel is the product of the mean dry weight per mussel and the concentration. The mean maturity scores for the reproductive cycle of females placed in Retention Pond Nos 2 and 4 placed in Retention Pond Nos 2 and 4 during the long-term uptake study and then returned to Mudginberri are shown in Fig. 20.

The concentrations of Cu, Pb, Mn, Zn, U, Mg, Ca and S and the pH and turbidity in the water of Mudginberri and Retention Pond Nos 2 and 4 during the long-term uptake study are shown in Tables A59-A61 respectively.

The samples in this study were analysed by three laboratories: AMDEL, SGS and OSS. All the samples taken on Day 0 were analysed by AMDEL. The samples taken from Day 14 to Day 289 from

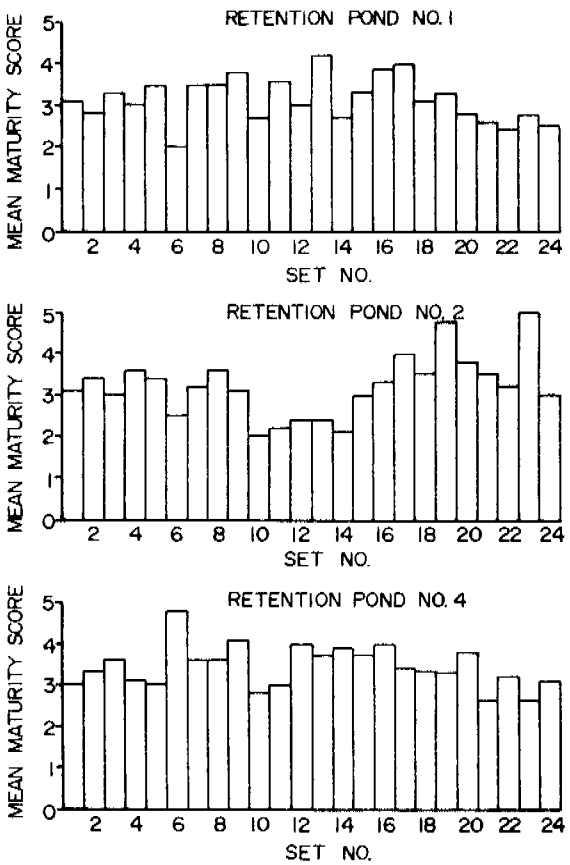


Figure 17. Mean maturity scores for the reproductive cycle of females placed in the Retention Ponds then returned to Mudginberri Billabong

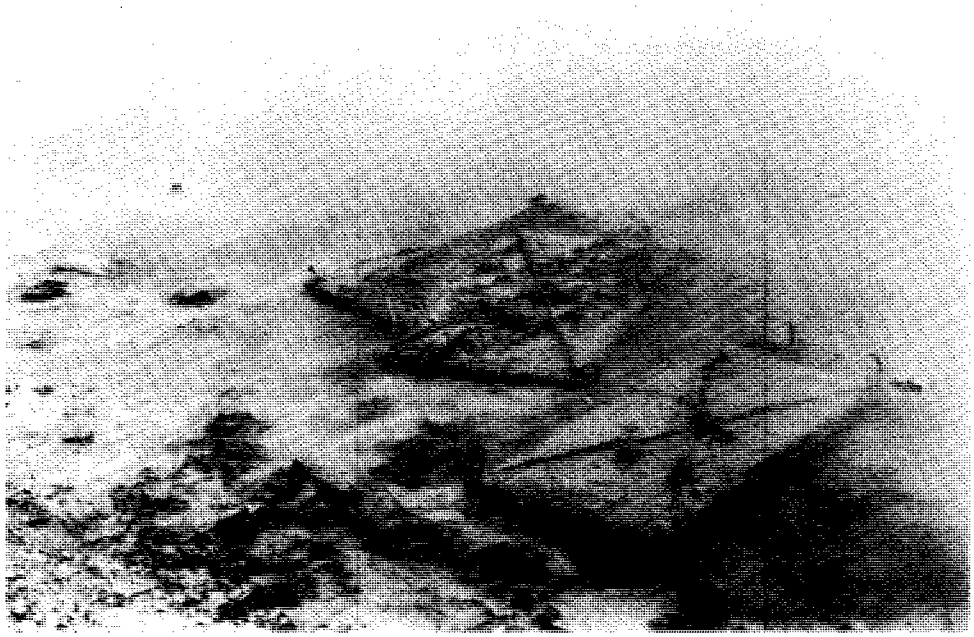


Figure 18. Mussel cages in Retention Pond 2 after four weeks during the short-term uptake study

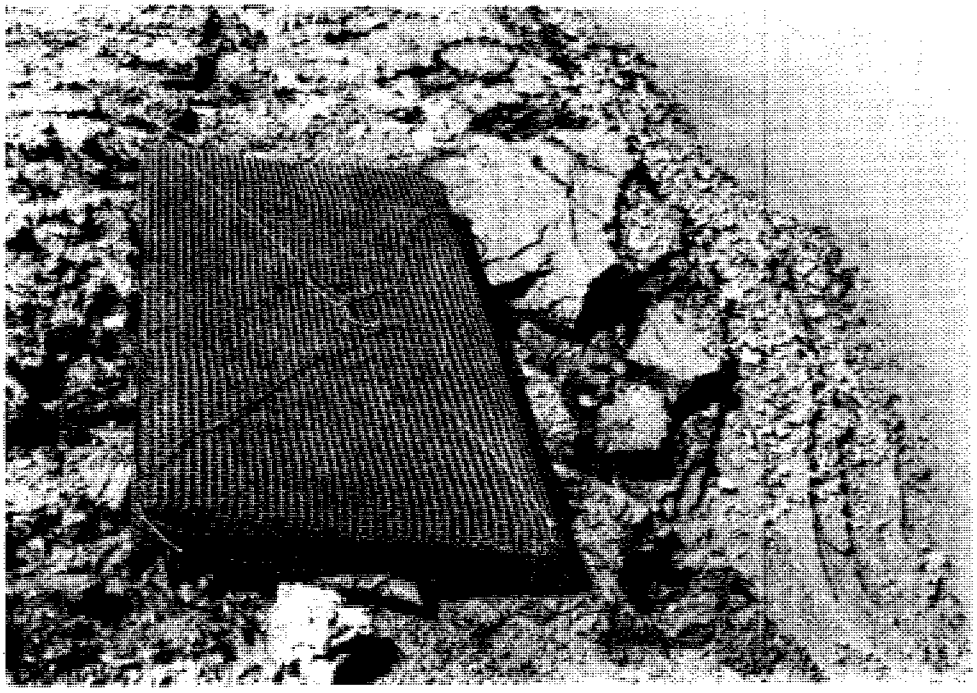
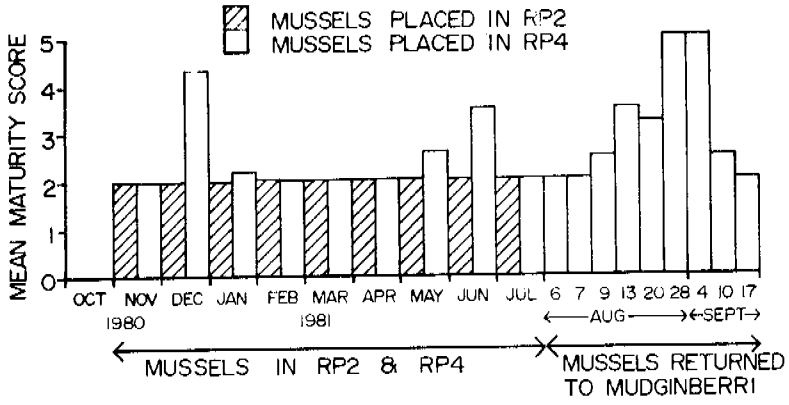


Figure 19. A mussel cage in Retention Pond 4 after four weeks during the short-term uptake study



Maturity scale: 2 - eggs in gonads; 3 - embryos in gills; 5 - glochidia in gills

Figure 20. Mean maturity scores for the reproductive cycle of females placed in retention ponds 2 and 4 then returned to Mudginberri Billabong

Retention Pond No. 2 were analysed by SGS. The samples taken from Day 14 to Day 226 from Retention Pond No. 4 were analysed by SGS for Al, As, Hg, S, Se and U and by OSS for Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn. Therefore, observed changes in element concentrations may be attributed to inter-laboratory variation. A summary of analyses of variance between SGS and AMDEL on the above samples is given in section 2.7.

Regression equations were calculated for U, Mg and Mn (Table A62) because there appeared to be uptake (U) and loss (Mg and Mn) during the period of exposure to the retention pond water. A comparison of the concentrations of U in mussels and in the water of Retention Pond Nos 2 and 4 is shown in Table A63. The mean dry weights per mussel during the course of the long-term uptake in Retention Pond Nos 2 and 4 are shown in Fig. 21.

Enclosure studies

Gulungul Billabong. The mean concentrations of eight of the 14 elements in the soft parts of mussels, and the ages and reproductive stages of females in four regimes are recorded in Fig. 22; the mean concentrations in the soft parts of the mussels, SD, CV, and 95% CL are given in Tables A64-A67. A ranked representation, using LSD, of the elements with treatments for mussels in the enclosures is shown in

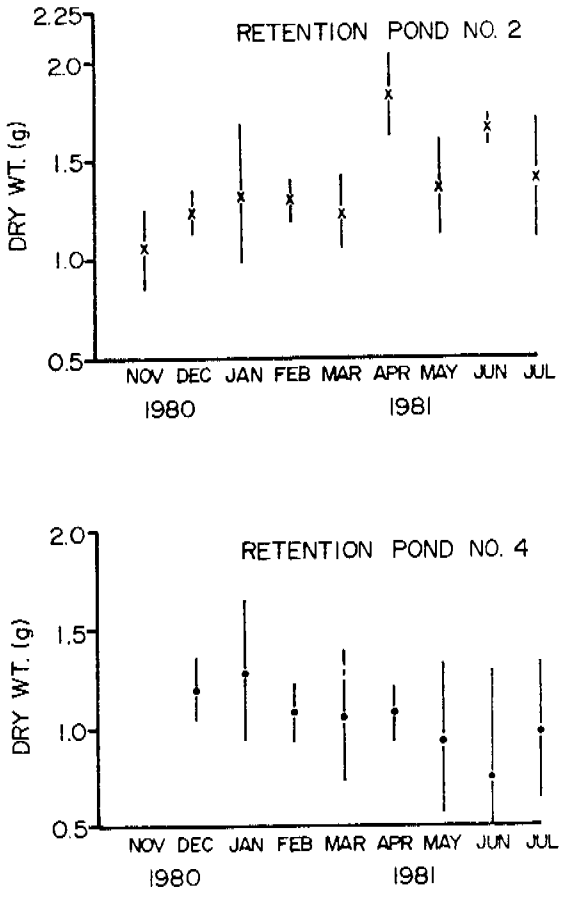
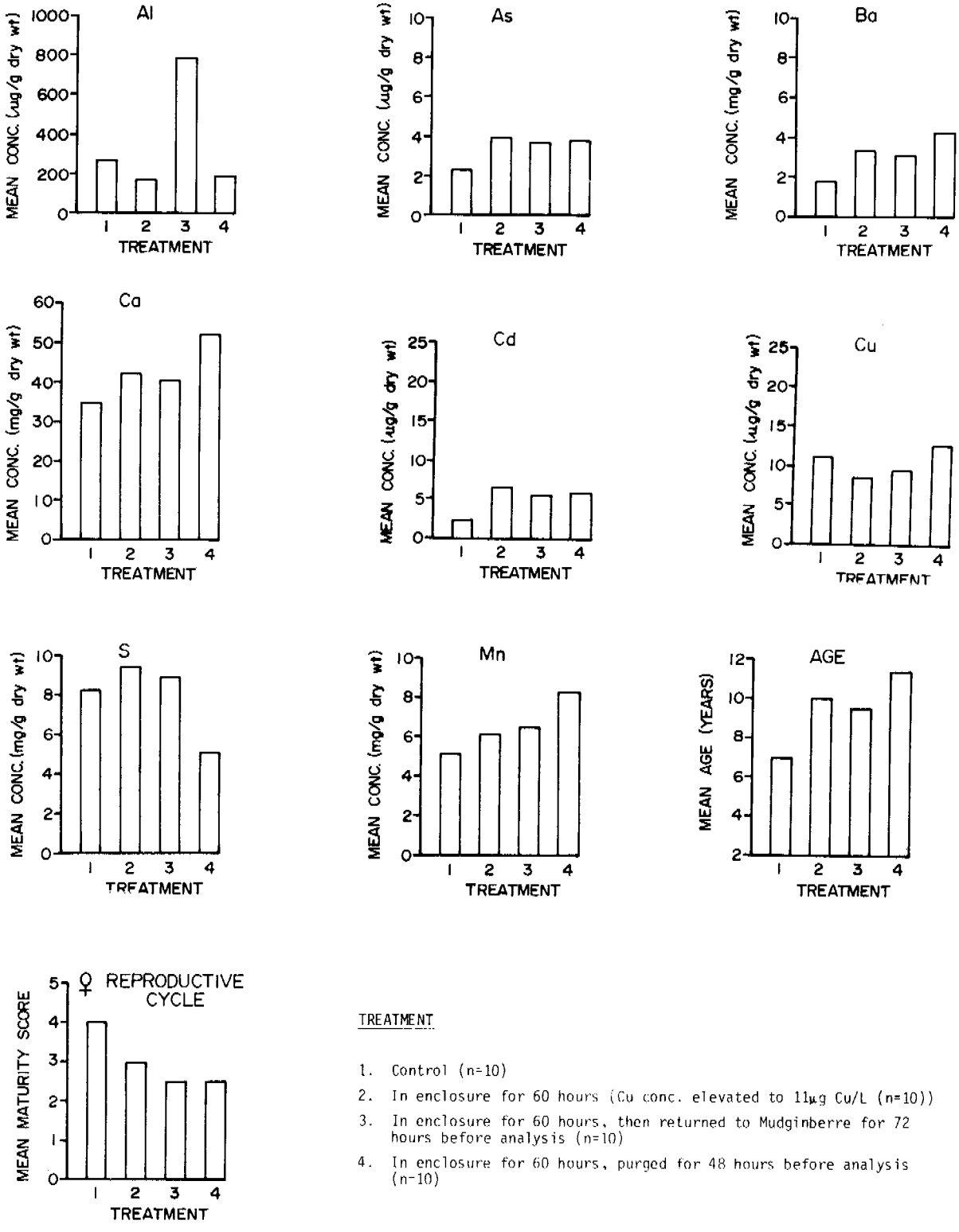


Figure 21. Mean dry weight (± 95% CL) of mussels during the uptake period in Retention ponds 2 and 4



TREATMENT

1. Control (n=10)
2. In enclosure for 60 hours (Cu conc. elevated to 11µg Cu/L (n=10))
3. In enclosure for 60 hours, then returned to Mudginberre for 72 hours before analysis (n=10)
4. In enclosure for 60 hours, purged for 48 hours before analysis (n=10)

Figure 22. Mean concentrations (dry wt) of aluminium, arsenic, barium, calcium, cadmium, copper, manganese and sulphur in mussels in the Gulungul uptake study
The mean age of the mussels and the mean maturity score for the reproductive cycle of females are also shown

Fig. 23. The total Cu concentrations in surface water, macrophyte and epiphyte samples taken from the enclosure during the experiment are shown in Fig. A121 and the Cu concentrations (total and filtered) in the surface and bottom water, macrophyte and epiphyte samples taken from the enclosure are recorded in Table A68. As the bottom sample was taken at 50 cm depth this does not represent the water layer which the mussels would be filtering.

Island Billabong. The concentrations of Zn, Mn, Cu, Cd, Ca, Mg, Pb, S and U in mussels in five treatments in the Island Billabong enclosure study are shown in Fig. A122; the age, mean dry weight and lengths of mussels are also shown. Tables A69-A74 show the mean concentrations, SD, CV and 95% CL of the elements in the soft parts of the mussels in each of the treatments. The length of the dead mussel found floating in the Cu enclosure after 11 days was 74 mm, a length greater than those selected for the study, therefore the mussel must have been in place when the enclosure was installed and was not one of the mussels transplanted (in cages) into the enclosure.

	Highest concentration		Lowest concentration	
Al	3	1	4	2
As	4	3	2	1
Ba	4	3	2	1
Ca	4	3	2	1
Cd	4	2	3	1
Cu	1	4	3	2
Hg	2	3	4	1
Mg	3	4	1	2
Mn	4	3	2	1
Pb	4	1	2	3
S	1	3	2	4
Se	3	4	1	2
U	4	2	3	1
Zn	4	3	1	2

1: Control (n = 10)
2: In enclosure for 60 h; initial Cu concentration elevated to 11 µg/L (n = 10)
3: In enclosure for 60 h then returned to Mudginberri for 72 h before analysis (n = 10)
4: In enclosure for 60 h, purged for 48 h in 1 µm filtered water before analysis (n = 10)

Figure 23. A ranked representation using LSD ($P < 0.05$) of elements with treatments for mussels placed in the enclosure in Gulungul Billabong

A ranked representation using LSD of the elements in the soft parts of the mussels placed in the enclosures in this study is shown in Fig. A123. The variations in the Cu, Mn and Zn fractions (ion-exchangeable, non-ion-exchangeable and particulate) in the water over the study period are shown in Fig. A124. In all cases the trace metal concentrations in the water decreased with time.

3.8 Leichhardt Billabong mussel kill

The concentrations of elements in the soft parts, dry weights and the lengths of mussels found floating on the surface of Leichhardt on the 8 January 1982 are shown in Table A75. Similar information is shown for the baseline mussel samples taken the previous month and the following month.

3.9 Finniss River study

The mean concentrations for the elements in the soft parts, the shell lengths, the wet weights and the wet weight/dry weight ratios for male and female mussels from locations 1 to 5 are shown by bar graphs in Figs A125-A127. Tables A76-A80 show, in addition, the CV and the 95% confidence limits for each of the above values.

Because the variances were found to be linearly dependent on the concentrations of all elements, logarithmic transformations ($\ln(x+1)$) were made to the data, (x+1) being used as many values were less than one. The following analyses of variance were applied:

1. each site using two groups of 15 mussels to measure the variance of each sample. For location 4, two groups of 12 mussels were used;
2. all five locations together;
3. both 'clean' locations (4 and 5) together;
4. all 'polluted' locations (1, 2 and 3) together; and
5. 'clean' vs 'polluted' locations, calculated by difference between the components of variance from (3) and (4).

A summary of the results of the analyses is shown in Table A81. Figure A128 shows a comparison among sites using the method of the least significant difference ($P < 0.05$). Discriminant analysis was also applied to the data from the five locations in order to identify groupings based on the concentrations of elements in the soft parts of the mussels. This was done because: (a) significant differences had been found in the analyses of variance and LSD; and (b) location in relation to the mines allowed identification of possible clean and polluted sites.

4 DISCUSSION

4.1 Comparison of concentrations of elements in the soft parts of mussels from Georgetown, Mudginberri and Leichhardt billabongs (March 1980)

Statistically significant sample sizes. The project did not have analytical facilities at hand at the beginning of the study. There was no option other than to commence the baseline sampling program before knowledge of element concentrations in the soft parts of the mussels was available. Subsequent delays in the receipt of results and changes to alternative analytical facilities accentuated the problem. For the baseline investigation, a sample of 20 mussels (later divided into five groups of four mussels of one sex) was chosen as suitable when balanced against sampling effort, mussel availability (in all locations) and cost of analyses (also see section 2.1). The following gives an evaluation of subsequent checks on this sampling strategy.

The variance of the concentrations of elements was dissimilar among sites and between sexes (see Section 2.1). Similar findings in *Mytilus californianus* by Gordon et al. (1980) caused these authors to suggest that the mean and the variance of each metal of interest should be calculated for each population studied. Seven-year-old mussels were used here to estimate the population mean and variance of element concentrations when determined by SGS. Once such estimates were obtained from a number of analyses, they were used to determine the future sampling strategy, i.e. the number of samples required to produce the lowest possible variance with respect to economy of analytical effort.

Figures A1 and A2 show how the sample size required to show a particular per cent difference between element concentrations in the soft parts varied between males and females and amongst the billabongs Georgetown, Mudginberri and Leichhardt. These graphs are based on the variation found in one age class (seven-year-old). Greater variation, shown by one sex, was dependent on the element and such instances were slightly more numerous for males. This higher variability in males reflected the finding of greater variation in condition of males in the accompanying biological studies (Humphrey & Simpson, in press). As an example of how to apply the findings on selection of sample size, consider the element showing the greatest variance - i.e. Pb in males from Leichhardt (Table A13 and Fig. A2). To detect a 20% difference ($P < 0.05$) between means for Pb a sample size of 80 would have to be analysed, and to detect a 10% difference ($P < 0.05$) a sample size of 300 would be required. For a two-fold increase in resolution there has to be approximately a four-fold increase in sample size. Future investigators must decide what resolution they wish

to detect and sample accordingly. When the mussels are to be used for the analyses of several elements such as in this study, the sample size must be based on the most variable element. Thus in this case of three sites, 80 mussels would have to be sampled to detect a 20% difference between means for Pb concentrations. However, it could be decided to accept a resolution of 25%-30% for Pb and cut down the sample size by half to 40 mussels - which would be a more economical sampling strategy.

To reduce the number of samples to be analysed, Mackay et al. (1975) and Goldberg et al. (1978) suggest that individual mussels may be pooled into a single sample. Once a sampling program has started using pooled samples, the numbers in each pool must remain constant for ease of valid statistical analysis. There are disadvantages to pooling mussels into one sample, one of which is loss of the ability to recognise a change in the variance. For example, in the present study it has been shown that as the concentration increases, the variance increases.

Measurements of the concentrations of elements in the soft parts of individual mussels allows the best estimate of variance; however, the analytical effort and costs are prohibitive in large surveys. In order to reduce the number of analyses and still retain the ability to detect changes in variance, individual mussels may be grouped to form a number of samples, each made up of a set number of mussels. The above estimates of sample size were calculated on material analysed by SGS. Earlier, sample sizes for detection of 10% and 20% differences between means were calculated from determinations by OSS of concentrations for some elements in mussels of 61-65 mm in length, which were of variable age. Table A16 shows the results for these calculations for mussels from Mudginberri. In the females the concentrations of Al, As, Cu, Mn, Pb and U and in males Al, As, Ba, Ca, Cu, Hg, Mn and U were age dependent. Therefore it was expected that results would be more variable when based on mussel length (61-65 mm) than when based on mussels of one age (e.g. seven-year-olds). This was not the case except for Ba, Cd and Pb (in males), however, this is most likely a function of greater variability in the results from SGS (see Allison & Simpson 1983).

A sample size of twenty mussels would appear to be sufficient to detect 20% differences between means and, in some cases, 10% differences - if rigorous analytical procedures are followed as was done by OSS. Some elements may still show high variability (for whatever reason) but it was not considered worth extra sampling effort to increase the sample size in order to attempt to reduce the variability for those elements.

Concentrations of elements in the soft parts of mussels in relation to age

It has been well documented that body size is a variable which can influence soft part metal concentrations in molluscs (Boyden 1977; Phillips 1980; Latouche & Mix 1982). If such significant variations due to size occur, then this factor must be taken into consideration when a sampling strategy is adopted. Most workers have equated increase in body size with increase in age (see review by Phillips 1980). For freshwater mussels, Renzoni & Bacci (1976) equated increases in length with increases in age whereas Jones & Walker (1979) suggested shell volume as a measure of age. However, the relationship between body size and age can be variable, particularly owing to environmental influence - as was found to be the case in *Velesunio angasi* (Humphrey & Simpson, in press). In marine mussels, *Mytilus edulis*, Lobel & Wright (1982 *b,c*) reported that allometric growth ratios gave a better indication of age than some absolute measure of body size. Any extrapolation for age need only be invoked if there is some problem in accurately ageing the animals by more direct means. The accompanying biological studies on *V. angasi* established a reliable ageing method (based on annular growth rings) for this mussel (Humphrey & Simpson, in press).

The patterns of concentration of elements in the soft parts of mussels in relation to age were inconsistent among billabongs. The results suggested that element concentrations were independent of age in mussels from Mudginberri more so than in mussels from Georgetown or Leichhardt, although this may be confounded by the smaller number of samples from this

site. Nine of the fourteen elements in mussels from Mudginberri showed no significant relationship with age. These were Ca, Cd, Cu, Hg, Mg, Pb, Se, U and Zn (Fig. 11). Barium and Mn showed increasing concentrations with age and Al showed decreasing concentration with age. Arsenic and selenium showed differences between some ages with a slight tendency to increase with age (Fig. 11). Different elements showed different trends with respect to concentration versus age within any one billabong. For example, in Georgetown (Fig. 11) the concentrations of the elements Al, Ba, Ca, Cd, Cu, Hg, Mg, Mn, Pb, U and Zn all have a tendency to increase with age. Arsenic concentrations decreased with age contrary to the trend for the concentrations of this element in mussels from Mudginberri. Selenium concentrations also decreased with age; however, S concentrations were independent of age. The mussels from Leichhardt showed an independent relationship with age for the concentrations of the elements Cd, Hg, Mg and U in their soft parts. Age classes 1 and 5 in Leichhardt showed no significant differences in the concentrations of Al and Zn but were significantly different from the other age classes for Al although age class 1 was not significantly different from 2, 3 and 4 for Zn. Those elements which showed a trend of decreasing concentrations with age were As, Cu and Se while Ca, Mn and Pb showed a trend of increasing concentrations with age although only age class 1 was significantly different ($P < 0.05$) from the others for the latter two elements and age classes 1 and 2 for Ca were significantly different ($P < 0.05$) from the others (Fig. 11). The concentrations of Ba and S showed no clear relationships with age, the latter showed significantly ($P < 0.05$) lower concentrations in age classes 2 and 5 and higher in age class 1. Age classes 3 and 4 were significantly different from both of those. Barium showed a significant difference ($P < 0.05$) between age classes 1 and 3, and age class 2.

The concentration of As decreased with age in the soft parts of mussels from Georgetown and Leichhardt but not in the soft parts of mussels from Mudginberri (Fig. 11). In the mussels from Georgetown, Cu increased with age compared with those from Leichhardt in which the trend was to decrease with age. Age class 1 was significantly ($P < 0.05$) lower than age classes 2, 3, 4 and 5. There was an independent relationship with age for Cu in mussels from Mudginberri. These inconsistencies in geographically separate populations are contrary to the results for body size versus concentrations of some metals in the marine bivalves *Ostrea edulis*, *Mytilus edulis* and the limpet *Patella vulgata* by Boyden (1977), who found that comparisons between populations from 'clean' and 'contaminated' environments indicated that regression co-efficients may be constant but with increased intercepts in the metal elevated areas.

Georgetown, Mudginberri and Leichhardt represent the three main billabong types (backflow, channel and floodplain) which by the end of the dry can be distinguished by the nature of their water chemistry (Walker & Tyler 1982). Mudginberri remains consistent in chemical quality throughout the year. For the period November 1978 to August 1981 the mean (± SD) turbidity value in Mudginberri was 8.1 (± 6.8) NTU compared with 260 (± 710) NTU for Georgetown (Table A14). Records for Leichhardt between April 1978 and May 1982 show a mean yearly turbidity of 5-8 NTU (Humphrey & Simpson in press). The trace metal concentrations, turbidity and pH in the water are also shown in Table A14. All of the variables (except pH) shown in Table A14 have higher concentrations in the water of Georgetown than in Mudginberri.

Concentrations of elements in the soft parts of mussels in relation to sex

Sex of the mussels had an influence on the concentrations of 12 of the 14 elements determined in the soft parts (Fig. 13). Only Ba and Cd were independent of sex. On most occasions the males had significantly ($P < 0.05$) higher concentrations than females except for Al in females in Georgetown and Ca and S in Leichhardt. Males were significantly higher in Cu, S and Zn in Georgetown; Al, Hg, Mg, Mn, Pb and Zn in Mudginberri; and As, Mn, Pb, Se, U and Zn in Leichhardt. Inconsistencies occurred in the relationships between concentrations of elements and sexes among sites, as was found in the relationships

with age. For example, Al was higher in females in Georgetown but lower in females in Mudginberri; S was higher in males in Georgetown but lower in males in Leichhardt.

Bryan (1973) and Latouche & Mix (1982) stated that gonadal material in marine bivalves is metal-poor. Since females contain relatively more gonadal material than males, one would expect that on a dry weight basis the females would have lower concentrations of most elements except for those which are associated with oogenesis. As the embryos develop one would expect an increase in Ca as the shells of the larvae form. However, in this study, Ca concentrations in the soft parts of female mussels were higher (compared with male mussels) for mussels from Leichhardt but not Georgetown or Mudginberri. Latouche & Mix (1982) found that female *M. edulis* contained higher levels of Mn and Zn. Orren et al. (1980) reported that, when both sexes had reproductively mature gonads, concentrations of Cu, Fe, Mn and Zn were significantly higher ($P < 0.05$) in females than males compared with non-significant differences ($P > 0.05$) when the gonads were not reproductively mature.

Concentrations of elements in the soft parts of mussels between sexes within sites. A summary of the results of a variance ratio test (Table A15) shows that, generally, the mean concentrations of elements in the soft parts of the male were significantly ($P < 0.05$) greater than in females. The elements could be split into four groups:

1. Mn - the concentration in the soft parts of males was significantly greater than in females in all three billabongs.

2. Ba, Ca, Cd, Mg, U and Zn - the concentration in the soft parts of males was significantly greater ($P < 0.05$) than in females in some billabongs.

3. Cu, Hg, S - the concentration in the soft parts of females was significantly greater ($P < 0.05$) than in males in some billabongs.

4. Al, As, Pb, Se - there was inconsistency among the billabongs.

The higher variance in the concentration of elements in the soft parts of males may be accounted for by the concentrations of some elements being significantly higher ($P < 0.05$) in males than in females (see Fig. 13). (Variance was shown to increase with increasing concentrations of an element.) However, although females had significantly ($P < 0.05$) higher concentrations of Ca, males again showed greater variance.

Because gametogenesis in both males and females did not follow a seasonal cycle (the gonads were active at all seasons) gametogenic stages were not scored in relation to element concentrations. However, the habit of retaining the embryos in a brood pouch was considered likely to influence the concentrations of elements in whole body measurements. therefore, changes in such reproductive stages in females were recorded. Whatever the reason for the higher variance in males, the results showed that if males are to be used for biological monitoring then a greater sample size than that for females would need to be taken in order to obtain a similar per cent differences between means.

Latouche & Mix (1982) recognised that size and sex affected metal concentrations and that the resulting variation may be eliminated by using specimens of a similar sexual maturity and size. Cossa et al. (1979) and Orren et al. (1980) suggested the use of immature individuals because variation in metal concentration increased when animals became reproductively active. Manly & George (1977) reported an opposite finding in the freshwater mussel, *Anodonta anatina* in the River Thames, in that variation in heavy metal concentrations was more extensive in immature individuals. In drawing any conclusions from studies on marine bivalves, mostly from temperate climate zones, it should be noted that such animals usually have highly seasonal reproductive cycles, unlike the non-seasonal cycle found in *V. angasi*. Any differences in concentration attributable to differences in the sex of *V. angasi* could be minimised by taking equal numbers of males and females in a sample.

Also, for those elements where variance in concentrations between sexes among billabongs were inconsistent (Al, As, Pb and Se), a collection of equal numbers of males and females would be an appropriate strategy.

Concentrations of elements in the soft parts of mussels in relation to sex and age

The effect of age on the concentrations of the 14 elements was inconsistent among the three billabongs studied. The relationships can be split into six groups (Table A20):

1. Mn - significant increase ($P < 0.05$) with age which is consistent for both males and females.

2. Ca, Cd, Pb - generally significant ($P < 0.05$) increase with age but with non-significant ($P > 0.05$) results for some cases.

3. S and Se - generally non-significant results but with significant ($P < 0.01$) negative slope for mussels from Georgetown except for Se in males.

4. Mg and Zn - generally non-significant result but with a significant ($P < 0.01$) positive slope for male mussels from Georgetown.

5. Al, As, Ba, Hg, U - consistency of either significant ($P < 0.05$) increases or decreases between sexes within a billabong but not among billabongs.

6. Cu - both male and female mussels in Mudginberri had significant negative slopes ($P < 0.01$) but in Leichhardt the males had a significant ($P < 0.01$) positive slope while females had a significant ($P < 0.01$) negative slope.

Figure 12 shows that the amount of granular material (as measured by the extent of surface area covered) increased with age in mussels from Leichhardt. A similar effect could be expected in mussels from Georgetown and Mudginberri. The increase in granular material approached a plateau at approximately six to seven years. Ch'ng-Tan (1986) showed that in the freshwater mussel, *Velesunio ambiguus* these granules are largely made up of inorganic phosphates (96%) which have high concentrations of Ca, Fe and Mn; lower concentrations of Mg and Ni and trace amounts of Se, Zn, Na and Pb. George et al. (1982) reported that the granules in *Mytilus edulis* contained principally Fe, Zn, S and Ca and were low in Mg and Mn. In a companion study on *V. angasi* from the same area, Jeffree & Simpson (pers. comm.) have recorded the presence of Ca, Mg, Ba, P, Fe, Al and Mn in granular deposits. George et al. (1982) indicated that elements are immobilised and detoxified by cellular compartmentation within these granules which are then eventually excreted in the urine. In a system such as Magela Creek which is very low in most metals and major anions and cations their presence in the granular material of the mussels represents a high expenditure of energy and great ability to concentrate elements from very low levels in the water. Therefore the incorporation of Ca into granules which eventually are excreted appears to be wasteful. There are two possible explanations for this: (1) that the function of the granular material is primarily for the detoxification and excretion of metals, as suggested by George et al. (1978) and Guary & Negrel (1981), Ca could be used in the granules to co-precipitate metals, thereby removing the metals from the body fluids and detoxifying them in the process; or (2) conversely, that the granular material acts as a store for Ca, and chemically similar elements are also taken up because the animal cannot discriminate between them - as postulated by Simkiss (1976) and Jeffree & Simpson (pers. comm.).

In Figs A3-A16 from Georgetown and Leichhardt the first two sets of points (ages < 3 years) were analysed in a separate batch from the others. If the determinations for those age groups were omitted then there may not have been any change with age for the elements Al, As, Cd, Cu, Hg, Pb and Se; however, there would still be an increase with age in both

males and females in Mudginberri. A marked increase in the concentration of As in females is evident in the eight-year-olds. Some seven to nine years prior to the sampling date in 1980, a program of pasture improvement was started at Mudginberri Station (information from manager Mr J. Pendavis). A phosphate based fertilizer was applied for a period of three years. A possible explanation for the elevated concentration of As in the eight-year-old mussels could be that when there was an increase of As in the water (for example, caused by surface runoff from fertilized ground) the concentration of As in the tissues of mussels also increased at this time. When the source of the As in the water was removed the As in the tissues has either very gradually been excreted or has remained stored in the body, that is, As has a long biological half-life.

Associations between the dashed lines and the solid lines (which represent the mean concentrations) show the relationships between concentration, load and weight in mussels from Georgetown, Mudginberri and Leichhardt. Young mussels in both Georgetown and Mudginberri had a dry weight of much less than one gram as shown by the dashed line below the solid line for mean concentration. The dashed line slowly approaches the solid line reaching an asymptotic value at five-years-old for male mussels in Georgetown and four-years-old in Mudginberri. This is demonstrated in Fig. A8 for Cu which was independent of age in males. Less than one-year-old mussels in Leichhardt had a mean dry weight of just under one gram. The mean dry weight of male mussels increased in a linear fashion up to ten years of age. No mussels of greater than ten-years-old were analysed from Leichhardt.

The use of non-linear models may provide a better fit to the data than linear models. However, until analytical variation is reduced to more acceptable levels, the fitting of more definitive models is inappropriate. Linear regressions have simply been applied to indicate possible trends in the existing results.

Concentrations of elements in the soft parts of female mussels in relation to the reproductive cycle

Studies on the marine bivalve, *Mytilus edulis*, have provided the bases for most of the information on the use of bivalves as biological monitors for aquatic pollution (Goldberg et al. 1978). Sexual maturity and the reproductive cycle have often been quoted as sources of variation in metal concentrations (Simpson 1979; Cossa et al. 1979, Latouche & Mix 1982). As indicated by Phillips (1976), Simpson (1979) and Lobel & Wright (1982*a*), variations in concentrations of metals in relation to the reproductive cycle of *M. edulis* were the result of weight changes in the course of the cycle rather than as a result of reproductive changes themselves.

Cossa et al. (1979) reported increased variation of metal concentration with the onset of sexual maturity of *M. edulis* and proposed the use of immature animals to reduce such variation. Sexual maturity in the animals in their study was reached in the third season. However, females of *V. angasi* can gain sexual maturity in their first year. Females also have the potential to develop and release glochidia at any time of the year (Humphrey & Simpson, in press). That is, the gonads are gametogenically active throughout the year with no spent phase as occurs in a temperate seasonal breeding mussel, such as *M. edulis*. Recruitment in *V. angasi* only occurs in the Wet season because the viability of the post-parasitic juvenile is dependent on the favourable water quality at that time.

The percentage composition of the various reproductive stages of females in Georgetown, Mudginberri and Leichhardt at any one time varied (Fig. 14). The relationship between high concentrations of zinc and gametogenesis has been noted in *M. edulis* by Latouche & Mix (1981). In *V. angasi*, Zn showed a tendency to decrease with progressive reproductive stages in female mussels from both Georgetown and Leichhardt but in mussels from Mudginberri the tendency was to increase. Generally, results showed that the different reproductive stages of females did not affect the concentrations of the elements determined.

Therefore female mussels in different reproductive stages need not be separated out in any sampling strategy.

Concentrations of elements in the individual organs of male and female mussels from Mudginberri (March 1980)

The distribution of elements among the tissues analysed differed (Figs 9-15 and Tables A25-A28). The marked higher concentrations of Al, Ba, Ca, Cu, Mn, Pb, Se and Zn in the adductor muscles of females are suspect; that is, the tissues from males and females were analysed in different batches and shortage of material necessitated a pooled single sample. Therefore, there is no information about variation. In the other results the following trends can be seen. The elements Ba, Ca, Mn and Pb have high concentrations in mantle, gills and palps, and visceral mass. Copper has a high concentration in the mantle, gills and palps, and kidney of both males and females but the females have higher concentrations in the visceral mass than do the males. Both males and females concentrate Cd in the kidney but not in the other organs. However, it should be noted that, for the heart and kidney, there was only a single sample for both males and females pooled from 20 mussels for each.

The concentration of zinc was high in the gills of both males and females and was lowest in the heart. The other organs had very similar concentrations, around 300 μg Zn/g. If the aim of a study is to monitor one particular element, then the organ with the highest concentration could be chosen for ease of analysis. However, if that organ is very small such as the heart and kidney in *V. angasi*, large numbers of mussels would be required for one sample. This has to be balanced against the economy of sampling.

The weights of the mantle, gills and palps, and visceral mass of males and females were not significantly different ($P > 0.05$). The variance of the weights of the mantle and the visceral mass were significantly greater ($P < 0.05$ and $P < 0.01$ respectively) for males than for females (Table A29). The visceral mass makes up the greatest proportion of the total weight of the soft parts of the mussels and so will have the greatest influence on changes in the total weight of the soft parts of the mussel. This was consistent with the results of the study of the biology and ecology of *V. angasi* (Humphrey & Simpson, in press) in which the condition index of males was more variable than that of females.

4.2 Comparison of concentrations of elements in the soft parts of mussels purged of their gut contents and not purged of their gut contents

Purging of the gut contents for 48 hours did not significantly ($P > 0.05$) alter the mean concentrations of any of the elements in the soft parts of mussels taken from Mudginberri and from Retention Pond Nos 2 and 4 (Table A30-A35), except for Al in those from Retention Pond No. 4. In Retention Pond No. 4 the Al concentration decreased from 610 ± 266 μg Al/g to 142 ± 20 μg Al/g (mean ± 95% CL) after purging of the gut contents. Three mechanisms for the loss of metals in bivalves have been described by Bryan (1971): excretion across the body surface or gills; excretion via the gut; and excretion via the urine. Another possible mechanism to explain the loss of Al from the soft parts in the mussels in this study could be that, if the mussels were taken from a location which may have high concentrations of elements in the sediments, it is possible that a reduction in the total concentration over a 48-hour period may occur due to loss of particulate matter (with high element concentration) as pseudofaeces from the gill surface, in addition to possible loss by the mechanisms mentioned above. The water from Retention Pond Nos 1, 2 and 4 was sampled on 6.7.81 and the concentration of Al in a filtered sample was below the analytical detection limit of 0.006 mg/L in all three ponds, however, sediments were not analysed.

The concentration of Cu in the soft parts of non-purged mussels was significantly greater ($P < 0.001$) than in purged mussels from Retention Pond No. 2. Similarly, the concentration of Al in the soft parts of mussels was much greater ($P < 0.01$) in non-purged

mussels taken from Retention Pond No. 4. The mussels from Retention Pond Nos 2 and 4 were sampled nine months after being placed into those ponds.

The results in Table A36 showed that the concentrations of Al, Cu, Hg, Mg, and Zn in the non-purged mussels were significantly greater ($P < 0.05$) than in purged mussels.

However, the concentrations of four (Al, Hg, Mg, Zn) of the fourteen elements analysed in the soft parts of mussels taken from Mudginberri and purged of their gut contents were reduced. Similarly concentrations of Cu in the soft parts of mussels from Retention Pond No. 2 and Al in mussels from Retention Pond No. 4 showed significantly lower concentrations ($P < 0.01$) in purged mussels.

It should be noted that the results for the purged and the non-purged mussels from Mudginberri were analysed in different batches whereas this was not the case for samples from Retention Pond Nos 2 and 4. Consequently, because the Mudginberri results are suspect this leaves Cu and Al as the only clear results with respect to a decrease in concentration when mussels were purged.

Even from locations with high concentrations of elements in the sediments and water, the small amount of material in the gut may not significantly increase the concentrations or the variance of concentrations of elements in mussels, the variance of determinations increases thereby concealing the small effect from elevated amounts in the gut.

4.3 Comparison of concentrations of elements in mussels collected from a sandy substrate and a detrital substrate in Mudginberri Billabong (February 1982)

Mussels collected from Mudginberri from two substrate types, sand and detritus, showed no significant ($P < 0.05$) differences for any of the elements determined in the soft parts.

4.4 Studies related to Aboriginal activities

Comparison of the concentrations of elements in the soft parts of uncooked and cooked mussels from Mudginberri (August 1981)

When mussels were cooked in an aluminium billy in the manner of the local Aboriginals the concentration of Al increased significantly ($P < 0.05$) from a mean value of 43 μg Al/g to 317 μg Al/g. The concentrations of As, Hg and Se significantly ($P < 0.05$) decreased.

The billycan used to cook the mussels was one which had previously been used and discarded by Aboriginals from Mudginberri. It was noted that a number of different types of cans were used for this purpose, from milk powder cans to flour cans. The billycan used in this experiment was made from aluminium which no doubt contributed to the large increase in aluminium concentration in the soft parts of the mussels. The decrease in the concentrations of As, Hg and Se were likely to have been caused by volatilisation of these elements during the cooking process. Again there is some reservation about these results because the cooked and uncooked mussel were analysed in different batches.

Estimation of dietary intake of mussels by local Aboriginals

Mussels form part of the traditional diet of the local Aboriginals in the Alligator Rivers Region. However, absolute figures in terms of numbers of mussels eaten are not available. In this study it has been estimated, by collecting discarded shells, that Mudginberri Aboriginals consumed (per person; see Table A42) 60 mussels (0.54 kg wet weight of soft parts) in the Dry season of 1980 and 288 mussels (2.59 kg wet weight of soft parts) in the Dry season of 1981 (Table A42). No attempt was make to take account of mussels eaten at

camps away from the billabongs and hence the estimates given here could be lower than the actual amounts consumed. For this reason, the estimates of mussel intake do not represent 'the worst possible case' philosophy, or the 'critical group' comsumption, as would be required for radiological dose estimates (Carter 1983).

The method of collection used by Aboriginals was by hand in shallow water or, where necessary, by shallow dives in the Dry season although the latter appears to be a less common means of gathering. Mussels are collected by Aboriginals in the Dry seasons only when the water recedes making the mussels more accessible. During the Wet season the water becomes too deep or too swiftly flowing to allow collection in the creek itself. Mussels are collected in the creek when the water level becomes very low, exposing the lower banks and *Pandanus* roots, in approximately June or July. There are relatively fewer mussels in the creek itself than in the billabongs and therefore once initial collections have been made from a site the mussel population is depleted; this is not the case in the billabongs. Mussels were still being taken from the billabongs at the end of the Dry season (e.g. on the 24 November 1981 from Georgetown).

Aboriginals do not appear to select mussels by size; the size distribution of the discarded shells (Fig. 16) showed close agreement with the size distribution of the mussels collected at each site Humphrey & Simpson (in press). All the mussels collected by the Aboriginals were cooked and eaten, with the exception of two very small mussels (length 31-35 mm) which were found with the flesh still in them.

Two methods of cooking mussels are used in this region according to the local Aboriginals: boiling in salted water; and placing in hot coals until the shell opens. If mussels were boiled in an aluminium billycan, the aluminium concentration in the mussels' soft parts increased. The numbers of mussels taken from each location differed widely (Table A41). In 1980, for example, 1141 mussels were taken from Corndorl compared with none in the following year. These year-to-year variations may occur when the return per unit collecting effort at a particular site becomes low, in which case the Aboriginals may move to another site which has not had collections made from it for a couple of years. They then may successively crop the billabongs on the basis of return per unit effort.

The concentrations of all the elements measured in the soft parts of mussels were below the recommended levels for those elements in foodstuffs (NH & MRC standards - Table A44). Therefore there is no health risk from the elements determined in eating mussels at the time of this study (1980-1982). For example, in comparison with the amount of minerals in a mineral supplement table (Table A43) the amount of Cu ingested per person in 1980 from mussels is approximately the same as that in one tablet and 5 times that in the 1981 intake. As another example the amount of As ingested over the Dry season (approximately six months) was 0.211 mg and 1.01 mg per person in 1980 and 1981 respectively, i.e. 0.006 mg As per person per day in 1981. A study in the USA estimated a mean intake of 0.19 mg As per person per day (Schroeder & Balassa 1966 cited in Friberg 1979).

4.5 Baseline concentrations of elements in the soft parts of mussels

Magela Creek

Figures A17-A30 show the concentrations and loads of elements in the soft parts of mussels from 13 locations in Magela Creek between March 1980 and February 1982. Each element will be considered in turn and any outlying values will be discussed. The results between April and October 1980 were determined by AMDEL and those after that date by SGS. Values from AMDEL and SGS on the same material have been shown to be significantly different (section 2.7). All concentrations are expressed on a dry weight basis.

Loads (body contents of elements) are plotted along with concentrations to evaluate any effects of changing weights on the metal concentrations. That is, does a concentration decrease simply because the weight has increased with no corresponding intake of metal or, alternatively, does a concentration increase simply because the weight has decreased with no corresponding loss of metal? Also the weight may rise or fall yet the concentration remain the same because metal had been taken in or lost; this would be shown by a corresponding rise or fall in the load. The possible relations among these parameters is summarised below:

	Concentration	Load	Weight
1	↓	=	↑
2	↑	=	= ↓
3	=	↑	↑
4	=	↓	↓

↑ Increase ↓ Decrease = Remains constant

It was possible to look at relationships between concentrations in the water and in the soft parts of the mussels for eight elements (Ca, Cd, Mg, Mn, Pb, Se, U and Zn). Of these, Ca, Mg and U showed a positive trend, S and Zn showed a negative trend and there was no relationship for Cd, Mn and Pb.

Aluminium. The concentrations of Al reported by AMDEL were much greater than those reported by SGS. The samples were digested by an HNO_3:HClO mixture by both and then determined by inductively coupled plasma atomic emission spectroscopy (AMDEL) or atomic absorption spectroscopy (SGS). The different methods of analyses of the samples may account for the differences in the concentrations reported by the two companies although each included the analyses of NBS SRMs with batches of samples.

A peak of Al in the soft parts of mussels was recorded in December 1981 for Ja Ja (NE) and for Nankeen, but not for Leichhardt. These three billabongs were sampled before the first flush of water for the Wet season entered them. The spread of concentrations for Ja Ja (NE) was wide and therefore the peak may not be significant. However, the spread of concentrations for Nankeen is narrow and all are values higher than for the samples taken in November 1981 and February 1982. Noller (1983) has shown that soluble Al increases in the water at this time, arising from particular changes in physico-chemical conditions in the water. The increased concentration of Al in the tissues of the mussels in December 1981 may have resulted from this increase.

A study of the water of Jabiluka revealed increased concentrations of filterable Al as well as of Ca, Mg, SO_4, Mn, Ni, Zn and an increase in conductivity for waters associated with the first flush. The presence of soluble Al has been implicated as a possible cause of fish deaths which occurred at that time in Jabiluka (Noller 1983) and has been linked with mussel deaths in Leichhardt (Morley et al. 1983). These pools had low pH (3.1) and high Al (2.8 mg/L) concentrations (form of Al was not specified) in the water (Morley et al. 1983). (Fish were also killed in pools, with no above ground inflow of flood water, on the flood plain northwest of Ja Ja.)

The highest mean concentrations of Al recorded in the soft parts of mussels were from Goanna (883 μg/g) followed by Jabiluka (275 μg/g), Georgetown (264 μg/g) and

Mudginberri (224 μg/g). The lowest concentrations of Al in the soft parts of mussels were from Ja Ja (NE) (60 μg/g), Gundur (49 μg/g) and Island (26 μg/g).

Arsenic. In general, concentrations were low during the Wet season months of January to April and higher during the Dry season months of June to December, for As in mussels in the billabongs from Corndorl downstream to Nankeen. This trend was apparent for the samples analysed by both companies.

In the mussels in Nankeen the trends in the mean load of As in the soft parts (Fig. A17) reflected similar trends in the condition (relationship between shell length and weight of soft parts) (Fig. A31). The mean weight of mussels peaked in August 1980 and in August 1981 with a much smaller peak in February 1981. These peaks in tissue weight reflected the periods of the year when algae, as a food source, were abundant and when the other limnological parameters were conducive to growth, i.e. adequate concentrations of dissolved oxygen and low turbidity. Similarly the weights of mussels and the As concentration were lowest in Mudginberri at the end of the Wet season when the water flow through the billabong was greatest and algal production was lowest (Humphrey & Simpson, in press). The standard mussel of length 61-65 mm had a range of mean dry weights of 1.2-1.4 g, therefore in the graph mean load appears just above mean concentration. An example of the inter-relationships of mean concentration, mean load and mean dry weight can be seen in the graphs for Nankeen (Figs A18 and A31). That is, the mean concentration for June 1981 onwards remained constant whereas the load increased from June to August then decreased, as did the weight of the mussels. The animals would have taken up some As and lost it again but the concentration remained the same.

In Georgetown a peak in the concentration of As occurred in December 1980. These samples were not analysed until the latter part of the work - i.e. in analysis batch number 51, containing samples from other locations in which all the As determinations were of the same order of magnitude, which was higher than all previous determinations for Georgetown. Thus it is possible that this peak is a result of analytical variation.

The overall mean concentrations of As were highest in mussels from Bowerbird (2.9 μg/g), Georgetown (2.5 μg/g), Gulungul (2.4 μg/g), Mudginberri (2.6 μg/g) and Nankeen (2.9 μg/g) and were lowest for Goanna (0.7 μg/g), Corndorl (1.3 μg/g) and Gundur (1.0 μg/g) (Table A45).

Barium. The results for Ba show low variability on some occasions and high variability on others (Fig. A19). The results in June and August 1981 were all similar in comparison with those in October and December 1981. It was shown (Allison & Simpson 1983) that if S (as the sulphate) is high in the same sample (as it is in the mussels from Ja Ja (NE)) Ba will precipitate out of the solution, with time, as $BaSO_4$. Variations in analytical technique may have increased the variability of the results.

Mussels from Gulungul (1.76 mg/g), Corndorl (2.45 mg/g), Gundur (1.92 mg/g), Mudginberri (1.81 mg/g) and Nankeen (1.3 mg/g) had the highest Ba concentrations while Bowerbird (0.59 mg/g), Georgetown (0.92 mg/g)) and Island (0.55 mg/g) had the lowest concentrations in the soft parts.

Calcium. The results for 1980 showed that the concentrations of Ca in the soft parts of mussels in Georgetown, Corndorl, Mudginberri, Jabiluka and Nankeen reached minima in August. However, in 1981 only the concentrations in the soft parts of mussels from Corndorl showed a similar dip in concentration. These decreases in the mean concentrations in mussels from Georgetown and Nankeen may be accounted for by the corresponding increases in dry weights of the mussels at this time (Fig. A31). That is, there had been an increase in tissue weight without any increase in level of Ca, which in effect lowered the concentration.

The concentrations of Ca in the soft parts of mussels in Nankeen showed an increase from April to August 1981. The peak in June 1981 in the mean concentration was the result of one very high determination (which is off the scale - Fig. A20). Over all, the trends in 1981 were different from those in 1980 in the mussels in Mudginberri and Nankeen.

Although there were apparent trends in the data their significance is questionable because of the changing variance in the concentrations at different time periods and the overall precision of determinations.

The mussels from Georgetown (32.72 mg/g), Corndorl (44.60 mg/g), Mudginberri (35.29 mg/g) and Nankeen (36.40 mg/g) had relatively high mean Ca concentrations in the soft parts compared with those in mussels from Island (9.12 mg/g) which were lower (Table A45). There was a positive trend between the mean concentration in water of the billabongs (for the period between November 1978 and August 1982, Table A46) and the mean concentration in the soft parts of the mussels (for the period between March 1980 and February 1982, Table A45). It would appear that there is no homeostatic control of Ca by these mussels.

Cadmium. The concentrations of Cd were lowest in the soft parts of mussels from all billabongs sampled in October 1980. Over the two year period only very small fluctuations occurred. Of all the mussels analysed, those from Bowerbird had the highest mean concentration of 4.29 μg Cd/g, followed by Gulungul with a mean concentration of 2.45 μg Cd/g. It is not known if the Cd concentration in the water was higher at these two locations (they were not sampled by Water Division, Department of Transport and Works). However, it is possible that the low concentrations of major ions in the water (Ca, Mg and Mn) of Bowerbird (as measured by Water Division, Department of Transport and Works - Table A46) may have enhanced the uptake of Cd by the mussels in Bowerbird. In an experimental situation with the marine oyster *Saccostrea echinata*, Cd absorption increased as the seawater concentration decreased, the major cause being the reduction in the Ca ion concentration (Allison 1982). This response was also reported for Cd uptake in the marine crab *Carcinus maenas* (Wright 1977 *a,b*).

Copper. The Cu concentrations in the soft parts of mussels from all billabongs showed only small fluctuations. The highest mean concentrations were recorded from mussels in Corndorl (17.99 μg/g) and Gulungul (20.69 μg/g) and the lowest from Island (4.89 μg/g) and Retention Pond No. 1 (5.14 μg/g). The mean concentration of Cu (total and residue) in the water of Georgetown was 9.9 μg/L, between five and ten times higher than that of the other billabongs measured which ranged between 1.0 and 2.3 μg/L. However, the concentration of Cu in the soft parts of the mussels from Georgetown was not correspondingly higher at 9.96 μg/g, approximately midway in the concentration of Cu in the soft parts of the mussels measured. In these molluscs Cu appears to be homeostatically controlled in the soft parts.

Mercury. Variation in Hg concentrations was high, partially because the concentrations in the tissues were very low, at the limits of detection of the analytical method.

In Corndorl and Mudginberri the mean concentrations of Hg showed a trend towards increasing over the 1981 Dry season. The loads followed the same trend thereby indicating that these changes in concentration were not merely functions of changes in weight. As the mean concentration increased the variances of the samples also increased. For example, the mean concentration in mussels from Corndorl in April 1981 was 0.20 μg/g with a range between 0.10 μg/g and 0.30 μg/g whereas in December 1981 the mean concentration was 0.95 μg/g with a range between 0.55 μg/g and 1.10 μg/g. The concentrations increased until the late Dry season 1981 and then all decreased in the 1981-1982 Wet season.

The highest overall mean concentrations of Hg were found in the soft parts of mussels from Gulungul (0.52 μg/g) and Corndorl (0.41 μg/g) and the lowest in Goanna 0.18 μg/g

and Georgetown, Island and Leichhardt with mean concentrations between 0.21 and 0.23 μg/g.

Magnesium. Minor fluctuations occurred in the concentrations of Mg in the soft parts of mussels from all billabongs. Over the two-year period two peaks occurred in the concentrations of Mg in mussels from Georgetown. One peak occurred between October and December 1980 and one in June 1981, i.e. at late-Dry to early-Wet and early- to mid-Dry respectively.

The highest overall mean concentrations of Mg were found in the soft parts of mussels from Georgetown (1.37 μg/g), Nankeen (1.31 μg/g and Goanna (1.18 μg/g). The lowest concentrations were found in mussels from Retention Pond No. 1 (0.41 μg/g), Gundur (0.46 μg/g) and Island (0.51 μg/g). There was a positive correlation (r^2 = 0.29) between Mg in the water of the billabongs and Mg in the soft parts of the corresponding mussels.

Manganese. Minor fluctuations of the concentrations of Mn in mussels occurred throughout the two years of the study with small peaks in mid-1981 in Georgetown, Corndorl, Mudginberri and Nankeen.

The highest overall mean concentrations were found in the soft parts of mussels from Mudginberri (8.59 mg/g), Gundur (8.20 mg/g) and Corndorl (10.99 mg/g). These three billabongs are within 2 km of one another, and Corndorl and Gundur are within 500 m of each other. The lowest concentrations were recorded in mussels from Retention Pond No. 1 (0.19 mg/g) and Bowerbird (1.47 mg/g). There was no correlation between the concentration of Mn in the water of the billabongs (Table A46) and in the soft parts of the corresponding mussels (Table A45).

Lead. The trends for 1980 showed increases in Pb concentrations in mussels from April to June followed by decreases in concentrations from June to October in Corndorl, Mudginberri and Nankeen. The mussels from Jabiluka showed a decrease in Pb concentrations from June to October of 30 μg/g to 5 μg/g. A similar range of decrease was also recorded for Corndorl. These trends in 1980 were not repeated in 1981.

In those samples analysed by SGS (i.e. December 1980 onwards), there were only small fluctuations in the mean concentrations. A large unexplained peak in the concentrations appeared for mussels sampled in August 1981 from Bowerbird.

The highest overall mean concentration of Pb in mussels was recorded from mussels in Gulungul 27.05 μg/g which did not have the highest Pb concentration (total plus residue) in the water (1.6 μg/L) (Table A46). The lowest concentrations were recorded from Leichhardt (2.80 μg/g), Ja Ja (NE) (3.35 μg/g) and Retention Pond No. 1 (3.82 μg/g). There was no correlation between the concentration of Pb in the water of the billabongs (Table A46) and in the soft parts of the corresponding mussels (Table A45).

Sulphur. The concentrations of S in the mussel soft parts in Georgetown and Corndorl during the period March to October 1980 and in August for the mussels in Mudginberri, Leichhardt and Nankeen were relatively constant with only a small decrease in concentrations in June. For Georgetown, Mudginberri, Island, Leichhardt and Nankeen, from December 1980 onwards there was a general trend in which the concentrations of S were low in the late-Dry and early-Wet season of 1980-1981. The concentrations subsequently increased reaching peaks in the mid-Dry season of 1981 before decreasing in the late Dry- and early-Wet of 1981-1982 in a similar way to the previous year.

These patterns in Georgetown and Nankeen were consistent with those for the increases and decreases in dry weight of the mussels (Fig. A31). The mean load increased more than the concentration, indicating that as the mussels gained weight they took up correspondingly more S.

The highest overall mean concentration of S was recorded in the soft parts of mussels in Bowerbird (17.46 mg/g) and the lowest mean concentration was recorded from mussels in Island (6.08 mg/g) (Table A45). There was a negative correlation between the concentration of S in the water of the billabongs (Table A46) and in the soft parts of the corresponding mussels (Table A45).

Selenium. The low concentrations of Se in the tissues was one of the causes of the high variance in the results as the levels were at or below the limits of analytical detection. Small variations occurred over the two years. There was a trend for concentrations in the soft parts of mussels from Bowerbird, Georgetown, Corndorl, Mudginberri, Island, Leichhardt and Nankeen to increase in the mid-Dry season.

The highest overall mean concentrations of Se were found in mussels from Gulungul (3.23 μg/g), Gundur (2.52 μg/g) and Georgetown (2.10 μg/g). The lowest mean concentrations were found in Goanna (0.32 μg/g), Jabiluka (0.77 μg/g) and Island (1.12 μg/g).

Uranium. The concentrations of U in the soft parts of mussels at all locations varied little throughout the two years, except for mussels in Georgetown which showed high concentrations and high variation for U with the overall mean being 1.66 μg/g. The mussels from Retention Pond No. 1 also had relatively high concentrations, with a mean of 0.87 μg/g, compared with the mean concentrations in mussels from other locations: Island (0.22 μg/g), Ja Ja (NE) (0.16 μg/g) and Leichhardt (0.14 μg/g).

Georgetown is the closest naturally occurring billabong, containing mussels, to the Ranger uranium ore bodies. Retention Pond No. 1 is a relatively recent waterbody formed by damming the Coonjimba Creek catchment. The mean concentrations ± SD between July 1981 and December 1981 for the water in Georgetown and Retention Pond No. 1 were 5.5 ± 1.5 μg/L and 1.1 ± 1.0 μg/L respectively. If the mussels are in equilibrium with the concentrations in the water, then concentration factors for U (dry weight) were 300 and 790 for Georgetown and Retention Pond No. 1 respectively. In other words, increasing the water concentration five-fold (1.1 μg/L to 5.5 μg/L) caused a tissue increase of two-fold (0.87 μg/g to 1.65 μg/g) under the conditions in the two waterbodies. There was a positive correlation (r^2 = 0.85) between the concentration of U in the water of the billabongs (Table A46) and in the soft parts of the corresponding mussels (Table A45).

Zinc. The variations in the concentrations of Zn were low over the two-year period except for Ja Ja (NE) in December 1981. The highest overall mean concentrations were recorded in the soft parts of mussels from Ja Ja (NE) (562 μg/g), Corndorl (489 μg/g), and Nankeen (449 μg/g). The lowest mean concentrations were recorded in mussels from Retention Pond No. 1 (199 μg/g), Island (282 μg/g) and Goanna (332 μg/g).

Other studies. Three previous studies have recorded concentrations of metals in the soft parts of *V. angasi* in the Alligator Rivers Region (Davy & Conway 1974; Noranda Australia Limited 1978; Pancontinental Mining Limited 1981). A summary of the results for mean concentrations for each study are given in Table A50. Only those metals included in the present study are shown in the table.

Davy & Conway (1974) did not standardise the size of mussels collected; in fact, they reported that there were biases towards 'juveniles' or very large specimens in some collections. Collections were made in the Dry seasons of 1971 and 1972. Noranda Australia Limited (1978) did not record the sizes of mussels in their sampling program. Sampling was undertaken in the early Dry season (1978). Pancontinental Mining Limited (1981) stated that mussels in a length range of 60-75 mm were preferentially chosen. Before analyses, mussels were purged in clean water, opened and allowed to drain for five minutes. Determinations on larger and smaller specimens showed no relationships between metal concentrations and size (shell length or tissue weight) although no details were reported. All mussel collections

in the Pancontinental study were taken during the Dry seasons of 1978 and 1979. Pancontinental Mining Limited (1981) reported that the similarity in mean values found for *V. angasi* in the billabongs sampled in the Magela Creek flood plain indicated that such values were representative of baseline values for the area. The qualification that this would apply only to the Dry season should also be added. There was some indication that Cu in sediments caused higher Cu concentrations in mussels in Winmurra Billabong.

Generally, the mean concentrations of some elements in mussels from these three studies were within the ranges of those determined in the two Dry seasons of the present study - in mussels from the same billabongs or creeks (when the areas were specified in the other studies).

Nourlangie Creek, Cooper Creek and Jim Jim Creek

The initial determinations by AMDEL of concentrations of elements in the soft parts of mussels from Long Harry's and, in particular, Gunirdul were often widely different from the determinations made by SGS (e.g. for Al, As, Ca, Cu, Mg, Mn). Apart from this difference, the concentrations of elements in mussels varied little with time. There were some peaks of concentration in April in the soft parts of mussels from Long Harry's (e.g. for Ca, Mg and Zn) but these peaks may be simply the result of decreases in weight which would be expected at this time.

The concentrations of all elements in mussels from Murganella were not significantly different ($P > 0.05$) from those in Gunirdul. The former billabong lies approximately 50 km, and the latter 8 km, downstream from Nabarlek.

Mussels were collected from two escarpment creek sites, Magela Creek and Jim Jim Creek, upstream from billabongs (Bowerbird and Graveside respectively) which may have been disturbed by the building of gauging stations. In each area the creek flows perennially and the sites were chosen as examples of pristine environments. The concentrations of the elements determined in the mussels from these two locations were very similar to each other; only the mean concentrations of As (20.25 μg/g and 2.17 μg/g for Jim Jim Creek and Magela Creek respectively) and Mn (3.12 mg/g and 1.09 mg/g respectively) were significantly different ($P < 0.05$) between the two locations. The mean (± SD) concentration of As in the soft parts of mussels from the Jim Jim Creek was considerably higher (20.25 μg/g [10.97]) compared with all other sites which had mean concentrations between 0.72 μg/g and 2.90 μg/g. This translates to a wet weight concentration of approximately 2.8 μg/g which exceeds the maximum permitted concentration in molluscs (1.0 μg/g wet weight) recommended by the NH&MRC.

4.6 Concentrations of elements in soft parts of mussels transplanted between billabongs

Chemical analysis of both marine and freshwater bivalves has been shown to be capable of indicating polluted waters from the concentrations of the pollutants in the soft parts of the animals. This discrimination using mussels has been applied to point source industrial discharges and to more generally polluted sites - versus unpolluted areas (Bedford et al. 1968; Lord et al. 1975; Smith et al. 1975; Foster & Bates 1978; Harris et al. 1979; Popham et al. 1980; Burns & Smith 1981; Talbot & Chegwidden 1982). One strategy in such studies was to transplant mussels from clean environments to ones where pollution is suspected in order to measure any elevation of levels of potential pollutants in the mussel soft parts.

Results of the baseline study showed that mussels from Mudginberri had higher concentrations of Mn in the soft parts than did mussels from either Georgetown or Nankeen. The mussels from Georgetown had higher levels of U in the soft parts than the mussels from either Mudginberri or Nankeen. These three billabongs were chosen as

providing suitable study sites for transplanting mussels to gauge responses by the mussels to changes in environmental levels of elements.

As well as investigating increases of element concentrations, it is constructive to record decreases when the source of the element is removed or when mussels are transplanted from billabongs with high element concentrations to areas of low element concentration. It may be possible to calculate the biological half-life as well as establishing whether concentration factors can be calculated for each element.

Mussels transplanted from Mudginberri to Nankeen and vice versa showed no changes in the concentrations of U with time (Fig. A49). However, mussels transplanted from Mudginberri into Georgetown showed an increase in U concentration in the soft parts. The mussels transplanted from Georgetown to Mudginberri retained their high concentration of U and there was no loss of U over a period of 12 months.

These results showed that U which had accumulated in the tissues throughout the life of the mussels was not lost over a period of 12 months, possibly being located in a permanent store. The biological half-life of U, accumulated over the mussels' lifetime, must therefore be very long. The transplant experiments were not continued long enough to establish the steady state concentration of U in the mussels transplanted into Georgetown. It should be noted that loss of U from the soft parts of mussels occurred following induced elevations of U in the relatively short-term ($\leq$ 1 year) uptake studies (see section 4.7).

The mussels taken from Mudginberri initially had higher concentrations of Mn and Zn than mussels from Georgetown (approximately 10 mg Mn/g and 0.4 mg Zn/g against approximately 5 mg Mn/g and 0.3 mg Zn/g respectively). The concentrations of Mn and Zn in mussels from Nankeen were approximately 5 mg Mn/g and 0.35 mg Zn/g.

The results for Mn for all the combinations of transplants are shown in Fig. A45, in which there was a tendency for Mn to increase in all transplants. The range of Mn concentrations was much greater in mussels transplanted into Georgetown than in any of the other three transplants. Mussels transplanted into Georgetown showed an increase in the mean from 10 mg Mn/g to 15 mg Mn/g after six months, thereafter reaching a plateau. These results are not consistent with what would be expected based on the ambient concentrations of Mn in the soft parts of the mussels. From the initial concentrations it would have been expected that in mussels transplanted from Mudginberri, in which Mn concentrations in the soft parts were higher, to Georgetown (in which concentrations of Mn in the soft parts for mussels are lower), there would have been a net decrease in concentration or there would have been no change.

Similarly the concentrations of zinc in mussels transplanted into Georgetown increased for a period of six months and then the mean concentration remained relatively constant over the next six-month period. Trends of this nature were also recorded for the other three transplanting regimes.

Because there were increases and decreases in concentrations of elements in transplanted mussels, which did not follow relationships between concentrations of elements and concentrations in receiving waterbodies, it could be interpreted that some other environmental or physiological effects caused these increases and decreases. However, if this was the case one would expect that the mussels sampled in the baseline study would have shown the same trends; but they did not. Therefore, unfortunately, one must suspect that these changes in the concentrations of elements recorded in the mussels were the result of analytical methodology - most likely the effects of determinations in different batches.

4.7 Uptake and loss studies

Retention ponds

Short-term uptake and loss of elements in the soft parts of mussels. The aim of placing mussels in the retention ponds was to expose them to slightly raised water concentrations of elements in order to gauge their response to the most likely pollution eventuality - that is, low chronic pollution or greatly diluted contamination from a spillage. In this section no attempt has been made to analyse the data statistically, except for U, owing to the conclusions reached on the analytical methodology (Allison & Simpson 1983). It should be borne in mind that significant differences in variation ($P < 0.05$) were introduced due to analyses made at different times i.e. effect of 'batches'.

The concentrations of the elements determined in the water of Mudginberri were mostly lower than those in the retention ponds. The ranked order of the concentrations in the water of the four locations were:

Cu	$M < 4 \leq 1 \leq 2$
Pb	$M < 4 \leq 1 \leq 2$
Mn	$1 \leq M \leq 2 \leq 4$
Zn	$M < 4 \leq 1 \leq 2$
U	$M < 1 \leq 4 \leq 2$
Mg	$M < 1 < 4 < 2$
Ca	$M < 1 < 4 < 2$
S	$1 < M < 4 \leq 2$

M = Mudginberri
1 = Retention Pond No. 1
2 = Retention Pond No. 2
4 = Retention Pond No. 4

During the course of the six-week period when the mussels were in the retention ponds, water was pumped from Retention Pond No. 4 into Retention Pond No. 2. The elements - Zn, U, Mg, Ca and S - were all lower in Retention Pond No. 4 than in Retention Pond No. 2; however no reduction in the concentrations of these elements was measured in Retention Pond No. 2 (Tables A56 and A57). The volume of water in Retention Pond No. 4 was very much smaller than that of Retention Pond No. 2 and therefore there was not sufficient dilution effect to alter the concentrations of elements in Retention Pond No. 2.

Aluminium. No information exists on the concentrations of Al in the water at these locations. The concentration range of Al in the soft parts of mussels during the uptake period (set nos 1 to 11 in Figs A51-A54) was much greater than during the loss period in all three retention ponds. A high peak occurred at set no. 6 for the concentrations in age class 1 (less than one-year-old) mussels in Retention Pond No. 1. The mussels from age class 1 were of low weight and five mussels were grouped to make each sample; therefore there was only one determination per set no.

On the 24 October 1980 (equivalent to set no. 9 for age class 1 and set no. 10 for all other age classes - see Table A54) a quantity of aluminium sulphate, a flocculating agent was sprayed into Retention Pond No. 2. The aim was to clarify the water by precipitating out the heavy metals and particulate matter so that water could be reused in the milling process. The concentration of Al in the water was not determined at this time.

The Al concentrations in the soft parts of mussels of age class 1 in Retention Pond No. 2 had a peak at set no. 7 (after 2 weeks) but the concentration then decreased to approximately 0.4 mg Al/g on a par with the concentration at time zero. None of the elements determined in the water of Retention Pond No. 2 showed an increase or a decrease in concentration corresponding with these times and therefore there was no reason to suspect that any changes in Al would have occurred.

The other three age classes had similar trends to those of age class 1 except that the mean concentration in mussels of age class 1 was approximately 1.5 mg Al/g and for the older age classes the mean concentration was between 0.5 and 1 mg Al/g.

Arsenic. There were fluctuations in the concentrations of As determined in the soft parts of mussels in age class 1 during the uptake period but these should be viewed against the very low concentrations of As - close to the lowest limits of detection of the method used. The high peak for Retention Pond No. 1 mussels at set no. 18 cannot be explained by any major changes such as those which occurred in the water of Mudginberri. The first flush of water into Mudginberri was a significant event which may have remobilised metals rendering them available to the biota; however, this event occurred at a time after the peak for concentration of As in the mussels, between set nos 19 and 20 (Table A54). The concentrations of As in age class 2 for the three retention ponds showed a trend of increasing concentrations to set nos 9 or 10 and a decrease at set nos 10 or 11.

Peaks of concentrations occurred at set nos 17 and 18 for all age classes which again were unrelated to any significant limnological event in Mudginberri. The peaks and troughs in the concentrations followed a similar pattern to the peaks and troughs in the concentrations in the analytical control samples (Table A57) thereby relating trends in the experimental results to those in the analytical performance.

Barium. The trends shown for age classes 2, 3 and 4 in the three retention ponds were all similar; concentrations increased to maxima around set nos 11, 12 and 13. However, large fluctuations occurred in the concentrations during the uptake part of the experiments (set nos 1 to 11). After set nos 12 or 13 the concentrations decreased and the magnitude of the fluctuations also decreased.

There was also a trend for Ba to reach higher maximum concentrations in older mussels, the values decreasing for mussels in the sequence: Retention Pond Nos 1, 2 and 4.

The concentrations of Ba appeared to increase during the period that the mussels were placed in the retention ponds and then showed rapid decrease corresponding with the time when the mussels were replaced into Mudginberri. However, it is known that the low precision of Ba analyses was caused by the precipitation of $BaSO_4$ when there was also high S in the solution during analysis and therefore the variation in these results may be due to analytical variability (Allison & Simpson 1983). The analyses of the OSS mussel reference materials (wet) (Table A57) showed similar trends to those of the experimental samples. Thus these increases and decreases in the Ba concentrations appear to be simply coincident with analytical performance.

Calcium. The maximum concentrations of Ca eventually reached in the mussels increased with age: 30 mg Ca/g, 30 mg Ca/g, 50 mg Ca/g and 60 mg Ca/g for age classes 1, 2, 3 and 4 respectively in Retention Pond No. 1. The mean concentrations decreased in the order Retention Pond No. 4 < Retention Pond No. 2 < Retention Pond No. 1. As the concentrations of Ca increased, the magnitude of the fluctuations also increased. These last two trends bear similarities to those for Ba.

Cadmium. The concentration of Cd in the soft parts of mussels was very low and close to the lowest limits of detection of the analytical method used.

There appeared to be a decrease in the concentrations of Cd between set nos 12 and 13 (a time period of 24-hours) for age classes 2, 3 and 4 in all three retention ponds. This reduction may have been a response to the removal of the mussels from the retention ponds to Mudginberri; however, similar fluctuations occurred throughout the period of uptake and, as for As and Ba, results of analytical controls mirrored these events. Therefore no significance can be placed on the changes which occurred between set nos 12 and 13.

Copper. The mean Cu concentration in the water of Retention Pond No. 2 was twice that of Retention Pond No. 1 and Retention Pond No. 4 although not significantly so because of wide variation. Concentrations in all three ponds were higher than in Mudginberri.

During the period of uptake (set nos 1 to 11) the fluctuations in concentrations of Cu in the soft parts of mussels were greater than in the loss period particularly in mussels in age class 1 in all three retention ponds and age class 2 in Retention Pond Nos 1 and 2. There was no uptake of copper during the six-week period by any of the mussels. The mean concentrations in the soft parts of mussels across all situations was approximately 10 μg Cu/g.

The peaks of Cu concentrations at set no. 6 (after one week) for mussels in age class 4 in Retention Pond No. 2 was mirrored by results from Retention Pond No. 1 and to a lesser extent from the results from Retention Pond No. 4. The concentrations of elements in Retention Pond No. 2 varied over a period of time, whereas Retention Pond No. 1 was essentially a natural body of water formed by a dam wall being built across Coonjimba Creek and, in comparison, was stable in limnological characteristics. The coincidence of the peaks of Cu concentrations in mussels from both these retention ponds, despite their different water qualities, together with the fact that the samples were analysed in the same batches would suggest that the peaks were caused by analytical methodology.

Mercury. Over the course of the experiment there were wide fluctuations in the concentrations of Hg in the soft parts of the mussels. However, the low concentrations (near the lowest limits of detection) did not allow any reasonable interpretation of these fluctuations.

Magnesium. The concentrations of Mg in the water of Mudginberri and Retention Pond Nos 1, 2, and 4 were 0.39 μg/L, 2.4 μg/L, 13.12 μg/L and 4.9 μg/L respectively.

Similar trends in concentrations in the mussels appeared in all four age classes. There were increases in concentrations up to set nos 9, 10 or 11. At set 12, the mussels were returned to Mudginberri and the concentrations decreased to levels below the initial concentration determined in the mussels when they were removed from Mudginberri. During uptake, there was a general trend towards increased concentration with correspondingly large fluctuations. Fluctuation of less magnitude occurred during the period of loss. That is, variance appeared to be concentration dependent.

There were definite trends in the fluctuations of the concentrations in the mussels in the three retention ponds. However, these fluctuations were dependent on the batch number in which the samples were analysed. The analyses of the OSS reference material (wet) did not follow the trends of the experimental samples but remained lower (range 0.9 to 1.6 mg/g) compared with a range of 0.4 to 3.4 mg/g for the uptake period.

The maximum concentration of Mg in the soft parts per mussel increased with age. The highest maximum concentrations reached in age classes 3 and 4 were in mussels from Retention Pond No. 1. The mussels in age class 2 from all three retention ponds showed the same maximum concentrations, whereas the mussels in age class 1 from Retention Pond No. 4 reached a higher concentration than similarly aged mussels from Retention Pond Nos 1 and 2. These results did not reflect the ranked order for the concentrations of Mg in the water from these locations: the highest concentration was in Retention Pond No. 2, but the mussels in Retention Pond Nos 1 and 4 gained higher concentrations than those in Retention Pond No. 2.

These results were not consistent with those for other elements in marine bivalves in which the rate of uptake and the maximum concentrations were positively dependent on the concentration of that element in the water (Ni - Friedrich & Filice 1976, Allison 1982; Cd - Ward 1976, Allison 1982; $Fe(OH)_3$ - George et al. 1976; Pb - Schulz-Baldes 1974). However,

similarities between uptake studies elsewhere and those performed here in the retention ponds would be expected only if the elements were in the same chemical form. Unfortunately, there is no information available on the chemical speciation of the elements in the retention ponds, and the biological availability of Mg may have been different among the retention ponds.

Manganese. The concentrations of Mn in the soft parts of mussels from Mudginberri were dependent on age (see section 3.1). This was also indicated by the increase in concentrations at set no. 1 with increase in age class. These results are contrary to the results for Mn in *Velenusio ambiguus* recorded by Jones & Walker (1979) who found that Mn concentration decreased with age.

As was found with other elements, the magnitude of the fluctuations increased as the concentrations increased, that is, were greatest in age class 4. The mean concentrations of Mn in the water of Mudginberri, Retention Pond Nos 1, 2, and 4 were 13.7 μg/L, 10.2 μg/L, 24.9 μg/L and 30.5 μg/L respectively.

The determinations of Mn in the OSS mussel reference material (wet) ranged from 5.6 mg Mn/g to 14.8 mg Mn/g which were similar in range to those in the experimental samples, 3 mg Mn/g to 15 mg Mn/g, with only two peaks exceeding these values. Therefore any of the fluctuations recorded in the experimental samples may have arisen through analytical variability.

Lead. The Pb concentrations in the filtered water of Mudginberri, Retention Pond Nos 1, 2 and 4 were 0.4 μg Pb/L, 2.08 μg Pb/L, 2.24 μg Pb/L and 1.3 μg Pb/L. The concentrations in the latter three locations were not significantly different ($P > 0.05$) from one another. The determinations of Pb in the water were variable (Table A55).

The concentrations of Pb in the soft parts of the mussels were independent of the retention pond in which they were placed. However, peaks of Pb occurred at the same times in all three retention ponds in mussels of age class 1, as did peaks for mussels of age classes 2 and 4 in Retention Pond Nos 1 and 2. The mean concentration of Pb in the mussels for all age classes fluctuated around 7 μg Pb/g.

The rate of Pb uptake in *M. edulis* has been shown to be linearly dependent on the concentration in the water between 5-500 μg Pb/L and the rate of Pb loss was dependent on the concentration in the soft parts at the start of the loss period (Schulz-Baldes 1974). Mussels placed in water with concentration of 5 μg Pb/L had an initial Pb concentration in the soft tissues of 3 μg Pb/g and attained 30 μg Pb/g after 6 weeks exposure (Schulz-Baldes 1974). Ritz et al. (1982) also showed that the rate of uptake of Cd, Cu, Pb and Zn by *Mytilus edulis planatus* was dependent on the external concentration of those metals.

Sulphur. The concentration of S in the water of Retention Pond No. 2 (45.7 mg S/L, total) was much greater than in Mudginberri (1.1 mg S/L, filtered) and in Retention Pond Nos 1 and 4 (0.3 and 2.7 mg S/L, total). However, as most of the S in the water was likely to be in the form of SO_4 which in most cases is insoluble, it was unlikely that the S in the water was readily available to the mussels.

Fluctuations of similar magnitudes occurred in the S concentrations in mussels in all three retention ponds. The greatest fluctuations occurred in the mussels in age class 1. The range of mean concentrations for all situations was 10-15 mg S/g.

Selenium. The concentrations of Se in the mussels were independent of age and of the retention pond in which they were placed. Also, wide fluctuations in concentrations occurred, the mean concentrations in the soft parts of the mussels were around 3 μg Se/g.

Uranium. The mean concentrations of U in the water (filtered) in Mudginberri (< 0.04 μg U/L) were lower than in any of the retention ponds. The mean concentration in Retention Pond No. 2 was 154 μg U/L (filtered) compared with 0.63 μg U/L (filtered) and 2.6 μg U/L (filtered) for Retention Pond Nos 1 and 4 respectively.

The results for U in the soft parts of the mussels, despite large fluctuations, showed marked differences between the three retention ponds. In the mussels placed in Retention Pond No. 1 there were no changes in the concentrations of U in the tissues of mussels in any of the age classes. The mussels of all age classes in Retention Pond No. 2 showed increases in concentrations up to set no. 11. A large peak at set no. 8 occurred for age classes 2, 3 and 4 in Retention Pond No. 4 which attained or exceeded the maximum concentrations found in the mussels of Retention Pond No. 2 at that time.

Acknowledging that there were wide fluctuations in the results, the maximum concentrations in the soft parts reached over the period of uptake were greatest in the youngest mussels: 90 μg U/g, 22 μg U/g, 45 μg U/g and 25 μg U/g for age classes 1, 2, 3 and 4 respectively from an initial concentration in the soft parts of less than 1 μg U/g for all age classes.

Linear regression models were applied to concentrations, as well as to logarithmic transformations of the concentrations, against time. In Retention Pond No. 2 which had a mean water concentration of 154 μg U/L the best fit was a regression on the untransformed data (Table A58). However, the data were very variable resulting in low r^2 values. The results of uptake of U in the mussels of Retention Pond No. 4 were best described by a regression using a logarithmic transformation of the concentration. The slopes of the lines were consistently low (0.05) compared with those in Retention Pond No. 2 which ranged between 0.02 and 0.58, depending on age. The r^2 value for age class 2 was high (0.78) whereas for the other age classes the r^2 value was low. Therefore, there is only a small fraction of the variation of the concentration that can be explained by the regression.

There was no consistent trend between rates of uptake and age in Retention Pond No. 2 whereas the rate of uptake was age dependent in mussels in Retention Pond No. 4 which had a lower concentration of U than Retention Pond No. 2. The rate of uptake in the soft parts increased as the concentration in the water increased. Over all the age classes, after six weeks, there was a seven-fold increase in uptake rate for a 59-fold increase in the water concentration.

The loss of U from the tissues was best described by regressions using double logarithmic transformations in all cases, except age class 1 in Retention Pond No. 2 in which case logarithmic transformation (of the concentration data only) proved to be a better model.

The rates of loss of U from the soft parts of mussels in Retention Pond Nos 2 and 4 were similar. Therefore unlike other elements, e.g. Zn (Bryan 1968) in marine crustaceans and bivalves and Pb (Schulz-Baldes 1974), the rate of loss was independent of the initial concentrations in the tissues. When U uptake has taken place over a short period of time e.g. 6 weeks, the biological half-life of U in *V. angasi* was very short, approximately two days. This suggests that uranium taken up over a short time period, such as six weeks, may enter a temporary store in the tissues which is lost readily to the aquatic medium when returned to water with a lower U concentration in comparison with the long biological half-life of U when accumulated over the life (6 years) of the mussel (see transplants between billabongs).

There is an alternative hypothesis. In filter feeding organisms the routes of uptake may be many - from solution, food, inorganic particles or oil droplets (Bryan 1979). In the marine mussel *M. edulis* it was shown that metals such as Zn, Mn, Cd and Se must largely be absorbed from suspended particles (Pentreath 1973). Adsorption onto the surface of the animal may also be important and may be the most rapid method for first stage increase in concentration; however, as internal accumulation proceeds the amount adsorbed may become

relatively unimportant. The kinetics of U uptake and loss would also support this alternative hypothesis - i.e. that a large part of the increased concentration may be due to adsorption of elements which are then lost rapidly when returned to a 'clean' environment.

Zinc. The water concentrations (filtered) of Zn in Mudginberri and Retention Pond Nos 1, 2 and 4 were 4.1 μg Zn/L, 11.7 μg Zn/L, 26.6 μg Zn/L and 9.5 μg Zn/L.

The concentrations of Zn in the soft parts of the mussels were independent of age and of the retention pond in which the mussels were placed. The fluctuations in Zn concentrations in the mussels were within the range of fluctuations of the analytical controls.

The mean concentrations in the soft parts of mussels ranged between 0.3 and 0.4 mg Zn/g for all age classes and all retention ponds.

Reproductive stages of females during the short-term uptake study. Female mussels in Mudginberri have the capacity to reproduce, and for eggs to develop to the glochidia stage, at all times of the year. However, the water conditions for the growth and development of the larval mussels are suitable only in the Wet season when dissolved oxygen is high and little stratification of the water column takes place (Humphrey & Simpson in press). The mussels placed in the retention ponds had development scores between two and five. That is, some had eggs only in the gonads (score = 2), some had embryos in the gills (score = 3), and some had glochidia in the gills (score = 5). For illustrative purposes, the scores for reproductive stages are treated here as continuous data (Fig. 17).

The results showed that the initial mean score for maturity of the reproductive cycle varied little in the mussels in Retention Pond No. 1 and Retention Pond No. 4 throughout the uptake period of six weeks. However, the mean maturity score was considerably lower in mussels in Retention Pond No. 2 from set no. 10 to set no. 14, after which the mean maturity score increased to the pre-experimental level and higher when replaced into Mudginberri.

These results indicate that the reproductive capacity of mussels was impaired when placed in Retention Pond No. 2 for six weeks. However, this was not a long-term effect as the maturity score increased four days after the mussels were replaced into Mudginberri (set no. 15).

Three major environmental factors which have a bearing on the successful larval production of mussels were identified in the accompanying biological studies (Humphrey & Simpson in press), and these could have applied to the situation in Retention Pond No. 2: dissolved oxygen concentration in the water; food availability - algal production; turbidity of the water. If any one of these impose a stress on the mussels, larval development will be impaired. For example, in Georgetown algae may be plentiful but because the turbidity is very high at the end of the Dry season there will be no larval development.

The algal growths in Retention Pond Nos 2 and 4 were different, see the photographs in Figs 18 and 19 respectively. After four weeks in Retention Pond No. 2 dense mats of filamentous green algae had grown on the cages and on the sediments. In Retention Pond No. 4 the filamentous green algae were not present; however, other forms of algae were present which was indicated by the slightly green colouration of the water. The presence of the algae (a food source) was also indicated by the mussels' ability to maintain weight during the course of the long-term experiment conducted immediately prior to the short-term study.

The algal mats in Retention Pond No. 2 may not necessarily mean that food was abundant or suitable for the mussels, i.e. in a suspended form which would be available to the mussels. These mats may also have caused depletion of the dissolved oxygen concentrations, which would have been stressful to the mussels.

Long-term uptake and loss. The results of this study must be assessed in the light of the conclusions on the analytical variability introduced by SGS (Allison & Simpson 1983) and also on a comparison of results obtained by SGS and AMDEL (Tables A9 and A10). The results for As, Cd, Cu, Mg, Pb, Se, S and Zn in the soft parts of the mussels in Retention Pond No. 2 have been discussed in length in the above report. One of the major conclusions reached was that the time at which the samples were analysed (i.e. the batch) had a significant effect on the results. Since there were statistically significant differences ($P < 0.05$) between batches, little can be gained from statistically analysing the relationships between the concentrations in the water and the determinations of the concentrations in the mussels or the concentrations along the time series from the above analyses.

The determinations of Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn in the soft parts of mussels from Retention Pond No. 4 from day no. 14 to 226 were made by OSS. These results have between batch precisions of: Ba - 100.0%; Ca - 10.3%; Cd - 30%; Cu - 1.3%; Mg - 6.7%; Mn - 6.9%; Pb - 46.9%; Pb - 46.9%; and Zn - 7% (based on OSS mussel reference material (dry) in Table A7).

Simple linear regressions of the concentrations of Mg and Mn against time, for mussels in Retention Pond No. 4, were significant ($P < 0.05$) (Table A62 and Figs A114-A115). Both of these regressions have negative slopes, i.e. the concentration in the mussels decreased with time. The concentration of Mg in the water of Retention Pond No. 4 was approximately three times higher than that in Mudginberri, from where the mussels had been taken. The Mn concentration in the water of Retention Pond No. 4 was not significantly ($P > 0.05$) different from the concentration in the water in Mudginberri. Although the concentration of Mg in the water was higher in Retention Pond No. 4 than in Mudginberri there were also higher pH levels and concentrations of Ca and these factors may have reduced the uptake of Mg and Mn. That is, the different chemical composition of the water in Retention Pond No. 4 may have rendered the Mg and Mn less available to the mussels.

Interesting comparisons can be made on the concentrations of U in the soft parts of mussels in Retention Pond Nos 2 and 4 during the course of the short-term (six weeks) and the long-term (ten month) uptake studies. The long-term uptake study commenced on the 20.10.80 and ended when the mussels were returned to Mudginberri on 6.8.81. In the following month the short-term uptake study commenced (15.9.81). For the three months (August, September and October 1980) prior to the uptake experiments the mussels in Mudginberri were exposed to very low water concentrations of U (< 0.1 - < 0.7 μg/L). The concentration of U in the water of Mudginberri remained low and when mussels were returned in August 1981, the water concentration was < 0.4 μg U/L and did not rise above this concentration during the following three months (Table A59). The mean concentrations of U in the water of the two retention ponds into which the mussels were placed during the short and long-term studies did not significantly ($P > 0.05$) change. In Retention Pond No. 2 the mean monthly maximum U concentration in the water was initially 63.4 μg/L and increased to 575 μg/L in January 1981 after which it gradually decreased over the next seven months to 46.8 μg/L (Table A60). In Retention Pond No. 4 the U concentration was initially 1.8 μg/L, increased to 10.2 μg/L in December 1980 (a suspect value), was 2.9 μg/L in March 1981 and then decreased to be 0.7 μg/L in July 1981 (Table A61).

The concentrations in the soft parts of mussels in Retention Pond No. 4 during the short-term study were much more variable than during the long-term study. In the latter a steady state plateau concentration of 3.18 μg U/g was reached in the tissues of the mussels with relatively low concentrations of U in the water (mean 2.7 μg U/L $\pm$ 3.2 SD). During this steady state of tissue concentration, the rate of loss was equal to the rate of uptake and at this point the concentration factor was 1178, i.e. concentration in the soft parts (dry weight)/concentration in the water.

In Retention Pond No. 2 the U concentration in the soft parts of the mussels increased rapidly over the first 14 days after which the rate of increase was reduced until a maximum

concentration of 33.35 μg U/g was reached on day no. 197. The concentration then declined rapidly to approximately 15.3 μg U/g on day no. 259. This decrease may have represented a loss from the tissues because of a reduction of the U concentration in the water although this was not evident from the water analyses. There was a decrease in the water concentration after day no. 109; however, the concentrations in the mussels increased beyond this point in time.

The uptake of U in mussels in Retention Pond No. 2, both in the short-term (age class 4) and long-term studies, can be described by linear regressions ($y = 0.36x + 3.64$, $r^2 = 0.26$; and $y = 0.11x + 6.51$, $r^2 = 0.76$ respectively). In the long-term study, the regression refers to uptake between day no. 14 and day no. 196. The slopes of the lines indicate that the rate of uptake was much slower during the course of the long-term uptake experiment. At the higher concentration of U in the water of Retention Pond No. 2, compared with Retention Pond No. 4, the concentration of U in the soft parts of the mussels did not reach a steady state plateau concentration within the duration of the uptake (197 days).

Female mussels in both retention ponds had reduced reproductive maturity scores. For the duration of the study the female mussels in Retention Pond No. 2 had eggs in the gonads only. If the eggs had been transported to the gills they must have been immediately aborted as they were not present in the gills when the mussels were sampled. Female mussels in Retention Pond No. 4 had eggs in the gonads only on most sampling occasions but some had glochidia in the gills in December 1980 (day no. 46), May 1981 (day no. 197) and June 1981 (day no. 226). In January 1981, some females had embryos in the gills. The mussels which remained in Retention Pond No. 4 at the end of the uptake period were returned to Mudginberri, where, after three days, some females had embryos in the gills and after seven days glochidia were present in the gills of some females. On 20 August and 4 September 1981 all the females sampled had glochidia in the gills (see Fig. 20). Because of the loss of some cages, there were no mussels left in Retention Pond No. 2 for replacement into Mudginberri. In summary, although the reproductive capacity of the mussels was inhibited for a period of ten months, when they were returned to a suitable waterbody (Mudginberri) larval development returned to a more normal pattern.

As previously mentioned, the three major environmental factors which affect larval production are dissolved oxygen, food availability (algal production) and turbidity. In Retention Pond No. 4 ample food was available, demonstrated by the mussels' ability to maintain their weight; however larval production was inhibited. It was unlikely that the cause was turbidity as the values were low. Unfortunately there were no records of dissolved oxygen levels. Larval production may have been inhibited by other factors in the water which stressed the mussels e.g. metals and major ions and an increase in pH.

The mean dry weight of mussels in Retention Pond No. 2 decreased over the ten months of the study, in comparison the mussels in Retention Pond No. 4 did not lose weight (Fig. A94). In Retention Pond No. 2 it was possible that the reduction in the weight of the mussels was due to low food availability. This factor alone may have inhibited larval production. Retention Pond Nos 2 and 4 are adjacent but receive water and seepage from different sources. Figures 18 and 19 show the cages of mussels from Retention Pond Nos 2 and 4 respectively during the short-term experiment (the photographs taken six weeks after the end of the long-term experiment show what the conditions were like in the ponds). The cages in Retention Pond No. 2 were covered in mats of filamentous green algae whereas there was no such algal production in Retention Pond No. 4, although other types of algae were present in the water column. The following reasons could explain the reduction in weight in all mussels and the inhibition of larval production in female mussels in Retention Pond No. 2:

1. the filamentous algal mats caused a reduction in dissolved oxygen levels which would stop the mussels filtering and cause them to take in less food;

2. the algae produced are not a source of food for the mussels;

3. the algae produced in Retention Pond No. 2 are of a toxic nature to the mussels compared with those produced in Retention Pond No. 4; and

4. the water quality, whether one or a combination of parameters, is detrimental to mussel growth.

Evaluation of the uptake and loss studies. The aim of exposing mussels to the concentrations and combinations of elements in the retention ponds in 1980 and the early part of 1981 was to examine the effect of slightly elevated water concentrations of elements on the mussels under field conditions. The changes in concentrations in the soft parts would be expected to be small, if changes were to occur at all. Detection of small, genuine differences in concentrations was impossible in this study, because of the low precision of the analyses. It was shown that as concentrations increased, the variance of the results increased also; therefore, in conjunction with the low precision of analyses any differences in tissue concentrations may have been lost in the high analytical variation. This applied to 13 of the 14 elements determined by the commercial analytical companies.

The results of the determinations of U in both the short and the long-term studies appeared to be more conclusive. In the short-term studies, uranium concentrations rapidly increased in the soft parts of the mussels, in a linear manner which was dependent on the water concentration, and then decreased rapidly when the mussels were returned to Mudginberri. (The biological half-life of uranium was approximately two days.) The concentrations of U in the soft parts of the mussel responded rapidly to increases and decreases in the water concentration of U. In the long-term studies, the uptake of U in the soft parts reached a maximum steady-state plateau which was related to the water concentration. These findings suggested that the U was in temporary stores, either in the body or adsorbed onto membrane surfaces.

The condition of the mussels, as gauged by either their mean dry weight or larval development status, reflected the water quality. In both Retention Pond Nos 2 and 4 adult mussels were able to survive although they lost weight in the former. However, the mussels were unable to develop larvae in Retention Pond No. 2 and showed only spasmodic larval development in Retention Pond No. 4. The implications are, therefore, that any escape of the water from either Retention Pond No. 2 or Retention Pond No. 4 at the height of the Wet season flow could possibly have short-term effects both on the U concentration in the soft parts of the mussels and the viability of mussel larvae in adjacent waterbodies. This would be dependent on the dilution factor. The Wet season is the only time of the year in which mussel larvae develop. If this development was impeded at such a crucial time in the life cycle it is possible that mussel populations would decrease in any affected billabongs. Thus, if natural waterbodies ever attained the water quality of these retention ponds of 1980-81, the mussel populations would ultimately die out due to lack of recruitment.

Enclosure studies

Gulungul Billabong. The mean Cu concentration in the soft parts of mussels placed in the enclosure for 60 hours and analysed immediately on removal was 8.5 μg Cu/g. This concentration was lower than that in the controls (11.0 μg Cu/g) and in those which were returned to Mudginberri for 72 hours (10.7 μg Cu/g) and in those purged in the laboratory for 48 hours (12.8 μg Cu/g) (Tables A59-A67 and Fig. 22).

The concentrations of Al, As, Ba, Ca, Cd and Mn showed differences among treatments. Cadmium, As and Ba concentrations were much lower in the controls than in the three test treatments; the concentrations in the latter were similar. The Al concentration in mussels returned to Mudginberri for 72 hours were much higher than the controls and the

two other test treatments. Calcium concentrations were higher in those mussels which were purged for 48 hours after exposure for 60 hours. The concentrations of Mn increased from 5.1 mg Mn/g in the controls to a maximum mean concentration of 8.3 mg Mn/g in treatment 4 (purged for 48 hours in the laboratory after exposure).

Mussels, because of their filter-feeding habit, would appear to be an appropriate organism to monitor elements when those elements are in both particulate (if the metals are biologically available) and in an ionic phase. Therefore, the most important of the determinations performed by Hart et al. (1982) is that for total Cu, which would include Cu on particulate matter as well as that in the ionic phase. The total Cu concentration increased to 17.8 μg Cu/L in the surface water after the addition of copper and rapidly decreased to 8.32 μg Cu/L (after 2 hours 20 minutes). The Cu rapidly disappeared from the water. A Cu budget was calculated (Hart et al. 1982) in which it was shown that 30-60% of the Cu was associated with aquatic plants (*Najas tenuifolia*), 15-20% was left in the water column and the remainder was presumably associated with other biota, sediments and the enclosure walls.

There were no significant differences ($P > 0.05$) among the Cu concentrations in the water across all treatments and no uptake of Cu by the mussels over the 60 hours of exposure to these conditions of elevated Cu water concentrations.

Island Billabong. The concentration of Cu in the soft parts of the one remaining mussel exposed to the Cu treatment was 42 μg Cu/g compared with 4-8 μg Cu/g in the soft parts of the control mussels and those exposed to increased concentrations of Mn and Zn.

The mean Mn concentration (3.16 mg Mn/g) in the soft parts of the mussels in the enclosure to which Mn and Zn had been added in combination was not significantly different ($P > 0.05$) from that of the control mussels (1.94-2.52 mg Mn/g) and of mussels in the Cu treatment (3.16 mg Mn/g). However, the mean Zn concentration in the soft parts of mussels in this enclosure was significantly different ($P < 0.05$) from mussels in the control billabong and control enclosure after 48 days but only marginally different from the mussels in the control enclosure after one month (Tables A69-A74). Although the concentrations of all three elements (Cu, Mn and Zn) in the water were elevated to ten-fold that of the ambient water concentrations, only the concentrations of Cu and Zn increased in the tissues of the mussels - Mn did not.

The ionic metals added to the enclosures became distributed into three main forms: ion-exchangeable, non-ion-exchangeable and particulate for Cu and Zn; and two forms for Mn, principally the particulate form and to a lesser degree the ion-exchangeable form. The non-ion-exchangeable form was always less than 0.3 μg/L (see Fig. A124).

As filter feeders, mussels draw large volumes of water across the gill surfaces, by means of ciliary action. Any particulate matter which adheres to the mucus layer on the gill surfaces is sorted there. Digestible particles are passed towards the labial palps and mouth. The rejected material is extruded from between the shells as pseudofaeces. Any metals associated with the particulate matter will be ingested and either absorbed or not, depending on their bioavailability.

It has been suggested that marine bivalves are good bioaccumulating monitors of pollutants when the elements are associated with particulate matter (Pentreath 1973; Bryan 1979). In this study 92% of the Mn, approximately 50% of the Zn and 23% of the Cu was present in the particulate form. Therefore, it would have been expected that all three elements, especially Mn, would have been taken up in the tissues, which was not the case. This situation may have arisen in three ways:

1. The Mn initially added to the enclosures was converted to MnO_2, on the particulates, possibly by bacteria, and then settled to form part of the sediment layer. This is

presently under investigation (Hart pers. comm.). Manganese dioxide is highly insoluble and is not likely to be biologically available, accounting for the lack of increase in the tissues.

2. The uptake of the elements was mostly by absorption of the ion-exchangeable form across the membrane surfaces; therefore there was little or no uptake of Mn, as the concentration of Mn in this form was so low.

3. The measured concentration of any element in the mussels' soft parts is the end result of uptake and excretion. Although rates of absorption may be almost directly proportional to levels of availability of the element in the water, there is no certainty that the concentrations finally achieved in the organism will be similarly related to the environment (Bryan 1979). This author reported at least three types of relationships between concentrations in organisms and the environment, which depend on the organisms' ability to excrete contaminants: (i) the rate of excretion is proportional to the body burden, (ii) the organism stores the contaminant rather than excreting it; and (iii) the organism excretes most of any additional input. If so, Cu and Zn may be accumulated according to either (i) or (ii) whereas Mn is not accumulated according to (iii).

Although it had been attempted to mix the Cu homogeneously throughout the water in the enclosure, it was likely that distribution throughout the water column occurred only eight to ten days after the Cu spike was added (Hart pers. comm.). Therefore, the Cu concentrations in the water around the mussels on days eight to ten were approximately 13 μg Cu/L (ion-exchangeable), 7 μg Cu/L (particulate) and 4 μg Cu/L (non-ion-exchangeable). The mean $\pm$ SD of the total Cu concentrations in the water of Island in the late Dry seasons of 1980 and 1981 were 0.8 $\pm$ 0.4 μg Cu/L and 2.2 $\pm$ 2.1 μg Cu/L respectively (Hart et al. 1985). Therefore, the mussels were exposed to a Cu concentration at least 11 times higher than the ambient concentration. The ion-exchangeable forms (i.e. the free ions) of Cu predominated (68%). It has been reported that free Cu ions are the most toxic to the biota (Spear & Pierce 1979; Miller & Mackay 1980). The toxicity of the element depends on its capacity to interfere with metabolic pathways. However, mussels have been shown to detoxify Cu and Zn (and other metals) by biochemical mechanisms - i.e. incorporation into inorganic granules (George et al. 1978) or binding with low molecular weight proteins e.g. metallothioneins (Olafson et al. 1979; Allison 1982).

4.8 Leichhardt mussel kill

Recent studies on the causes of fish kills in billabongs of the Magela Creek (Noller 1983; Morley et al. 1983) have suggested the following physico-chemical parameters to be of significance in such natural events: dissolved oxygen concentration, pH, conductivity, sulphate, dissolved organic carbon and, particularly, total and filtered Al. The importance of pH in determining the toxicity of Al has been stated by Odonnell et al. (1984) in their review of the toxicity of Al in freshwater. In the present study, mussels found floating on the surface of Leichhardt had higher concentrations of Al in the soft parts than had mussels sampled before and after the mussel kill (Table A75). Although the lengths of the dead mussels were much greater than those in the baseline samples, the dry weights were much less. It was likely that the mussels had died a number of days prior to being found and decomposition and the resulting production of gases caused the mussels to float to the surface. Only large mussels were found floating, possibly as a result of the fact that in smaller mussels the build-up of gases was not great enough to cause them to come to the surface. Therefore, the numbers of mussels found floating probably did not represent the total number which had died. In the early Wet season of 1981-1982, Morley et al. (1983) reported 25 dead mussels in Leichhardt while 40 dead mussels were found during surveys in the present study. These numbers represent the death of only 0.02% of the population in the billabong (Humphrey & Simpson in press).

Decomposition of the soft parts had reduced the mean dry weight to 0.5 g for mussels of mean length 79 mm compared to 2.29 g for mussels of mean length 66 mm in the baseline study. The mean dry weight for mussels of length 75 mm sampled on 24.12.80 was 3.4 g; therefore the dead mussels had decreased six-fold in their dry weight. If there was no reduction in Al load in the dead mussels during this six-fold decrease in weight, then the concentration would consequently increase six-fold. Thus, the high concentrations of Al in the dead mussels were largely due to loss in weight. Also, the concentrations of Ba, Ca, Cd, Cu, Mn, S, U, and Zn were all higher in the tissues of the dead mussels than in the healthy mussels sampled immediately prior to and after the mussel kill (Table A75). However, the concentrations of As, Hg, Mg, Pb and Se were similar to those in the healthy mussels. The reasons for non-relationship between weight and concentration for the latter five elements are unclear, although such factors as concentrations near detection limits (As, Hg and Se) and analytical variability (Pb) may have been influential. Also, the reciprocity between concentration and weight may be more obvious for those elements which are held in permanent stores (such as granules) and hence not readily released during weight loss or decomposition.

Morley et al. (1983) reported a mean concentration of 234 μg Al/g in the soft parts of 25 dead mussels taken from Leichhardt on 14.12.81. For live mussels from Island and Jabiluka sampled by Morley et al. (1983) at the end of the 1981 Dry season (immediately prior to the Leichhardt fish kill), there was a mean concentration of 68 μg Al/g. (Leichhardt was not sampled for concentrations in live mussels by Morley but a mean concentration of 62 μg Al/g was recorded in in the soft parts of mussels from Leichhardt in the present study in December 1981.) Morely et al. (1983) concluded that a combined Al/pH effect was probably the cause of death of the mussels although they made no allowances for the fact that there would have been a reduction in flesh weight caused by decomposition and a corresponding increase in Al concentrations. However there is evidence to suggest an association between soluble aluminium and fish deaths (Noller 1983).

4.9 Finniss River study

This study is an evaluation of the present levels of all 14 elements under investigation in the soft parts of *V. angasi* at 5 locations in the Finniss/East Finniss rivers area (Fig. 9). This catchment receives contaminated water each Wet season from the abandoned Rum Jungle Uranium Mine, located on the East Finniss River. The Finniss River has permanent flow from approximately 26 km upstream of the East Finniss confluence. However, the East Finniss flows only during and after the Wet season in the months December to June.

There is extensive mineralisation in the area (U, Cu, Co, Ni, Pb, and Mn) which led to a number of mines being opened: White's, Whites Extended, Dyson's, Mount Burton, Rum Jungle Creek South, Intermediate and Mount Fitch. The first mine commenced operation in 1953 and the last ceased in 1971. From 1960 onwards some small attempt was made to control the discharge of effluent. An environmental study was undertaken by the Australian Atomic Energy Commission in 1973-74 (Davy 1975) in which it was reported that the existing mine environment contributes a pollution load of approximately 50 tonnes of Cu, 50 tonnes of Mn and 20 tonnes of Zn per year to the Finniss River system during years of normal rainfall. The Department of Transport and Works, Water Division undertook a more recent study on the pollution loads in the water in the 1980-81 Wet season (Alcock & Johnston 1981). In the latter study, calculations were made on the loads of metals transported in the East Finniss River between January and February (periods of high discharge). From the start of flow on 18 December 1980 until the end of January 1981, 15.6 t of Cu, 1.8 t of Zn, 2.7 t of Mg and 540 t of SO_4 were transported down the East Finniss River. They found that about 50% of Mg was associated with the suspended material.

Figures A125-A127 show that female mussels from location 1 have higher concentrations of all elements in the soft parts than do males.

The locations were split into two groups: locations 1, 2 and 3 ('polluted') - billabongs which were downstream of any likely source of contamination and locations 4 and 5 upstream ('clean') - location 5 was in the Finniss River itself and location 4 was a billabong close by. Analyses of variance (Table A81) showed that there were very significant differences ($P < 0.001$) between sites. Between the 'clean' and 'polluted' locations there were very significant differences ($P < 0.001$) for all elements except Ca and Mg. Within the 'polluted' locations significant differences occurred for Al, As, Ba, Cu, Hg, Mg, Pb, Se, U and Zn ($P < 0.001$) and for Mn ($P < 0.01$). Calcium, Cd and S were not significantly different ($P > 0.05$). It can also be seen that even between the mussels from the 'clean' sites, i.e. billabong versus river site, significant differences ($P < 0.05$) existed for the elements Ba, Cu, Hg, Mn, and Pb.

Except for Hg in mussels from location 5, the concentrations were always highest in mussels from either location 1 or 2. Using the test of least significant differences (Fig. A128) an attempt can be made to deduce the relationships of elements in the mussels among the locations. The concentrations of elements in the soft parts of mussels from location 1 were either significantly ($P < 0.05$) different from all the others or were similar to those of location 2.

Discriminant analysis was applied to three combinations of the 5 sites: i) the clean sites only (5 and 6); ii) the 'polluted' sites only (1, 2, 3); and iii) all sites. Using this method, the two clean sites could be discriminated between on the basis of a combination of higher concentrations of Zn, Mn, Al and S and lower concentrations of Ca, Cu and Mg in mussels in location 4. The 'polluted' sites could be discriminated between using 2 functions. The first function separated location 1 from 2 and 3 on the basis of low concentrations of Mn and Cd, and high Ba, Pb, U and As. The second function separated location 2 from locations 1 and 3 on the basis of high concentrations of Cu and S and low concentrations of As and U.

Overall, it has been shown that mussels from different locations in the Finniss/East Finniss rivers catchment have significantly different element concentrations in their soft parts.

Alcock & Johnston (1981) have shown the existence of two pollution regimes; a first period of intermittent flow, with high acid and metal concentrations and a second period of continuous flow, with lower acid and metal concentrations. At these times, high concentrations of Cu, Zn, Mn and SO_4 are transported down the East Finniss River, which overflows into locations 1 and 2. The concentrations of these elements in the soft parts of the mussels were significantly higher at locations 1 and 2 than at locations 3, 4 and 5.

No data for the concentrations of the other elements in the water are available; therefore any relationships with the concentrations in mussel soft parts are speculative. The elements Al, As, Ba, Cd, Pb, Se and U also showed increased concentrations in the soft parts of the mussels at location 1. Therefore the concentrations of these elements were also likely to be high in the water.

The NH&MRC recommended levels for certain metals are given in Table A44. The soft parts of mussels from locations 1, 2 and 3 have concentrations of Pb in excess of the recommended level of 2.5 μg Pb/g wet weight (i.e. approx. 20 μg Pb/g dry weight). In the mussels from location 1 the mean Pb concentration was 210 μg Pb/g dry weight, over ten times the recommended level of Pb in foodstuff. Although the concentrations of other elements were somewhat high they did not exceed the recommended levels.

The range of concentrations of elements in the soft parts of mussels from the Finniss River region 'clean' sites were similar to those for mussels from the Magela Creek sites. For As, Cd, Cu, Se, and particularly Pb, mean concentrations in the mussels from the Finniss River region 'polluted' sites were significantly higher ($P < 0.05$) than those from Magela

Creek - although the result for Cu was marginal because of high concentrations in mussels from Gulungul which elevated the mean value. There were higher concentrations of Ba and U in mussels from both clean and polluted Finniss River sites, as against concentrations in mussels from Magela Creek sites - except for U in mussels from Georgetown where the concentrations were significantly higher ($P < 0.05$) than for mussels from other Magela Creek sites. The mean Al concentration in mussels from the polluted Finniss River sites were markedly higher than those for mussels from Magela Creek sites except for those from Goanna.

5 CONCLUSIONS

Variability

There was greater variability in chemical analyses than would be expected from present chemical technology. The extent of this variability is outlined in Allison & Simpson (1983). Determinations on standard reference material throughout the study enabled the identification of those cases which could be considered to be representative of the element concentrations in the mussels.

Effects of age

Differences in the element concentrations in the soft parts of the mussels in three billabongs were associated with differences in age, but these differences were not consistent among billabongs. For example, although the concentration of five of the elements determined were age dependent in mussels from Mudginberri, thirteen of the elements were aged dependent in mussels from Georgetown.

Effects of sex

The variance, as well as the measured concentrations, differed between sexes. In general, the greatest variation was exhibited in male mussels which, in most but not all cases, had the highest concentrations.

Effects of reproductive cycle of females

The stage of maturity in the reproductive cycle of females did not have a significant effect on the concentrations of the elements measured, primarily due to the seasonal nature of the female reproductive cycle.

Effects of condition

The concentrations of most elements did not change over the period of greatest change in weight of the mussels (i.e. from low to peak condition). This implied that the mussels took up and lost elements rapidly with gain and loss in body weight.

Use of particular organs

The uptake of elements differed among organs of the mussels. This may facilitate determinations of overall low concentrations for some elements in the body by analysing only those organs that showed the highest concentrations. However, the high risk of cross contamination between organs would be a distinct disadvantage. Also, the required dissections would greatly increase the work load.

Effect of substrate type

Different substrate types had no effect on the concentrations of the elements in the mussels within a billabong.

Effect of purging

Emptying the mussels of their gut contents by purging them for 48 hours did not significantly change the concentrations of elements (except for Al in one situation) nor reduce the variances (except for Cu in one situation) to warrant purging the mussels as part of a routine sampling method.

Effect on larval development

The survival of young (embryos and glochidia) was impeded when mussels were placed in Retention Pond No. 2 for six weeks. In Retention Pond No. 4 this also occurred over nine months. The normal development of glochidia quickly resumed when mussels were replaced into a natural waterbody.

Sample size

Determinations of elements in individual mussels were used to calculate sample sizes that would detect 10-20% differences between means. A sample size of 20 mussels was deemed to be appropriate.

Baseline

Differences in magnitude of element concentrations in the soft parts of the mussels were observed among billabongs in the baseline study. However, no marked seasonal trends were observed for the elements. The first flush of water through the system, one of the main limnological events of the year, did not cause any significant changes in the concentrations of the elements in the soft parts of the mussels. The ranges of concentrations of elements in the soft parts of the mussels in the present study showed close agreement with those found in three other studies in the Region.

Results from the present study firmly established a natural baseline for all fourteen elements in the soft parts of *V. angasi* throughout the Magela Creek system and also in Nourlangie and Cooper creeks.

Aboriginal diet

Over the course of the study the concentrations of none of the fourteen elements determined in the soft parts of mussels from Magela, Nourlangie and Cooper creeks exceeded NH&MRC standards for those elements in foodstuff. A minimum value for the annual amount of mussel soft parts eaten per person in 1980 and 1981 was calculated as 0.54 kg and 2.59 kg respectively.

Uptake and transplant studies

Changes in concentrations of elements in mussels in response to changes in ambient concentrations were ill-defined owing to wide analytical variation. Low levels of some elements may also have adversely affected the results. However, elevated levels of U in the water in the retention pond studies and elevated levels of Zn in the water in the enclosure studies caused significant uptake of these elements by the soft parts of the mussels. Also, on return to cleaner water, the mussels showed rapid loss of U from their soft parts.

Mussel kills

A small fraction (0.02%) of the mussels in Leichhardt Billabong died in December 1981 - January 1982. A major factor causing the high levels of some elements in the mussels was the decrease in weight caused by decomposition.

Finniss River study

Elevated levels of some elements still occurred in the soft parts of the mussels in billabongs immediately downstream of the point sources of pollution from the abandoned Rum Jungle and other mines. Lead concentrations were particularly high (and to a lesser degree those of As) in the mussel soft parts. Comparisons among concentrations in mussels both between Finniss River sites and between Finniss River and Magela Creek sites showed that mussels could be used to indicate sources of contamination.

Use of the mussel in a future monitoring program

A sample size of 20 mussels (with sexes combined and from the one size class - at least over 60 mm in length) should be sufficient to allow the detection of a 10-20% difference between means of concentrations of elements in the soft parts of mussels, from different sampling occasions (if proper analytical procedures are carried out). Further refinement on the detection of differences between mean concentrations would be possible by consideration of sampling for particular ages or sexes, for particular elements and for particular billabongs. At least a record of ages of mussels in a sample should be kept to later view the results in the light of any age versus concentration relationship. However, if a wide sampling regime (in terms of both locations and numbers of elements) is required, such further qualifications upon the sampling technique would greatly increase the effort and would require the collection of a larger number of mussels. This would have to be balanced against the objectives of any monitoring program.

Although recent studies on marine bivalves advocate transplanting mussels (in some form of enclosure) from the one population to areas to be monitored, we do not recommend this here where there are existing resident populations. This is because baseline levels for mussels in locations, throughout the Magela Creek system, that are likely to warrant monitoring have been included in this study. Also, transplanting, maintenance and checking of cages would require considerable effort - especially during the Wet season.

As yet we cannot confirm the mussels as providing a biological 'early warning' system for pollution. Attempts to assess the use of mussels in this way in uptake and transplant studies in the field were thwarted by analytical variation. However, at higher concentrations for two situations (U in retention ponds and Zn in the enclosure studies), there were signs that mussels could respond to, and indicate, raised environmental levels of pollutants. Further evidence in this regard was provided by the increased levels of some elements in the tissues of mussels downstream of point source pollution from abandoned mines in the Finniss River region.

We recommend further studies, in both the field and the laboratory, on the mussels' response to elevated concentrations of elements. The main purpose of such work would be to correlate the concentration of elements in the soft parts of mussels with measured concentrations in the water.

For a future monitoring program, a basic question would be when has a change in concentrations of elements occurred that is significantly higher than baseline concentrations and hence indicative of an unnatural change? Table A45 shows mean concentrations for all elements in mussels for each Magela Creek billabong in the study and purposely contains a number of sources of variability: results from three analytical facilities, across all seasons, different sample sizes, and determinations in males and females. The 'standard' mussel of

61-65 mm in length was used in most billabongs except in the floodplain billabongs and in Bowerbird and Goanna.

Thus, in any future monitoring program, a mean concentration (from a sampling method that allowed variation about the mean of that estimated) significantly higher than a mean concentration in Table A45 would suggest an unnatural change i.e. potential pollution.

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7 REFERENCES

Alcock, J.F. & Johnston, G. (1981). Project 129 Finniss River pollution study, 1980-81 Wet season. Water Division, Department of Transport and Works, Darwin.

Allison, H.E. (1982). The uptake and release of nickel and cadmium in the Black Lip oyster (*Saccostrea echinata*). M.Sc. thesis, James Cook University of North Queensland (unpublished).

Allison, H.E. & Simpson, R.D. (1983). The metal contents of the freshwater mussel, *Velesunio angasi*, in Magela Creek - analytical variability. Open File Record 25. Office of the Supervising Scientist for the Alligator Rivers Region.

Ayling, G.M. (1974). Uptake of cadmium, zinc, copper, lead and chromium in the Pacific oyster, *Crassostrea gigas*, grown in the Tamar River, Tasmania. *Wat. Res.* **8**, 729-738.

Bayly, I.A.E. & Lake, P.S. (1979). The use of organisms to assess pollution of fresh waters: a literature survey and review. Environmental Studies Series Publication No. 258. Victorian Ministry for Conservation.

Bayne, B.L. (1978). Mussel watching. *Nature* **275**, 87-88.

Bedford, J.W., Roelofs, E.W. & Zabik, M.J. (1968). The freshwater mussel as a biological monitor of pesticide concentrations in a lotic environment. *Limnol. Oceanogr.* **13**, 118-126.

Boyden, C.R. (1977). Effect of size upon metal content of shellfish. *J. Mar. Biol. Ass. U.K.* **57**, 675-714.

Boyle, P.R. (1981). Molluscs and man. The Institute of Biology's Studies in Biology No. 134. Edward Arnold, London.

Bronmark, C. & Malmqvist, B. (1982). Resource partitioning between unionid mussels in a Swedish lake outlet. *Holarc. Ecol.* **5**, 389-395

Bryan, G.W. (1968). Concentrations of zinc and copper in the tissues of decapod crustaceans. *J. Mar. Biol. Ass. U.K.* **48**, 303-321.

Bryan, G.W. (1971). The effects of heavy metals (other than mercury) on marine and estuarine organisms. *Proc. R. Soc. Lond.* B 177, 389-410.

Bryan, G.W. (1979). Bioaccumulation of marine pollutants. *Phil. Trans. R. Soc. Lond. B.* **286**, 483-505.

Burns, K.A. & Smith, J.L. (1981). Biological monitoring of ambient water quality: the case for using bivalves as sentinel organisms for monitoring petroleum pollution in coastal waters. *Estuar. Coast. Shelf Sci.* **13**, 433-443.

Butler, P.A., Andrew, L., Bonde, G.J., Jernelov, A. & Reish, D.J. (1971). Monitoring organisms, *in* 'FAO technical conference on marine pollution and its effects on living resources and fishing. Suppl. 1: methods of detection, measurement and monitoring of pollutants in the marine environment'. FAO Fisheries Reports No. 99, pp. 101-102. Rome, 1970.

Cairns, J., Jr. (1979). Biological monitoring - concept and scope, *in* J. Cairns, Jr., G.P. Patil & W.E. Waters (eds), 'Environmental biomonitoring, assessment, prediction and management - certain case studies and related quantitative issues', pp. 3-20. International Co-operative Publishing House, Fairland.

Cairns, J., Jr & Van der Schalie, W.H. (1980). Biological monitoring. Part I - early warning systems. *Wat. Res.* **14**, 1179-1196.

Campbell, I.C. (1982). Biological water quality monitoring: an Australian viewpoint, *in* B.T. Hart (ed.), 'Water quality management', pp. 39-66. Chisholm Institute of Technology and Australian Society for Limnology, Melbourne.

Capuzzo, J.M., Moore, M.N. & Widdows, J. (1988). Effects of toxic chemicals in the marine environment : predictions of impacts from laboratory studies. *Aquatic Toxicology* **11**, 303-311.

Carter, M.W. (1983). Critical paths and critical people, *in* 'Environmental Protection in the Alligator Rivers Region', Supervising Scientist for the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol II, No. 77, 14 pp.

Ch'ng-Tan, K.S. (1968). Some aspects of renal and excretory physiology in the Australian freshwater mussel, *Velesunion ambiquus* (Philippi) (Mollusca, bivalvia). Ph.D. thesis, Monash University.

Cossa, D., Bourget, E., & Piuze, J. (1979). Sexual maturation as a source of variation in the relationship between cadmium concentration and body weight of *Mytilus edulis* L. *Mar. Pollut. Bull.* **10**, 174-176.

Davey, G.W. (1980). The use of biological parameters for the assessment of water quality - a literature review, Environment Protection Authority of Victoria, Publication 99.

Davy, D.R. (ed.) (1975). Rum Jungle Environmental Studies. AAEC, Lucas Heights.

Davy, D.R. & Conway, N.F. (1974). Environmental studies, Northern Territory Uranium Province, 1971-73. Report III *in* P.J.F. Newton (ed.), 'The Alligator Rivers Area Fact

Finding Study. Four AAEC Reports'. Report E305, Australian Atomic Energy Commission. AAEC, Sydney.

Elliott, J.M. (1979). Some methods for the statistical analysis of samples of benthic invertebrates. Scientific Publication No. 25, Freshwater Biological Association, U.K.

Forester, A.J. (1980). Monitoring the bioavailability of toxic metals in acid-stressed shield lakes using pelecypod molluscs (clams, mussels), *in* D.D. Hemphill (ed.), 'Trace substances in environmental health'- XIV, pp. 142-147. University of Missouri, Columbia.

Foster, R.B. & Bates, J.M. (1978). Use of freshwater mussels to monitor point source industrial discharges. Environ. Sci. Technol. **12**, 958-962.

Friberg, L. (ed.) (1979). Handbook on the toxicology of metals. Elsevier/North Holland Biomedical Press.

Friedrich, A.R. & Filice, F.P. (1976). Uptake and accumulation of the nickel ion by *Mytilus edulis*. *Bull. Environ. Contam. Toxicol.* **16**(6), 750-755.

George, S.G., Pirie, B.J.S., Cheyne, A.R., Coombs, T.L. & Grant, P.T. (1978). Detoxification of metals by marine bivalves: an ultrastructural study of the compartmentation of copper and zinc in the oyster *Ostrea edulis*. *Mar. Biol.* **45**, 147-156.

George, S.G., Coombs, T.L. & Pirie, B.J.S. (1982). Characterization of metal-containing granules from the kidney of the common mussel, *Mytilus edulis*. *Biochimica et Biophysica Acta.* **716**, 61-71.

Goldberg, E.D. (1975). The mussel watch - a first step in global marine monitoring. *Mar. Pollut. Bull.* **6**, 111.

Goldberg, E.D., Bower, V.T., Farrington, J.W., Harvey, G., Martin, J.H., Parker, P.L., Risebrough, R.W., Robertson, W., Schneider, E. & Gamble, E. (1978). The mussel watch. *Environ. Conserv.* **5**, 101-125.

Gordon, M., Knauer, G.A., & Martin, J.H. (1980). *Mytilus californianus* as a bioindicator of trace metal pollution: variability and statistical considerations. *Mar. Pollut. Bull.* **11**, 195-198.

Guary, J.C. & Negrel, R. (1981). Calcium phosphate granules: a trap for transuranics and iron in crab hepatopancreas. *Comp. Biochem. Physiol.* **68**, 423-427.

Hammond, L.S. (1982). A review and evaluation of Australian and New Zealand data on *Mytilus edulis* L. (Mollusca, Bivalvia, Mytilidae) relevant to use of the species as a biological indicator of environmental pollution by heavy metals. Report for Biological Indicator Systems Program, October 1982, 38 pp.

Harris, J.E., Fabris, G.J., Statham, P.J., & Tawfik, F. (1979). Biogeochemistry of selected heavy metals in Western Port, Victoria, and use of invertebrates as indicators with emphasis on *Mytilus edulis plantus*. *Aust. J. Mar. Freshw. Res.* **30**, 159-178.

Hart, B.T., Jones, M.J., & Breen, P. (1982). *In situ* experiments to determine the uptake of copper by the aquatic macrophyte *Najas tenuifolia*. Technical Memorandum 11, Supervising Scientist for the Alligators Rivers Region. Australian Government Publishing Service, Canberra.

Hart, B.T., Jones, M.J. & Bek, P. (1983). Behaviours of trace metals added to billabongs, *in* 'Environmental protection in the Alligator Rivers Region'. Supervising Scientist for the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol. II, No. 69, 12 pp.

Hart, B.T., Currey, N.A., Jones, M.J. (1985). Fate of trace metals in Magela Creek system, Northern Australia: experiments involving the addition of copper, manganese and zinc to plastic enclosures placed in Island Billabong. Report to: Supervising Scientist, Department of Home Affairs and Environment. Technical Report No. 24, Water Studies Centre, Chisholm Institute Of Technology. Studies Centre, Technical Report No. 24.

Haug, A., Melson, S. & Omang, S. (1974). Estimation of heavy metal pollution in Norwegian fjord areas by analysis of the brown alga *Ascophyllum nodosum*. *Environ. Pollut.* 7, 173-193.

Herricks, E.E. & Cairns, J., Jr. (1982). Biological monitoring. Part III - receiving system methodology based on community structure. *Wat. Res.* **16**, 141-153.

Hespe, E.D. (1983). On the quantitative assessment of impact, *in* 'Environmental protection in the Alligator Rivers Region', Supervising Scientist for the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol. II, No. 84, 8 pp.

Humphrey, C.L. & Simpson, R.D. (In press). Biology and ecology of the freshwater mussel, *Velesunio angasi*, in the Magela Creek, Alligator Rivers Region, N.T. Research Report No 5, Supervising Scientist for the Alligator Rivers Region. Australian Government Publishing Service.

Jones, W.G. & Walker, K.F. (1979). Accumulation of iron, manganese, zinc and cadmium by the Australian freshwater mussel *Velesunio ambiquus* (Phillippi) and its potential as a biological monitor. *Aust. J. Mar. Freshw. Res.* **30**, 741-751.

Jeffree, R.A. & Simpson, R.D. (1986). An experimental study of the uptake of Ra-226 by the tissue of the tropical freshwater mussel *Velesunio angasi* (Sowerby) under varying Ca and Mg water concentrations. *Hydrobiologia* **139**, 59-80.

Klump, D.W. & Burdon-Jones, C. (1982). Investigations of the potential of bivalve molluscs as indicators of heavy metal levels in tropical marine waters. *Aust. J. Mar. Freshw. Res.* **33**, 285-300.

Latouche, Y.D. & Mix, M.C. (1981). Seasonal variation in soft tissue weights and trace metal burdens in the bay mussel, *Mytilus edulis*. *Bull. Environ. Contam. Toxicol.* **27**, 821-828.

Latouche, Y.D. & Mix, M.C. (1982). The effects of depuration, size and sex on trace metal levels in bay mussels. *Mar. Pollut. Bull.* **13**, 27-29.

Lobel, P.B. & Wright, D.A. (1982*a*). Gonadal and nongonadal zinc concentrations in mussels. *Mar. Pollut. Bull.* **13**, 320-323.

Lobel, P.B. & Wright, D.A. (1982*b*). Relationship between body zinc concentration and allometric growth measurements in the mussel *Mytilus edulis*. *Mar. Biol.* **55**, 145-150.

Lobel, P.B. & Wright, D.A. (1982*c*). Total body zinc concentration and allometric growth ratios in *Mytilus edulis* collected from different shore levels. *Mar. Biol.* **66**, 231-236.

Lobel, P.B., Mogie, P., Wright, D.A., & Wu, B.L. (1982). Metal accumulation in four molluscs. *Mar. Pollut. Bull.* **13**, 170-174.

Lord, D.A., Breck, W.G. & Wheeler, R.C. (1975). Trace elements in molluscs in the Kingston Basin, *in* 'Water quality parameters', American Society for Testing and Materials. Special Technical Publication No. 573, 95-111.

Mackay, N.J., Williams, R.J., Kacprzac, J.L., Kazacos, M.N., Collins, A.J. & Auty, E.H. (1975). Heavy metals in cultivated oysters (*Crassostrea commercialis = Saccostrea cucullata*) from the estuaries of New South Wales. *Aust. J. Mar. Freshw. Res.* **26**, 31-46.

Manly, R. & George, W.O. (1977). The occurrence of some heavy metals in populations of the freshwater mussel *Anodonta anatina* (L.) from the River Thames. *Environ. Pollut.* **14**, 139-154.

Matthews, R.A., Buikema, A.L., Cairns, J., Jr. & Rodgers, J.H. Jr. (1982). Biological monitoring. Part IIA - receiving system functional methods, relationships and indices. *Wat. Res.* **16**, 129-139.

Miller, T.G. & Mackay, W.C. (1980). The effects of hardness, alkalinity and pH of test water on the toxicity of copper to rainbow trout (*Salmo gairdeneri*). *Wat. Res.* **14**, 129-133.

Morley, A.W., Koontz, D.V., Sanderson, N.T. & Spratt, W. (1983). Fish kills in the Magela Creek, *in* 'Environmental protection in the Alligator Rivers Region', Supervising Scientist for the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol. II, No. 62, 8 pp.

National Academy of Sciences, (1980). The international mussel watch. National Academy of Sciences, Washington, D.C., U.S.A.

Noller, B.N. (1983). Physico-chemical aspects of natural fish kills on the Magela Creek system, *in* 'Environmental protection in the Alligator Rivers Region.' Supervising Scientist for the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol. II, No. 61, 15 pp.

Noranda Australia Limited. (1978). Koongara Project. Draft Environmental Impact Statement. Noranda Australia Ltd, Melbourne.

Odonnell, A.R., Mance, G. & Norton, R. (1984). A review of the toxicity of aluminium in freshwater. Technical Report No. 197, Water Research Centre, Marlow, England.

Olafson, R.W., Kearns, A. & Sim, R.G. (1979). Heavy metal induction of metallothionein synthesis in the hepatopancreas of the crab *Scylla secrata*. *Comp. Biochem. Physiol* **62B**, 417-424.

Orren, M.J., Eagle, G.A., Hennig, H.F-K.O., & Green, A. (1980). Variations in trace metal content of the mussel *Choromytilus meridionalis* (Kr.) with season and sex. *Mar. Pollut. Bull.* **11**, 253-257.

Pancontinental Mining Limited. (1981). Chapter 10 - Trace metal analysis of the freshwater mussel, *in* 'A review of Jabiluka environmental studies'. Pancontinental Mining Ltd, Sydney.

Pentreath, R.J. (1973). The accumulation from water of ^{65}Zn, ^{54}Mn, ^{58}Co, ^{59}Fe by the mussel, *Mytilus edulis*. *J. Mar. Biol. Ass. U.K.* **53**, 127-147.

Phelps, D.K., Thurberg, F.P., Gould, E., & Dawson, M.A. (1981). Comparison of several physiological monitoring techniques as applied to the blue mussel, *Mytilus edulis*, along a gradient of pollutant stress in Narragansett Bay, Rhode Island, *in* F.J. Vernberg,

A. Calabrese, F.P. Thurberg & W.B. Vernberg (eds), Biological monitoring of marine pollutants, pp. 335-355. Academic Press, New York.

Phillips, D.J.H. (1976). The common mussel *Mytilus edulis* as an indicator of pollution by zinc, cadmium, lead and copper. I. Effects of environmental variables on uptake of metals. *Mar. Biol.* **38**, 59-69.

Phillips, D.J.H. (1977). The use of biological indicator organisms to monitor trace metal pollution in marine and estuarine environments - a review. *Environ. Pollut.* **13**, 281-318.

Phillips, D.J.H. (1980). Quantitative aquatic biological indicators. Applied Science Publishers Ltd., London.

Popham, J.D., Johnson, D.C. & D'Auria, J.M. (1980). Mussels (*Mytilus edulis*) as 'point source' indicators of trace metal pollution. *Mar. Pollut. Bull.* **11**, 261-263.

Rand, G.M. & Petrocelli, S.R. (1985). Fundamentals of aquatic toxicology. Hemisphere Publishing Corp., Washington.

Renzoni, A. & Bacci, E. (1976). Bodily distribution, accumulation and excretion of mercury in a freshwater mussel. *Bull. Env. Contam. Toxicol.* **15**, 366-373.

Ritz, D.A., Swain, R. & Elliot, N.G. (1982). Use of the mussel *Mytilus edulis planatus* (Lamarck) in monitoring heavy metals in seawater. *Aust. J. Mar. Freshw. Res.* **33**, 491-506.

Schulz-Baldes, M. (1974). Lead uptake from sea water and food, and lead loss in the common mussel *Mytilus edulis*. *Mar. Biol.* **25**, 177-193.

Sill, C.W. (1976). Problems in sample treatment in trace analysis, *in* P.D. La Fleur (ed.), 'Accuracy in trace analysis: sampling, sample handling, and analysis', Proc. 7th IMR Symposium, Oct. 1974, Gaithersburg, Md, pp. 463-490. US Dept of Commerce.

Simkiss, K. (1976). Intracellular and extracellular routes in biomineralisation, *in* J.C. Duncan (ed.), 'Calcium in biological systems', pp. 423-444. Cambridge University Press, Cambridge.

Simkiss, K., Taylor, Marina & Mason, A.Z. (1982). Metal detoxification and bioaccumulation in molluscs. *Mar. Biol.Letters* **3**, 187-201.

Simpson, R.D. (1979). Uptake and loss of zinc and lead by mussels (*Mytilus edulis*) and relationships with body weight and reproductive cycle. *Mar. Pollut. Bull.* **10**, 74-78.

Simpson, R.D. (1982). The use of biological monitors. Ecotoxicology Symposium, Australian Academy of Sciences, Canberra.

Simpson, R.D. (1983). The role of aquatic biological monitors - with particular reference to the Alligator Rivers Region, *in* 'Environmental protection in the Alligator Rivers Region', Supervising Scientist of the Alligator Rivers Region, Scientific Workshop, Jabiru, N.T., May 1983. Vol. II, No. 59, 12 pp.

Smith, A.L., Green, R.H., & Lutz, A. (1975). Uptake of mercury by freshwater clams (Family Unionidae). *J. Fish. Res. Board. Can.* **32**, 1297-1303.

Spear, P.A. & Pierce, R.C. (1979). Copper in the aquatic environment: chemistry, distribution and toxicology, National Research Council of Canada - NRCC Associate Committee of Scientific Criteria for Environmental Qualtity.

Talbot, V. & Chegwidden, A. (1982). Cadmium and other heavy metal concentrations in selected biota from Cockburn Sound, Western Australia. *Aust. J. Mar. Freshw. Res.* **33**, 779-788.

Walker, T.D. & Tyler, P.A. (1982). Chemical characteristics and nutrient status of billabongs of the Alligator Rivers Region, N.T. Australian Government Publishing Service, Canberra, 1982.

Ward, T.J. (1976). Accumulation and effects of cadmium in the oyster *Crassostrea commercialis*. Ph.D thesis, Australian National University.

Ward, T.J. (1982). Effect of cadmium on particle clearance by the Sydney Rock Oyster, *Saccostrea commercialis* (I. & R.). *Aust. J. Mar. Freshw. Res.* **33**, 711-715.

Williams, W.D. (1980). Biological monitoring, *in* W.D. Williams (ed.) 'An ecological basis for water resource management', Chapter 19. ANU Press, Canberra.

Wright, D.A. (1977*a*). The uptake of cadmium into the haemolymph of the shore crab *Carcinus maenas*: the relationship with copper and other divalent cations. *J. Exp. biol.* **67**, 147-161.

Wright, D.A. (1977*b*). The effect of calcium on cadmium uptake by the shore crab *Carcinus maenas*. *J. Exp. Biol.* **67**, 163-173.

APPENDIX 1

TABLES

Table A1. Locations in Nourlangie, Cooper and Magela creeks sampled for baseline study

Name	Map No.	Grid Ref.	
Nourlangie Creek			
Long Harry's	5472	259 600	857 6200
Creek upstream of Graveside	5371	236 500	853 1400
Cooper Creek			
Gunirdul	5573	319 700	864 8500
Nimbuwah	5573	290 700	865 0500
Murganella	5573	319 900	865 0500
Magela Creek			
Creek below Bowerbird	5572	288 000	858 6600
Georgetown	5472	275 250	859 6250
Gulungul	5472	270 050	860 2650
Goanna	5472	269 100	860 0150
Corndorl	5472	268 750	850 3250
Gundur	5472	269 200	860 4200
Creek between Mudginberri and Corndorl	5472	269 500	860 6100
Mudginberri	5472	269 150	860 7000
Island	5472	269 600	861 0750
Ja Ja (NE)	5472	270 100	861 5000
Leichhardt	5473	267 500	862 1400
Jabiluka	5473	269 000	862 0750
Nankeen	5473	267 500	862 5400

Table A2. AMDEL - analyses of reference materials as a check for contamination

Concentrations are in μg/g or mg/g(*). Determination 1 - ICPAES; determination 2 - AAS

	NBS SRM 1577 Bovine liver					NBS SRM 1571 Orchard leaves					Fish Meal Standard				
	Not homogenised Determination		Homogenised Determination		Cert. value	Not homogenised Determination		Homogenised Determination		Cert. value	Not homogenised Determination		Homogenised Determination		Value[a]
	1	2	1	2	(2 SD)	1	2	1	2	(2 SD)	1	2	1	2	(2 SD)
Al	< 100		< 100		-	300		300		-	< 100		< 100		
As	< 0.2		< 0.2		0.055 (0.005)	2.3		2.4		10 (2)	2.1		2.1		
Ca*	< 0.50		< 0.5		0.012 (0.006)	25.5		26.6		20.9 (0.3)	3.20		3.70		
Cd	1.7		0.3		0.27 (0.04)	< 0.2		0.2		0.11 (0.01)	< 0.1		0.2		< 0.15
Cr	1.3		2.5		0.088 (0.012)	2.5		3.8		2.6 (0.3)	2.5		2.5		< 0.9
Cu	55	100	55	100	193 (10)	8		8		12 (3)	3		3		2.23 (0.47)
Hg	0.035		0.028		0.016 (0.002)	0.131		0.141		0.155 (0.015)	1.75		1.56		
Mg*	0.9	0.61	0.8	0.53	0.60 (0.9)	9.0		9.1		6.2 (0.2)	3.00		2.90		
Mn*	< 0.1		< 0.1		0.01 (0.001)	0.1		0.1		0.09 (0.004)	< 0.10		< 0.1		< 0.01
Pb	< 1		< 1		0.34 (0.08)	9	40	10	40	45 (3)	< 1		< 1		< 1.0
S*	27.0		26.0			7.0		6.5		1.9**	33.5		35.0		
Se	0.6		0.6		1.1 (0.1)	< 0.2		< 0.2		0.08 (0.01)	3.6		4.0		
U										0.029 (0.005)					
Zn	260		240		130 (13)	25		25		25 (3)	30		25		24.3 (0.2)

** non-certified value

[a] determination by Dr B Noller (OSS) (n = 3)

Table A3. Enclosure experiments in Island Billabong

Study lasted 11 weeks (15.9.81-28.11.81). Metals were added to the enclosures one month after they had been placed in the billabong.

Cage no.	Addition of metals	Treatment
1	Yes	Enclosure 1: Cu to 10 times natural concentration
2	Yes	Enclosure 2: Mn and Zn to 10 times natural concentration
3	No	Enclosure 3: control
4		Billabong control

Table A4. Sampling locations in Finniss/East Finniss river

Map no.	Grid ref.		Code no.	Description
5072	710 600	856 7000	1	Billabong on east bank of Finniss R., 1 km downstream of confluence with East Finniss River
5072	711 200	856 5500	2	Billabong on west bank of Finniss R., 0.5 km upstream of confluence East Finniss River (locally known as Hanna's Pool)
5072	712 800	856 5200	3	Billabong south of Mt Burton on east bank of Finniss River, 0.5 km downstream from drainage from Mt Burton Mine overburden heap
5071	714 400	855 5200	4	Billabong on west bank of Finniss R., upstream from drainage areas of mines.
5071	714 600	855 4800	5	River location on Finniss R., 0.3 km upstream from location 4

Table A5. OSS - precision and accuracy data for certified reference materials

Precision = % relative standard deviation; accuracy = % relative error; n = no. of determinations.

Metal	Technique	Certified Value	n	Mean ± SD	Precision	Accuracy
<u>NBS SRM 1566 'Oyster tissue'</u>						
Calcium (%)	Flame AAS Diluted 1:100 in 10% HNO_3 + 1000 µg/mL Cs/La	0.15 ± 0.02	21	0.16 ± 0.02	12.5	6.7
Magnesium (%)	Flame AAS Diluted 1:100 in 10% HNO_3 + 1000 µg/mL Cs/La	0.128 ± 0.009	20	0.115 ± 0.004	3.5	10.2
Zinc (µg/g)	Flame AAS Diluted 1:100 in 10% HNO_3 + 1000 µg/mL Cs/La	852 ± 14	20	884 ± 87	10	4
Manganese (µg/g)	Flame AAS	17.2 ± 1.2	21	19.1 ± 0.5	2.6	9.1

Table A5. cont.

Metal	Technique	Certified Value	n	Mean ± SD	Precision	Accuracy
Copper (μg/g)	Flame AAS	63.0 ± 3.5	18	61.7 ± 1.6	2.5	2.1
	Graphite Furnace AAS Diluted 1:100 Direct Calibration	63.0 ± 3.6	16	56.0 ± 2.7	4.8	11.1
	Graphite Furnace AAS Diluted 1:100 Standard Addition	63.0 ± 3.5	16	55.3 ± 4.7	8.5	12.2
Cadmium (μg/g)	Flame AAS	3.5 ± 0.4	18	3.1 ± 0.2	6.5	11.4
	Graphite Furnace AAS Diluted 1:10 Direct Calibration	3.5 ± 0.4	18	3.8 ± 0.6	15.8	8.6
	Graphite Furnace AAS Diluted 1:10 Standard Addition	3.5 ± 0.4	15	2.5 ± 0.9	36.0	28.6
Lead (μg/g)	Graphite Furnace AAS Diluted 1:10 Standard Addition	0.48 ± 0.04	19	0.50 ± 0.21	42.0	45.6
Iron (μg/g)	Flame AAS	195 ± 34	5	202 ± 8	4	4
Nickel (μg/g)	Flame AAS	1.03 ± 0.19	5	1.5 ± 0.6	40.0	45.6
NBS SRM 1577 'Bovine liver'						
Copper (μg/g)	Graphite Flame AAS Diluted 1:100 Standard Addition	193 ± 10	18	191 ± 39	20	1
Cadmium (μg/g)	Graphite Furnace AAS Diluted 1:10 Standard Addition	0.27 ± 0.04	9	0.28 ± 0.03	10.7	3.7
Lead (μg/g)	Graphite Furnace AAS Diluted 1:10 Standard Addition	0.34 ± 0.08	50	0.37 ± 0.19	51.4	8.8
NBS SRM 1571 'Orchard leaves'						
Strontium (μg/g)	Flame AAS Microsampling Mode 2000 μg/mL K	37 ± 1	16	31 ± 3	10	16
Barium (μg/g)	Flame AAS Microsampling Mode 2000 μg/mL K	(44) (not certified)	12	57 ± 4	7	(30)

Table A6. OSS - precision within batch on four OSS mussel reference materials (dry) - from Noller (1983)

Undertaken during methodological evaluation. Figures given are the mean ± SD; n = the number of results. CV is given in brackets.

	Reference material							
Element (dry wt)	1	n	2	n	3	n	4	n
Calcium %	2.49 ± 0.057 (2.3%)	5	3.64 ± 0.10 2.7%)	5	2.04 ± 0.06 (2.9%)	5	2.22 ± 0.05 (2.3%)	5
Magnesium %	0.141 ± 0.004 (2.8%)	5	0.134 ± 0.002 (1.5%)	5	0.093 ± 0.002 (2.2%)	5	0.133 ± 0.002 (1.5%)	5
Manganese %	0.411 ± 0.012 (2.9%)	5	0.535 ± 0.008 (1.5%)	5	0.343 ± 0.006 (1.7%)	5	0.384 ± 0.007 (1.8%)	5
Zinc (μg/g)	314 ± 8 (3%)		395 ± 16 (4%)	5	329 ± 14 (4%)	5	280 ± 9 (3%)	5
Copper (μg/g)	11.1 ± 0.3 (2.7%)	5	5.9 ± 0.3 (5.1%)	5	4.0 ± 0.1 (2.5%)	5	10.9 ± 0.6 (5.5%)	5
Cadmium (μg/g)	0.53 ± 0.09 (17%)	8	0.42 ± 0.08 (19%)	10	0.48 ± 0.05 (10.4%)	8	0.71 ± 0.17 (23.9%)	11
Lead (μg/g)	11.6 ± 3.2 (27.6%)	12	15.8 ± 5.5 (34.8%)	25	10.6 ± 2.8 (26.4%)	13	8.8 ± 1.5 (17.0%)	15
Barium %	0.024 ± 0.003 (12.5%)	5	0.033 ± 0.005 (15.2%)	5	0.025 ± 0.002 (8%)	5	0.031 ± 0.002 (6.5%)	5
Strontium %	0.024 ± 0.003 (12.5%)	7	0.052 ± 0.005 (9.6%)	5	0.028 ± 0.002 (17.1%)	5	0.020 ± 0.001 (5%)	5

Table A7. OSS - precision between batch on four OSS mussel reference materials (dry) - from Noller (1983)

Figures given are the mean ± SD; n = the number of results. CV is given in brackets.

	Reference material							
Element (dry wt)	1	n	2	n	3	n	4	n
Calcium %	2.35 ± 0.16 (6.8%)	15	3.44 ± 0.21 (6.1%)	18	1.84 ± 0.19 (10.3%)	18	2.09 ± 0.15 (7.2%)	15
Magnesium %	0.135 ± 0.008 (5.9%)	16	0.127 ± 0.008 (6.3%)	20	0.090 ± 0.006 (6.7%)	18	0.133 ± 0.010 (7.5%)	15
Zinc (μg/g)	239 ± 30 (10%)	16	375 ± 26 (7%)	18	322 ± 23 (7%)	19	281 ± 24 (9%)	15
Copper (μg/g)	10.5 ± 1.2 (11.4%)	16	6.1 ± 0.4 (6.6%)	14	4.5 ± 0.6 (13.3%)	11	10.2 ± 1.5 (14.7%)	15
Cadmium (μg/g)	0.82 ± 0.22 (26.8%)	14	0.60 ± 0-15 (25%)	176	0.62 ± 0.19 (30.6%)	17	0.96 ± 0.24 (25%)	13
Lead (μg/g)	10.0 ± 4.2 (41.6%)	14	11.3 ± 5 (35.4%)	16	9.8 ± 4.6 (46.9%)	14	9.2 ± 2.4 (26.2%)	13
Barium %	0.05 ± 0.04 (80%)	14	0.07 ± 0.09 (129%)	17	0.07 ± 0.07 (100%)	19	0.07 ± 0.05 (71.4%)	13

Table A8. Accuracy of results by AMDEL based on concealed NBS SRM 1577 (Bovine liver) and 1571 (Orchard leaves)

	Accuracy (%)			
	NBS SRM 1577 Determination no.		NBS SRM 1571 Determination no.	
	1	2	1	2
As	-	-	77	-
Ca	-	-	22	-
Cd	530	-	4	-
Cu	72	48	33	-
Hg	119	-	15	-
Mg	50	2	45	-
Pb	-	-	80	11
S	4	-	268*	-
Se	45	-	-	-
Zn	100	-	0	-

* Accuracy based on a non-certified value but included as a guide

Data based on results shown in Table A3 for not homogenised material

$$\text{Accuracy} = \frac{\text{Observed - Expected}}{\text{Expected}} \times 100$$

Table A9. Concentrations of elements in two replicates of five samples analysed by SGS (S) and AMDEL (A)

Concentrations are in µg/g or mg/g(*) dry weight

		Replicate Group 1					Replicate Group 2				
Sample No.		1	2	3	4	5	1	2	3	4	5
As	S	1.2	1.5	1.4	1.1	1.0	1.2	1.1	0.9	1.4	1.0
	A	1.0	1.0	0.9	0.9	0.9	0.8	0.7	0.7	0.9	0.8
Ca*	S	0.10	0.93	0.75	0.85	0.88	0.32	0.30	0.25	0.26	0.19
	A	3.56	2.87	2.34	2.71	2.66	0.96	0.90	0.69	0.74	0.53
Cd	S	0.6	0.4	0.4	0.6	0.7	0.8	0.2	0.3	0.3	0.6
	A	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.2
Cu	S	3.7	4.4	4.2	3.8	3.0	9.7	2.7	2.1	2.1	2.4
	A	8.0	8.0	8.0	8.0	5.0	5.0	5.0	5.0	5.0	5.0
Mg*	S	0.58	0.60	0.60	0.60	0.62	0.44	0.40	0.39	0.36	0.34
	A	1.30	1.40	1.30	1.40	1.40	0.80	0.80	0.70	0.70	0.60
Mn*	S	0.086	0.098	0.081	0.086	0.091	0.075	0.070	0.058	0.053	0.038
	A	0.23	0.26	0.22	0.23	0.24	0.22	0.19	0.16	0.15	0.11
Pb	S	1.9	0.7	1.9	1.0	1.7	3.8	4.9	5.9	6.4	5.9
	A	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
S*	S	0.60	0.76	1.17	0.73	0.56	0.99	0.63	0.58	0.76	0.85
	A	1.00	1.00	1.10	0.95	0.95	1.00	0.90	0.90	0.90	0.90
Se	S	1.5	1.3	2.4	1.6	1.2	0.7	1.6	1.1	1.9	1.5
	A	0.8	0.4	0.2	0.2	0.4	0.2	1.6	0.2	0.1	0.1
U	S	0.46	0.28	0.18	0.18	0.46	0.18	4.87	0.28	0.09	0.37
	A	0.2	0.2	0.3	0.3	0.3	0.2	1.6	0.2	0.1	0.1
Zn	S	148	148	140	133	138	93	101	85	91	100
	A	410	400	380	380	390	250	260	240	260	260

Table A10. Summary of analyses of variances between SGS and AMDEL on two replicates of five samples

NS - $P > 0.05$; * - $P < 0.05$; ** - $P < 0.01$

Source	Al	As	Ba	Ca	Cd	Cu	Hg	Mg	Mn	Pb	S	Se	U	Zn
Homogeneity of errors between samples	-	NS	-	NS	NS	NS	-	**	NS	NS	NS	NS	*	**
Between companies	-	**	-	**	*	*	-	**	**	**	*	**	NS	**
Between groups	-	NS	-	**	NS	NS	-	**	**	**	NS	NS	NS	**
Company by group interaction	-	NS	-	**	NS	NS	-	**	NS	**	NS	NS	NS	**

Table A11. Sample size required to estimate a 10% and 20% difference between means ($P < 0.05$) based on mussels aged seven years from Georgetown

Females - original mean and variance was calculated on sample size of 12; males - original mean and variance was calculated on sample size of 13

	Females		Males	
	10%	20%	10%	20%
Al	75	20	40	12
As	220	60	175	45
Ba	30	10	7	4
Ca	30	10	65	18
Cd	50	15	40	10
Cu	15	6	25	8
Hg	15	5	40	12
Mg	25	8	10	4
Pb	35	10	125	30
S	120	30	75	20
Se	30	8	35	10
U	40	14	50	14
Zn	25	8	8	4

Table A12. Sample size required to estimate a 10% and 20% difference between means ($P < 0.05$) based on mussels aged seven years from Mudginberri

Females - original mean and variance was calculated on a sample size of 14; males - original mean and variance was calculated on a sample size of 11

	Females		Males	
	10%	20%	10%	20%
Al	70	18	90	24
As	120	30	140	35
Ba	120	35	90	25
Ca	30	10	20	6
Cd	100	26	40	12
Cu	90	24	160	40
Hg	100	28	22	6
Mg	30	9	40	11
Mn	18	6	30	9
Pb	50	14	150	40
S	35	10	35	10
Se	35	10	70	18
U	120	30	70	18
Zn	22	6	35	10

Table A13. Sample size required to estimate a 10% and 20% difference between means ($P < 0.05$) based on mussels aged seven years from Leichhardt

Females - original mean and variance was calculated on sample size of 10; males - original mean and variance was calculated on sample size of 11

	Females		Males	
	10%	20%	10%	20%
Al	45	14	14	6
As	70	20	45	12
Ba	55	16	45	14
Ca	35	10	24	9
Cd	40	12	80	20
Cu	10	5	30	9
Hg	7	4	16	6
Mg	10	5	30	9
Mn	20	6	26	8
Pb	160	40	300	80
S	18	6	5	13
Se	26	8	16	6
U	170	45	170	40
Zn	30	9	18	6

Table A14. Mean concentrations and ranges for Cu, Pb, Zn, Cd, Mn, U, Mg, pH and turbidity in the total water plus residue of Georgetown (G) and Mudginberri (M) for the period November 1978 to August 1981

Concentrations are in $\mu g/L$

		Mean	SD	Min.	Max.
Cu	G	9.9	13	< 0.5	53
	M	1.0	1.5	< 0.5	6.5
Pb	G	2.2	2.5	< 0.5	10
	M	1.1	2.2	< 0.5	10
Zn	G	11	16	< 0.5	63
	M	7.5	9.5	< 0.5	49
Cd	G	0.12	0.17	< 0.05	0.65
	M	< 0.05	0.05	< 0.05	0.20
Mn	G	23	24	1.5	85
	M	12	5.7	1.0	22
U	G	2.1	2.9	< 0.1	9.9
	M	0.2	0.3	< 0.1	1.0
Mg	G	1.2	0.42	0.29	1.8
	M	0.78	0.24	0.28	1.3
pH	G	6.1	0.7	4.9	7.5
	M	6.1	0.6	3.8	7.2
Turbidity (NTU)	G	260	710	7	3000
	M	8.1	6.8	2.1	30

Table A15. Summary of the analysis of variance between the element concentrations in the soft parts of male and female mussels from Georgetown (G), Mudginberri (M) and Leichhardt (L)

a = concentration in males higher than in females
b = concentration in females higher than in males

	G	M	L
Al	$P < 0.001^b$	$P < 0.001^a$	NS
As	$P < 0.05^a$	NS	$P < 0.01^b$
Ba	NS	NS	$P < 0.01^a$
Ca	NS	NS	$P < 0.001^a$
Cd	NS	$P < 0.001^a$	NS
Cu	NS	NS	$P < 0.001^b$
Hg	$P < 0.001^b$	NS	NS
Mg	NS	$P < 0.001^a$	$P < 0.05^a$
Mn	$P < 0.05^a$	$P < 0.001^a$	$P < 0.001^a$
Pb	$P < 0.01^b$	$P < 0.001^a$	$P < 0.05^a$
S	NS	NS	$P < 0.001^b$
Se	NS	$P < 0.001^a$	$P < 0.001^b$
U	$P < 0.001^a$	NS	NS
Zn	NS	$P < 0.001^a$	$P < 0.001^b$

Table A16. Sample size required to detect 10% and 20% differences between mean concentrations ($P < 0.05$) of Ba, Ca, Cd, Cu, Mg, Mn, Pb and Zn

Calculated from determinations made by OSS on 20 individuals, for both males and females. Based on mussels of length 61-65 mm

	Females		Males	
	10%	20%	10%	20%
Ba	82	21	100	25
Ca	6	2	9	3
Cd	129	32	225	57
Cu	17	5	17	5
Mg	6	2	6	2
Mn	17	5	12	3
Pb	83	21	84	21
Zn	6	2	5	2

Table A17. Regression analysis, r^2 values and significance of element concentrations in the soft parts against age for male and female mussels from Georgetown

NS - $P > 0.05$; * - $P < 0.05$; ** - $P < 0.01$

	Males			Females		
	Regression Equation	r^2	Significance	Regression Equation	r^2	Significance
Al	y = 3.37x + 145.11	0.00	NS	y = 32.03x + 116.0	0.15	*
As	y = -0.44x + 3.48	0.61	**	y = -0.22 + 2.46	0.29	**
Ba	y = 0.67x + 0.38	0.37	**	y = 0.88x - 0.18	0.53	**
Ca	y = 5.10x + 11.55	0.63	**	y = 2.93x + 19.93	0.27	**
Cd	y = 0.23x + 1.05	0.25	**	y = 0.23x + 0.81	0.29	**
Cu	y = 0.42x + 10.17	0.07	NS	y = 0.63x + 13.32	0.11	NS
Hg	y = 0.02x + 0.15	0.13	*	y = 0.05x = 0.08	0.05	**
Mg	y = 0.11x + 1.00	0.51	**	y = 0.04x + 1.20	0.06	NS
Mn	y = 0.90x + 1.79	0.41	**	y = 0.41x + 3.21	0.16	*
Pb	y = 0.57x + 5.09	0.13	*	y = 1.16x + 4.76	0.23	**
S	y = -0.22x + 3.53	0.32	**	y = -0.28x + 3.58	0.28	**
Se	y = 0.88x + 9.52	-0.02	NS	y = -0.68x + 12.42	0.37	**
U	y = 0.08x + 1.3	0.01	NS	y = 0.13x + 0.72	0.21	*
Zn	y = 21.85 + 280.79	0.37	**	y = 3.74x + 342.85	-0.01	NS

Table A18. Regression analysis, r^2 values and significance of element concentrations in the soft parts against age for male and female mussels from Mudginberri

NS - $P > 0.05$; * - $P < 0.05$; ** - $P < 0.01$

	Males			Females		
	Regression Equation	r^2	Significance	Regression Equation	r^2	Significance
Al	y = -11.08x + 239.69	0.11	**	y = -5.84 + 160.32	0.11	**
As	y = 0.51x - 0.60	0.22	**	y = 0.34x + 0.40	0.13	**
Ba	y = -0.20x + 4.10	0.11	**	y = -0.09x + 3.08	0.03	NS
Ca	y = 0.92x + 28.28	0.06	*	y = 0.14x + 34.19	-0.01	NS
Cd	y = -0.05x + 2.42	-0.00	NS	y = -0.02x + 1.91	-0.01	NS
Cu	y = -1.05x + 17.46	0.31	**	y = -1.05x + 18 83	0.41	**
Hg	y = -0.02x + 0.41	0.06	*	y = -0.01x + 0.34	0.02	NS
Mg	y = -0.01x + 1.32	0.00	NS	y = -0.01x + 1.09	0.00	NS
Mn	y = 0.54x + 4.63	0.05	*	y = 0.35x + 3.55	0.16	**
Pb	y = 0.65x + 2.38	0.02	NS	y = 0.05x + 1.98	0.23	**
S	y = 0.08x + 2.21	-0.01	NS	y = 0.06x + 2.13	0.01	NS
Se	y = -0.12x + 7.63	0.01	NS	y = -0.35x + 11.87	0.02	NS
U	y = -0.02x + 0.64	0.05	*	y = -0.03x + 0.62	0.07	*
Zn	y = 17.75x + 471.56	-0.01	NS	y = -4.60x + 365.56	-0.00	NS

Table A19. Regression analysis, r^2 values and significance of element concentrations in the soft parts against age for male and female mussels from Leichhardt

NS - P > 0.05; * - P < 0.05; ** - P < 0.01; *** - P < 0.001

	Males			Females		
	Regression Equation	r^2	Significance	Regression Equation	r^2	Significance
Al	y = -3.10x + 89.50	0.02	NS	y = 1.68x + 53 65	-0.00	NS
As	y = -0.17x = 3.91	0.14	**	y = -0.302 + 3.50	0.25	**
Ba	y = 0.03x + 0.45	0.01	NS	y = 0.03x + 0.51	0.02	NS
Ca	y = 4.51x + 7.02	0.50	**	y = 3.32x + 19.45	0.47	**
Cd	y = -0.02x + 0.49	0.05	NS	y = 0.01x + 0.35	-0.00	NS
Cu	y = 0.20x + 3.82	0.17	**	y = -0.55 + 7.17	0.54	**
Hg	y = -0.002x + 0.15	0.001	NS	y = -0.01x + 0.19	0.27	***
Mg	y = -0.05x + 0.71	0.20	***	y = 0.04x + 0.93	0.17	***
Mn	y = 0.037x + 1.11	0.46	***	y = 0.035x + 1.87	0.51	***
Pb	y = 24.7x + 76.3	0.05	*	y = 0.84x + 1.98	0.25	***
S	y = -0.32x + 8.26	0.13	***	y = -0.10x + 7.65	0.01	NS
Se	y = -0.11x + 2.64	0.12	***	y = -0.16x + 2.72	0.14	***
U	y = -0.02x + 0.27	0.14	NS	y = -0.24x + 0.03	0.03	NS
Zn	y = 19.89x + 283.5	0.23	***	y = 6.42x +305	0.38	NS

Table A20. Summary of the regression analyses of element concentrations in the soft parts against age for male and female mussels from Georgetown, Mudginberri and Leichhardt

NS - P > 0.05; * - P < 0.05; ** - P < 0.01; *** - P < 0.001

	Georgetown		Mudginberri		Leichhardt	
	Males	Females	Males	Females	Males	Females
Al	NS	* 32.03 (+)	** 11.08 (-)	** 5.84 (-)	NS	NS
As	** 0.44 (-)	** -0.22 (-)	** 0.51 (+)	** 0.34 (+)	** 0.17 (-)	** 0.3 (-)
Ba	** 0.67 (+)	** 0.88 (+)	** 0.2(-)	NS	NS	NS
Ca	** 5.10 (+)	** 2.93 (+)	* 0.92 (+)	NS	** 4.51 (+)	** 3.32 (+)
Cd	** 0.25 (+)	** 0.23 (+)	NS	NS	NS	NS
Cu	NS	NS	** 1.0 (-)	** 1.05 (-)	** 0.2 (+)	** 0.55 (-)
Hg	** 0.02 (+)	** 0.05 (+)	* 0.02 (-)	NS	** 0.02 (-)	NS
Mg	** 0.11 (+)	NS	NS	NS	NS	NS
Mn	** 0.9 (+)	* 0.41 (+)	** 0.54 (+)	** 0.35 (+)	** 0.46 (+)	** 0.35 (+)
Pb	* 0.57 (+)	** 1.16 (+)	NS	** 0.50 (+)	** 0.54 (+)	** 0.50 (+)
S	** -0.22 (-)	** 0.2 (-)	NS	NS	NS	NS
Se	NS	** 0.68 (-)	NS	NS	NS	NS
U	NS	* 0.13 (+)	* 0.02 (-)	* 0.03 (-)	* 0.02 (-)	* 0.03 (-)
Zn	** (+)	NS	NS	NS	NS	NS

Table 21. Significant ($P < 0.05$) differences between mean concentrations in the soft parts of males and females in five age classes from Georgetown, Mudginberri and Leichhardt

a = concentration in the soft parts of males significantly higher; b = concentration in the soft parts of females significantly higher; * - $P < 0.05$; ** - $P < 0.01$

	Age Class														
	1			2			3			4			5		
	G	M	L	G	M	L	G	M	L	G	M	L	G	M	L
Al			**a				**a	**a	**a						**a
As			**a									*a			**a
Ba					*a									**a	
Ca			**b			**b	*a		**a						**a
Cd							**a								
Cu			**b												**a
Mn									**b				*a		
Pb		**a			**a			**a							**a
S					**a			**b				*b			
Se						*a									*a
Zn															**a

In Tables A22 and 23: concentrations are in $\mu g/g$ or mg/g(*) dry weight; maturity stages are: 2 = eggs in gonads, 3 = embryos in gills plus eggs in the gonads, 5 = glochidia in gills plus eggs in the gonads

Table A22. Chemical analyses of soft parts of female mussels from Georgetown, March 1981, with different stages in the reproductive cycle

	Maturity stage		
	2 (n = 12)	3 (n = 26)	5 (n = 4)
Al	308 ± 175	296 ± 165	307 ± 358
As	0.84 ± 0.62	0.97 ± 0.73	2.4 ± 2.08
Ba*	5.41 ± 2.79	5.57 ± 2.57	1.75 ± 3.17
Ca*	40.78 ± 12.59	39.31 ± 12.49	26.47 ± 10.0
Cd	2.41 ± 0.85	2.23 ± 1.04	1.07 ± 0.90
Cu	17.12 ± 4.57	17.96 ± 4.08	14.63 ± 5.19
Hg	0.37 ± 0.14	0.39 ± 0.12	0.13 ± 0.16
Mg*	1.49 ± 0.36	1.52 ± 0.33	1.11 ± 0.09
Mn	6.16 ± 2.78	6.10 ± 2.05	3.03 ± 1.23
Pb	12.54 ± 4.55	13.00 ± 4.71	5.02 ± 4.22
S	8.32 ± 2.61	8.30 ± 3.64	7.66 ± 2.96
Se	1.94 ± 0.91	2.00 ± 1.68	2.10 ± 1.03
U	1.47 ± 0.81	1.59 ± 0.70	1.05 ± 0.37
Zn	398 ± 70	353 ± 98	316 ± 26

Table A23. Chemical analyses of soft parts of female mussels from Mudginberri, March 1981, with different stages in the reproductive cycle

	Maturity stage		
	2 (n = 12)	3 (n = 26)	5 (n = 4)
Al	159 ± 63	214 ± 75	136 ± 46
As	1.56 ± 1.38	0.45 ± 0.43	1.48 ± 0.96
Ba*	3.31 ± 0.75	2.07 ± 0.14	3.48 ± 1.11
Ca*	30.4 ± 4.7	19.45 ± 1.92	40.39 ± 7.49
Cd	1.94 ± 0.71	2.01 ± 0.49	2.17 ± 0.66
Cu	14.57 ± 2.87	17.67 ± 0.42	15.55 ± 3.72
Hg	0.39 ± 0.16	0.32 ± 0.06	0.03 ± 0.16
Mg*	1.13 ± 0.17	1.06 ± 0.01	1.16 ± 0.18
Mn*	5.61 ± 2.52	3.92 ± 0.54	5.25 ± 1.6
Pb	6.01 ± 1.82	4.06 ± 0.40	3.45 ± 2.34
S	5.64 ± 2.94	11.94 ± 3.17	10.7 ± 10.5
Se	2.06 ± 0.74	1.27 ± 0.47	2.37 ± 0.75
U	0.49 ± 0.28	0.75 ± 0.14	0.48 ± 0.21
Zn	334 ± 32	371 ± 64	361 ± 48

Table A24. Chemical analyses of soft parts of female mussels from Leichhardt, March 1981, with different stages in the reproductive cycle

Concentrations are in μg/g or mg/g(*) dry weight

Maturity stages; 2 = eggs in gonads, 3 = embryos in gills plus eggs in the gonads, 5 = glochidia in gills plus eggs in the gonads

	Maturity stage		
	2 (n = 12)	3 (n = 26)	5 (n = 4)
Al	71 ± 60	65 ± 79	52 ± 23
As	2.27 ± 1.81	2.59 ± 1.68	1.89 ± 0.57
Ba*	0.613 ± 0.44	0.61 ± 0.51	0.66 ± 0.41
Ca*	34.67 ± 12.59	28.20 ± 11.07	36.44 ± 9.69
Cd	0.40 ± 0.16	0.45 ± 0.15	0.30 ± 0.13
Cu	4.60 ± 1.46	5.30 ± 2.67	4.63± 1.78
Hg	0.13 ± 0.08	0.14 ± 0.08	0.13 ± 0.04
Mg*	1.12 ± 0.24	1.07 ± 0.19	1.05 ± 0.17
Mn*	3.55 ± 1.26	3.21 ± 1.21	3.28 ± 1.14
Pb	6.35 ± 5.35	4.45 ± 2.6	5.1 ± 2.95
S	7.32 ± 1.95	7.79 ± 2.75	6.84 ± 1.17
Se	2.13 ± 0.94	1.79 ± 0.53	1.81 ± 0.52
U	0.10 ± 0.26	0.11 ± 0.19	0.06 ± 0.06
Zn	331 ± 55	324 ± 60	312 ± 80

Table A25. Chemical analyses of the mantles and mean lengths and ages of male (M) and female (F) mussels from Mudginberri (March 1980)

The means are of 5 samples, each sample being made up of 4 mussels. Concentrations are in μg/g or mg/g(*) dry weight.

		Mean ± SD	CV ± 95% CL
Length	M	63.7 ± 1.2	2 ± 1.49
	F	58.2 ± 12.6	22 ± 15.6
Age	M	9.2 ± 0.9	10 ± 1.12
	F	9.9 ± 1.2	12 ± 1.5
Al	M	89 ± 40	45 ± 50
	F	142 ± 54	38 ± 67
As	M	4.53 ± 1.18	26 ± 1.46
	F	3.29 ± 3.25	99 ± 4.03
Ba*	M	1.81 ± 0.34	19 ± 0.42
	F	2.66 ± 0.84	32 ± 1.04
Ca*	M	27.18 ± 5.61	21 ± 6.96
	F	35.37 ± 8.17	23 ± 10.14
Cd	M	2.93 ± 0.94	32 ± 1.17
	F	2.71 ± 0.86	32 ± 1.07
Cu	M	7.79 ± 1.51	19 ± 1.87
	F	7.98 ± 2.23	28 ± 2.77
Hg	M	0.56 ± 0.14	25 ± 0.17
	F	0.45 ± 0.07	16 ± 0.09
Mg*	M	0.56 ± 0.07	13 ± 0.09
	F	0.55 ± 0.08	15 ± 0.01
Mn*	M	5.83 ± 1.30	22 ± 1.61
	F	5.58 ± 1.69	30 ± 2.10
Pb	M	4.78 ± 1.33	28 ± 1.65
	F	6.59 ± 1.80	27 ± 2.23
S*	M	4.47 ± 1.71	38 ± 2.12
	F	15.42 ± 4.99	32 ± 6.19
Se	M	4.41 ± 1.13	26 ± 1.40
	F	3.08 ± 0.66	21 ± 0.82
U	M	0.26 ± 0.12	46 ± 0.15
	F	0.21 ± 0.09	43 ± 0.11
Zn	M	387 ± 54	14 ± 67
	F	333 ± 27	8 ± 34

Table A26. Chemical analyses of the gills and palps and mean lengths and ages of male (M) and female (F) mussels from Mudginberri (March 1980)

The means are of 5 samples, each sample being made up of 4 mussels. Concentrations are in $\mu g/g$ or mg/g(*) dry weight.

		Mean ± SD	CV ± 95% CL
Length	M	63.7 ± 1.2	2 ± 1.49
	F	58.2 ± 12.6	22 ± 15.6
Age	M	9.2 ± 0.9	10 ± 1.12
	F	9.9 ± 1.2	12 ± 1.5
Al	M	159 ± 35	22 ± 43
	F	86 ± 8	9 ± 10
As	M	5.04 ± 1.27	25 ± 1.58
	F	4.05 ± 2.67	66 ± 3.31
Ba*	M	2.92 ± 0.43	15 ± 0.53
	F	3.25 ± 0.80	25 ± 0.99
Ca*	M	52.00 ± 5.31	10 ± 6.59
	F	43.96 ± 5.88	13 ± 7.30
Cd	M	2.86 ± 0.71	25 ± 0.88
	F	2.07 ± 0.56	27 ± 0.69
Cu	M	7.04 ± 1.58	22 ± 1.96
	F	7.60 ± 0.22	3 ± 0.27
Hg	M	0.44 ± 0.05	11 ± 0.06
	F	0.48 ± 0.05	10 ± 0.06
Mg*	M	0.85 ± 0.05	6 ± 0.06
	F	0.66 ± 0.06	9 ± 0.07
Mn*	M	11.52 ± 0.40	3 ± 0.50
	F	7.84 ± 1.39	18 ± 1.72
Pb	M	4.19 ± 1.08	26 ± 1.34
	F	5.50 ± 0.97	18 ± 1.20
S*	M	6.32 ± 4.44	70 ± 5.51
	F	11.78 ± 2.52	21 ± 3.13
Se	M	5.58 ± 1.22	22 ± 1.51
	F	3.51 ± 1.83	52 ± 2.27
U	M	0.68 ± 0.75	110 ± 0.93
	F	0.50 ± 0.33	66 ± 0.41
Zn	M	831 ± 81	10 ± 101
	F	725 ± 56	8 ± 69

Table A27. Chemical analyses of the visceral mass and mean lengths and ages of male (M) and female (F) mussels from Mudginberri (March 1980)

The means are of 20 samples, each sample being made up of 1 mussel. Concentrations are in $\mu g/g$ or mg/g(*) dry weight.

		Mean ± SD	CV ± 95% CL
Length	M	63.7 ± 1.2	2 ± 1.49
	F	58.2 ± 12.6	22 ± 15.6
Age	M	9.2 ± 0.9	10 ± 1.12
	F	9.9 ± 1.2	12 ± 1.5
Al	M	129 ± 42	33 ± 52
	F	88 ± 36	41 ± 45
As	M	3.36 ± 1.45	43 ± 1.80
	F	3.17 ± 0.85	27 ± 1.05
Ba*	M	2.51 ± 1.19	47 ± 1.48
	F	3.12 ± 1.60	51 ± 1.99
Ca*	M	31.99 ± 12.48	39 ± 15.49
	F	36.66 ± 15.73	43 ± 19.52
Cd	M	1.65 ± 1.14	69 ± 1.41
	F	1.45 ± 1.03	71 ± 1.28
Cu	M	2.99 ± 1.38	46 ± 1.71
	F	6.43 ± 1.87	29 ± 2.32
Hg	M	0.31 ± 0.10	32 ± 0.12
	F	0.37 ± 0.09	24 ± 0.11
Mg*	M	0.59 ± 0.13	22 ± 0.16
	F	0.56 ± 0.14	25 ± 0.17
Mn*	M	6.75 ± 2.10	31 ± 2.61
	F	5.73 ± 2.43	42 ± 3.02
Pb	M	7.63 ± 4.03	53 ± 5.00
	F	7.60 ± 2.64	35 ± 3.28
S*	M	6.23 ± 2.78	45 ± 3.45
	F	9.52 ± 3.07	32 ± 3.81
Se	M	2.76 ± 0.88	32 ± 1.09
	F	3.25 ± 1.94	60 ± 2.41
U	M	0.37 ± 0.21	57 ± 0.26
	F	0.26 ± 0.17	65 ± 0.21
Zn	M	282 ± 81	29 ± 101
	F	249 ± 80	32 ± 99

Table A28. Chemical analyses of the adductor muscles, hearts and kidneys of female (F) and male (M) mussels from Mudginberri (March 1980)

The samples are made up from 20 mussels. Concentrations are in $\mu g/g$ or mg/g(*) dry weight

		Adductor muscles	Hearts	Kidneys
Al	F	239	119	114
	M	44	86	55
As	F	2.91	9.99	2.78
	M	4.70	5.02	5.39
Ba*	F	5.09	0.27	0.66
	M	0.13	0.18	0.49
Ca*	F	63.96	0.67	15.56
	M	2.98	0.72	12.08
Cd	F	3.63	1.33	12.28
	M	1.49	3.59	16.72
Cu	F	7.27	0.67	5.73
	M	2.24	0.72	4.65
Hg	F	0.36	0.6	0.57
	M	0.45	0.57	0.93
Mg*	F	0.76	0.39	0.50
	M	0.51	0.44	0.46
Mn*	F	10.25	0.49	2.62
	M	0.31	0.46	2.79
Pb	F	10.18	2.67	4.10
	M	1.49	2.87	3.72
S*	F	13.45	7.06	14.74
	M	13.19	11.76	23.41
Se	F	4.58	3.00	3.44
	M	0.52	1.08	3.72
U	F	0.15	0.33	2.70
	M	0.15	0.36	0.65
Zn	F	450	93	253
	M	126	114	278

Table A29. The mean dry weight ± 95% CL of the mantles, gill and palps and visceral mass for mussels collected from Mudginberri (March 1980)

Mussels of length 61-65 mm; NS - $P > 0.05$; * - $P < 0.05$; ** - $P < 0.01$

	Mean dry wt/mussel ± 95% CL (mg)	Significance males/females
Males		
Mantle	150 ± 15	*
Gills and palps	142 ± 16	NS
Visceral mass	865 ± 408	**
Females		
Mantle	190 ± 43	
Gills and palps	176 ± 35	
Visceral mass	801 ± 206	

Table A30. Chemical analyses of the soft parts of non-purged mussels from Mudginberri Billabong

The means are of 20 samples, each sample being made up of 20 male mussels. Concentrations are in $\mu g/g$ or mg/g(*) dry weight

	Mean	± SD	CV	± 95% CL
Age	9.5	2.7	28.5	1.3
Al	197	116	58.8	54.7
As	2.77	1.24	44.9	0.58
Ba*	2.10	1.15	54.8	0.54
Ca	32.19	9.36	29.1	4.40
Cd	2.30	1.64	71.2	0.77
Cu	9.25	3.06	33.1	1.44
Hg	0.55	0.22	40.6	0.10
Mg*	0.68	0.12	17.2	0.05
Mn*	5.65	1.79	31.7	0.84
Pb	3.62	1.17	32.3	0.55
S*	9.11	2.17	23.9	1.02
Se	2.55	0.72	28.2	0.34
U	0.42	0.26	62.6	0.12
Zn	448	133	29.7	62

Table A31. Chemical analyses of the soft parts of purged mussels from Mudginberri Billabong

The means are of 5 samples, each sample being made up of 4 male mussels. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	±SD	CV	±95% CL
Age	9.3	1.6	17.3	2.0
Al	133	24	18.8	31.0
As	2.72	0.67	24.7	0.83
Ba*	2.79	1.24	44.2	1.53
Ca*	38.07	8.59	22.6	10.66
Cd	2.31	0.78	33.8	0.97
Cu	10.10	1.30	12.8	1.61
Hg	0.32	0.05	15.3	0.06
Mg*	0.71	0.05	7.1	0.06
Mn*	6.98	1.65	23.6	2.04
Pb	4.48	0.93	20.7	1.15
S*	6.99	0.91	13.0	1.13
Se	2.36	0.36	15.1	0.44
U	0.30	0.09	28.8	0.11
Zn	523	34	6.7	43

Table A32. Chemical analyses of the soft parts of non-purged mussels from Retention Pond No. 2

The means are of 5 samples, each sample being made up of 4 mussels. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	13.1	2.1	16.3	2.6
Al	448	61	13.7	76.1
As	1.74	2.30	132.5	2.86
Ba*	4.81	2.98	61.9	3.70
Ca*	64.45	19.69	30.6	24.44
Cd	3.71	0.37	9.9	0.46
Cu	11.63	4.44	38.2	5.51
Hg	0.40	0.08	19.7	0.10
Mg*	2.61	0.30	11.3	0.37
Mn*	15.43	5.58	36.1	6.92
Pb	9.92	4.39	44.2	5.45
S*	9.70	5.91	60.9	7.33
Se	2.65	1.25	47.3	1.56
U	23.54	9.91	42.1	12.30
Zn	610	274	44.9	340

Table A33. Chemical analyses of the soft parts of purged mussels from Retention Pond No. 2

The means are of 5 samples, each sample being made up of 4 mussels. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	13.0	2.4	18.3	3.0
Al	310	126	40.9	157.4
As	3.35	1.34	40.0	1.66
Ba*	6.56	1.01	15.3	1.25
Ca*	60.85	12.46	20.5	15.46
Cd	3.93	1.37	34.9	1.70
Cu	8.36	0.83	9.9	1.03
Hg	0.29	0.09	32.0	0.11
Mg*	2.41	0.48	19.8	0.59
Mn*	16.68	7.01	42.0	8.70
Pb	8.78	1.64	18.7	2.04
S*	5.51	2.48	45.0	3.08
Se	2.59	1.09	42.3	1.36
U	24.13	6.38	26.5	7.92
Zn	490	113	23.2	140

Table A34. Chemical analyses of the soft parts of non-purged mussels from Retention Pond No. 4

The means are of 4 samples, each sample being made up of 4 mussels. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	12.2	1.3	10.3	2.0
Al	610	167	27.5	266.4
As	3.95	1.41	35.7	2.24
Ba*	1.44	0.15	10.8	0.25
Ca*	29.25	5.56	19.0	8.84
Cd	1.04	0.22	21.1	0.35
Cu	9.90	1.89	19.1	3.01
Hg	0.20	0.06	28.2	0.09
Mg*	0.97	0.09	9.0	0.14
Mn*	5.55	0.47	8.4	0.74
Pb	6.60	0.70	10.6	1.11
S*	4.90	1.38	28.1	2.19
Se	1.30	1.19	91.7	1.89
U	3.22	0.24	7.4	0.38
Zn	358	40	11.3	64

Table A35. Chemical analyses of the soft parts of purged mussels from Retention Pond No. 4

The means are of 4 samples, each sample being made up of 4 mussels. Concentrations are in $\mu g/g$ or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	16.2	1.4	8.6	2.2
Al	142	12	8.8	20.0
As	3.58	1.40	39.1	2.22
Ba*	1.75	0.26	15.1	0.42
Ca*	37.00	6.16	16.7	9.80
Cd	0.50	0.43	86.9	0.69
Cu	9.33	0.90	9.6	1.43
Hg	0.19	0.07	38.7	0.12
Mg*	0.90	0.10	11.0	0.16
Mn*	6.55	1.36	20.7	2.16
Pb	6.93	1.46	21.1	2.33
S*	2.67	2.37	88.7	3.77
Se	2.65	1.25	47.3	1.99
U	3.08	0.38	12.2	0.60
Zn	387	36	9.5	58

Table A36. Summary of analyses of variance for elements in the soft parts of purged and non-purged mussels from Mudginberri Billabong and Retention Pond Nos 2 and 4

NS - $P > 0.05$; * - $P < 0.05$; ** - $P < 0.01$; *** - $P < 0.001$

	Mudginberri	RP2	RP4
Al	**	NS	**
As	NS	NS	NS
Ba	NS	NS	NS
Ca	NS	NS	NS
Cd	NS	NS	NS
Cu	NS	***	NS
Hg	**	NS	NS
Mg	**	NS	NS
Mn	NS	NS	NS
Pb	NS	NS	NS
S	NS	NS	NS
Se	NS	NS	NS
U	NS	NS	NS
Zn	*	NS	NS

Table A37. Chemical analyses of the soft parts of mussels from a sandy substrate in Mudginberri Billabong

The means are of 20 samples, each sample being made up of 1 male mussel only. Concentrations are in $\mu g/g$ or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	9.5	2.7	28.5	1.3
Al	197	116	58.8	54.7
As	2.77	1.24	44.9	0.58
Ba*	2.10	1.15	54.8	0.54
Ca*	32.19	9.36	29.1	4.40
Cd	2.30	1.64	71.2	0.77
Cu	9.25	3.06	33.1	1.44
Hg	0.55	0.22	40.6	0.10
Mg*	0.68	0.12	17.2	0.05
Mn*	5.65	1.79	31.7	0.84
Pb	3.62	1.17	32.3	0.55
S*	9.11	2.17	23.9	1.02
Se	2.55	0.72	28.2	0.34
U	0.42	0.26	62.6	0.12
Zn	448	133	29.7	62

Table A38. Chemical analyses of the soft parts of mussels from a detrital substrate in Mudginberri Billabong

The means are of 20 samples, each sample being made up of 1 male mussel. Concentrations are in $\mu g/g$ or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	11.3	2.1	18.7	1.0
Al	201	85	42.2	50.1
As	2.93	1.12	38.2	0.53
Ba*	2.12	1.12	52.7	0.53
Ca*	34.78	11.27	32.4	5.30
Cd	2.37	1.13	47.9	0.53
Cu	8.67	3.22	37.1	1.51
Hg	0.55	0.17	31.1	0.08
Mg*	0.73	0.11	14.4	0.05
Mn*	6.68	2.23	33.3	1.05
Pb	4.28	1.36	31.8	0.64
S*	10.69	2.80	26.2	1.32
Se	2.47	0.68	27.7	0.32
U	0.42	0.25	60.5	0.12
Zn	474	100	21.1	47

Table A39. Chemical analyses of the soft parts of uncooked mussels from Mudginberri Billabong

The means are of 5 samples, each sample being made up of 4 male mussels. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	8.1	1.2	14.8	1.5
Al	84	26	31.3	32.8
As	3.32	0.41	12.3	0.51
Ba*	2.28	0.97	42.8	1.21
Ca*	51.71	11.98	23.2	14.87
Cd	2.98	1.66	55.7	2.06
Cu	11.29	2.76	24.4	3.42
Hg	0.74	0.25	34.3	0.31
Mg*	1.31	0.25	18.8	0.31
Mn*	11.87	2.72	22.9	3.38
Pb	8.49	3.67	43.3	4.56
S*	12.10	3.54	29.3	4.40
Se	2.47	0.20	8.1	0.25
U	0.36	0.17	46.4	0.21
Zn	674	179	26.6	222

Table A40. Chemical analyses of the soft parts of cooked mussels from Mudginberri Billabong

The means are of 20 samples, each sample being made up of 1 mussel, sex not determined. Concentrations are in μg/g or mg/g(*) dry weight.

	Mean	± SD	CV	± 95% CL
Age	7.2	2.4	33.6	1.1
Al	317	95	29.9	44.7
As	0.66	0.24	37.2	0.11
Ba*	1.05	0.50	47.9	0.24
Ca*	21.63	7.09	32.8	3.33
Cd	1.34	0.52	38.9	0.25
Cu	9.75	3.28	33.7	1.54
Hg	0.19	0.05	26.8	0.02
Mg*	0.97	0.54	55.5	0.25
Mn*	6.54	2.96	45.2	1.39
Pb	3.14	1.23	39.1	0.58
S*	7.83	1.97	25.1	0.92
Se	0.56	0.20	36.3	0.09
U	0.30	0.16	53.1	0.08
Zn	313	74	23.6	34

Table A41. Numbers of mussel shells discarded along Magela Creek in 1980 and 1981 by Mudginberri Aboriginals

Location	1980	1981
Corndorl	1141	-
Mudginberri	833	2720
Gundur	1224	7610
Magela Crossing	-	887
Georgetown	-	3067
Magela Creek between Mudginberri and Gulungul	399	1170
Magela Creek by Gulungul	-	380
TOTAL	3597	15834

Table A42. Estimated numbers of mussels consumed per person during the Dry seasons of 1980 and 1981 by Mudginberri Aboriginals

	1980	1981
No. of mussels eaten by Mudginberri Aboriginals per year	2373	11500
Average no. of mussels eaten per person per year assuming amount eaten by two children equals that of one adult	60	288
Average wet weight per mussel	9 g	9 g
Average weight of mussel tissue consumed per person	0.54 kg	2.59 kg

Table A43. Chemical analyses of soft parts in mussels from Mudginberri (August 1981) and intake of elements per person per year

Mean concentrations ± SD are in μg/g or mg/g(*).

	Mean ± SD (wet wt) August 1981	Intake of element per person per year (mg) 1980	1981	Weight of element in one mineral supplement tablet (mg)
Al	9.8 ± 1.8	5.29	25.40	
As	0.39 ± 0.05	0.211	1.01	
Ba	259 ± 70	13.99	671.34	
Ca*	6.00 ± 0.6	3240	155.52	83.3
Cd	0.33 ± 0.13	0.178	0.855	
Cu	1.32 ± 0.31	0.713	3.421	0.66
Hg	0.09 ± 0.03	0.049	0.233	
Mg	152 ± 2.7	82.08	393.98	9.90
Mn*	1.37 ± 0.08	740	3551	1.33
Pb	0.97 ± 0.27	0.524	2.514	
S*	1.32 ± 0.26	751	3603	
Se	0.29 ± 0.03	0.157	0.752	
U	0.04 ± 0.03	0.022	0.104	
Zn	78 ± 10	42.12	202.18	3.33

Table A44. National Health and Medical Research Council standards for metals in food, wet weight

Metal	Food	Maximum permitted (μg/g calculated as metal)
As	Molluscs	1.0
	Provided that levels for inorganic As in fish, crustacea and molluscs shall not exceed 1.0 μg/g	
Cd	Molluscs	2.0
Cu	Molluscs	70.0
Pb	Molluscs	2.5
Hg	Molluscs	0.5
Se	Molluscs	1.0
Zn	Oysters	1000.0
	Other foods	150.0

Table A45. Chemical analyses of the soft parts of mussels between March 1980 and February 1982 from 13 locations in Magela Creek catchment

Mean concentrations ± 95% CL are given in μg/g or mg/g(*) dry weight.

	Bowerbird	Georgetown	Gulungul	Goanna	Corndorl	Gundur	Mudginberri	Island	Ja Ja (NE)	Leichhardt	Jabiluka	Nankeen	RP1
Sample size (n)	100	84	45	11	52	20	112	48	32	71	28	65	10
Total no. of mussels in above samples	135	413	59	66	238	20	300	191	128	262	144	253	10
Mean length (mm)	50.3 ± 1.8	62.4 ± 0.8	60.9 ± 2.3	55.3 ± 5.1	62.6 ± 0.25	63.6 ± 4.3	62.7 ± 0.2	68.7 ± 1.3	66.4 ± 1.3	68.3 ± 1.4	74.5 ± 4.5	63.3 ± 0.3	59.0 ± 7.6
Mean age (years)	4.1 ± 0.4	6.4 ± 0.9	4.5 ± 0.7	1.9 ± 1.2	5.2 ± 0.3	4.5 ± 1.2	9.4 ± 0.5	4.3 ± 0.5	5.0 ± 0.4	3.2 ± 0.5	6.6 ± 1.3	5.6 ± 0.8	2.0 ± 0.9
Al	129 ± 27	264 ± 57	118 ± 27	883 ± 480	169 ± 58	49 ± 13	224 ± 36	26 ± 5	60 ± 19	119 ± 41	275 ± 154	165 ± 50	52 ± 15
As	2.90 ± 0.38	2.50 ± 0.46	2.40 ± 0.27	0.72 ±0.36	1.30 ± 0.17	0.96 ± 0.23	2.61 ± 0.30	1.22 ± 0.14	1.88 ± 0.38	1.87 ± 0.23	1.97 ±0.53	2.86 ± 0.37	1.96 ± 0.69
Ba*	0.59 ± 0.09	0.92 ± 0.22	1.76 ± 0.25	0.56 ± 0.54	2.45 ± 0.46	1.92 ± 0.64	1.81 ± 0.22	0.55 ± 0.08	1.24 ± 0.34	0.94 ± 0.14	0.80 ± 0.33	1.32 ± 0.25	0.12 ± 0.11
Ca*	14.23 ± 1.70	32.72 ± 2.33	25.23 ± 3.19	19.94 ± 5.29	44.60 ± 3.11	21.14 ± 4.51	35.29 ± 2.38	9.12 ± 1.73	30.65 ± 6.79	20.32 ± 1.90	27.96 ± 4.25	36.40 ± 3.29	2.96 ± 1.66
Cd	4.29 ± 0.52	1.78 ± 0.19	2.45 ± 0.36	1.25 ± 0.38	2.00 ± 0.23	1.22 ± 0.35	2.31 ± 0.23	1.23 ± 0.17	1.51 ± 0.23	1.00 ± 0.14	1.80 ± 0.32	1.36 ± 0.16	0.58 ± 0.26
Cu	11.60 ± 0.90	9.96 ± 0.84	20.69 ± 2.57	13.13 ± 2.22	17.99 ± 1.96	8.22 ±1.45	9.56 ± 0.58	4.89 ± 0.52	16.34 ± 3.28	6.77 ± 0.73	8.27 ± 1.40	6.77 ± 0.56	5.14 ± 0.71
Hg	0.34 ± 0.06	0.23 ± 0.04	0.52 ± 0.08	0.18 ± 0.09	0.41 ± 0.09	0.27 ± 0.10	0.44 ± 0.05	0.21 ± 0.03	0.35 ± 0.09	0.22 ± 0.03	0.30 ± 0.14	0.28 ±0.04	0.25 ± 0.58
Mg*	0.96 ± 0.09	1.37 ± 0.11	0.70 ± 0.05	1.18 ± 0.10	1.13 ± 0.09	0.46 ± 0.09	1.03 ± 0.10	0.51 ± 0.06	0.82 ± 0.12	0.77 ± 0.06	1.19 ± 0.19	1.31 ± 0.10	0.41 ± 0.05
Mn*	1.47 ± 0.18	5.65 ± 0.41	4.44 ± 0.68	4.32 ± 1.43	10.99 ± 0.98	8.20 ± 1.91	8.59 ± 0.71	1.93 ± 0.35	6.08 ± 1.50	1.98 ± 0.19	3.01 ± 0.40	5.33 ± 0.52	0.19 ± 0.05
Pb	5.30 ± 1.66	10.85 ± 1.35	27.05 ± 4.65	11.23 ± 2.77	14.05 ± 2.05	5.61 ± 1.26	5.27 ± 0.69	7.00 ±1.07	3.35 ± 0.54	2.80 ± 0.50	11.19 ± 2.55	8.99 ± 1.24	3.82 ± 1.35

Table A45 cont.

	Bowerbird	Georgetown	Gulungul	Goanna	Corndorl	Gundur	Mudginberri	Island	Ja Ja (NE)	Leichhardt	Jabiluka	Nankeen	RP1
S*	17.46 ± 1.78	8.66 ± 0.52	11.21 ± 1.49	10.41 ± 1.96	8.99 ± 0.70	7.70 ± 1.05	9.32 ± 0.58	6.08 ± 0.79	7.16 ± 0.95	8.72 ± 0.95	9.82 ± 1.15	8.68 ± 0.83	7.17 ± 0.95
Se	1.54 ± 0.28	2.10 ± 0.32	3.23 ± 0.31	0.32 ± 0.34	1.69 ± 0.31	2.52 ± 0.46	1.79 ± 0.20	1.12 ± 0.17	1.87 ± 0.29	1.30 ± 0.22	0.77 ± 0.24	1.72 ± 0.27	1.94 ± 0.04
U	0.28 ± 0.09	1.66 ± 0.17	0.43 ± 0.07	0.27 ± 0.11	0.29 ± 0.05	0.25 ± 0.10	0.37 ± 0.04	0.22 ± 0.20	0.16 ± 0.04	0.15 ± 0.03	0.26 ± 0.07	0.22 ± 0.04	0.87 ± 0.18
Zn	371 ± 23	342 ± 24	390 ± 32	332 ± 24	498 ± 36	363 ± 72	454 ± 24	282 ± 34	562 ± 106	363 ± 23	396 ± 25	443 ± 34	199 ± 27

Table A46. Chemical analyses of the water in Bowerbird, Georgetown, Goanna, Gulungul, Corndorl, Mudginberri, Island, Ja Ja (NE), Jabiluka and Nankeen for the period November 1978 to August 1982

All results by Water Division, Department of Transport and Works, N.T. Mean concentrations ± SD are in μg/L or mg/L(*)

	Bowerbird	Georgetown	Goanna	Gulungul	Corndorl	Mudginberri	Island	Ja Ja (NE)	Jabiluka	Nankeen
Ca*[a]	0.22 (0.18)	0.70 (0.31)	0.87 (0.29)	0.57 (0.33)	1.1 (1.1)	0.49 (0.12)	0.69 (0.29)	1.1 (0.83)	1.1 (1.0)	2.0 (1.6)
Cd[b]	< 0.05	0.12 (0.17)	0.06 (0.09)	< 0.05	0.06 (0.13)	< 0.05	0.03 (0.06)	0.06 (0.10)	0.05 (0.11)	0.06 (0.12)
Cu[b]	1.1 (1.8)	9.9 (13.0)	2.3 (1.7)	2.1 (2.5)	2.0 (2.0)	1.0 (1.5)	1.5 (2.0)	1.6 (1.6)	0.9 (1.1)	1.0 (1.0)
Mg*[a]	1.1 (2.6)	1.2 (0.42)	0.91 (0.35)	0.79 (0.38)	0.84 (0.50)	0.78 (0.24)	0.29 (0.38)	1.8 (1.4)	1.6 (1.1)	2.3 (1.5)
Mn[b]	3.8 (2.2)	23 (24)	29 (50)	16 (21)	22 (37)	12 (5.7)	30 (24)	85 (99)	34 (37)	70 (90)
Pb[b]	1.0 (2.2)	2.2 (2.5)	4.6 (4.6)	1.6 (2.1)	1.4 (2.0)	1.1 (2.2)	1.3 (2.1)	1.4 (2.0)	1.7 (1.6)	1.5 (1.5)
S*[a]	0.3 (0.2)	0.9 (1.0)	0.5 (0.5)	1.0 (1.5)	0.7 (1.1)	0.3 (0.2)	3.1 (3.1)	11 (11)	8.7 (9.8)	7.3 (6.8)
U[b]	< 0.1	2.1)2.9)	0.6 (0.8)	1.0 (1.7)	0.3 (0.4)	0.2 (0.3)	0.2 (0.4)	0.3 (0.5)	0.4 (0.5)	0.5 (0.7
Zn[b]	6.2 (9.9)	11 (16)	16 (40)	7.5 (8.6)	6.1 (5.7)	7.5 (9.5)	5.5 (6.1)	7.2 (5.0)	6.7 (5.7)	8.8 (8.7)
pH	5.9 (0.6)	6.1 (0.7)	6.4 (0.6)	6.0 (1.85)	6.2 (1.3)	6.1 (0.6)	5.7 (0.6)	5.4 (0.8)	5.7 (0.8)	5.9 (0.8)
Turbidity (NTU)	4.0 (3.7)	260 (710)	83 (64)	260 (890)	41 (93)	8.1 (6.8)	9.8 (11.0)	51 (56)	38 (42)	46 (64)

[b]total water and residue
[a]filtered

Table A47. Sampling dates and dates for flow events in Magela Creek during the 1980-81 and 1981-82 early Wet seasons

Sequence of events	1980-81		1981-82	
	Date of flow event	Sampling date	Date of flow event	Sampling date
Bowerbird	-	6 November	-	28 November
Georgetown backflows	5 December	8 December	27 November	3 December
Gulungul fills	-	-	-	1 December
Goanna fills	5 December	-	-	18 December
Corndorl backflows	20 December	23 December	2 December	18 December
Gundur	-	-	-	1 December
Enters Mudginberri	6 December	31 December	27 November	5 December
Flows across Oenpelli road	20 December	-	29 November	-
Enters Island	21 December	22 December	7-8 December	7 December
Enters Ja Ja	23 December	-	-	2 December
Enters Leichhardt	23 December	24 December	12 December	7 December
Enters Jabiluka	23 December	24 December	12 December	-
Enters Nankeen	23 December	5 January	-	6 December

Table A48. Mean lengths of mussels which were lower than or exceeded the standard mussel length (65 mm) in the baseline study

Date	Mean length (mm)				
	Bowerbird	Island	Ja Ja (NE)	Leichhardt	Jabiluka
April 1980				66	
August				69	90
October				75	73
December		72		75	77
February 1981		73		73	66
April		70	71	66	
June	54	74		71	
August	50	67		67	
October	45	66	68	67	
November	40				
December		66		66	

Table A49. Chemical analysis of elements in the soft parts of *V. angasi* from 3 previous studies in the ARR

	Cd (μg/g)	Cu (μg/g)	Mn (mg/g)	Pb (μg/g)	U (μg/g)	Zn (μg/g)
Davy & Conway (1974) (per wet wt)		1.38*		1.0*	0.0025-0.23[1]	30*
Noranda Australia Limited (1978) (per dry wt)[2]	0.9-1.4	8.4-11.8	3.9-8.75	3.0-5.3	< 0.1-1.1	340-420
Pancontinental Mining Limited (1981) (converted to per dry wt)[3]	1.8-3.0	8.4-21.1		7.8-11.4		295-391

* Averaged (by Davy & Conway) for mussels taken from Magela, Cooper, and Sawcut (on the Nourlangie System) creeks.

[1] Range of means from 15 locations in the Alligator Rivers Region

[2] Range of means from individual analyses and homogenates from mussels from Long Harry's Billabong.

[3] Range of means from mussels from Island, Buffalo, Jabiluka and Winmurra (east of Buffalo) billabongs.

Table A50. Sampling dates and flow events in Nourlangie and Cooper creeks during the 1980-81 and 1981-82 Wet seasons

	1980-81		1981-82	
Sequence of events	Date of flow event	Sampling date	Date of flow event	Sampling date
Nourlangie Creek:				
Long Harry's fills	19 December	1 December	-	29 November
Cooper Creek:				
Gunirdul	-	17 December (before billabong filled)	-	-

Table A51. Chemical analyses of the soft parts and length and age of mussels from Long Harry's Billabong (Nourlangie Creek) and Gunirdul and Murganella billabongs (Cooper Creek)

Mean concentrations ± SD are in $\mu g/g$ or mg/g* dry weight

	Long Harry's	Gunirdul	Murganella
Sample size (n)	22	35	4
Total number of mussels in above sample	108	80	14
Al	196 ± 343	481 ± 1065	150 ± 98
As	3.35 ± 1.04	2.60 ± 1.7	1.52 ± 0.47
Ba*	2.35 ± 1.16	0.76 ± 0.47	1.08 ± 0.22
Ca*	45.42 ± 13.39	13.81 ± 8.59	20.14 ± 10.53
Cd	3.09 ± 0.80	1.55 ± 0.78	1.75 ± 0.35
Cu	8.34 ± 3.56	9.86 ± 4.98	8.65 ± 1.34
Hg	0.67 ± 0.30	0.38 ± 0.32	0.29 ± 0.13
Mg*	1.15 ± 0.28	0.75 ± 0.32	0.81 ± 0.52
Mn*	10.71 ± 3.29	2.81 ± 2.10	2.81 ± 1.56
Pb	1.31 ± 1.82	4.45 ± 4.24	17.03 ± 24.
S*	11.66 ± 4.54	7.55 ± 1.44	7.08 ± 4.27
Se	2.48 ± 1.39	2.17 ± 1.21	1.87 ± 1.17
U	0.18 ± 0.10	0.30 ± 0.20	0.50 ± 0.64
Zn	512 ± 138	236 ± 66	279 ± 100
Length (mm)	62.5 ± 1.31	59.7 ± 4.0	56.38 ± 3.09
Age (years)	9.4 ± 2.3	5.2 ± 2.4	5.25 ± 2.06

Table A52. Chemical analyses of the soft parts and age, dry weight and length of mussels from an escarpment creek in the Jim Jim Creek catchment

Mussels were collected on 6.7.81; concentrations are in µg/g or mg/g(*) dry weight.
is = insufficient sample for analysis; l = low sample weights, analysis very variable.

Element	n	Mean	SD95% CL	
Al (l)	4	335	± 146	± 232
As (l)	4	20.25	± 10.97	± 17
Ba*	10	0.80	± 0.36	± 0.26
Ca*	10	21.89	± 8.97	± 6.46
Cd	10	6.33	± 4.29	± 3.09
Cu	10	11.23	± 6.07	± 4.37
Hg (is)				
Mg*	10	1.30	± 0.23	± 0.17
Mn*	10	3.12	± 2.07	± 1.49
Pb	10	1.3	± 0.74	± 0.53
S* (l)	4	24.58	± 8.48	± 13.48
Se (is)				
U (l)	4	1.21	± 1.41	± 2.24
Zn	10	341	± 62	± 44.64
Age (yr)		4.0	± 2.7	
Dry wt(g)		0.444	± 0.26	± 0.19
Length (mm)	10	39.2	± 7.5	

Table A53. Chemical analyses of the soft parts and age, dry weight and length of mussels from Magela Creek upstream from Bowerbird Billabong

Mussels were collected on 21.10.81; concentrations are in µg/g or mg/g (*) dry weight

Element	n	Mean	SD	95% CL
Al	20	101	± 48	± 22.56
As	20	2.17	± 1.00	± 0.47
Ba*	20	0.57	± 0.26	± 0.12
Ca*	20	14.69	± 6.17	± 2.90
Cd	20	4.58	± 1.37	± 0.64
Cu	20	12.14	± 3.30	± 1.55
Hg	20	0.55	± 0.15	± 0.07
Mg*	20	0.83	± 0.24	± 0.11
Mn*	20	1.09	± 0.79	± 0.37
Pb	19	1.99	± 0.71	± 0.33
S*	20	11.3	± 2.10	± 0.99
Se	20	2.18	± 0.5	± 0.24
U	20	0.25	± 0.20	± 0.9
Zn	20	360	± 48	± 23
Age (yr)	20	4.8	± 2.4	± 1.1
Dry wt(g)	20	0.601	± 0.175	± 0.08
Length(mm)	20	45.4	± 4.11	± 1.93

Table A54. Set numbers and corresponding dates during the short-term uptake and loss study

UPTAKE

	Age class/Date sampled		
Set no.	1	2-4	Time lapse
1	22.9.81	15.9.81	0
2	22	15	12 hours
3	23	16	day 1
4	24	17	day 2
5	26	19	day 4
6	29	22	week 1
7	6 October	29	week 2
8	13	6 October	week 3
9	20	13	week 4
10	27	20	week 5
11	3 November	27	week 6

LOSS

	Age class/Date sampled		
Set no.	1	2-4	Time lapse
12	3.11.81	27.10.81	12 hours
13	4	28	day 1
14	5	29	day 2
15	7	31	day 4
16	10	3.11.81	week 1
17	17	19	week 2
18	24	17	week 3
19	1.12.81[a]	24	week 4
20	8	1.12.81[a]	week 5
21	15	8	week 6
22	5.1.82	29	week 9
23	26	19.1.82	week 12
24	23.2.82	15.2.82	week 16

[a]27 November - first inflow of water into Mudginberri

Table A55. Concentrations of Cu, Pb, Mn, Zn and U in Mudginberri water (filtered) before mussels were collected and in Retention Pond Nos 1, 2 and 4 during the short-term uptake study

Date	Set no.	Cu (μg/L)	Pb (μg/L)	Mn (μg/L)	Zn (μg/L)	U (μg/L)
Mudginberri prior to the experiment						
5.8.81		< 0.5	0.5	17.5	6.5	< 0.4
7.9.81		< 0.5	0.3	9.9	5.0	< 0.4
Mean		< 0.5	0.4	13.7	5.8	< 0.4
Mudginberri during release phase[a]						
5.11.81		< 0.5	< 0.5	11.5	7.0	< 0.05
1.12.81		< 0.5	< 0.5	9.0	20.5	< 0.04
11.1.82		< 0.5	0.38	8.5	21.0	< 0.04
Mean ± SD		< 0.5	0.29 ± 0.07	9.7 ± 1.6	16.2 ± 7.9	< 0.04
Retention Pond No. 1[b]						
27.7.81		1.7	4.3	15.2	6.1	0.6
11.9.81		4.3	0.0	10.6	0.0	0.6
28.9.81	7	5.8	3.2	6.0	20.9	0.3
4.11.81		0.0	0.8	9.0	19.9	1.0
Mean ± SD		2.95 ± 2.59	2.08 ± 2.01	10.2 ± 3.8	11.73 ± 10.33	0.63 ± 0.29
Retention Pond No. 2[b]						
7.9.81		5.4	2.3	19.3	3.0	77.6
21.9.81	6	7.7	2.8	20.6	11.7	70.6
28.9.81	7	8.9	2.8	17.0	8.0	102.5
6.10.81	8	4.6	1.1	44.3	39.4	141.0
12.10.81	9	3.7	1.7	37.8	40.7	336.0
19.10.81	10	1.1	0.0	14.6	37.7	138.7
26.10.81	11	4.5	5.0	21.0	46.0	213.4
Mean ± Sd		5.13 ± 2.58	2.24 ± 1.57	24.9 ± 11.37	26.6 ± 18.2	154.1 ± 93.5
Retention Pond No. 4[b]						
27.7.81		0.2	2.0	17.6	4.4	0.7
1.9.81		4.6	0.0	20.1	12.0	1.1
28.9.81	7	3.7	1.9	57.3	21.4	1.7
4.11.81		0.0	1.3	30.5	9.5	2.6
Mean ± SD		2.1 ± 2.4	1.3 ± 0.9	30.5 ± 18.3	9.5 ± 9.4	2.6 ± 2.9

[a]Data supplied by Water Division, Department of Transport and Works, NT
[b]Data supplied by Environmental Section, Ranger Uranium Mines Ltd.

Table A56. Concentrations of Mg, Ca, and SO_4, the pH and turbidity in Mudginberri water before mussels were collected and in Retention Pond Nos 1, 2 and 4 during the short-term uptake study

Date	Set no.	pH	Turb. (NTU)	Mg (mg/L)	Ca (mg/L)	SO_4 (mg/L)
Mudginberri prior to the experiment (filtered)[a]						
5.8.81		6.3	8	0.75	0.40	0.2
7.9.81		6.1	38	0.88	0.37	2.0
Mean		6.2	5.9	0.82	0.39	1.1
Mudginberri during release phase (filtered)						
5.11.81		5.9	6.0	0.92	0.54	< 1.0
1.12.81		6.0	8.0	0.65	0.40	0.5
11.1.82		4.9	7.5	0.55	0.35	0.2
Mean ± SD		5.6 ± 0.6	7.2 ± 1.0	0.71 ± 0.19	0.43 ± 0.10	0.4 ± 0.17
Retention Pond No.1 (total)[b]						
27.7.81		7.4	8	2.59	0.10	0.3
1.9.81		7.4	11	2.17	0.67	0.3
28.9.81	7	7.5	7	2.38	0.56	0.4
4.11.81		7.9	16	2.33	0.44	0.1
Mean ± SD		7.5 ± 0.2	10.5 ± 4.0	2.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.13
Retention Pond No.2 (total)[b]						
7.9.81		9.1	2	14.04	1.33	48.0
21.9.81	1	8.9	4	13.71	12.55	57.2
28.9.81	7	9.0	4	14.26	13.44	67.3
6.10.81	8	8.2	10	12.02	13.46	55.2
12.10.81	9	9.1	5	12.04	14.97	41.1
19.10.81	10	9.8	4	12.62	21.40	5.4
Mean		9.0 ± 0.5	5 ± 3	13.12 ± 1.01	12.85 ± 6.5	45.7 ± 21.6
Retention Pond No. 4 (total)[b]						
27.7.81		7.0	2	4.72	0.99	2.9
1.9.81		8.0	3	4.39	2.09	0.6
28.9.81	7	7.7	96	4.65	1.06	9.1
28.9.81	7	7.6	9	5.21	1.87	0.7
4.11.81		7.7	35	5.63	2.31	0.3
Mean ± SD		7.6 ± 0.4	29 ± 40	4.9 ± 0.5	1.66 ± 0.60	2.7 ± 3.7

[a]Data supplied by Water Division, Department of Transport and Works, NT
[b]Data supplied by Environmental Section, Ranger Uranium Mines Ltd.

Table A57. Chemical analyses of the OSS mussel reference material (wet) analysed along with experimental samples in set nos 2, 8, 12, 16 and 18

Concentrations are in µg/g or mg/g(*) wet weight.

	Set no.				
	2	8	12	16	18
Al	46	100	125	95	80
As	0.07	0.50	0.60	0.35	0.32
Ba*	0.13	1.38	0.85	0.14	0.20
Ca*	0.56	0.80	0.57	0.25	0.60
Cd	0.33	0.40	0.65	0.11	0.27
Cu	1.8	1.4	2.3	0.80	1.7
Hg	0.03	0.02	0.04	0.05	0.05
Mg	183	165	200	115	180
Mn*	1.63	1.85	1.7	0.70	1.83
Pb	0.39	1.0	1.4	1.0	0.80
S*	0.88	1.11	2.15	1.25	1.25
Se	0.09	0.35	0.65	0.20	0.67
U	0.07	0.15	0.13	0.06	0.39
Zn	60	58	40	51	65

Table A58. Regression analysis for U uptake and loss in the soft parts of mussels in age classes 1-4 in Retention Pond Nos 2 and 4

Age class 1: < 1 year; age class 2: 1-2.9 years; age class 3: 3-6.9 years: and age class 4: ≥ 7 years.

Age class	Regression equation	r^2
UPTAKE: Set nos 1-11		
RP2		
1	y = 1.13 + 0.02x	0.06
2	y = 2.73 + 0.46x	0.51
3	y = 0.69 + 0.58x	0.52
4	y = 3.64 + 0.36x	0.26
RP4		
1	ln y = 0.90 + 0.05x	0.78
2	ln y = 0.14 + 0.05x	0.19
3	ln y = -0.53 + 0.05x	0.36
4	ln y = -0.47 + 0.06x	0.32
LOSS: Set nos 11-24		
RP2		
1	ln y = 3.35 - 0.04x	0.62
2	ln y = ln 2.45 - 0.32 lnx	0.46
3	ln y = ln 2.67 - 0.39 lnx	0.62
4	ln y = ln 2.30 - 0.37 lnx	0.54
RP4		
1	ln y = ln 2.12 - 0.46 lnx	0.47
2	ln y = ln 0.50 - 0.09 lnx	0.04
3	ln y = ln 0.91 - 0.26 lnx	0.45
4	ln y = ln 1.00 - 0.27 lnx	0.66

Table A59. Mean concentrations of Cu, Pb, Mn, Zn, U, Mg, Ca and S, pH and turbidity in the water (filtered) of Mudginberri before mussels were removed and when mussels were replaced into Mudginberri during the long-term uptake study

ND = not determined. Results are from Water Division, Department of Transport and Works, NT

Date		Cu (µg/L)	Pb (µg/L)	Mn (µg/L)	Zn (µg/L)	U (µg/L)	Mg (mg/L)	Ca (mg/L)	S (mg/L)	pH	Turb (NTU)
6.8.80		2	1.0	12.5	3.0	< 0.1	0.95	0.35	0.3	6.0	3.1
3.9.80		< 0.5	< 0.5	5.5	2.5	< 0.3	0.93	0.47	0.7	5.5	2.4
8.10.80		< 0.5	< 0.5	20.0	7.0	< 0.7	1.3	0.65	0.7	6.0	3.5
Mean	before	0.83	0.5	12.7	4.2	< 0.7	1.1	0.49	0.6	5.8	3.0
± SD		± 1.01	± 0.4	± 7.3	± 2.5	± ND	± 0.2	± 0.15	± 0.2	± 0.3	± 0.6
5.8.81		< 0.5	0.5	17.5	6.5	< 0.4	0.75	0.40	0.2	6.3	8.0
7.9.81		< 0.5	0.3	9.9	5.0	< 0.4	0.88	0.37	2.0	6.1	3.8
6.10.81		< 0.5	< 0.5	14.5	39.0	0.1	0.86	0.42	< 1.0	6.4	4.0
Mean	after	< 0.5	0.35	14.0	16.8	< 0.4	0.83	0.40	0.9	6.3	5.3
± SD		-	± 0.13	± 3.8	± 14.2	-	± 0.07	± 0.02	± 1.0	± 0.2	± 2.4

Table A60. Mean concentrations per month of Cu, Pb, Mn, Zn, U, Mg, Ca and S and the pH and turbidity in the water of Retention Pond No. 2 during the long-term uptake study

Results are from Environmental Section, Ranger Uranium Mines Ltd.

Date	Day no.	Cu* (μg/L)	Pb* (μg/L)	Mn* (μg/L)	Zn* (μg/L)	U* (μg/L)	Mg** (mg/L)	Ca** (mg/L)	S** (mg/L)	pH**	Turb** (NTU)
Oct. 80	0	5.3	2.4	12	10.2	63.4	3.1	1.3	1.6	7.5	195
Nov. 80	14	5.9	1.9	7.8	12.3	44.2	6.8	1.7	2.5	7.9	158
Dec. 80	46	21.0	50.2	30.9	20.4	358.0	2.5	1.8	1.8	7.9	333
Jan. 81	80	326.0	52.3	67.0	26.0	575.0	4.2	2.5	2.6	7.6	335
Feb. 81	109	38.6	32.8	34.0	37.3	232.7	1.8	2.8	3.2	7.9	350
Mar. 81	134	65.3	14.1	14.1	22.5	87.5	2.5	3.6	2.3	7.9	287
Apr. 81	165	31.9	7.0	13.6	27.9	106.6	4.1	4.8	7.0	7.7	180
May 81	197	3.3	ND	7.1	41.8	39.7	7.3	6.9	19.9	7.7	34
Jun. 81	226	4.9	0.05	7.4	27.0	26.0	9.2	7.3	17.3	8.2	37
Jul. 81	259	4.0	5.0	9.6	14.8	50.0	10.6	7.2	63.6	8.3	5
Aug. 81	289	6.2	0.8	16.5	12.8	46.8	11.7	10.2	44.9	8.6	2
Mean ± SD		46.6 ± 94.7	16.7 ± 20.7	20.0 ± 18.1	23.0 ± 10.3	148.1 ± 174.1	5.8 ± 3.5	4.6 ± 2.9	15.2 ± 20.7	7.9 ± 0.3	174 ± 139

ND not determined
* filtered
** total

Table A61. Concentrations per month of Cu, Pb, Mn, Zn, U, Mg, Ca and S and the pH and turbidity in the water of Retention Pond No. 4 during the long-term uptake study

Date	Day no.	Cu* (μg/L)	Pb* (μg/L)	Mn* (μg/L)	Zn* (μg/L)	U* (μg/L)	Mg** (mg/L)	Ca** (mg/L)	S** (mg/L)	pH**	Turb** (NTU)
27.10.80	0	2.8	0.0	13.5	7.0	1.8	3.07	1.42	1.2	7.1	62
26.11.80	14	25.5	0.0	6.8	7.6	1.8	7.69	1.93	1.2	8.0	35
22.12.80	46	2.2	13.3	50.5	29.8	10.2	1.54	0.73	0.7	7.6	205[a]
28.1.81	91	3.5	1.0	7.9	7.1	2.4	3.12	1.11	0.2	7.5	17
23.2.81	109	1.3	2.1	9.9	7.7	0.9	2.29	0.94	0.5	7.2	41
19.3.81	134	8.4	4.4	8.9	10.0	2.9	2.20	1.14	0.5	6.6	53
Apr.81	165	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
19.5.81	197	ND	ND	9.6	ND	ND	3.30	1.50	0.4	7.0	11
29.6.81	226	2.6	0.0	16.9	14.7	0.5	3.65	1.15	0.3	7.7	3
27.7.81	259	0.2	2.0	17.6	4.4	0.7	4.72	0.99	2.9	7.0	2
Mean ± SD		2.9 ± 2.4	2.9 ± 4.5	15.7 ± 13.6	11.0 ± 8.2	2.7 ± 3.2	3.51 ± 1.82	1.20 ± 0.36	0.88 ± 0.84	7.3 ± 0.4	28 ± 23

ND not determined
* filtered
** total
[a] error suspected, value not included in calculation of mean

Table A62. Regression analysis for concentrations of Mg, Mn and U in the soft parts of mussels against time for mussels placed in Retention Pond Nos 2 and 4

	Equation	r^2	Significance
Retention Pond No. 2			
U	y = 4.74 lnx - 2.101	0.52	P < 0.001
Retention Pond No. 4			
Mg	y = -0.004x + 2.05	0.61	P < 0.001
Mn	y = -0.014x + 10.56	0.17	P < 0.05
U	y = 0.57 lnx + 0.12	0.48	P < 0.001

Table A63. Mean uranium concentrations in mussels and in Retention Pond Nos 2 and 4 during the short- and long-term studies

Concentrations in mussels are in μg/g dry wt, concentrations in the Retention Ponds are in μg/L.

	Day no.	Short-term	Long-term
Retention Pond 2			
Water	mean	154.1 ± 93.5	148.1 ± 174.1
Mussels	0	0.38 ± 0.08	0.44 ± 0.05
	14	4.40 ± 3.08	7.99 ± 2.22
	42	25.70 ± 7.05	11.94 ± 1.59
	197	-	33.35 ± 12.70
Retention Pond 4			
Water	mean	2.6 ± 2.9	2.7 ± 3.2
Mussels	0	0.38 ± 0.08	0.44 ± 0.05
	14	0.88 ± 0.99	1.10 ± 0.25
	46	5.93 ± 0.75	1.54 ± 0.61
	91-290	-	3.18 ± 1.04 (steady-state plateau concentration)

Table A64. Chemical analyses of soft parts of mussels placed in Gulungul Billabong (controls) for 2.5 days

The means are of n = 10. (Each sample = one mussel; male:female ratio 6:4). Concentrations are in μg/g or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	7.0	1.1	15.1	0.8
Al	268	65	24.4	47.0
As	2.39	1.09	45.6	0.78
Ba*	1.70	0.74	43.5	0.53
Ca*	35.65	6.13	17.2	4.41
Cd	2.21	1.26	56.7	0.90
Cu	10.96	2.25	20.6	1.62
Hg	0.53	0.06	10.6	0.04
Mg*	0.64	0.05	7.1	0.03
Mn*	5.14	1.07	20.9	0.77
Pb	4.12	1.06	25.7	0.76
S*	8.28	2.52	30.4	1.81
Se	3.06	0.50	16.3	0.36
U	0.13	0.08	58.7	0.05
Zn	455	89	19.7	64

Table A65. Chemical analyses of the soft part of mussels placed in an enclosure in Gulungul Billabong for 2.5 days

The means are of n = 5. (Each sample = one mussel; male:female ratio 7:3). Concentrations are in μg/g or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	10.0	3.3	33.0	2.4
Al	172	48	28.0	34.6
As	3.97	1.57	39.5	1.13
Ba*	3.34	1.51	45.2	1.09
Ca*	42.66	10.56	24.8	7.60
Cd	6.69	2.92	43.6	2.10
Cu	8.47	1.79	21.2	1.29
Hg	0.64	0.16	25.5	0.12
Mg*	0.69	0.06	9.0	0.04
Mn*	6.15	1.84	29.8	1.32
Pb	4.62	1.20	26.0	0.86
S*	9.44	1.86	19.6	1.34
Se*	2.96	0.62	20.8	0.44
U	0.18	0.17	98.6	0.12
Zn	477	67	14.1	48

Table A66. Chemical analyses of soft parts of mussels placed in the enclosure in Gulungul Billabong for 2.5 days then returned to Mudginberri Billabong for 3 days

The means are of n = 10. (Each sample = one mussel; male:female ratio 6.4). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	9.8	2.1	21.4	1.5
Al	798	179	22.4	129
As	3.76	1.22	32.5	0.88
Ba*	3.11	1.03	33.2	0.74
Ca*	40.77	11.13	27.3	8.01
Cd	5.58	2.92	52.4	2.10
Cu	10.68	6.42	60.2	4.63
Hg	0.58	0.21	36.5	0.15
Mg*	0.75	0.10	13.3	0.07
Mn*	6.46	1.85	28.7	1.34
Pb	3.73	1.27	34.0	0.91
S*	8.91	1.59	17.8	1.14
Se	3.52	0.53	15.1	0.38
U	0.21	0.13	61.4	0.09
Zn	467	132	28.3	92

Table A67. Chemical analyses of the soft parts of mussels placed in the enclosure in Gulungul Billabong for 2.5 days then purged in filtered water for 2 days

The means are of n = 10. (Each sample = one mussel; male:female ratio 8:2). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	11.7	1.6	14.0	1.2
Al	193	120	62.2	86.5
As	3.81	1.20	31.5	0.86
Ba*	4.30	1.25	29.0	0.90
Ca*	52.74	8.10	15.4	5.83
Cd	5.96	2.34	39.3	1.69
Cu	12.79	10.92	85.4	7.87
Hg	0.55	0.19	33.4	0.13
Mg*	0.71	0.11	16.3	0.08
Mn*	8.34	2.81	33.7	2.02
Pb	4.79	1.82	38.0	1.31
S*	5.15	1.54	30.0	1.11
Se	3.27	1.00	30.5	0.72
U	0.45	0.34	74.4	0.24
Zn	561	151	27.0	109

Table A68. Copper concentrations in water, macrophyte and epiphyte samples taken from an enclosure in Gulungul Billabong (from Hart et al. 1982)

Copper spike added to the enclosure at 0856 on 19.3.81.

			Water ($\mu g/L$)				
Location	Date	Time (h)	surface/ bottom	total	filtered	Epiphyte ($\mu g/g$ dry wt)	Macrophyte ($\mu g/g$ dry wt)
Gulungul Billabong	18.3.81	1655	S	0.84	-	-	-
	19.3.81	0846	S	3.00	2.64	2.43	-
	20.3.81	1100	S	1.95	0.49	10.6	8.5
	20.3.81	1100	B	2.42	0.64	-	-
Enclosure	18.3.81	1056	S	2.48	-	-	-
	19.3.81	0850	S	1.90	1.63	4.38	14.1
			B	3.72	2.34	-	-
		0900	S	17.8	5.93	11.9	25.5
			B	5.39	4.89	-	-
		1120	S	8.32	4.80	32.8	25.5
			B	4.36	6.56[a]	-	-
		1305	S	4.68	6.78[a]	15.1	30.6
			B	4.16	19.2[a]	-	-
		1500	S	5.76	5.26[a]	13.1	42.4
			B	6.70	4.95	-	-
		1700	S	5.46	10.2[a]	11.6	40.3
			B	6.70	4.95	-	-
		1900	S	8.88	3.85	14.9	32.8
			B	4.25	13.5[a]	-	-
	20.3.81	0805	S	3.48	2.07	18.7	49.9
			B	3.33	5.96[a]	-	-
		1800	S	3.47	4.30[a]	15.5	33.8
			B	2.46	5.54[a]	-	-
	21.3.81	1840	S	3.79	1.45	14.1	41.1
			B	4.01	2.43	-	-

[a]contaminated during transport to Water Studies Centre

Table A69. Chemical analyses of the soft parts of mussels in Island Billabong before metals added to the enclosures

The means are of n = 5. (Each sample = one mussel; male:female ratio 2:3). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	3.6	0.5	15.2	0.7
Al	173	67	38.7	83.4
As	1.89	0.64	33.9	0.80
Ba*	0.78	0.24	30.4	0.30
Ca*	14.78	6.91	46.8	8.58
Cd	1.28	0.37	29.0	.46
Cu	7.01	2.81	40.1	3.49
Hg	0.31	0.08	26.7	0.10
Mg*	0.47	0.09	18.5	0.11
Mn*	2.20	0.55	25.1	0.68
Pb	2.45	1.31	53.6	1.63
S*	7.98	1.72	21.6	2.14
Se	1.44	0.23	15.8	0.28
U	0.08	0.03	39.1	0.04
Zn	343	101	29.6	126

Table A70. Chemical analyses of the soft parts of mussels in Island Billabong after 48 days

The means are of n = 5. (Each sample = one mussel; male:female ratio 2:3). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	2.8	0.4	16.0	0.6
Al	250	166	66.3	206.1
As	1.43	0.17	11.7	0.21
Ba*	0.60	0.14	23.1	0.17
Ca*	11.94	2.26	18.9	2.80
Cd	0.87	0.23	26.3	0.28
Cu	7.40	2.79	37.7	3.47
Hg	0.30	0.08	26.6	0.10
Mg*	0.42	0.06	14.6	0.08
Mn*	1.94	0.42	21.4	0.52
Pb	2.17	1.27	58.6	1.58
S*	6.29	3.63	57.8	4.51
Se	1.53	0.49	32.0	0.61
U	0.10	0.05	49.3	0.06
Zn	318	88	27.9	109

Table A71. Chemical analyses of the soft parts of mussels in the control enclosure in Island Billabong after 48 days

The means are of n = 5. (Each sample = one mussel; male:female ratio 4:1). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	3.0	0.0	0.0	0.0
Al	134	35	26.5	4.44
As	1.48	0.37	24.8	0.45
Ba*	0.58	0.20	35.2	0.25
Ca*	11.79	4.06	34.5	5.04
Cd	4.50	1.74	38.7	2.16
Cu	3.57	1.30	36.4	1.61
Hg	0.40	0.04	9.5	0.05
Mg*	0.42	0.11	25.7	0.14
Mn*	2.52	0.92	36.6	1.15
Pb	3.40	0.49	14.3	0.60
S*	6.24	1.44	23.1	1.79
Se	1.14	0.29	25.3	0.36
U	0.07	0.01	10.5	0.01
Zn	332	84	25.4	104

Table A72. Chemical analyses of the soft parts of mussels in enclosure 2 (manganese and zinc to x10 the natural concentration) in Island Billabong after 48 days

The means are of n = 5. (Each sample = one mussel; male:female ratio 0:5). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	3.2	0.4	14.0	0.6
Al	149	56	37.7	70.1
As	1.38	0.37	26.6	0.46
Ba*	0.61	0.10	17.2	0.13
Ca*	16.09	4.04	25.1	5.02
Cd	7.21	2.49	34.5	3.09
Cu	6.49	0.70	10.8	0.87
Hg	0.35	0.11	30.2	0.13
Mg*	0.43	0.07	15.8	0.08
Mn*	3.16	0.43	13.5	0.53
Pb	1.46	0.87	59.5	1.08
S*	6.65	1.37	20.6	1.70
Se	1.27	0.40	31.4	0.49
U	0.07	0.01	8.9	0.01
Zn	712	193	27.2	240

Table A73. Chemical analyses of the soft parts of one mussel in enclosure 1 (copper to x10 the natural concentration) in Island Billabong after 48 days

Concentrations are in µg/g or mg/g (*) dry weight.
Sex = female with mature glochidia in the marsupia.

Age	3.0
Al	122
As	1.75
Ba*	0.85
Ca*	16.67
Cd	17.55
Cu	42.11
Hg	0.35
Mg*	0.47
Mn*	3.16
Pb	3.51
S*	9.83
Se	1.14
U	0.09
Zn	298

Table A74. Chemical analyses of the soft parts of one mussel found floating in enclosure 1 in Island Billabong 11 days after copper was added

Concentrations are in µg/g or mg/g (*) dry weight.
Sex = female with embryos in the marsupia.

Age	7.0
Al	100
As	1.84
Ba*	1.97
Ca*	31.02
Cd	10.90
Hg	0.59
Mg*	0.23
Mn*	5.16
Pb	3.35
S*	11.40
Se	2.34
U	0.34
Zn	612

Table A75. Chemical analyses of the soft parts and mean length, dry weight and age of mussels in Leichhardt Billabong, December 1980, January 1981 (mussel kill) and February 1981

Concentrations are in µg/g or mg/g (*) dry weight

	Mean ± SD		
	7.12.81 (n = 5)	8.1.82 (n = 3)	16.2.82 (n = 5)
Al	62 ± 7.6	176 ± 115	51 ± 16
As	1.18 ± 0.23	1.23 ± 0.19	1.13 ± 0.08
Ba*	0.39 ± 0.67	1.39 ± 0.14	0.45 ± 0.10
Ca*	9.12 ± 3.96	36.95 ± 9.78	13.41 ± 2.76
Cd	0.75 ± 0.14	2.61 ± 1.19	0.63 ± 0.09
Cu	5.30 ± 1.06	12.67 ± 3.68	4.94 ± 0.37
Hg	0.17 ± 0.06	0.19 ± 0.03	0.27 ± 0.04
Mg*	0.34 ± 0.04	0.39 ± 0.09	0.46 ± 0.40
Mn*	0.68 ± 0.24	3.31 ± 0.84	0.90 ± 0.16
Pb	1.73 ± 0.46	2.24 ± 2.54	1.26 ± 0.04
S*	6.28 ± 0.72	14.07 ± 4.08	5.62 ± 0.50
Se	1.03 ± 0.14	0.75 ± 0.10	1.41 ± 0.17
U	0.13 ± 0.03	0.23 ± 0.11	0.08 ± 0.03
Zn	331 ± 48	485 ± 149	354 ± 20
Dry wt/ mussel (g)	2.29 ± 0.33	0.51 ± 0.01	2.46 ± 0.01
Length (mm)	66 ± 3	79 ± 14	64 ± 2
Age	2.8 ± 0.8	23 ± 1.2	2.5 ± 0.5

Table A76. Chemical analyses of the soft parts of mussels from location 1, Finniss/East Finniss river area

The means are of n = 30. (Each sample = one mussel; male:female ratio 14:16). Concentrations are in µg/g or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	5.4	2.6	47.5	1.0
Al	936	1343	143.5	497.1
As	5.02	2.80	55.8	1.04
Ba*	4.51	2.93	64.9	1.08
Ca*	36.32	22.62	62.3	8.37
Cd	7.87	4.55	57.8	1.68
Cu	27.75	13.82	49.8	5.11
Hg	0.31	0.09	29.9	0.03
Mg*	1.45	0.58	40.3	0.22
Mn*	6.43	4.46	69.4	1.65
Pb	211.33	173.66	82.2	64.25
S*	9.68	6.94	71.8	2.57
Se	5.54	3.00	54.1	1.11
U	1.60	0.99	61.6	0.37
Zn	485	214	44.1	79

Table A77. Chemical analyses of the soft parts of mussels from location 2, Finniss/East Finniss river area

The means are of n = 30. (Each sample = one mussel; male:female ratio 17:13). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	4.0	2.1	51.6	0.8
Al	364	323	88.8	119.5
As	4.32	2.05	47.3	0.76
Ba*	4.39	1.41	32.2	0.52
Ca*	32.57	10.73	32.9	3.97
Cd	6.28	2.68	42.7	0.99
Cu	15.36	4.79	31.2	1.77
Hg	0.26	0.10	39.1	0.04
Mg*	1.68	0.47	27.8	0.17
Mn*	7.01	2.45	35.0	0.91
Pb	37.51	31.79	84.8	11.76
S*	6.87	3.84	55.9	1.42
Se	4.32	1.59	36.9	0.59
U	0.99	0.45	45.3	0.17
Zn	811	1686	207.9	623

Table A78. Chemical analyses of the soft parts of mussels from location 3, Finniss/East Finniss river area

The means are of n = 30. (Each sample = one mussel; male:female ratio 19:11). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	4.3	2.5	59.3	0.9
Al	272	249	91.6	92.2
As	1.17	0.95	81.0	0.35
Ba*	3.14	1.75	55.7	0.65
Ca*	29.17	13.22	45.3	4.89
Cd	7.29	3.97	54.5	1.47
Cu	17.76	7.90	44.5	2.92
Hg	0.20	0.09	45.2	0.03
Mg*	1.23	0.42	34.4	0.16
Mn*	4.75	2.54	53.5	0.94
Pb	48.72	38.86	79.8	14.38
S*	9.49	3.75	39.5	1.39
Se	3.18	1.04	32.7	0.38
U	0.47	0.32	68.8	0.12
Zn	375	98	26.1	36

Table A79. Chemical analyses of the soft parts of mussels from location 4, Finniss/East Finniss river area

The means are of n = 25. (Each sample = one mussel; male:female ratio 14:11). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

	Mean	± SD	CV ± 95% CL	
Age	4.3	2.4	55.2	1.0
Al	194	206	106.3	84.7
As	1.30	0.74	56.8	0.30
Ba*	4.01	1.97	49.1	0.81
Ca*	29.07	10.13	34.9	4.15
Cd	4.66	1.98	42.4	0.81
Cu	9.69	3.75	38.7	1.54
Hg	0.30	0.10	34.5	0.04
Mg*	1.48	0.29	19.5	0.12
Mn*	5.02	2.14	42.7	0.88
Pb	16.19	10.13	62.6	4.15
S*	7.79	5.63	72.3	2.31
Se	3.38	1.30	38.5	0.53
U	0.92	0.48	51.9	0.20
Zn	345	77	22.4	31

Table A80. Chemical analyses of the soft parts of mussels from location 5, Finniss/East Finniss river area

The means are of n = 30. (Each sample = one mussel; male:female ratio 19:11). Concentrations are in $\mu g/g$ or mg/g (*) dry weight.

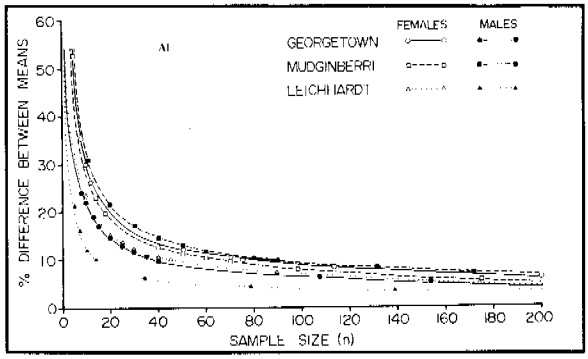
	Mean	± SD	CV ± 95% CL	
Age	6.5	2.6	39.5	1.0
Al	265	300	113.1	111.1
As	2.43	1.11	45.7	0.41
Ba*	2.49	0.81	32.7	0.30
Ca*	46.70	15.30	32.8	5.66
Cd	4.60	2.71	59.0	1.00
Cu	26.71	14.99	56.1	5.55
Hg	0.79	0.24	30.7	0.09
Mg*	2.46	0.70	28.4	0.26
Mn*	5.19	2.10	40.4	0.78
Pb	8.61	5.66	65.8	2.09
S*	10.26	10.63	103.5	3.93
Se	5.03	2.66	52.9	0.98
U	1.07	0.55	51.6	0.20
Zn	306	84	27.5	31

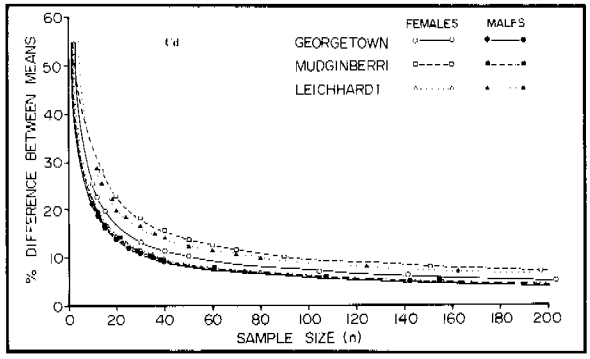
Table A81. Summary of analyses of variance of elements in mussels from five locations in Finniss/East Finniss river area

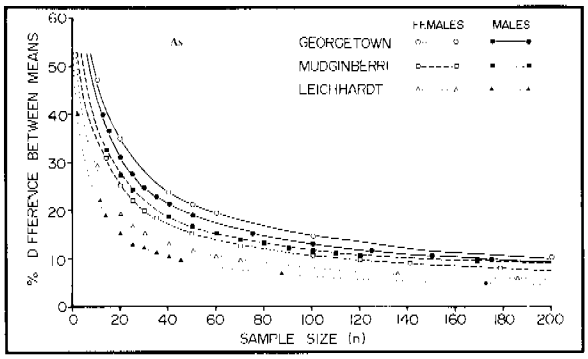
Source	Between locations	Within 'clean' locations	Within 'polluted' locations	'Clean' vs 'Polluted' locations
Al	***	NS	***	***
As	***	NS	***	***
Ba	***	***	***	***
Ca	***	NS	NS	NS
Cd	***	*	NS	***
Cu	***	***	***	***
Hg	***	***	***	***
Mg	***	NS	***	NS
Mn	***	*	**	***
Pb	***	**	***	***
S	***	NS	NS	***
Se	***	NS	***	***
U	***	NS	***	***
Zn	***	NS	***	***

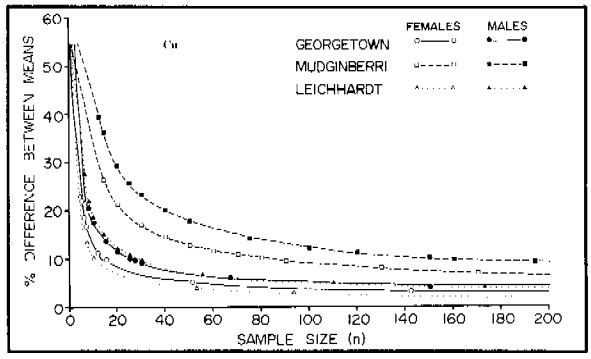
APPENDIX 2

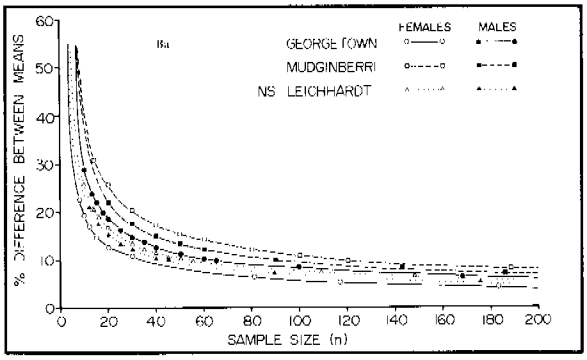
FIGURES

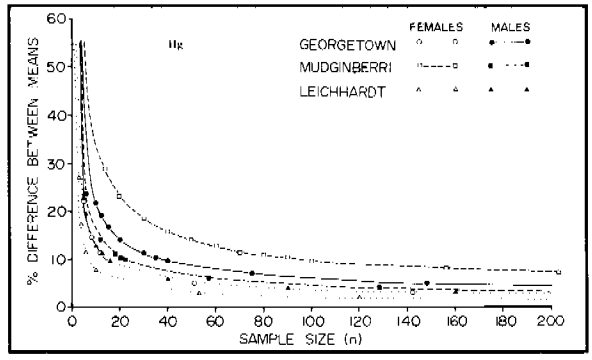












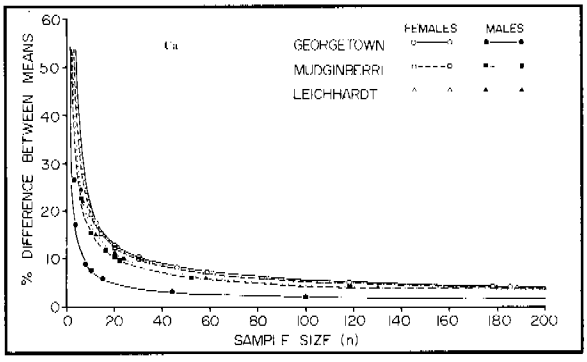
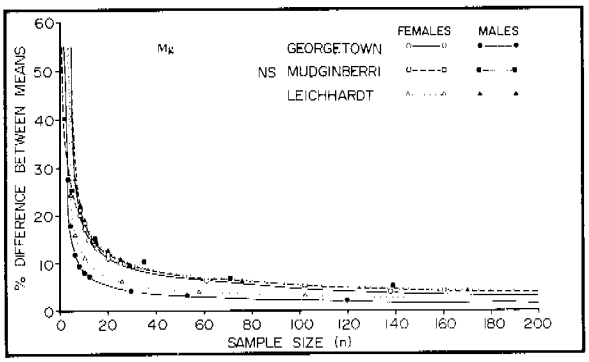
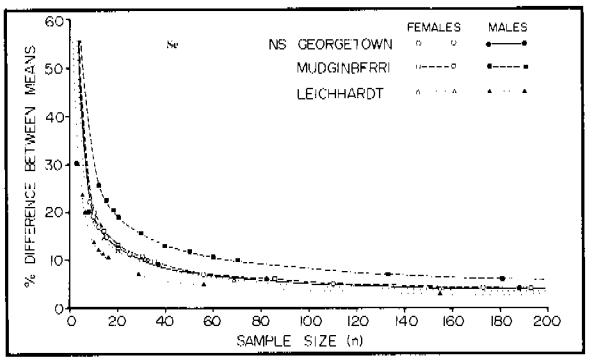
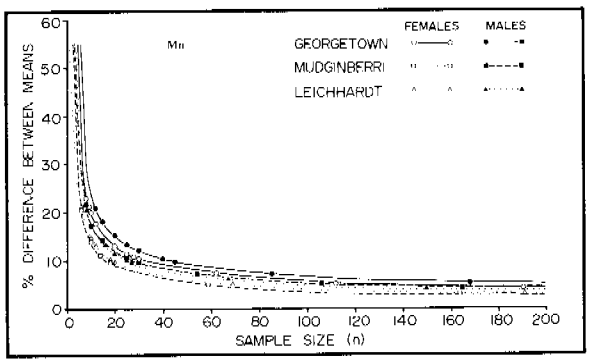
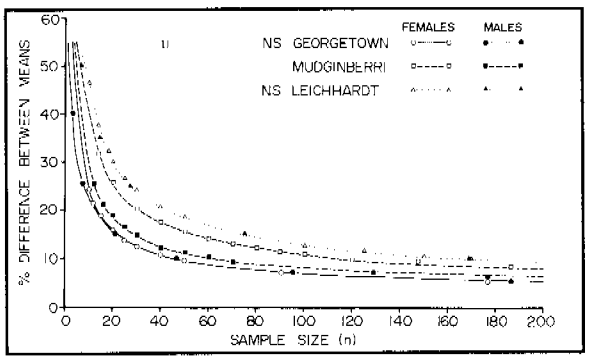


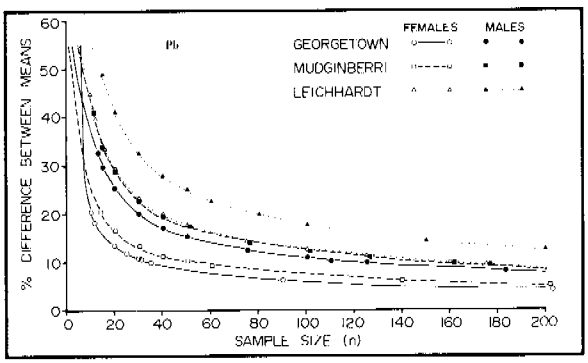
Figure A1. Relationship between sample size and percentage difference between means for aluminium, arsenic, barium calcium, cadmium, copper and mercury; based on seven-year-old male and female mussels from Georgetown, Mudginberri and Leichhardt billabongs

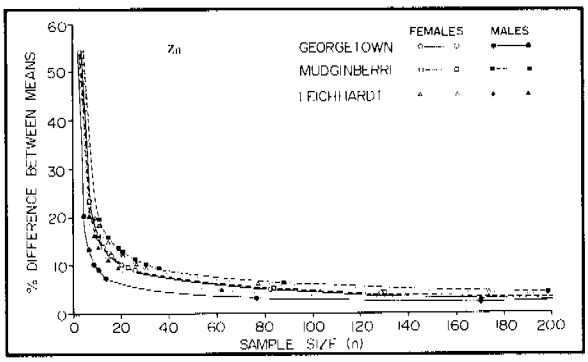












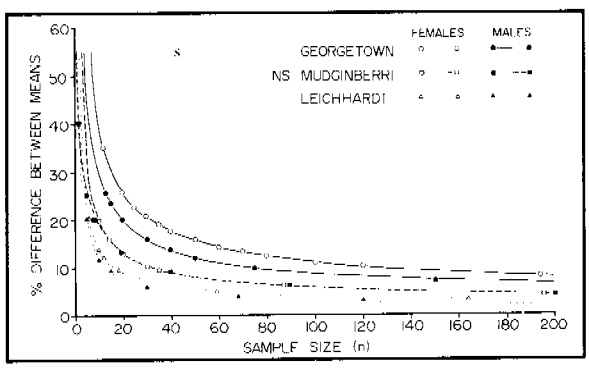


Figure A2. Relationship between sample size and percentage difference between means for magnesium, manganese, lead, sulphur, selenium, uranium and zinc; based on seven-year-old male and female mussels from Georgetown, Mudginberri and Leichhardt billabongs

NS = No significant difference ($P > 0.05$) between males and females, only single line shown

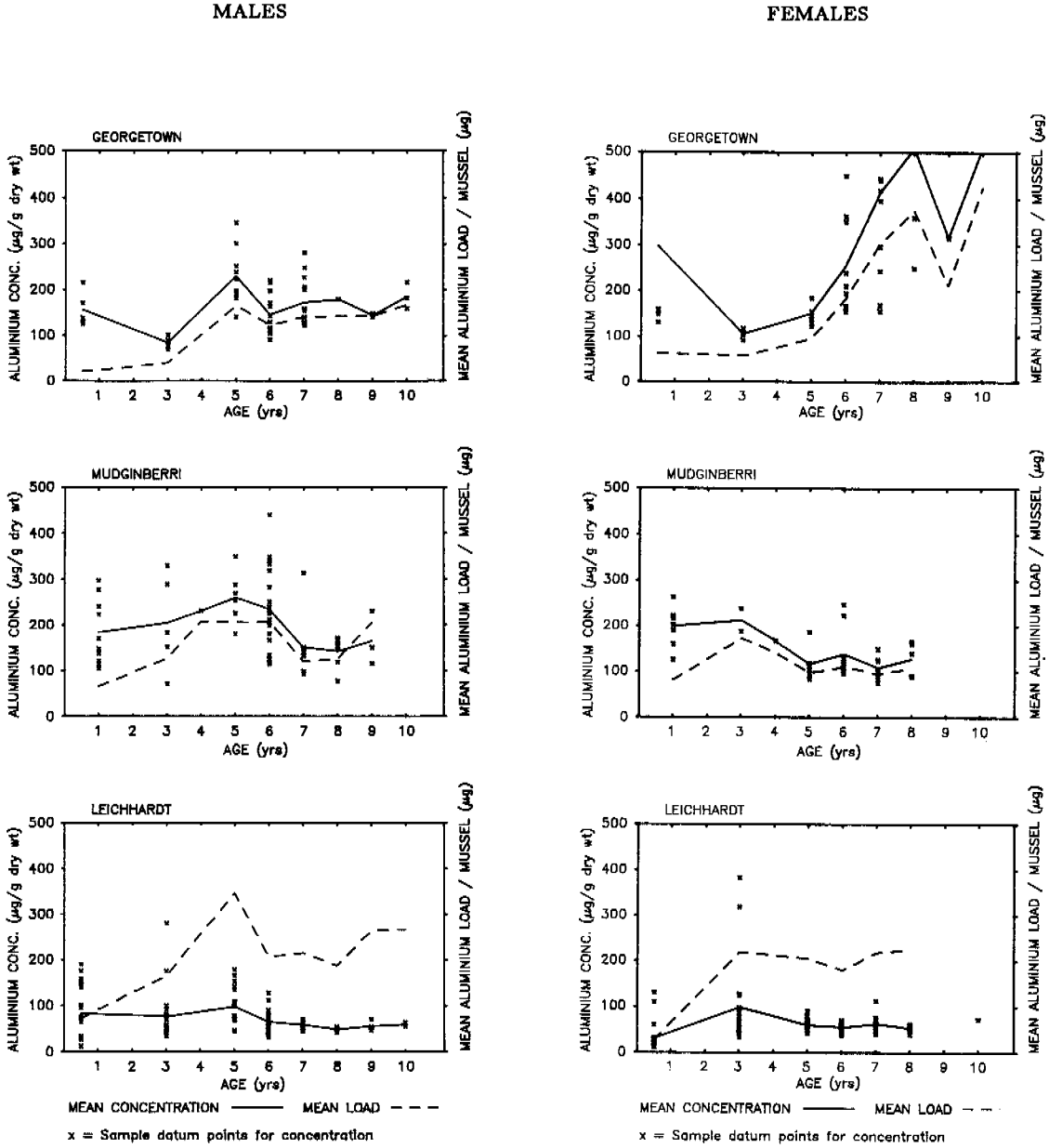


Figure A3. Concentrations and mean load per mussel of aluminium versus age in mussels from Georgetown, Mudginberri and Leichhardt

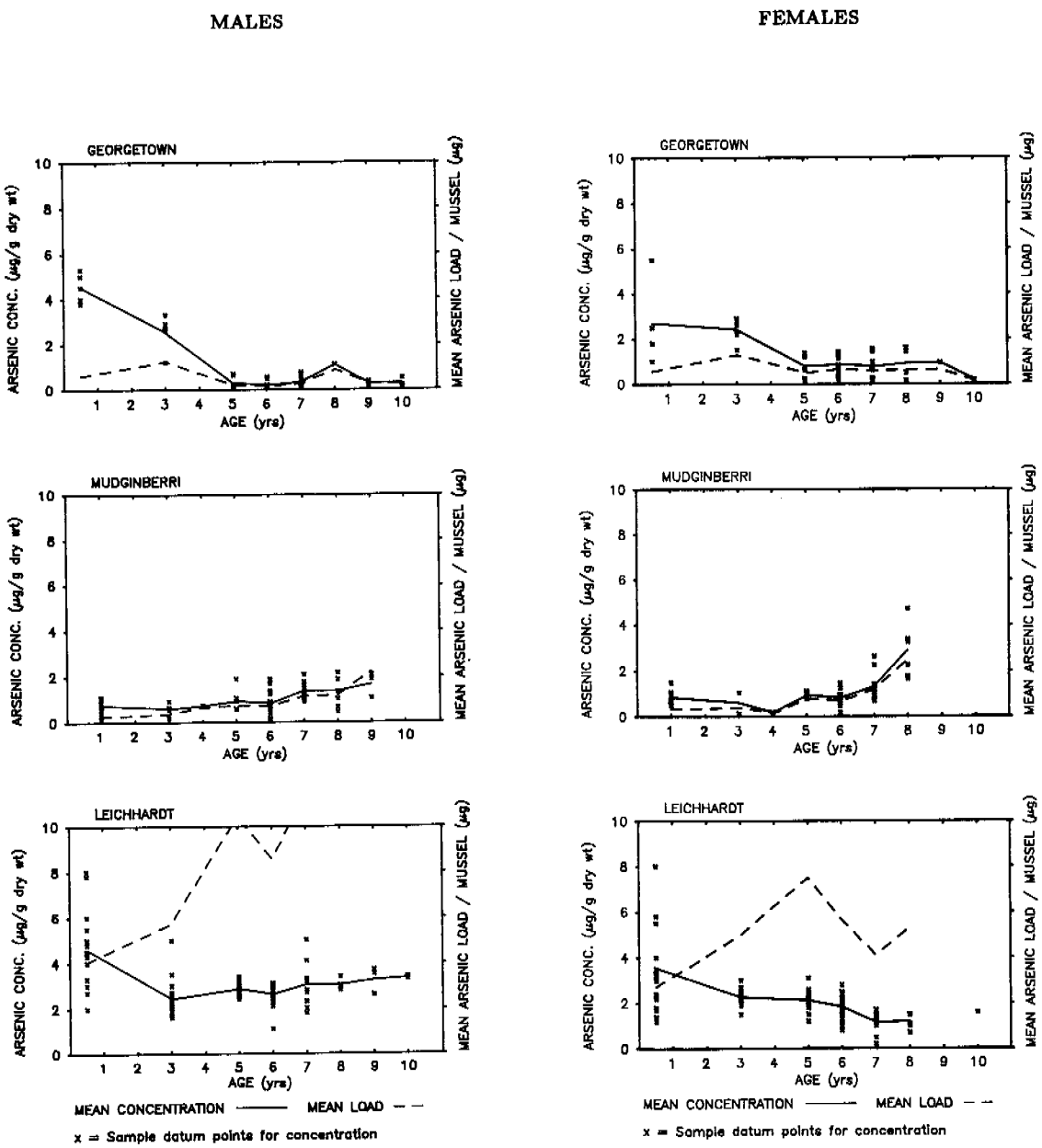


Figure A4. Concentrations and mean load per mussel of arsenic versus age in mussels from Georgetown, Mudginberri and Leichhardt

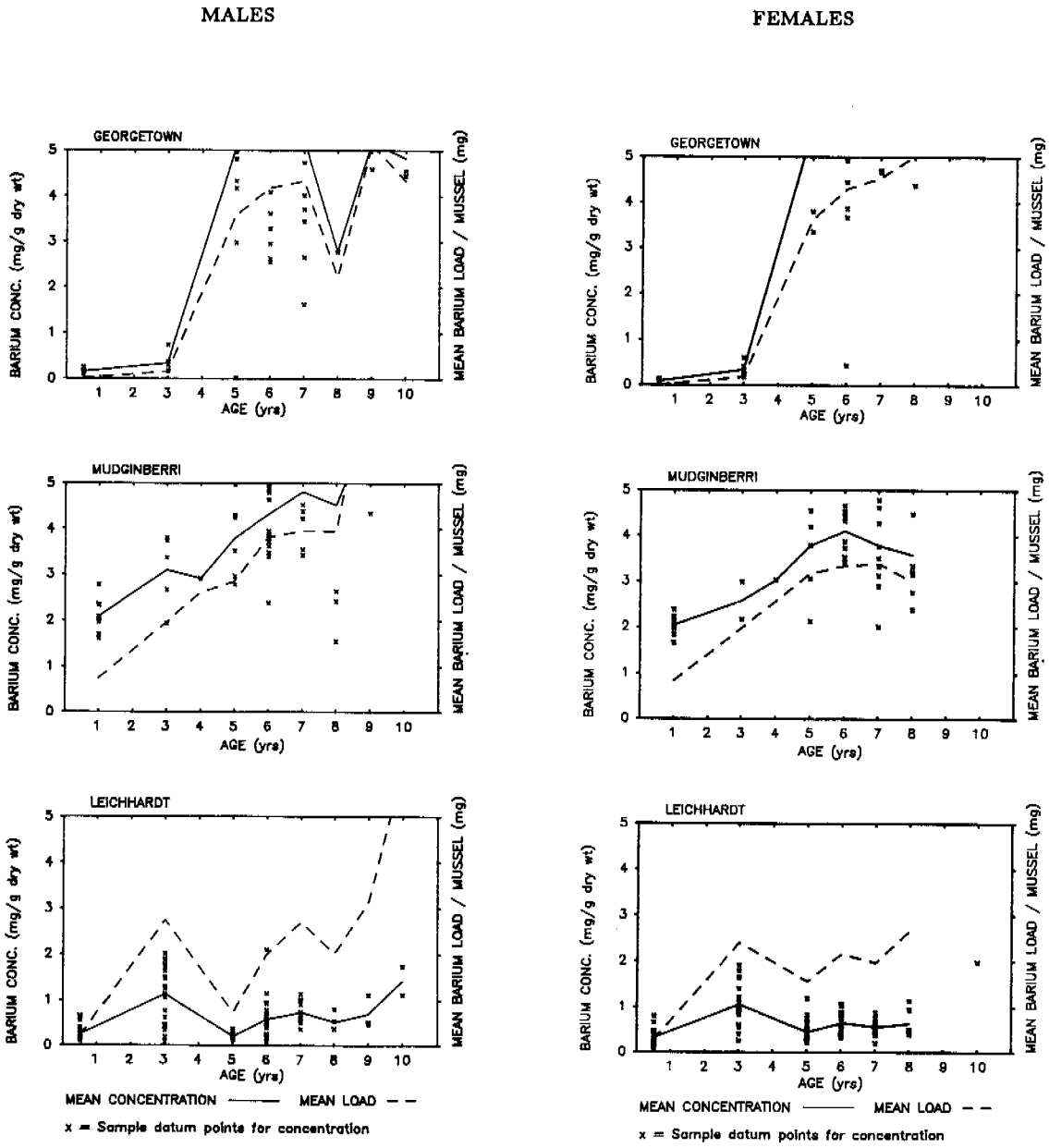


Figure A5. Concentrations and mean load per mussel of barium versus age in mussels from Georgetown, Mudginberri and Leichhardt

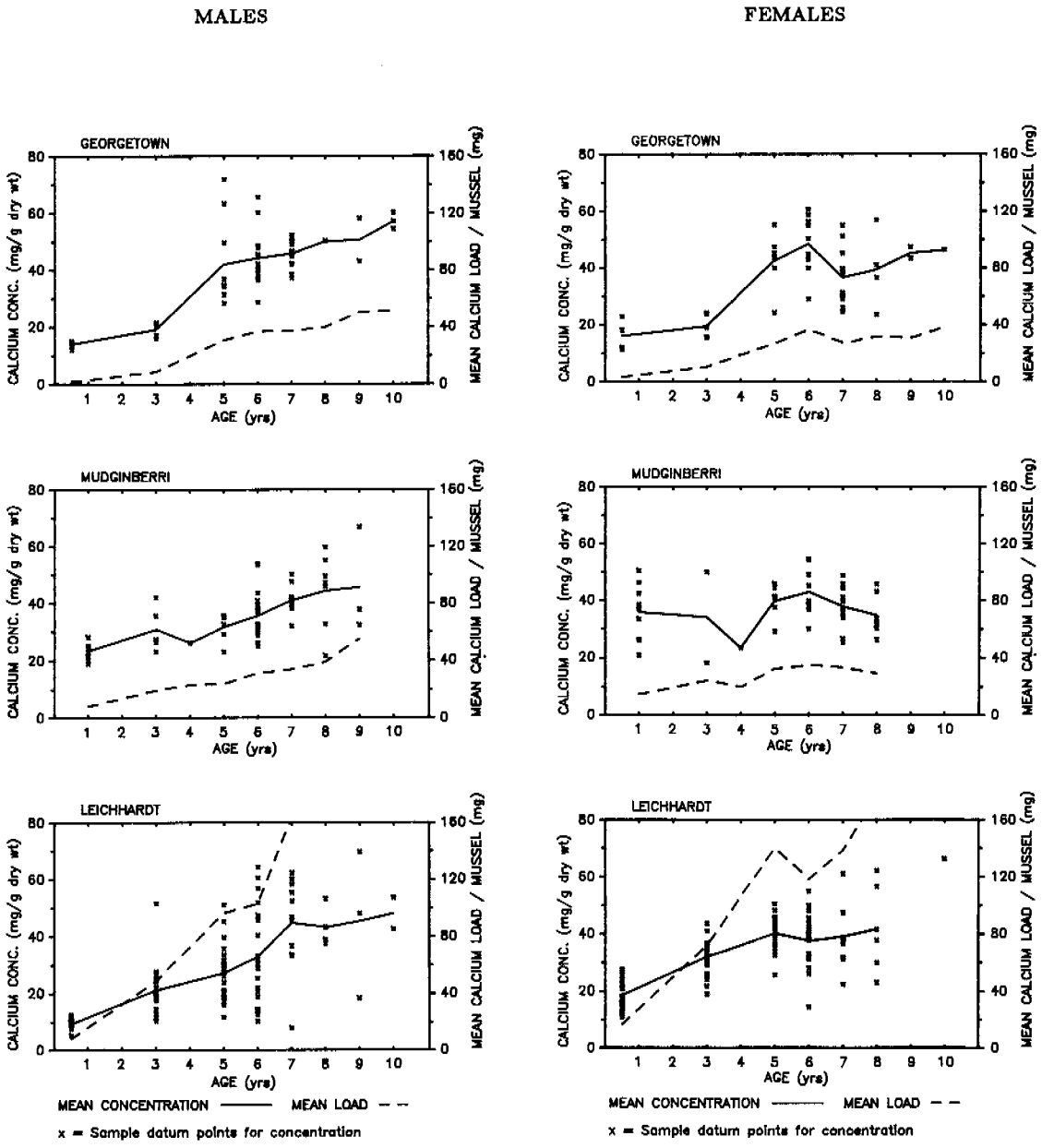


Figure A6. Concentrations and mean load per mussel of calcium versus age in mussels from Georgetown, Mudginberri and Leichhardt

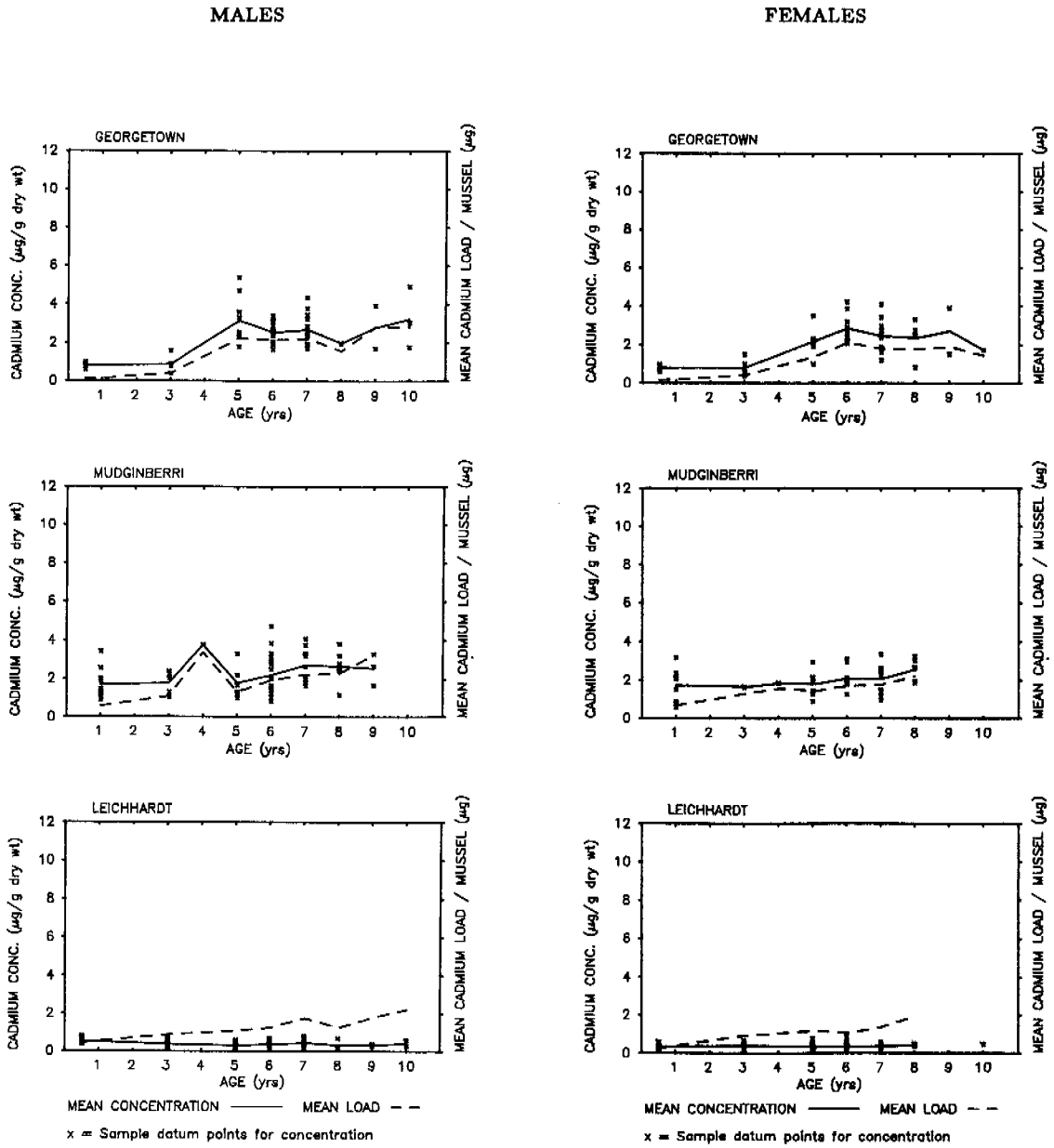


Figure A7. Concentrations and mean load per mussel of cadmium versus age in mussels from Georgetown, Mudginberri and Leichhardt

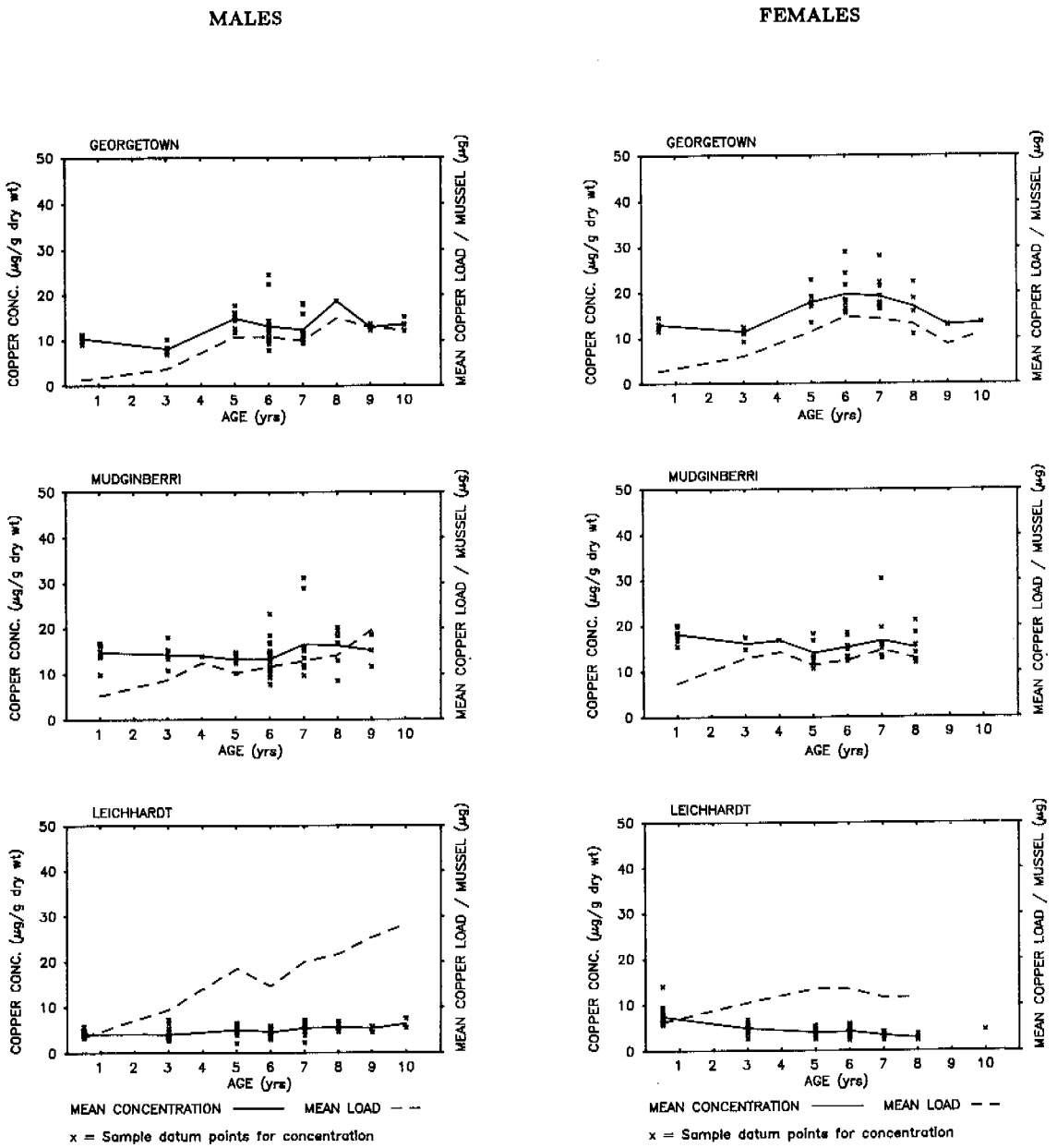


Figure A8. Concentrations and mean load per mussel of copper versus age in mussels from Georgetown, Mudginberri and Leichhardt

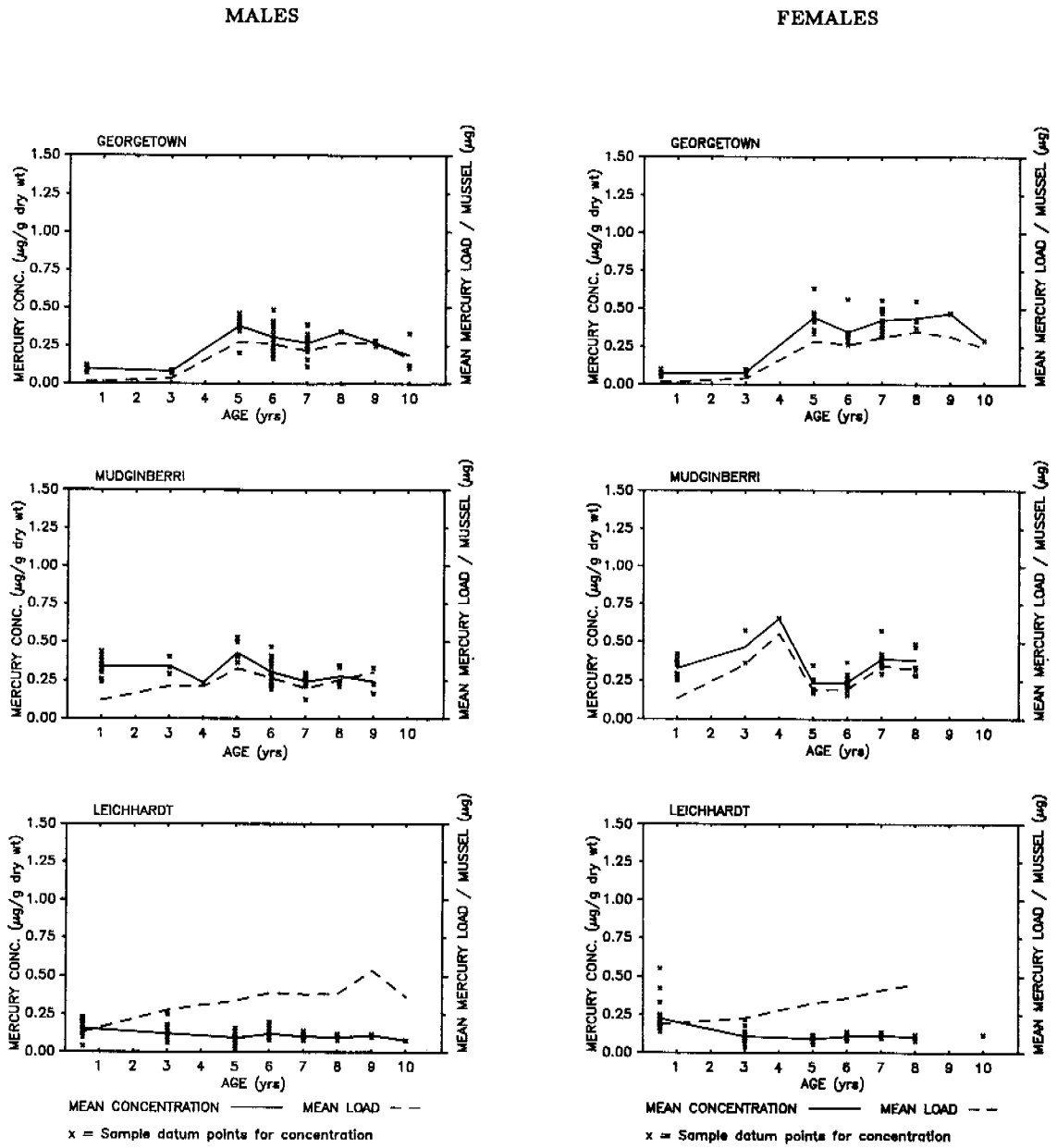


Figure A9. Concentrations and mean load per mussel of mercury versus age in mussels from Georgetown, Mudginberri and Leichhardt

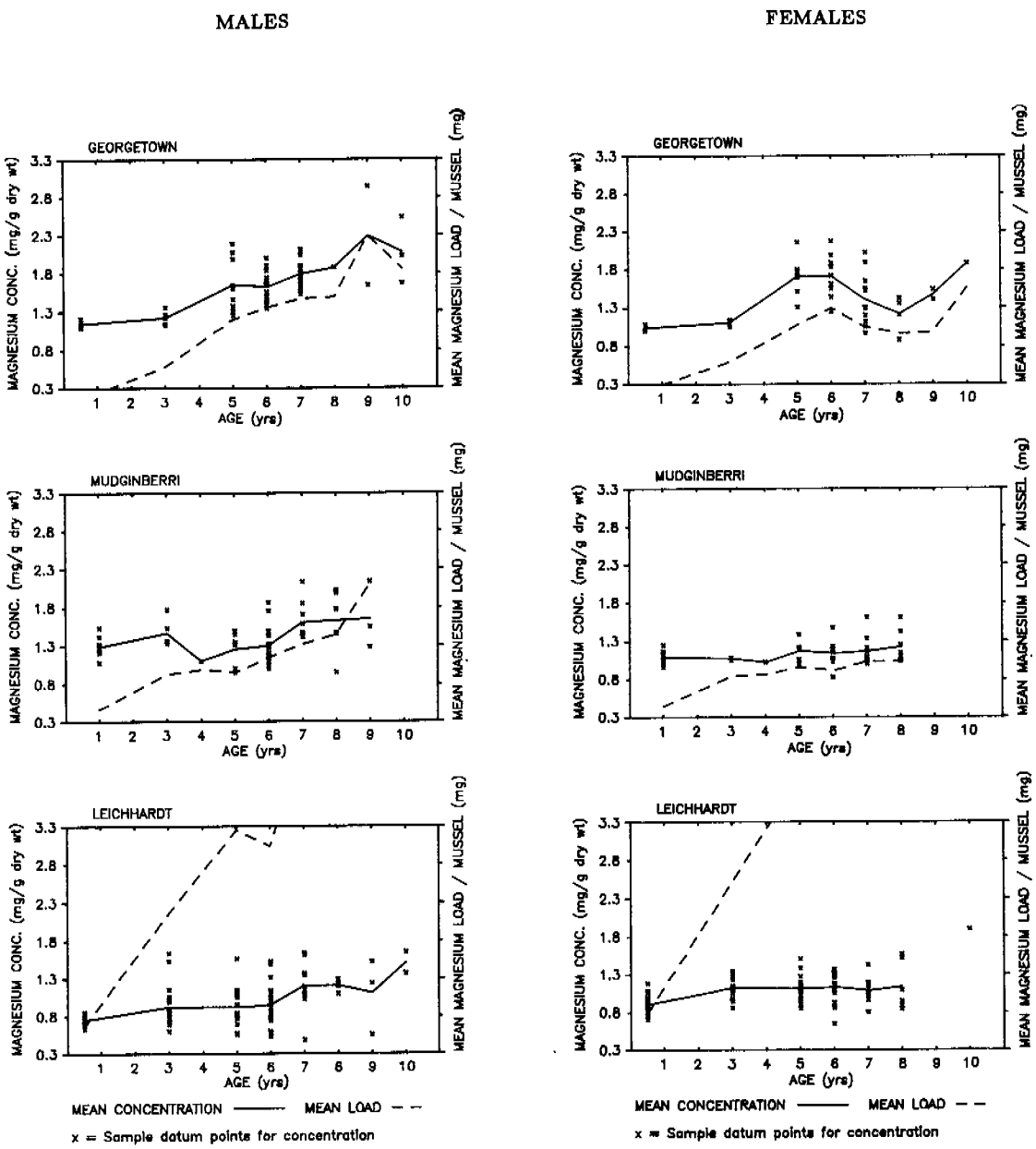


Figure A10. Concentrations and mean load per mussel of magnesium versus age in mussels from Georgetown, Mudginberri and Leichhardt

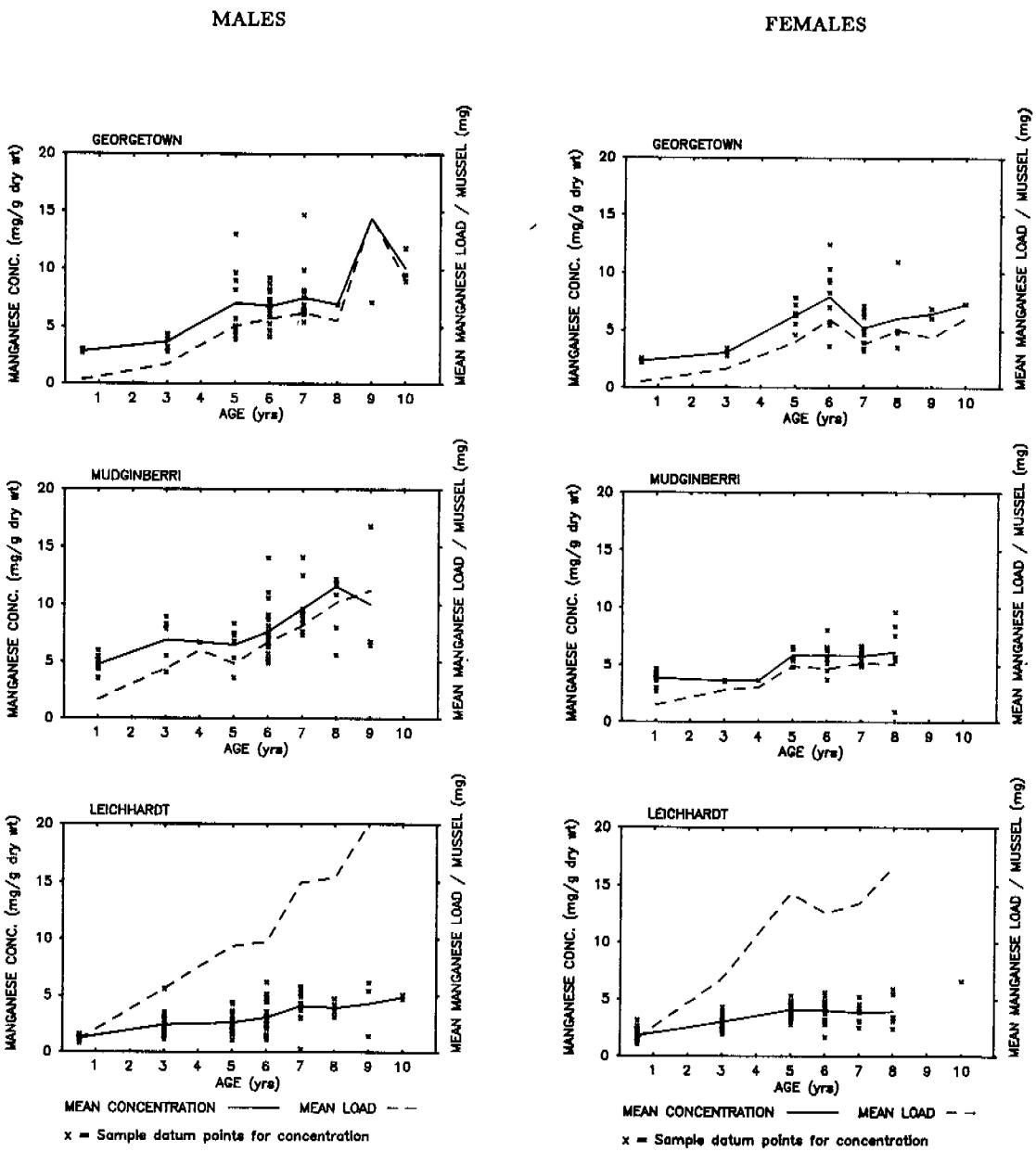


Figure A11. Concentrations and mean load per mussel of manganese versus age in mussels from Georgetown, Mudginberri and Leichhardt

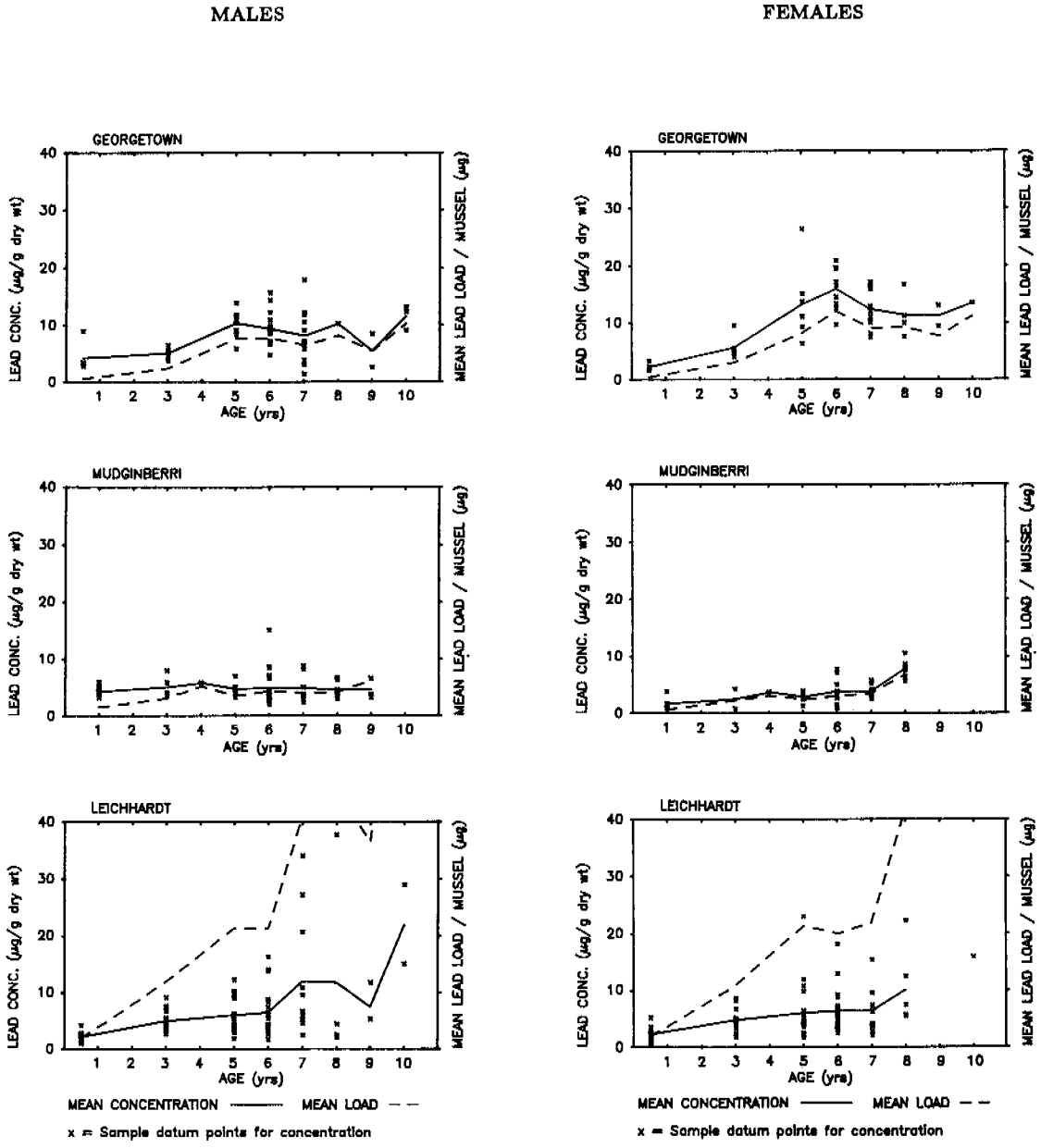


Figure A12. Concentrations and mean load per mussel of lead versus age in mussels from Georgetown, Mudginberri and Leichhardt

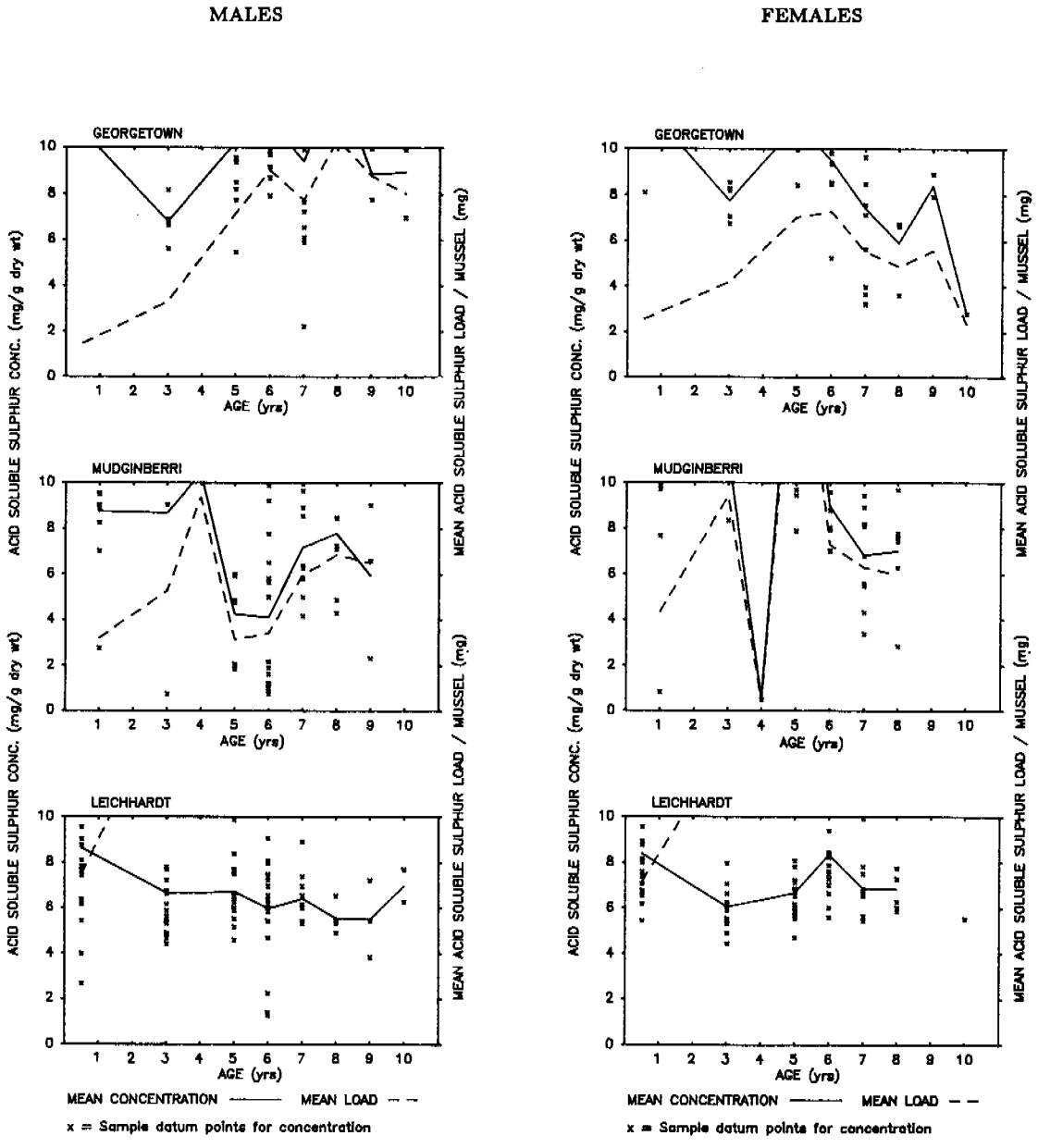


Figure A13. Concentrations and mean load per mussel of sulphur versus age in mussels from Georgetown, Mudginberri and Leichhardt

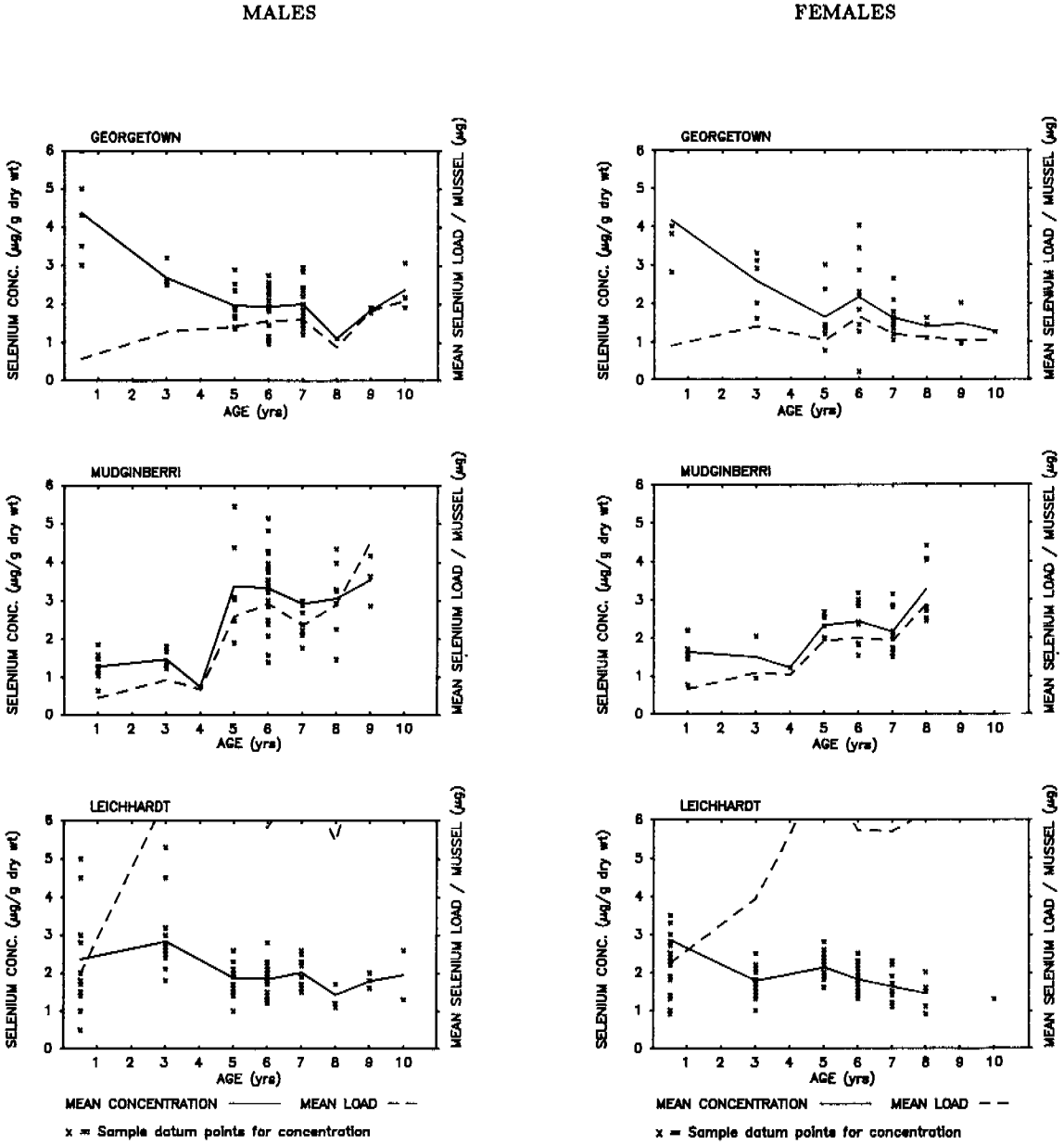


Figure A14. Concentrations and mean load per mussel of selenium versus age in mussels from Georgetown, Mudginberri and Leichhardt

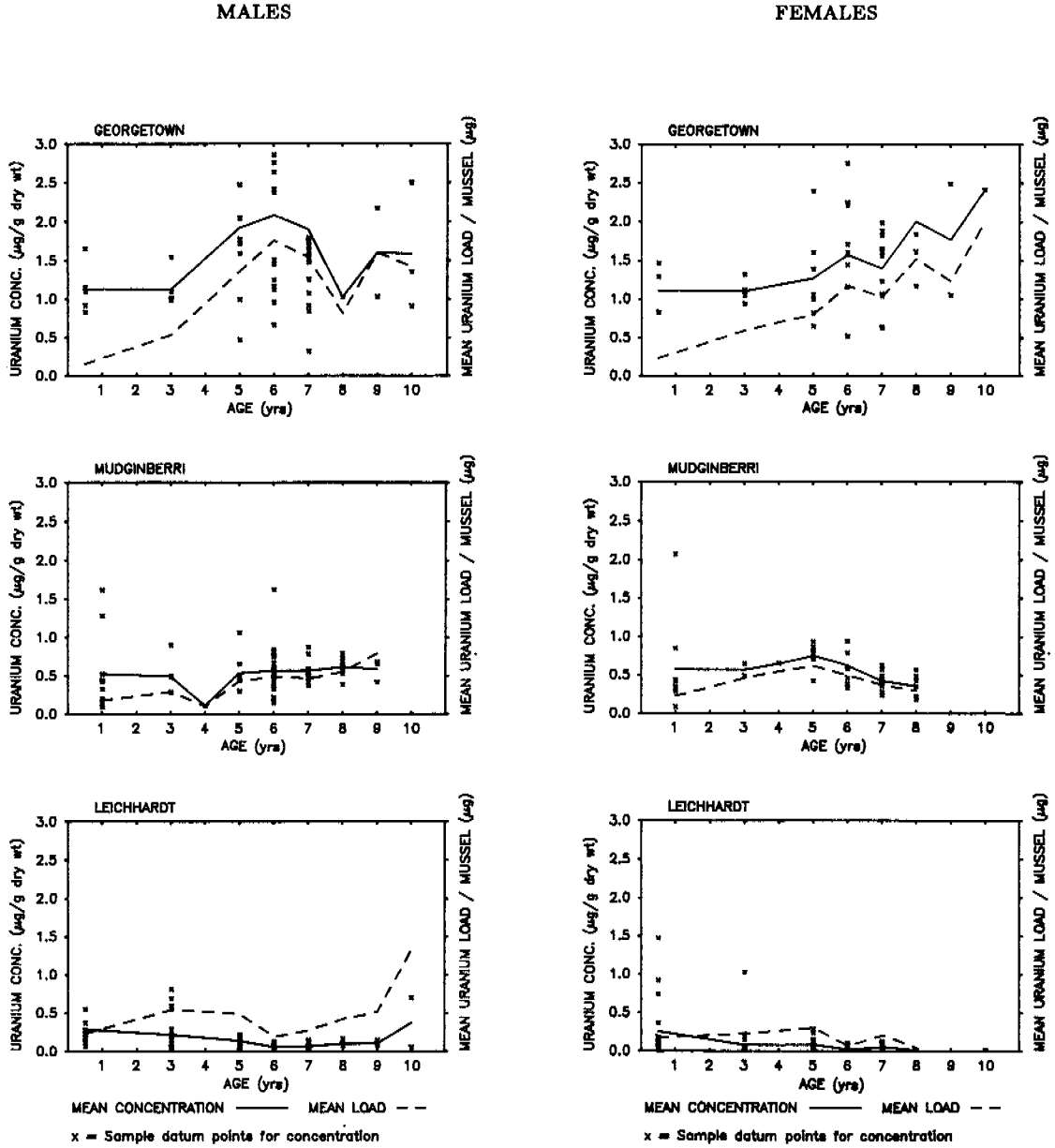


Figure A15. Concentrations and mean load per mussel of uranium versus age in mussels from Georgetown, Mudginberri and Leichhardt

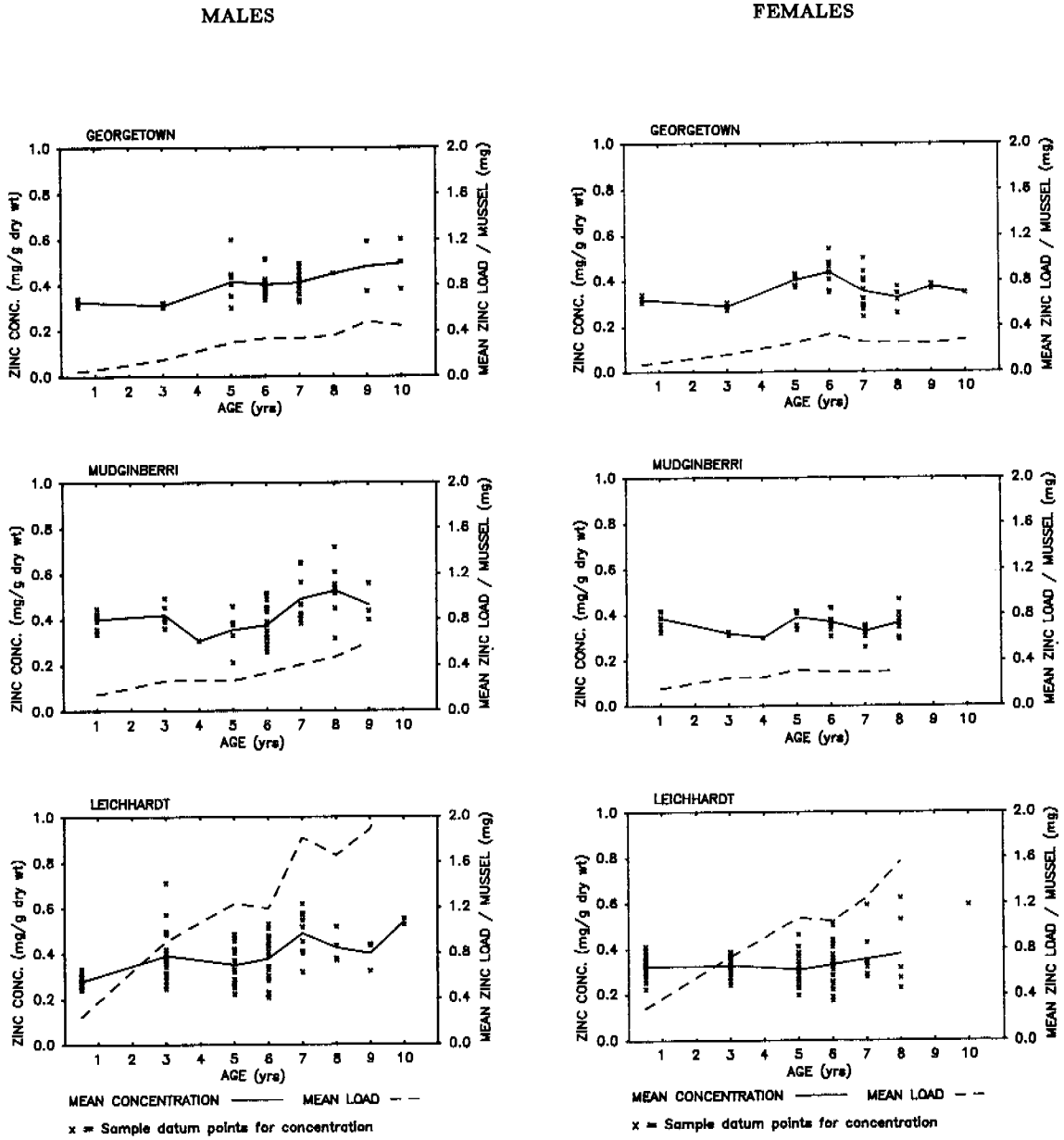


Figure A16. Concentrations and mean load per mussel of zinc versus age in mussels from Georgetown, Mudginberri and Leichhardt

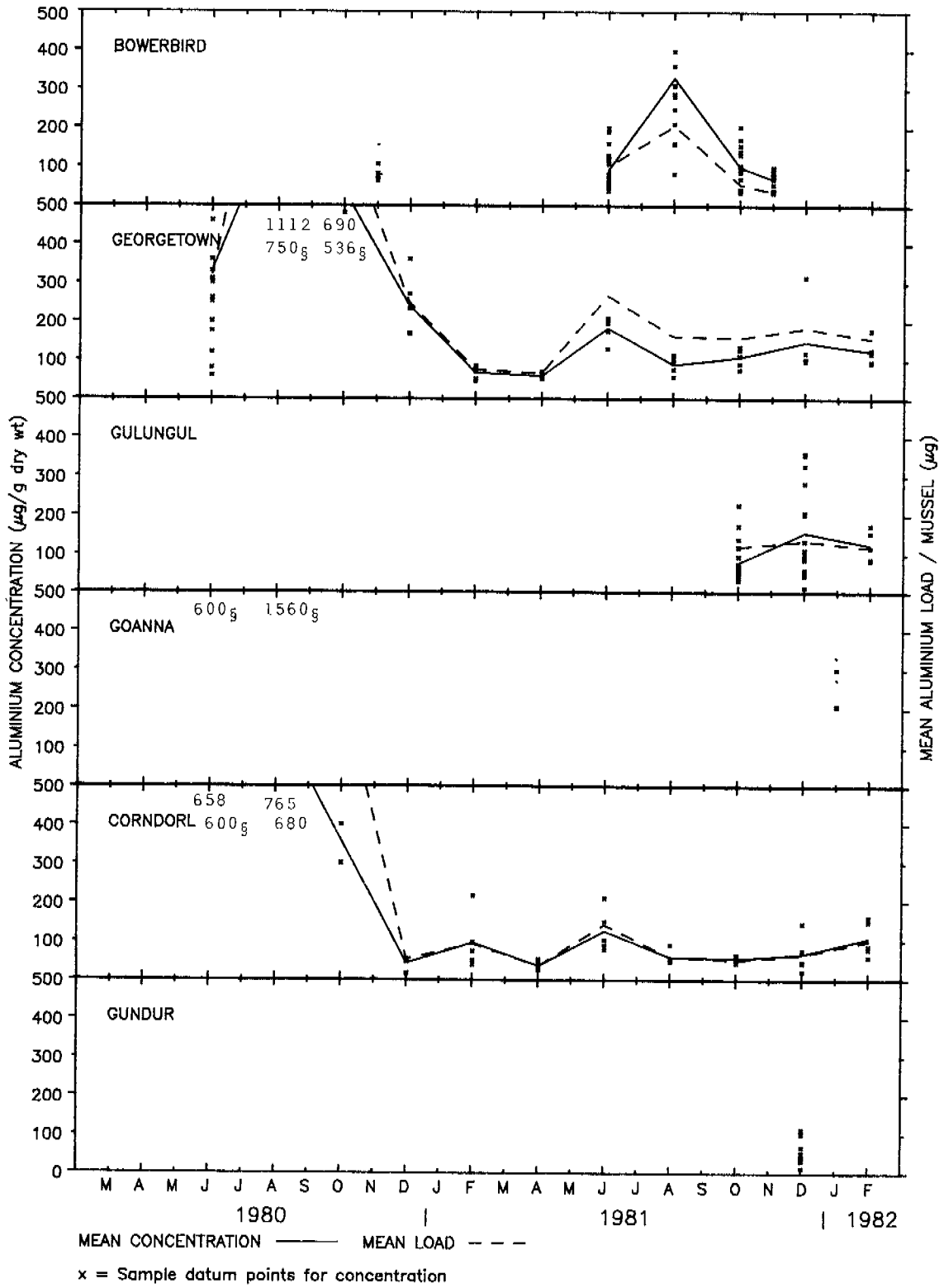
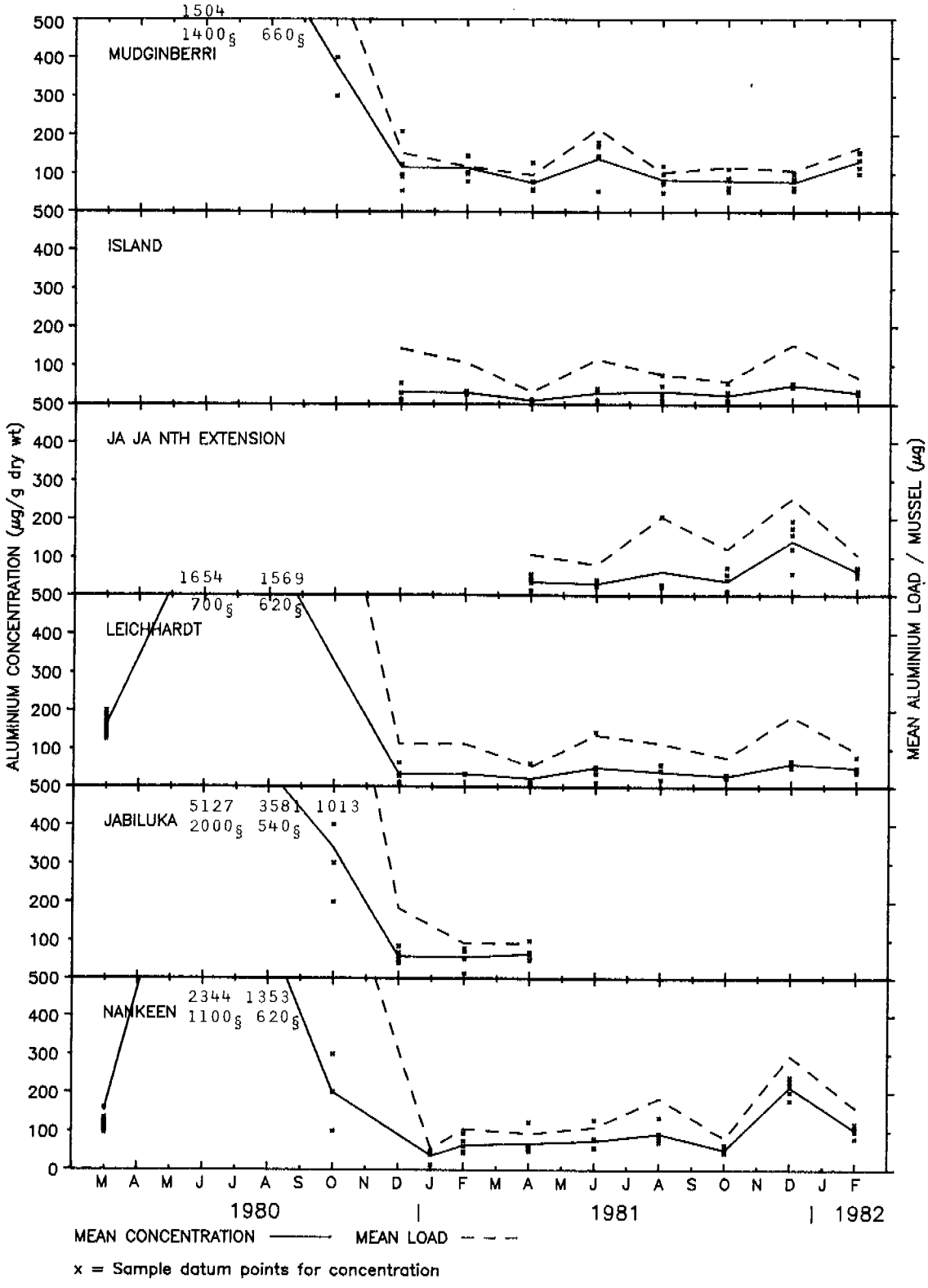


Figure A17.*(Above and opposite)* Concentrations and mean load of aluminium in the soft parts of mussels from various billabongs between March 1980 and February 1982


1504
1400§ 660§
MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
1654 1569
700§ 620§
LEICHHARDT
5127 3581 1013
2000§ 540§
JABILUKA
2344 1353
1100§ 620§
NANKEEN
ALUMINIUM CONCENTRATION (µg/g dry wt)
MEAN ALUMINIUM LOAD / MUSSEL (µg)
0 100 200 300 400 500
M A M J J A S O N D J F M A M J J A S O N D J F
1980 | 1981 | 1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

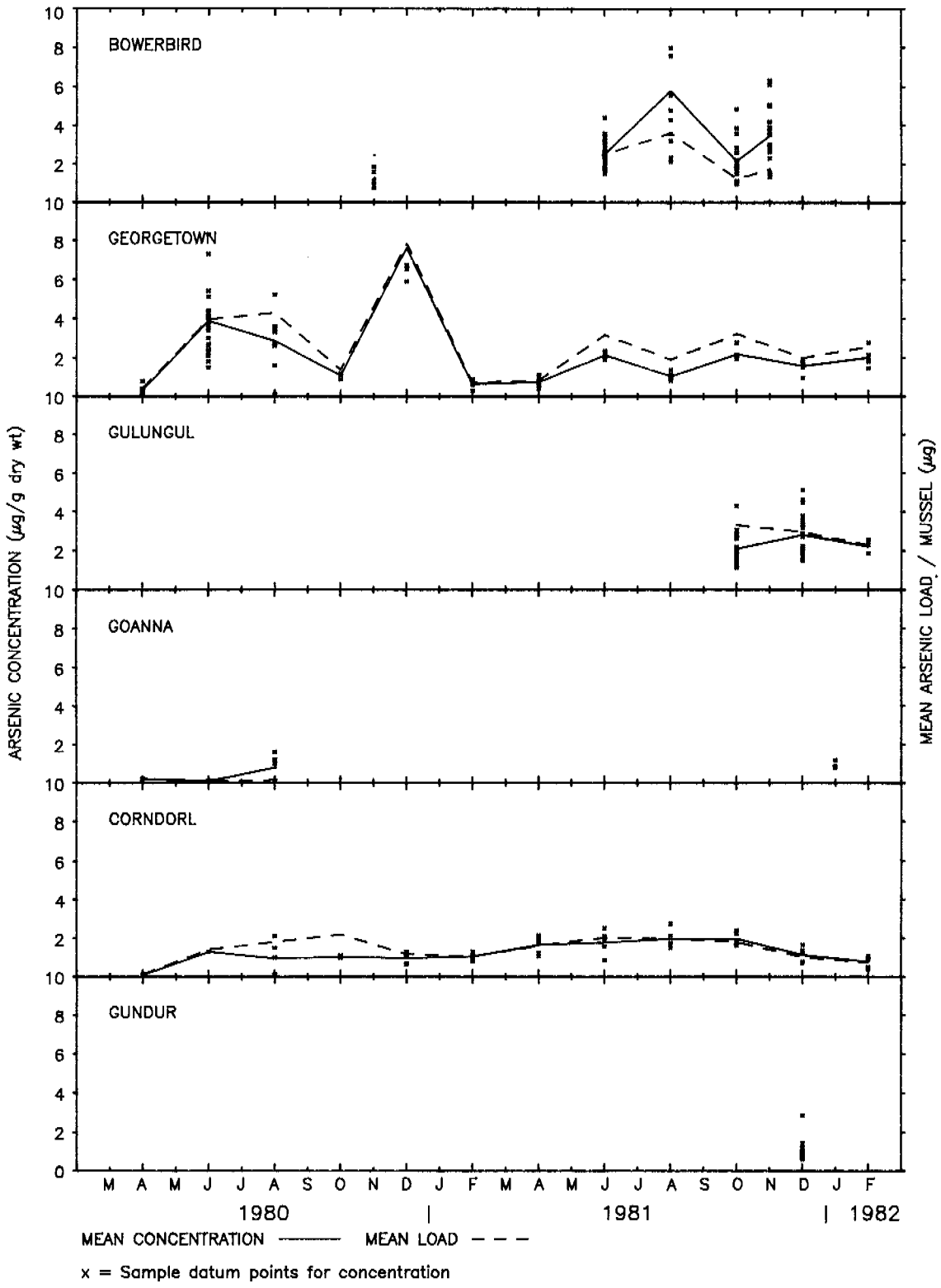
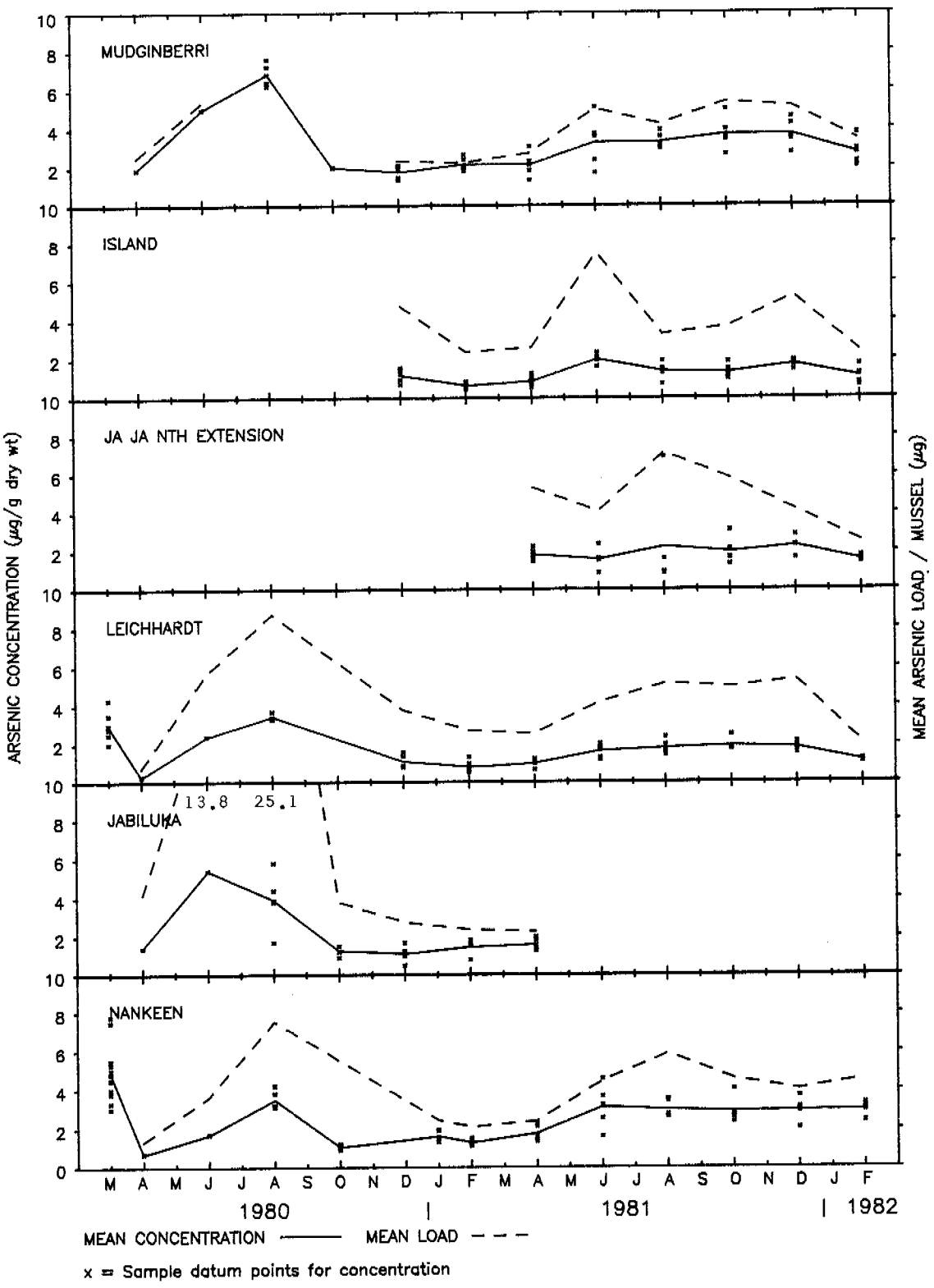


Figure A18. *(Above and opposite)* Concentrations and mean load of arsenic in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
13.8
25.1
NANKEEN
ARSENIC CONCENTRATION (µg/g dry wt)
MEAN ARSENIC LOAD / MUSSEL (µg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

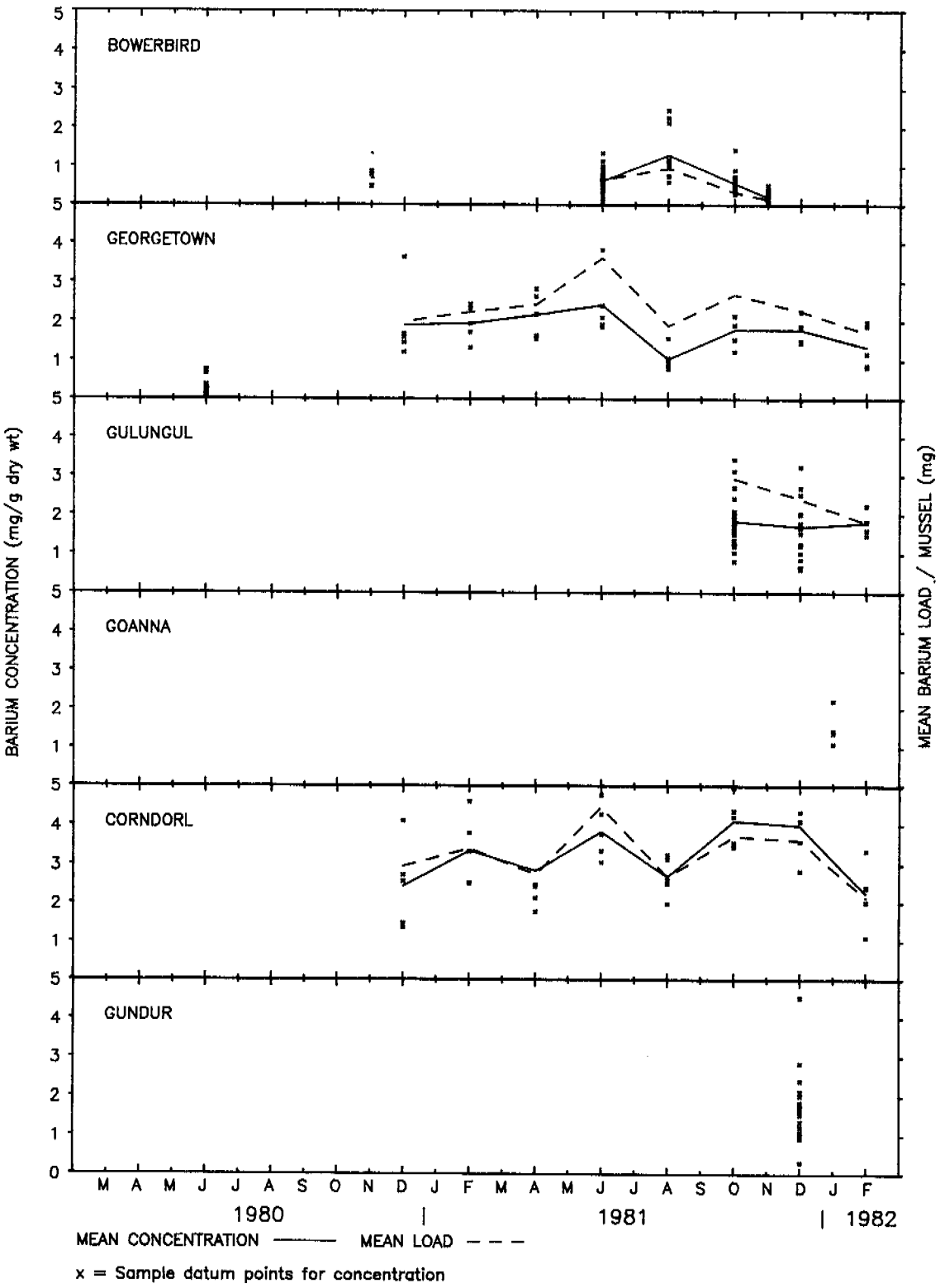
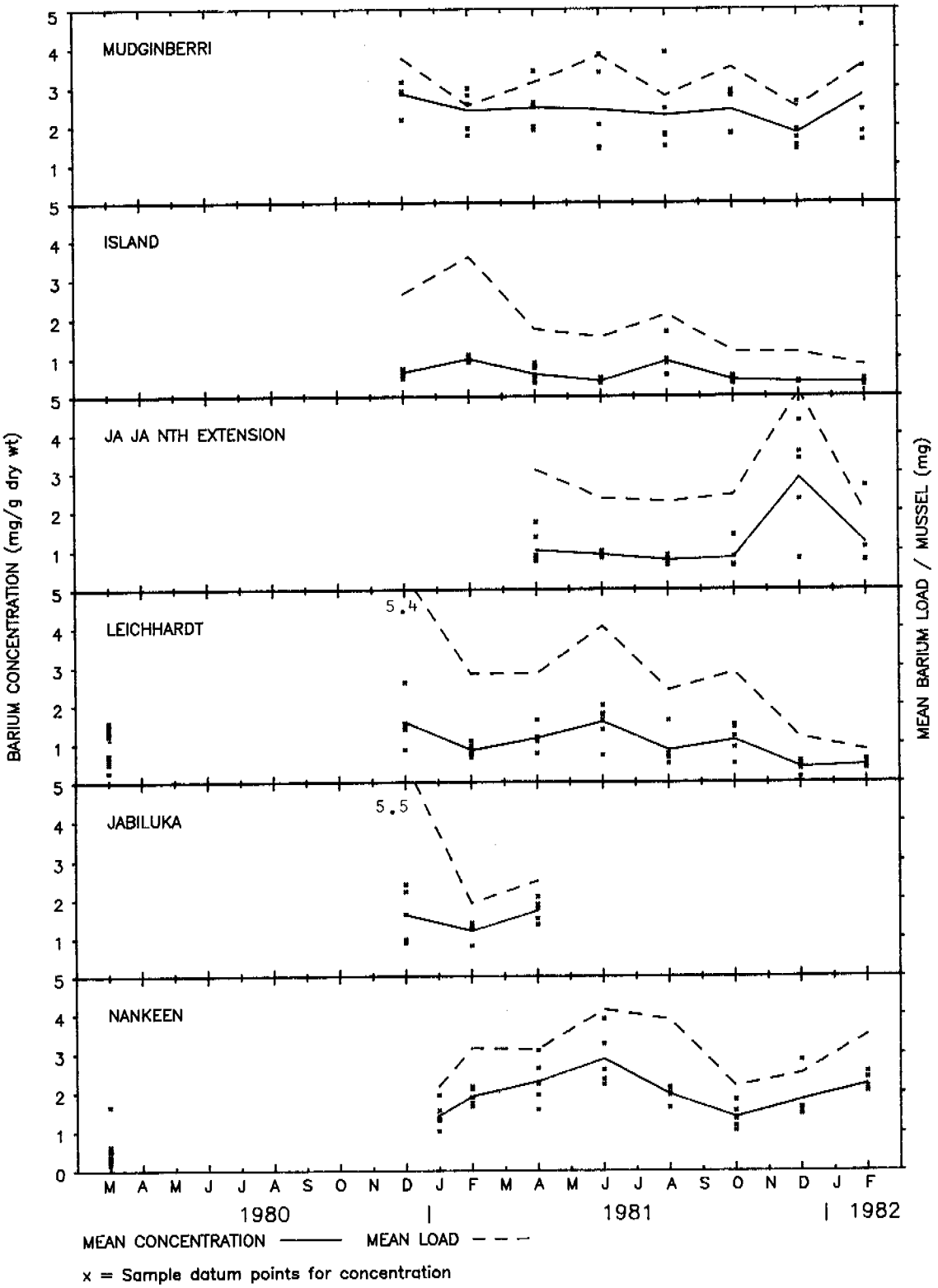


Figure A19. *(Above and opposite)* Concentrations and mean load of barium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
5.4
5.5
BARIUM CONCENTRATION (mg/g dry wt)
MEAN BARIUM LOAD / MUSSEL (mg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

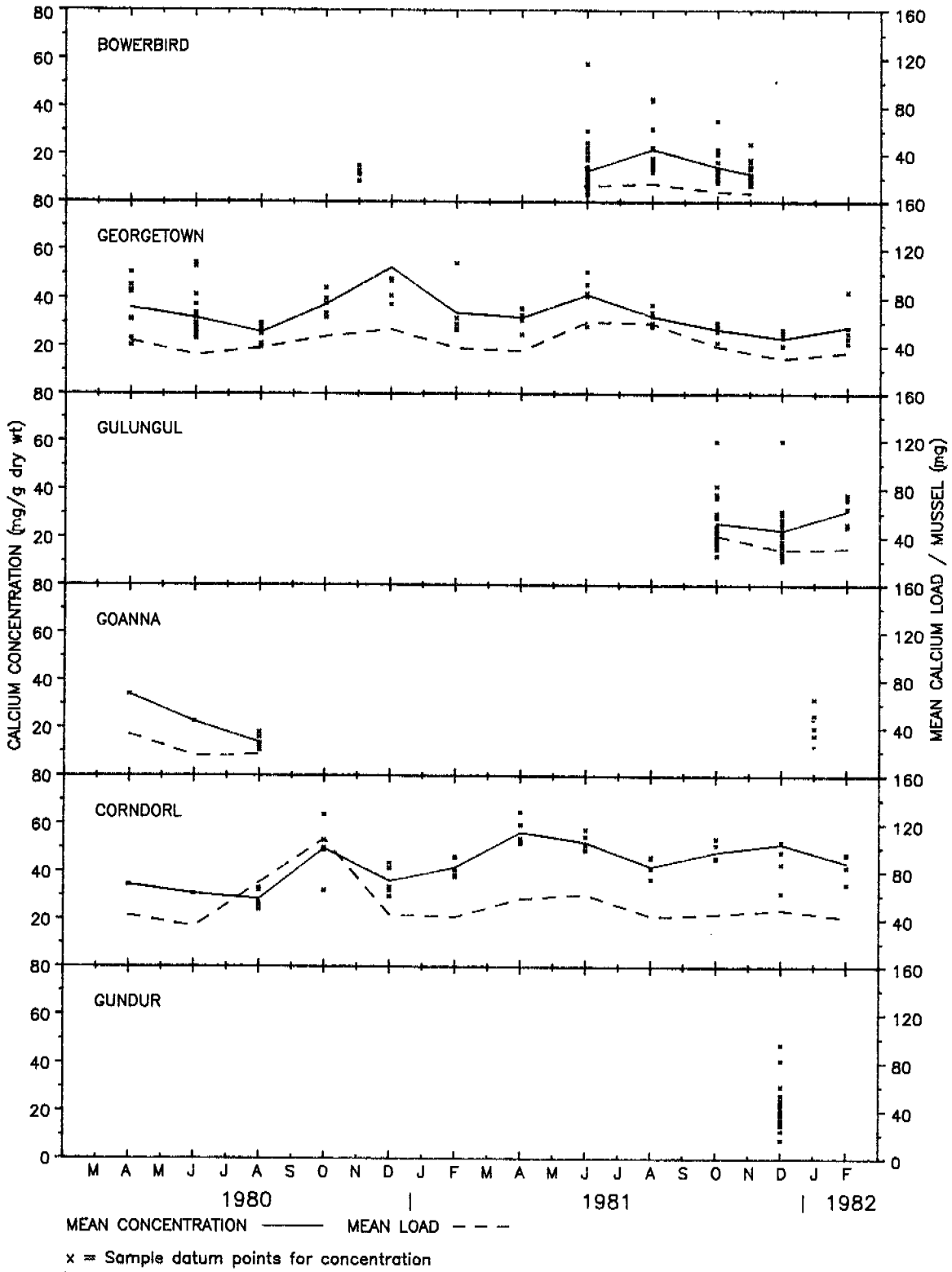
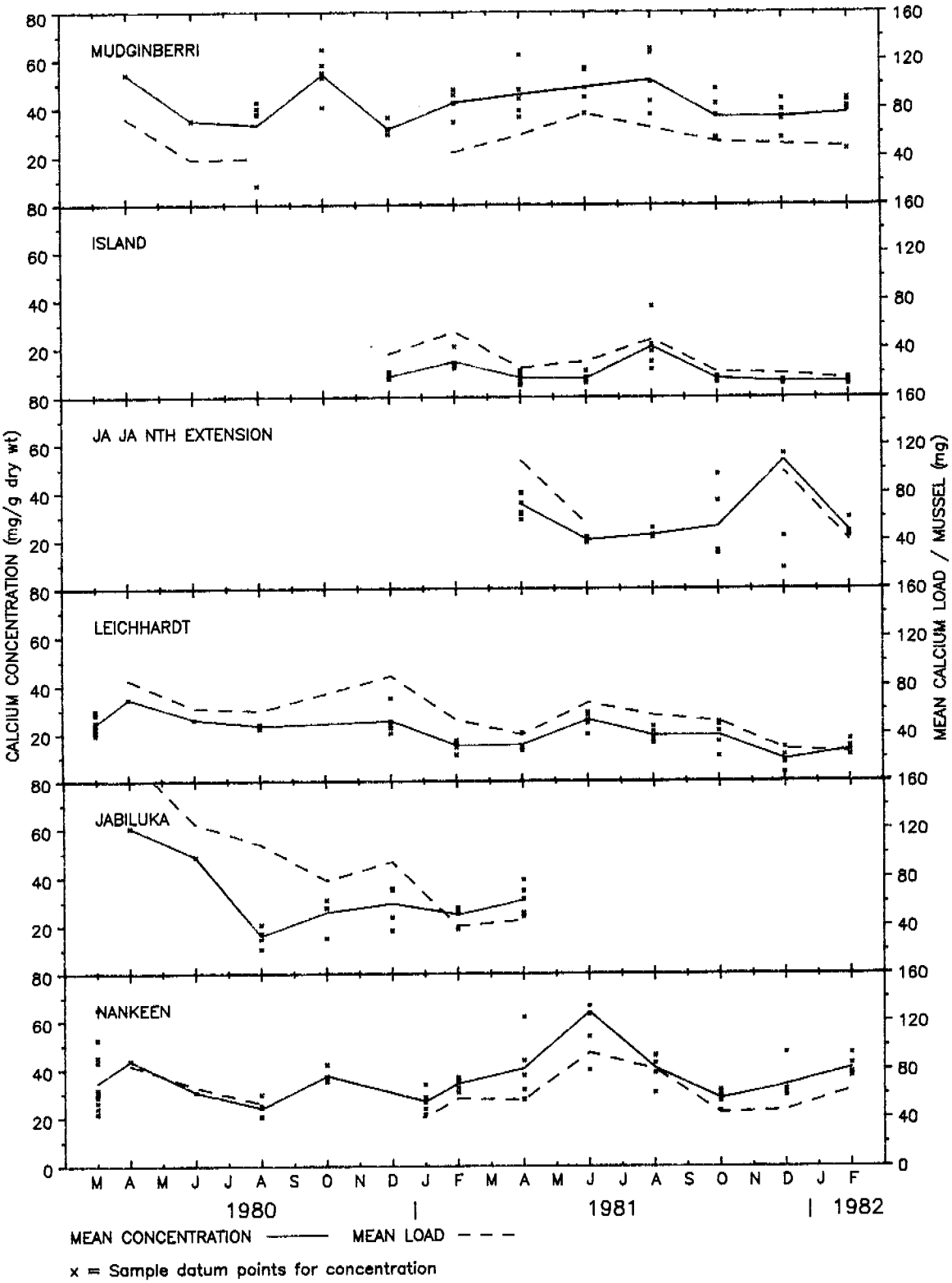


Figure A20. *(Above and opposite)* Concentrations and mean load of calcium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
CALCIUM CONCENTRATION (mg/g dry wt)
MEAN CALCIUM LOAD / MUSSEL (mg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

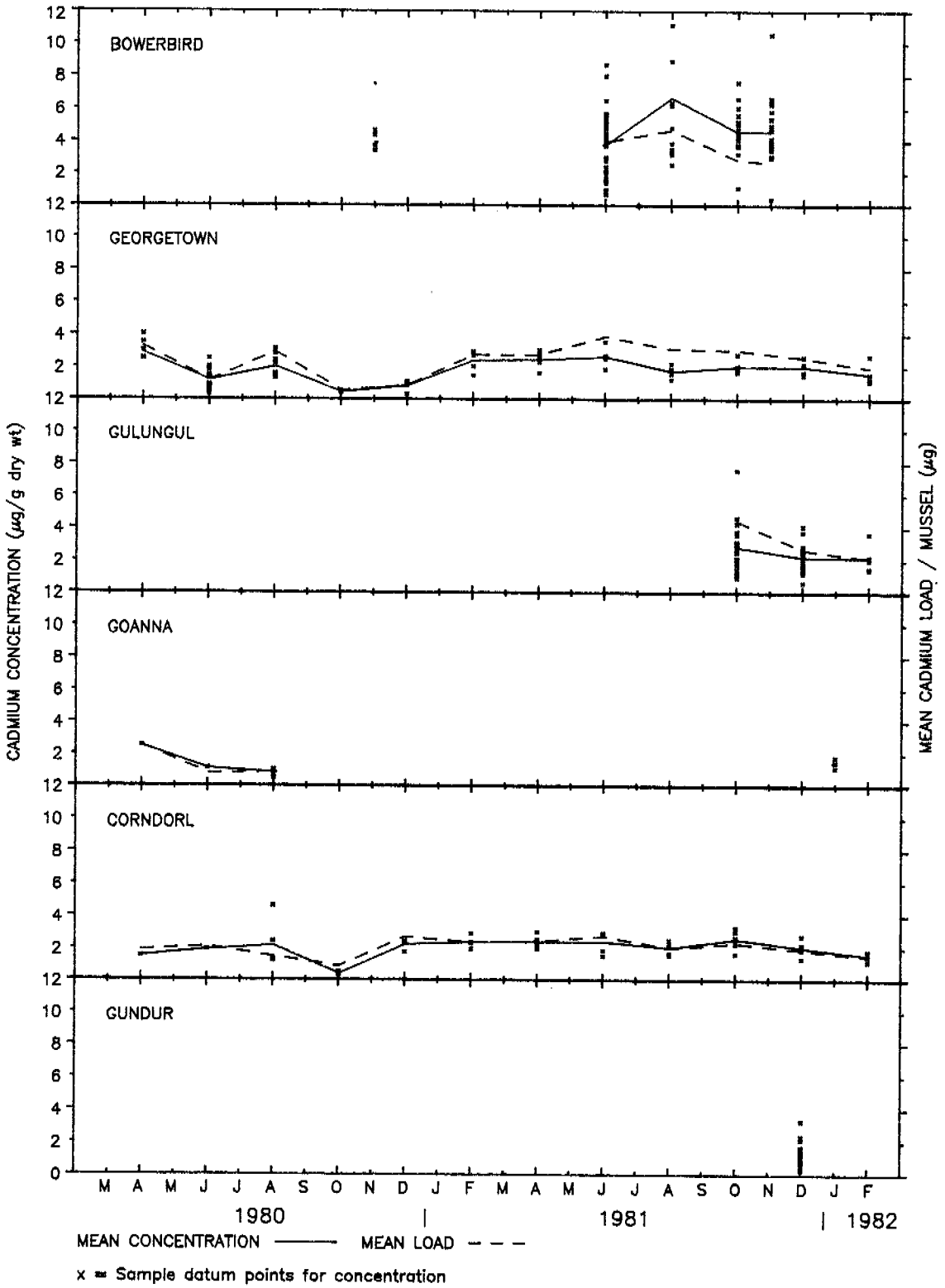
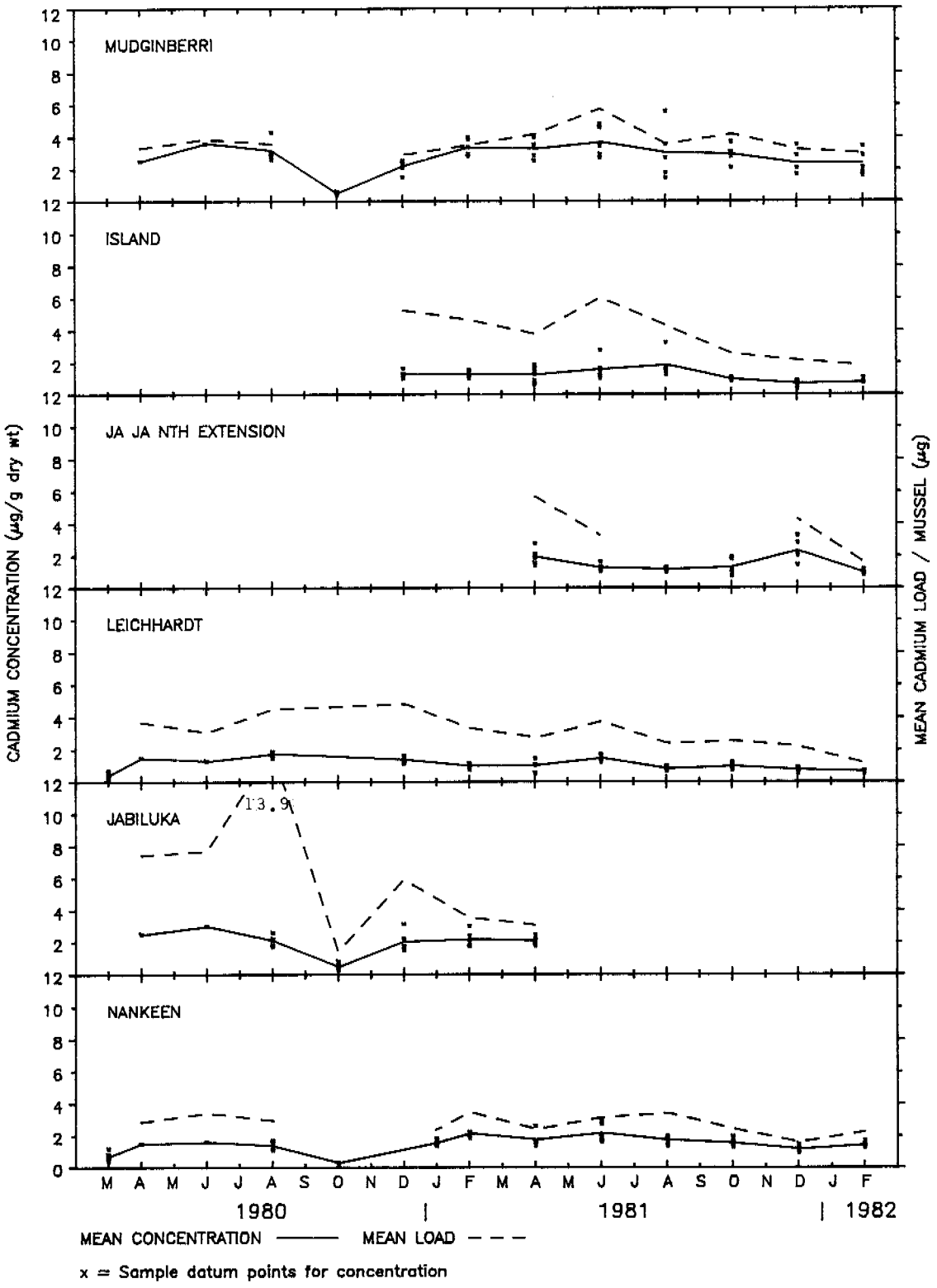


Figure A21. *(Above and opposite)* Concentrations and mean load of cadmium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
13.9
NANKEEN
CADMIUM CONCENTRATION (µg/g dry wt)
MEAN CADMIUM LOAD / MUSSEL (µg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

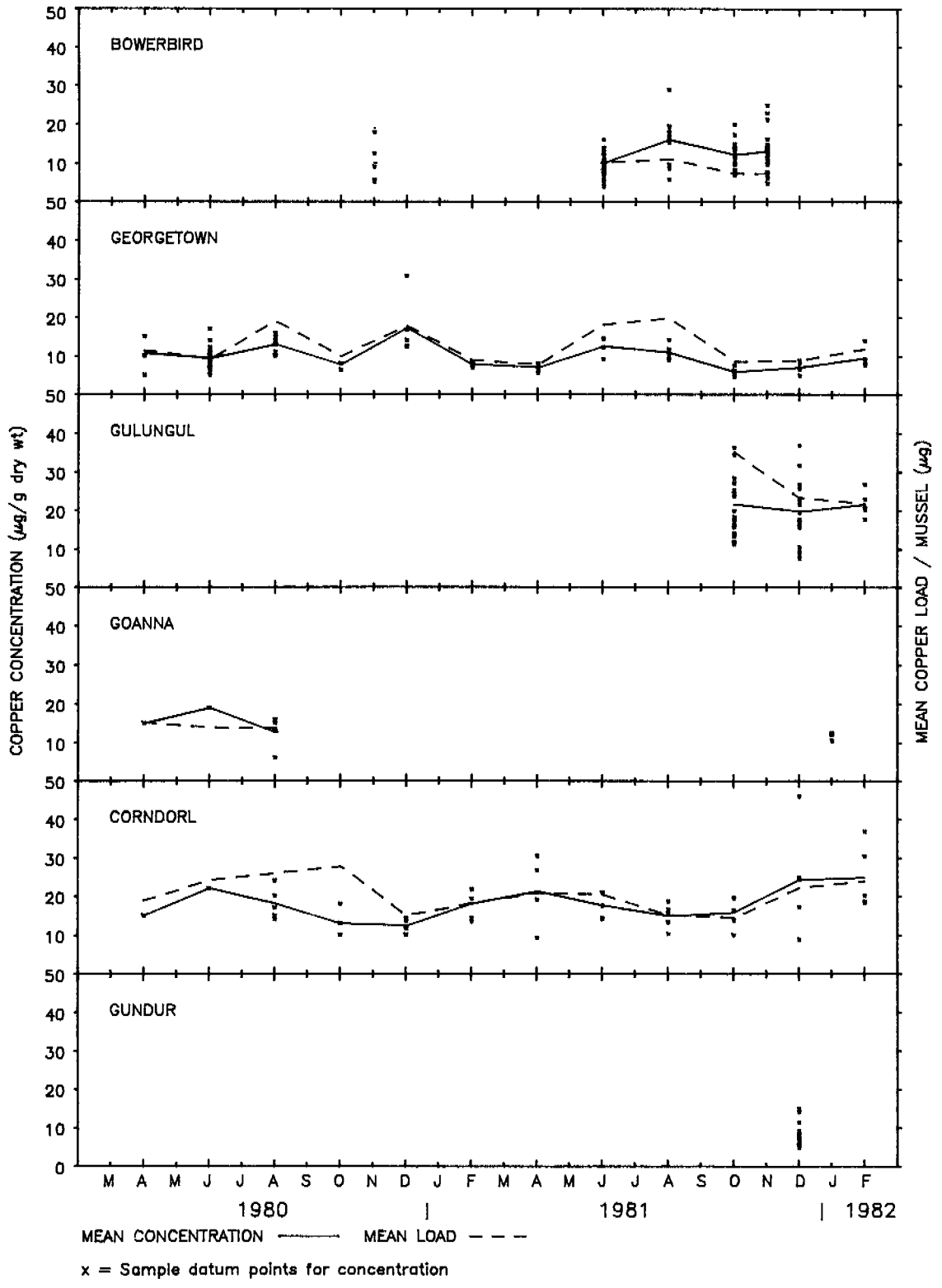
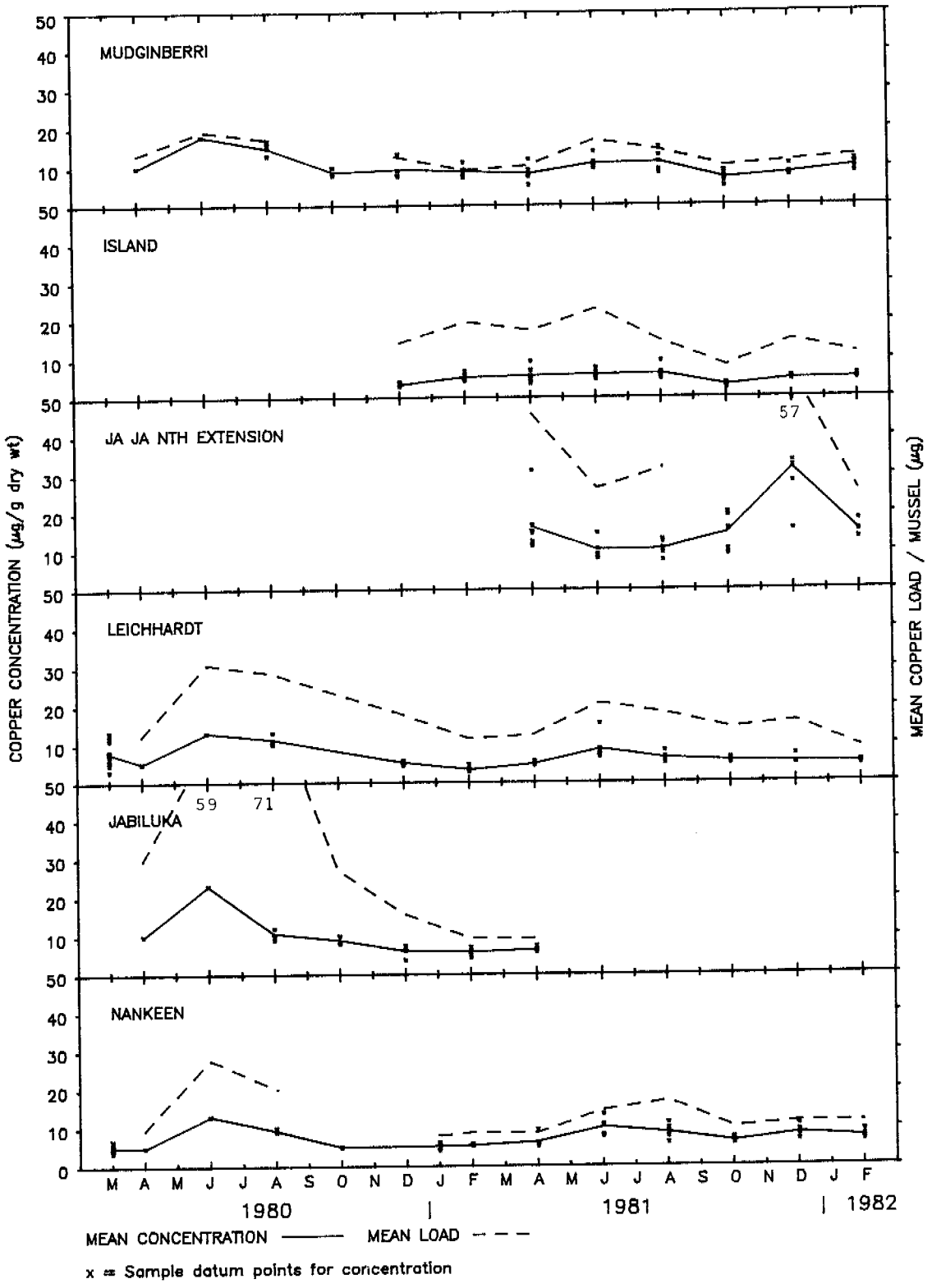


Figure A22. *(Above and opposite)* Concentrations and mean load of copper in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
57
59
71
COPPER CONCENTRATION (µg/g dry wt)
MEAN COPPER LOAD / MUSSEL (µg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

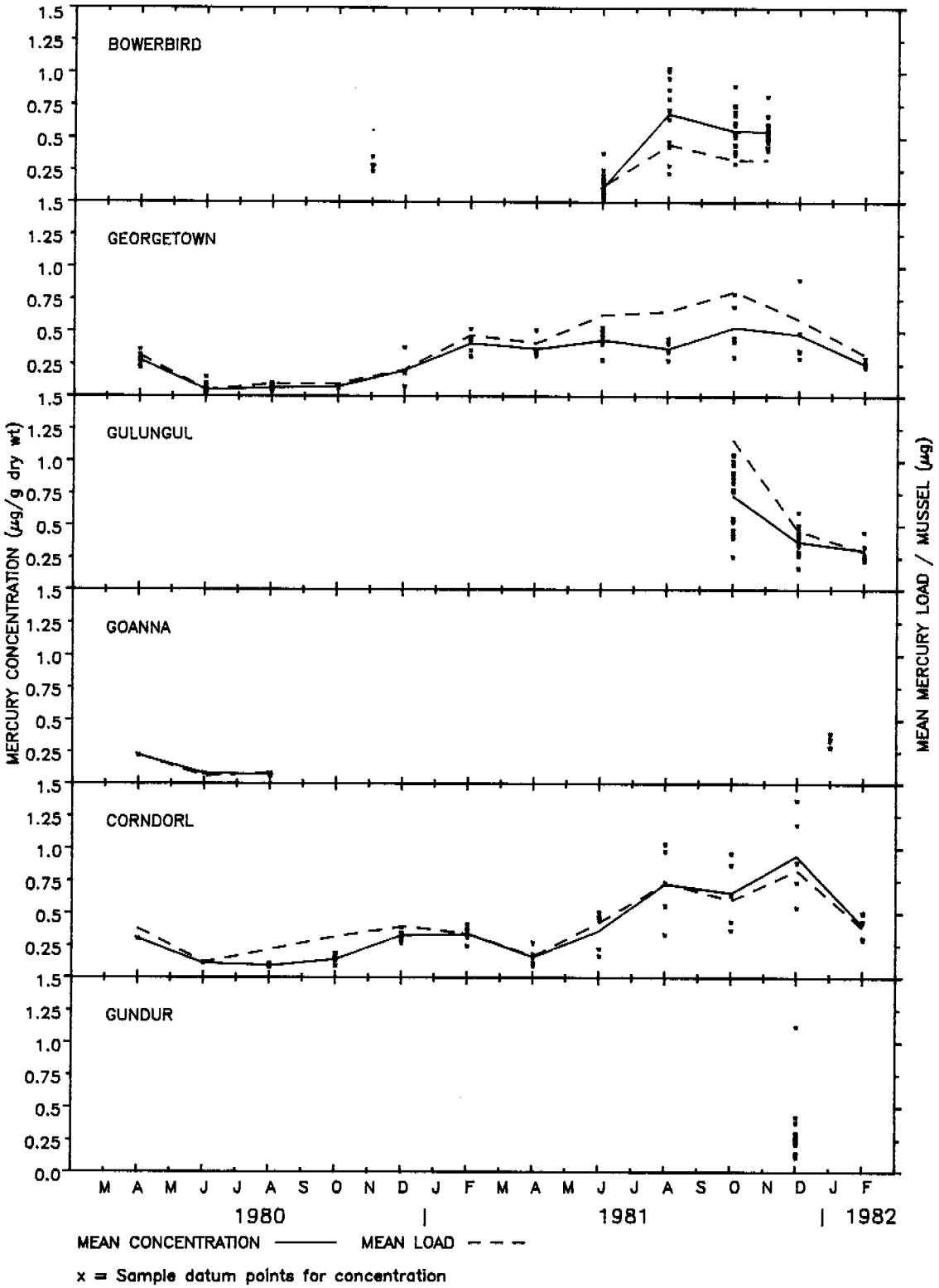
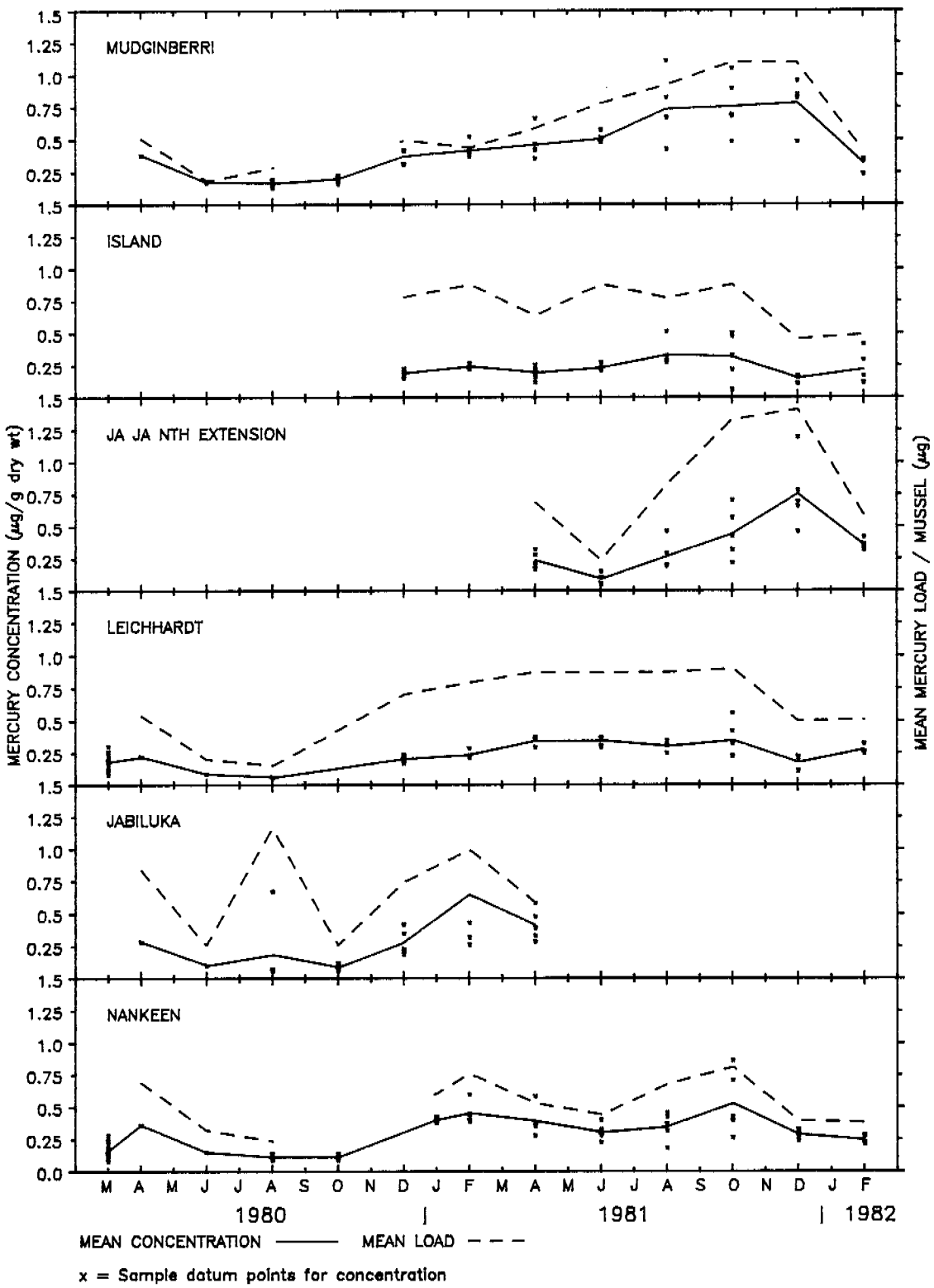


Figure A23. *(Above and opposite)* Concentrations and mean load of mercury in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
MERCURY CONCENTRATION (µg/g dry wt)
MEAN MERCURY LOAD / MUSSEL (µg)
1.5
1.25
1.0
0.75
0.5
0.25
0.0
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

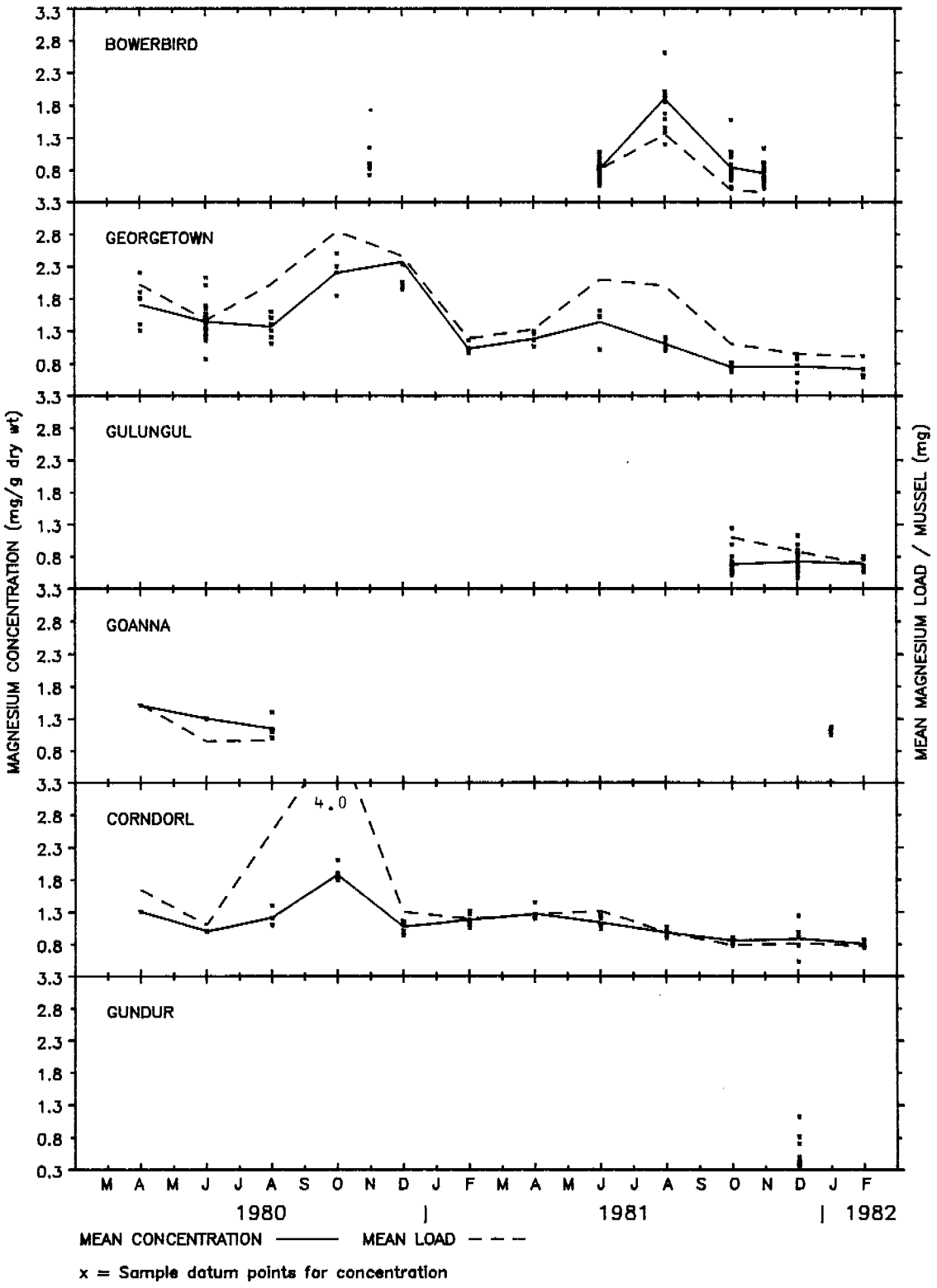
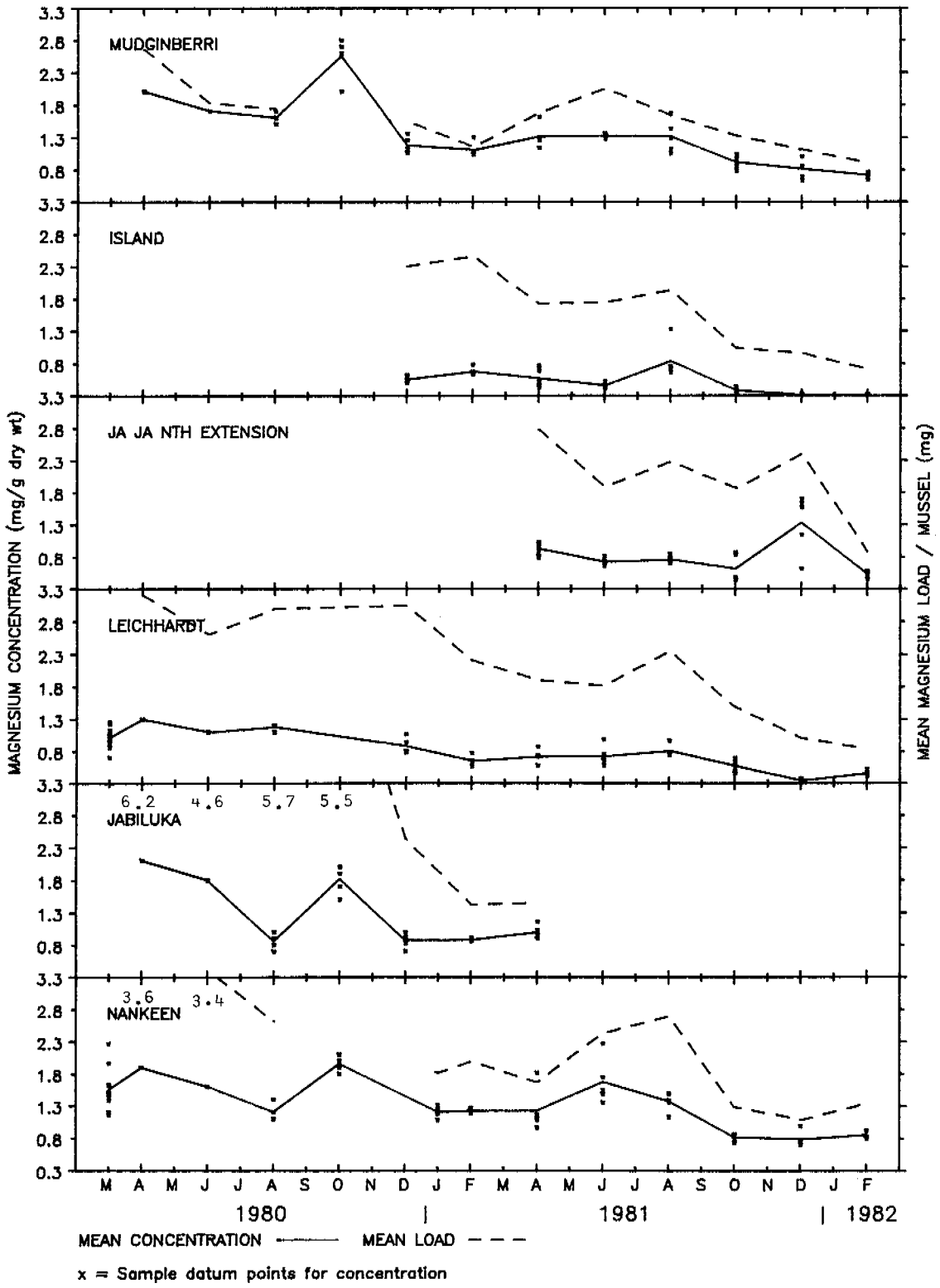


Figure A24. *(Above and opposite)* Concentrations and mean load of magnesium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
6.2
4.6
5.7
5.5
3.6
3.4
MAGNESIUM CONCENTRATION (mg/g dry wt)
MEAN MAGNESIUM LOAD / MUSSEL (mg)
3.3
2.8
2.3
1.8
1.3
0.8
0.3
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

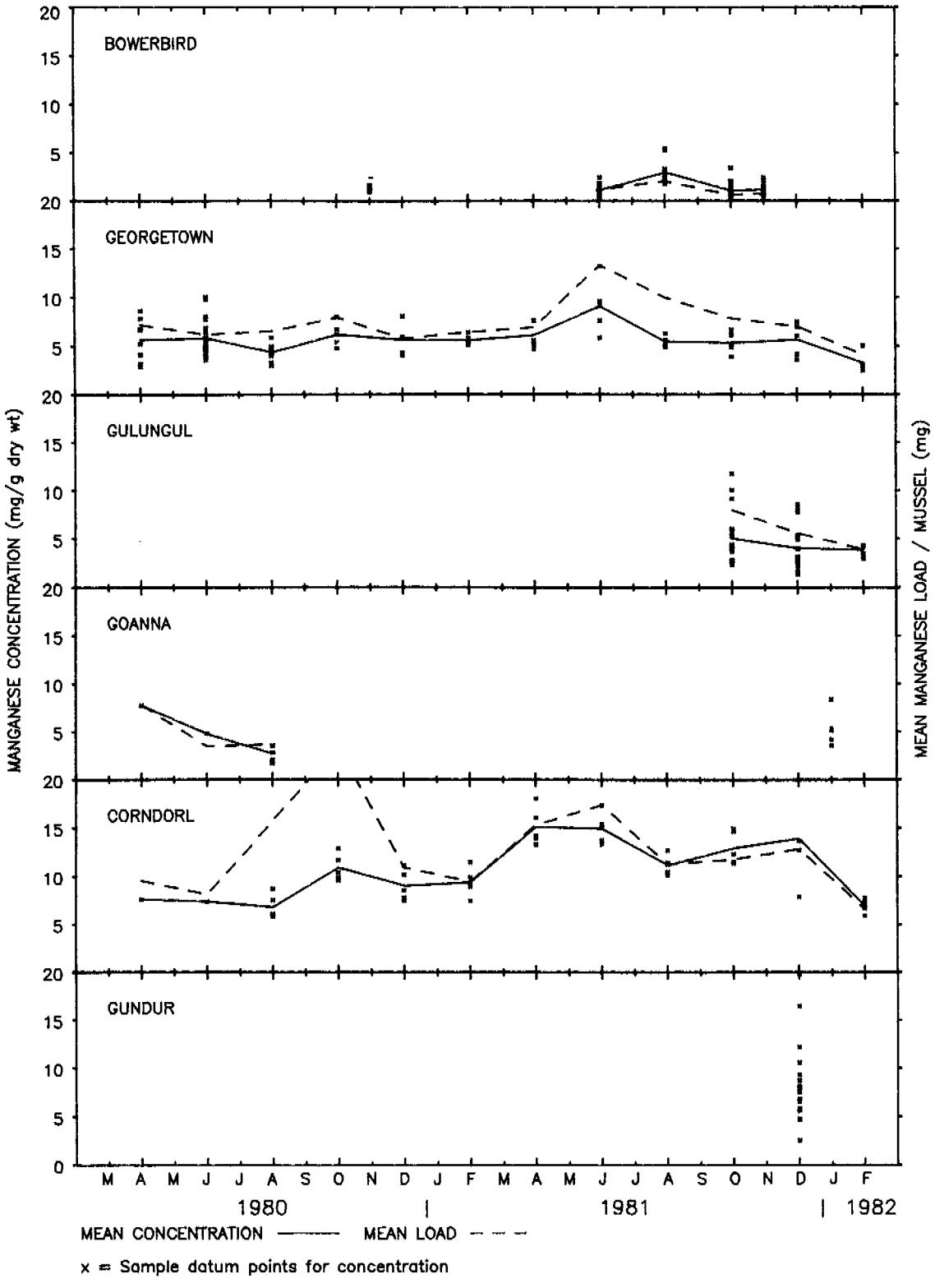
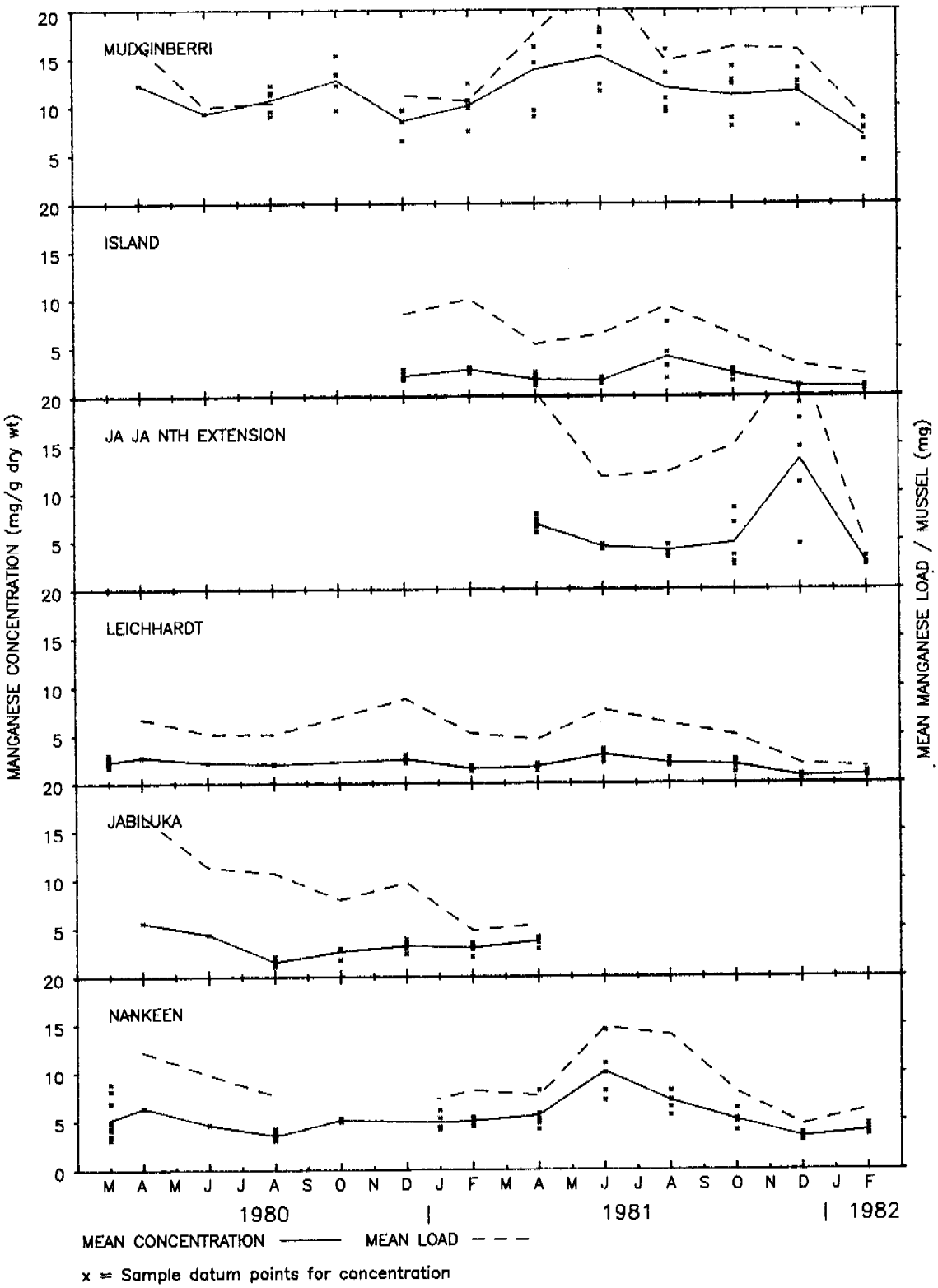


Figure A25. *(Above and opposite)* Concentrations and mean load of manganese in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABIRUKA
NANKEEN
MANGANESE CONCENTRATION (mg/g dry wt)
MEAN MANGANESE LOAD / MUSSEL (mg)
0
5
10
15
20
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

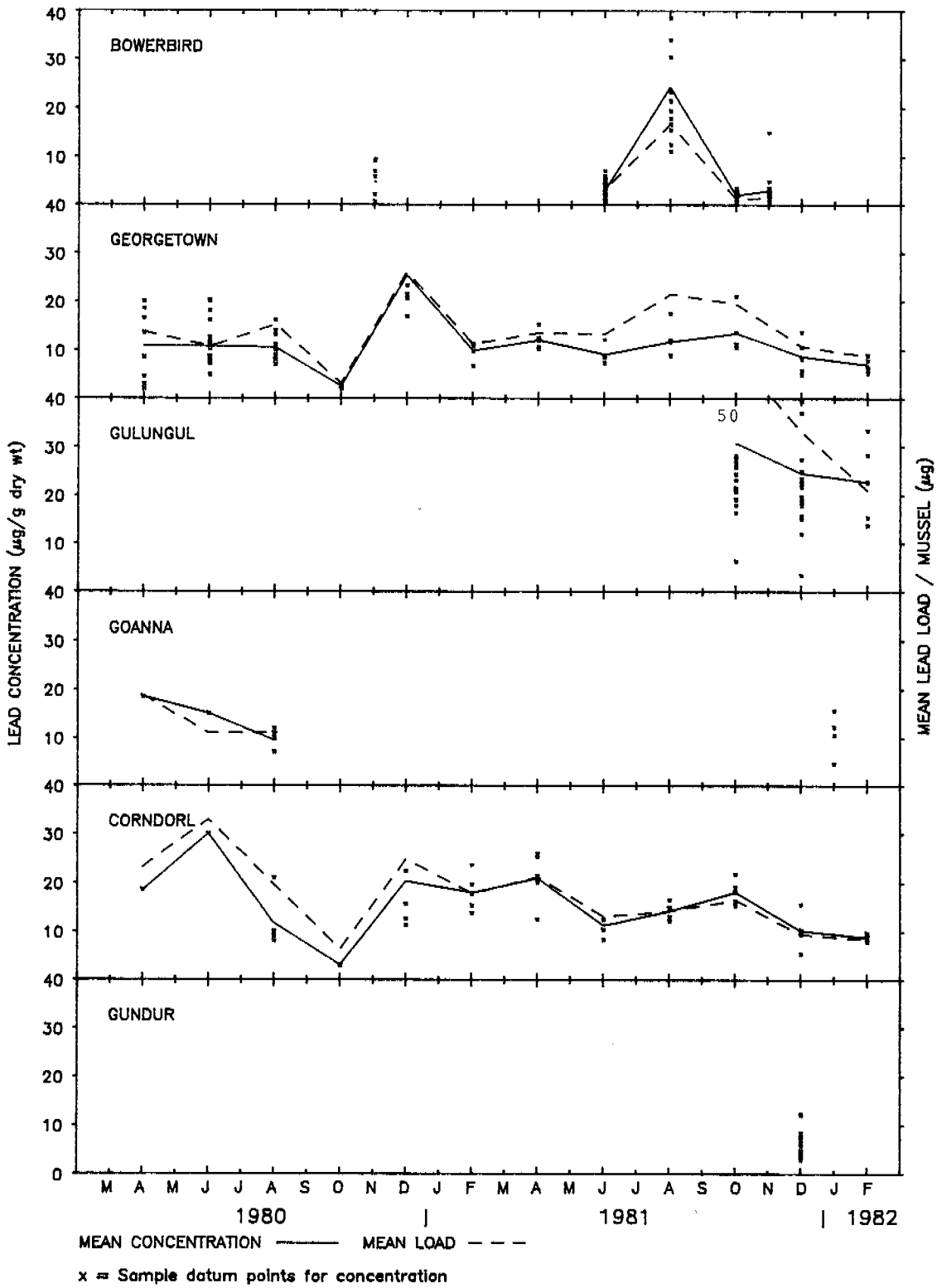
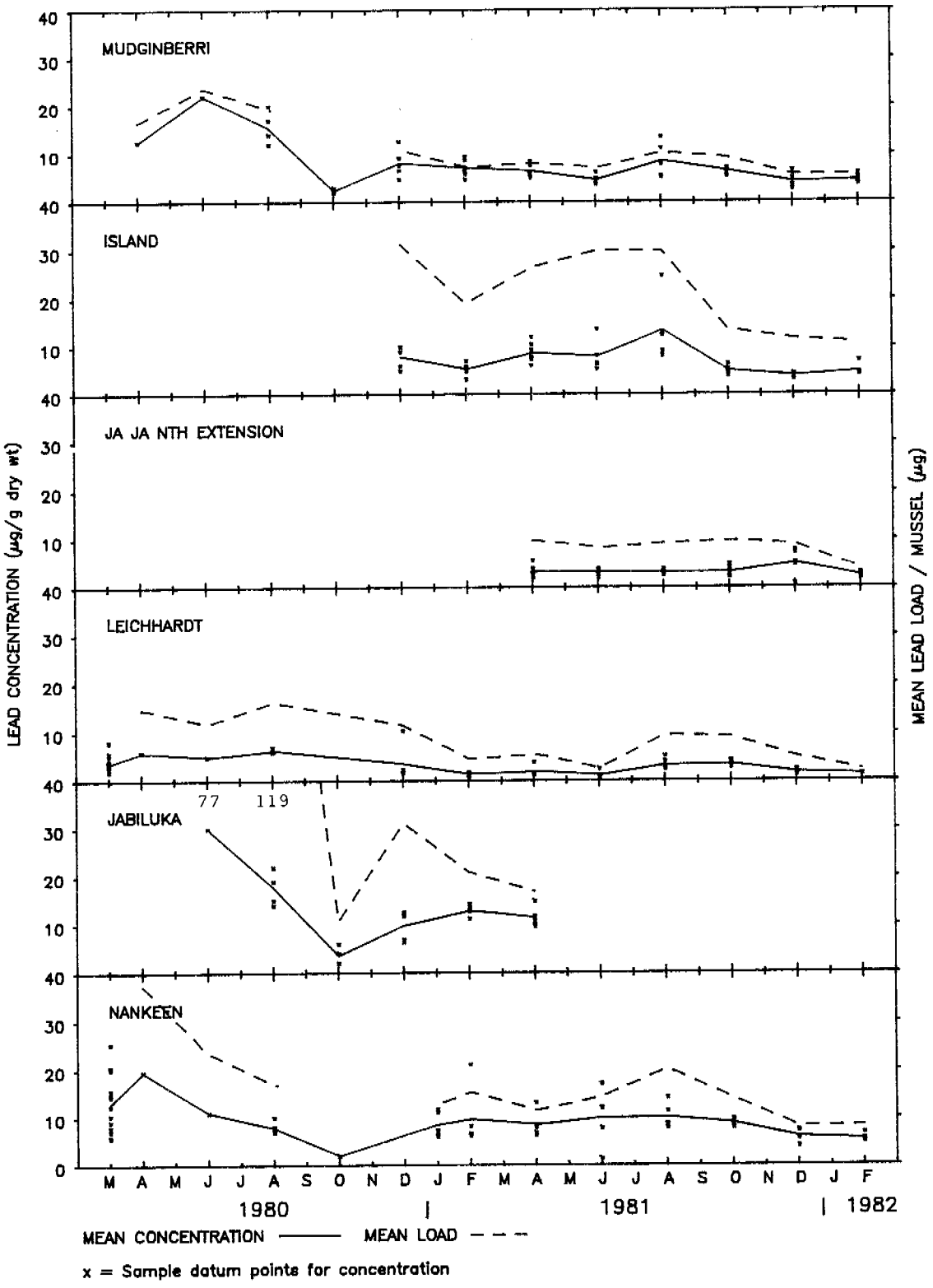


Figure A26. *(Above and opposite)* Concentrations and mean load of lead in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
77
119
LEAD CONCENTRATION (µg/g dry wt)
MEAN LEAD LOAD / MUSSEL (µg)
40
30
20
10
0
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

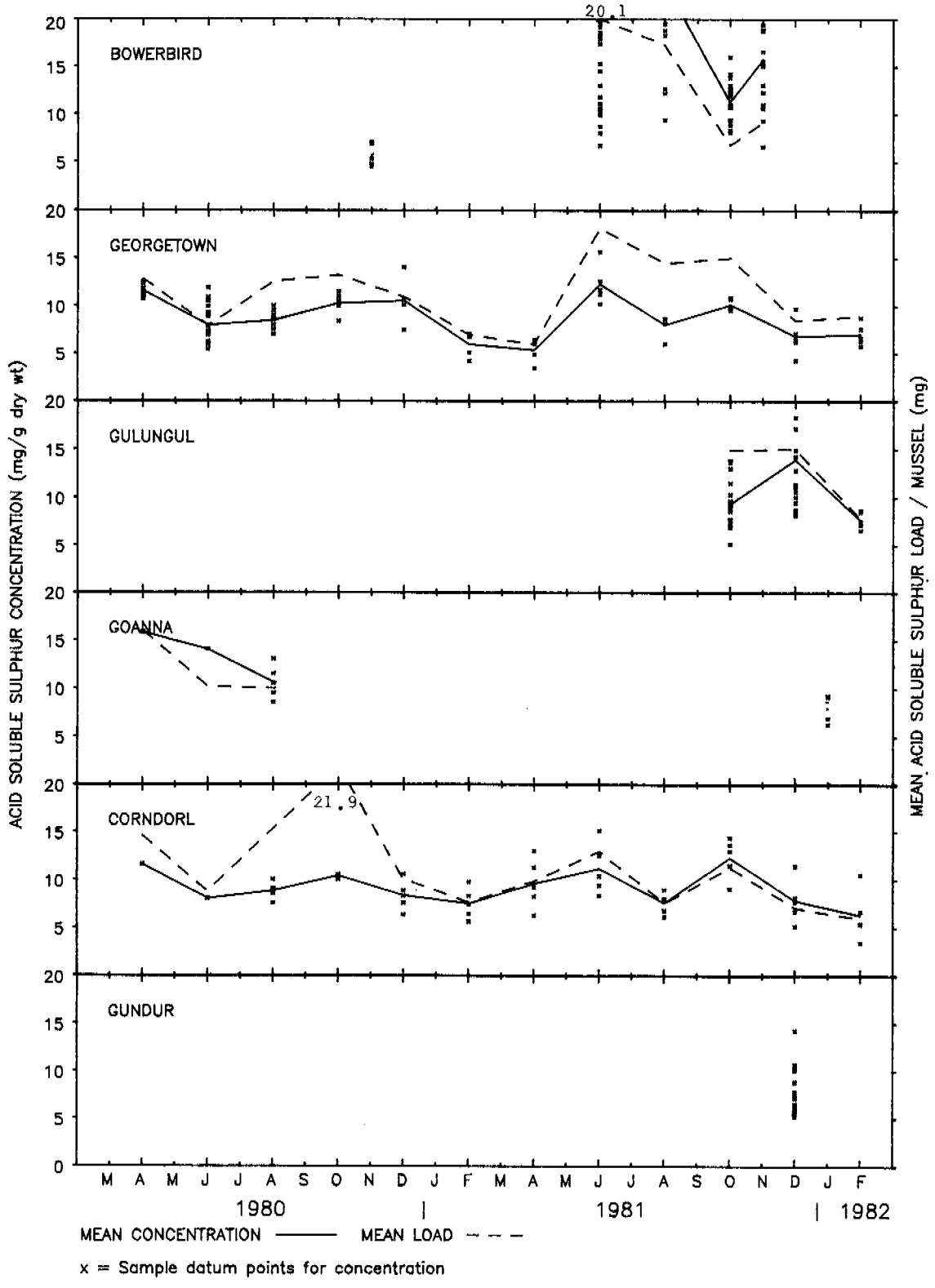
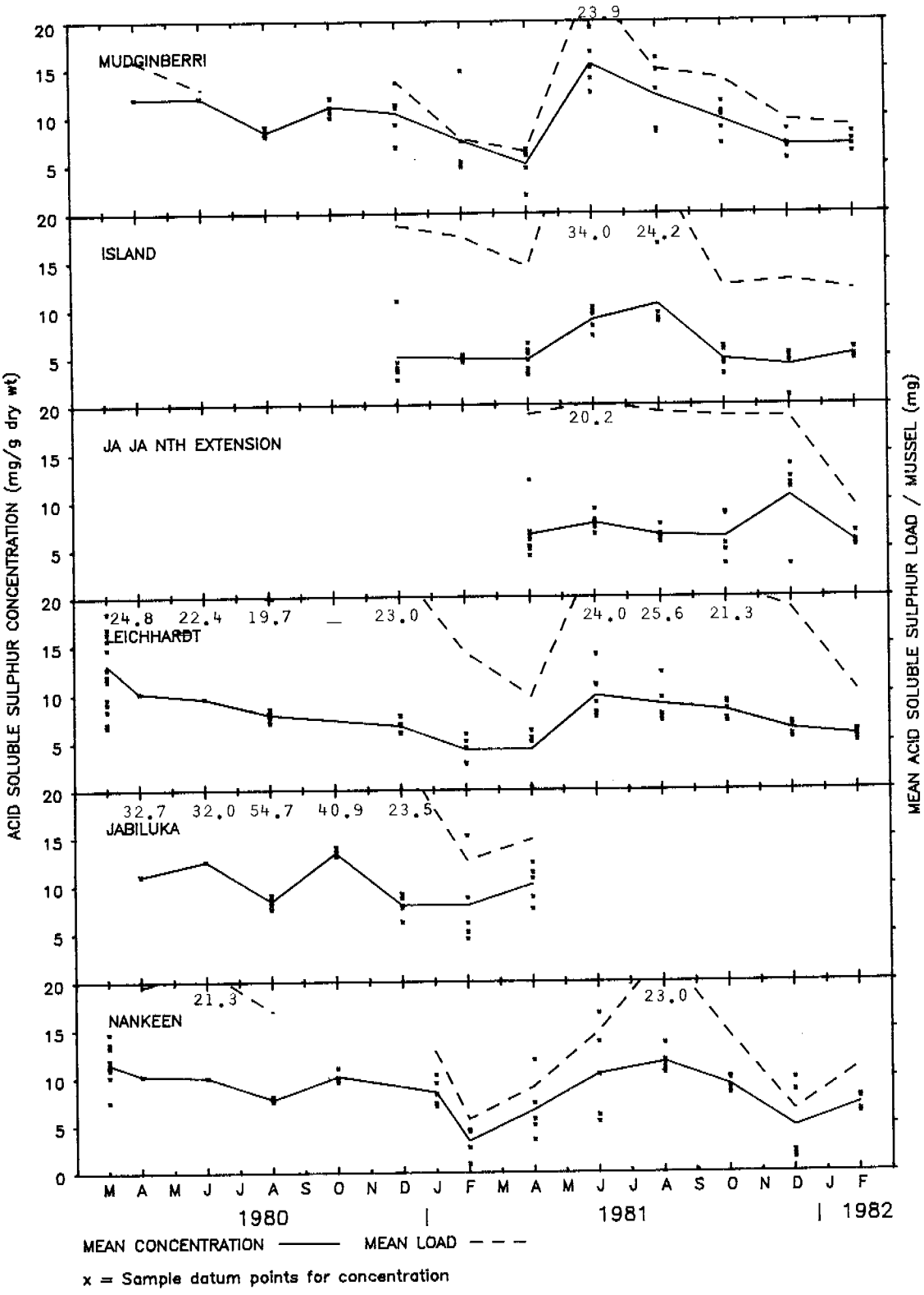


Figure A27. *(Above and opposite)* Concentrations and mean load of sulphur in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
23.9
ISLAND
34.0
24.2
JA JA NTH EXTENSION
20.2
LEICHHARDT
24.8
22.4
19.7
23.0
24.0
25.6
21.3
JABILUKA
32.7
32.0
54.7
40.9
23.5
NANKEEN
21.3
23.0
ACID SOLUBLE SULPHUR CONCENTRATION (mg/g dry wt)
MEAN ACID SOLUBLE SULPHUR LOAD / MUSSEL (mg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

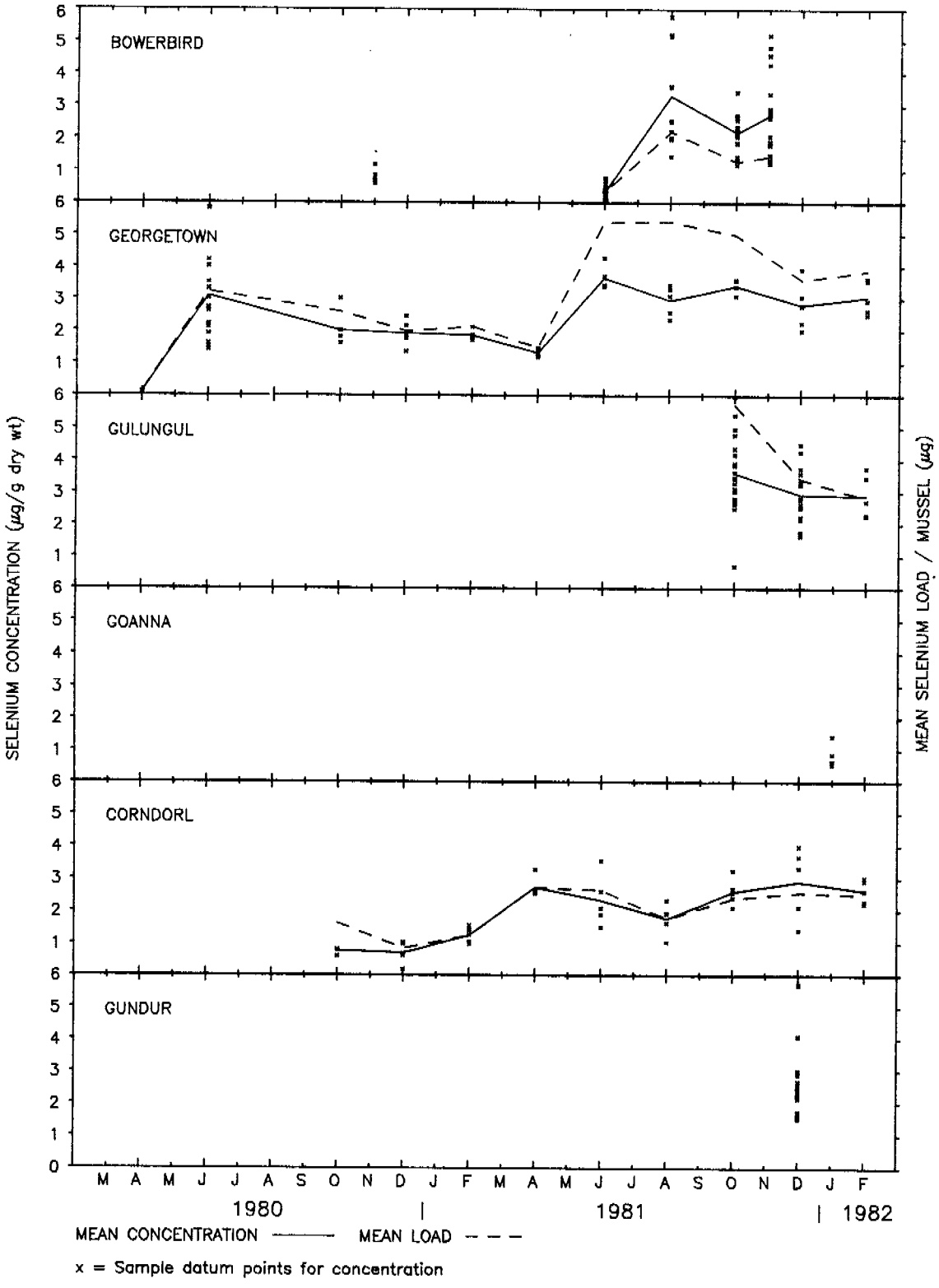
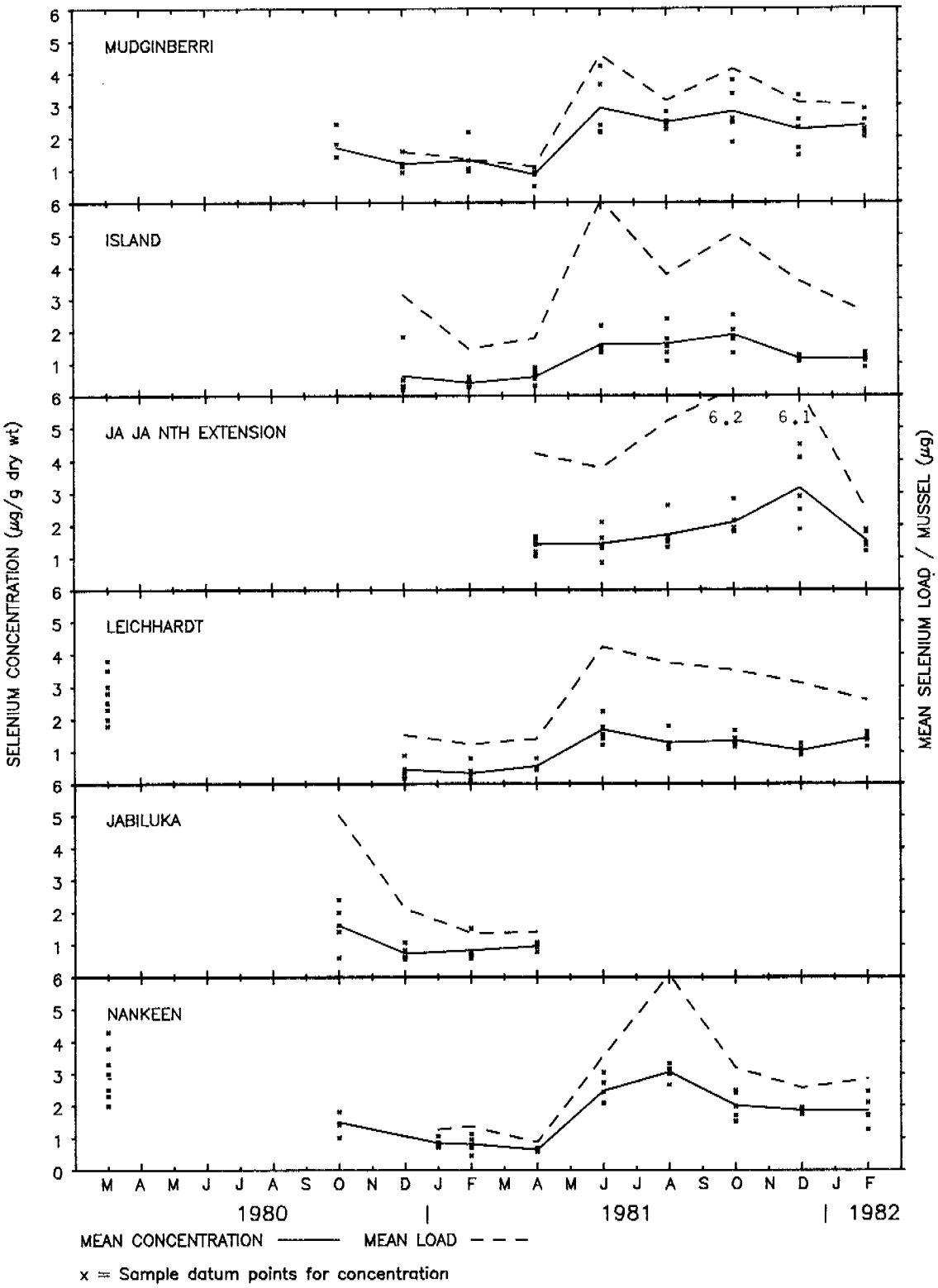


Figure A28. *(Above and opposite)* Concentrations and mean load of selinium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
6.2
6.1
LEICHHARDT
JABILUKA
NANKEEN
SELENIUM CONCENTRATION (µg/g dry wt)
MEAN SELENIUM LOAD / MUSSEL (µg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION ——— MEAN LOAD - - -
x = Sample datum points for concentration

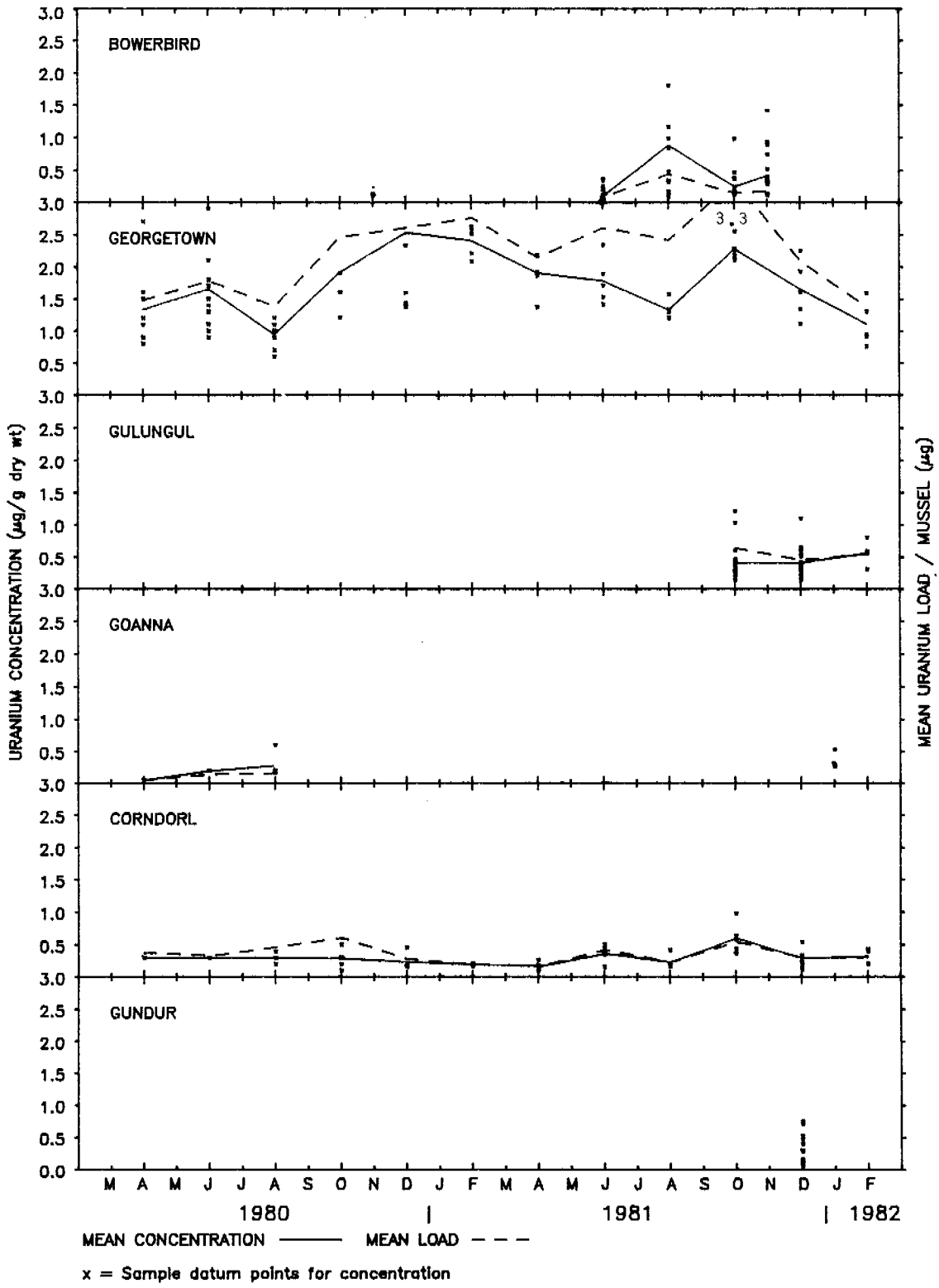
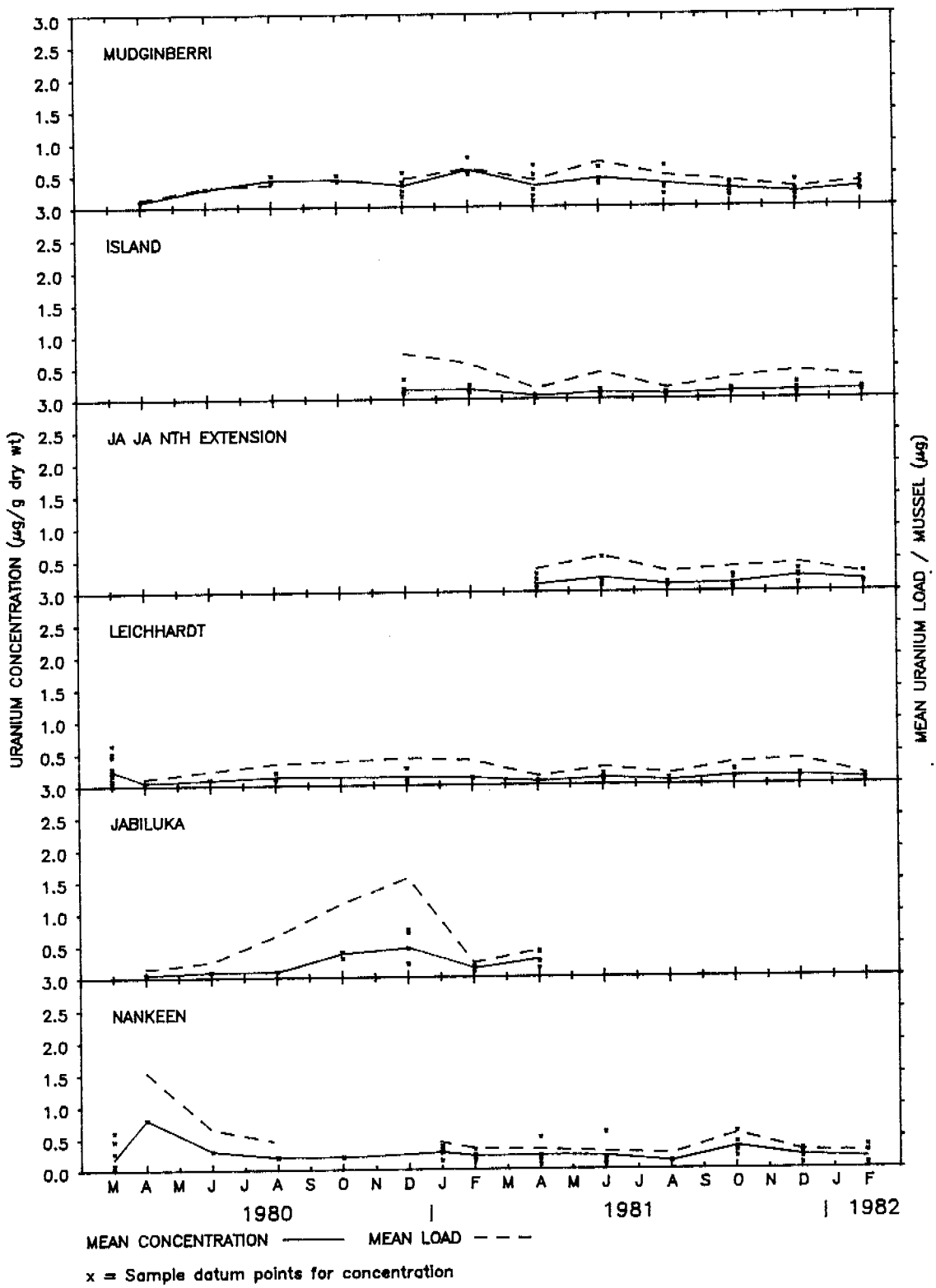


Figure A29. *(Above and opposite)* Concentrations and mean load of uranium in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
URANIUM CONCENTRATION (µg/g dry wt)
MEAN URANIUM LOAD / MUSSEL (µg)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

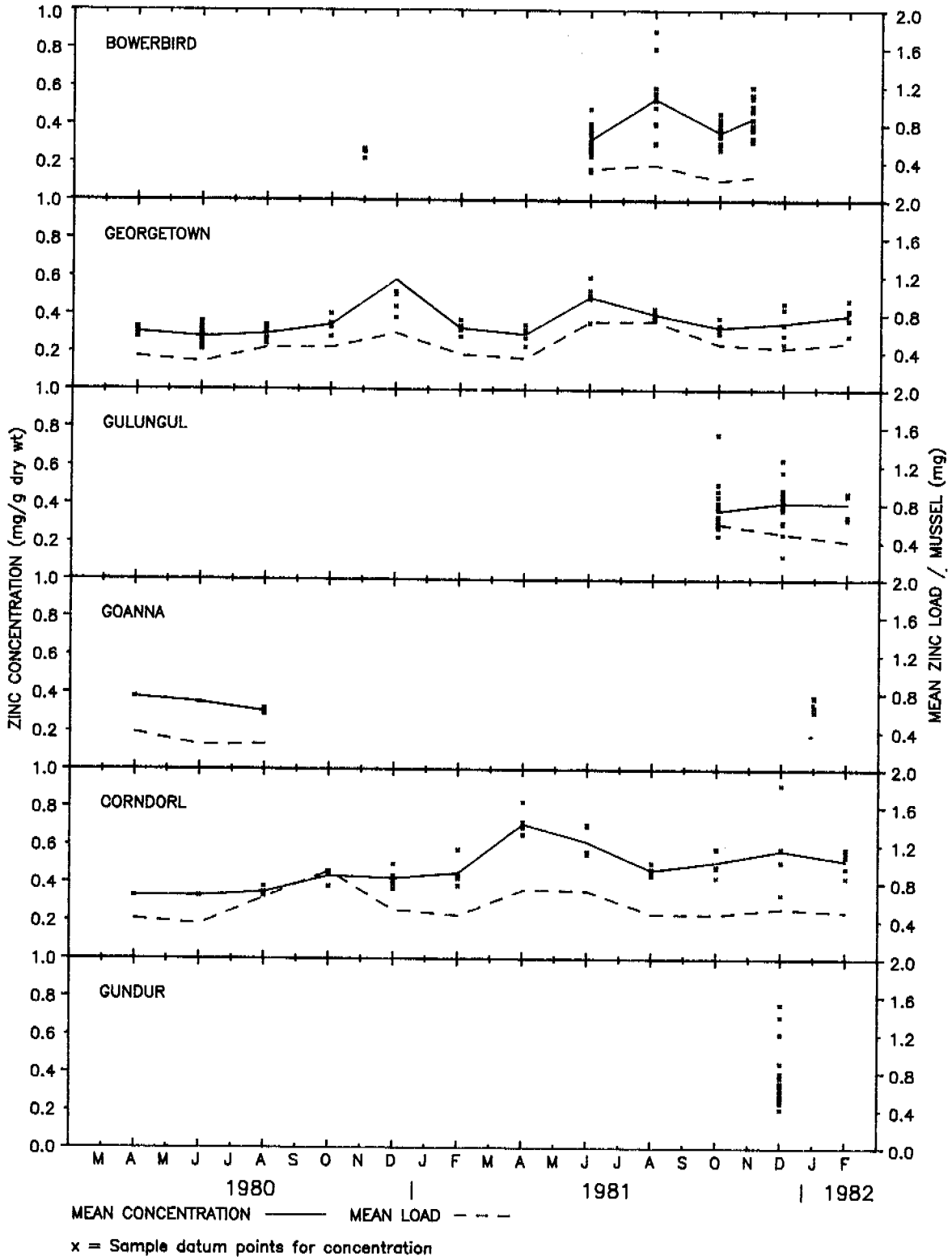
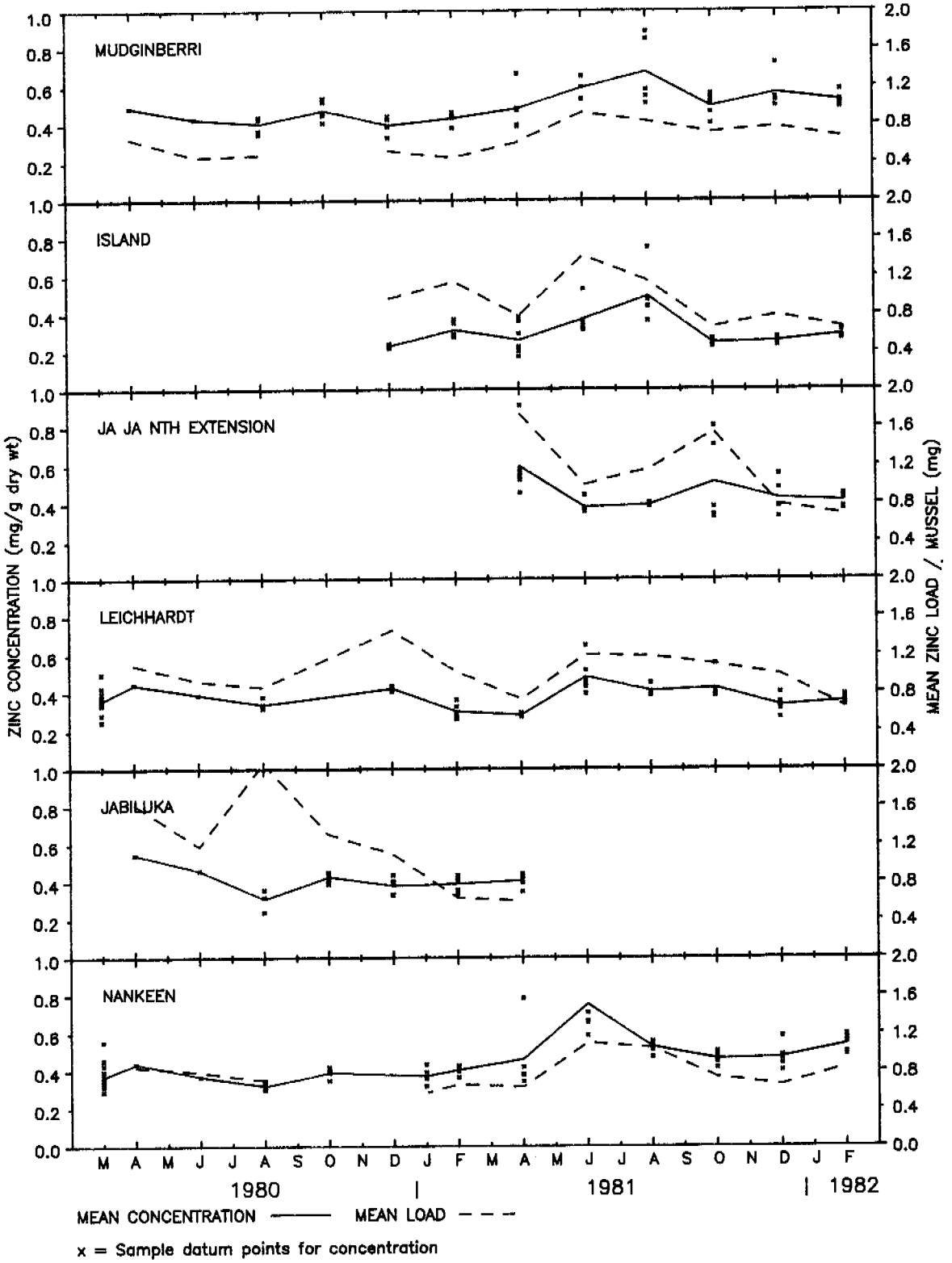


Figure A30. *(Above and opposite)* Concentrations and mean load of zinc in the soft parts of mussels from various billabongs between March 1980 and February 1982


MUDGINBERRI
ISLAND
JA JA NTH EXTENSION
LEICHHARDT
JABILUKA
NANKEEN
ZINC CONCENTRATION (mg/g dry wt)
MEAN ZINC LOAD / MUSSEL (mg)
M A M J J A S O N D J F M A M J J A S O N D J F
1980
1981
1982
MEAN CONCENTRATION
MEAN LOAD
x = Sample datum points for concentration

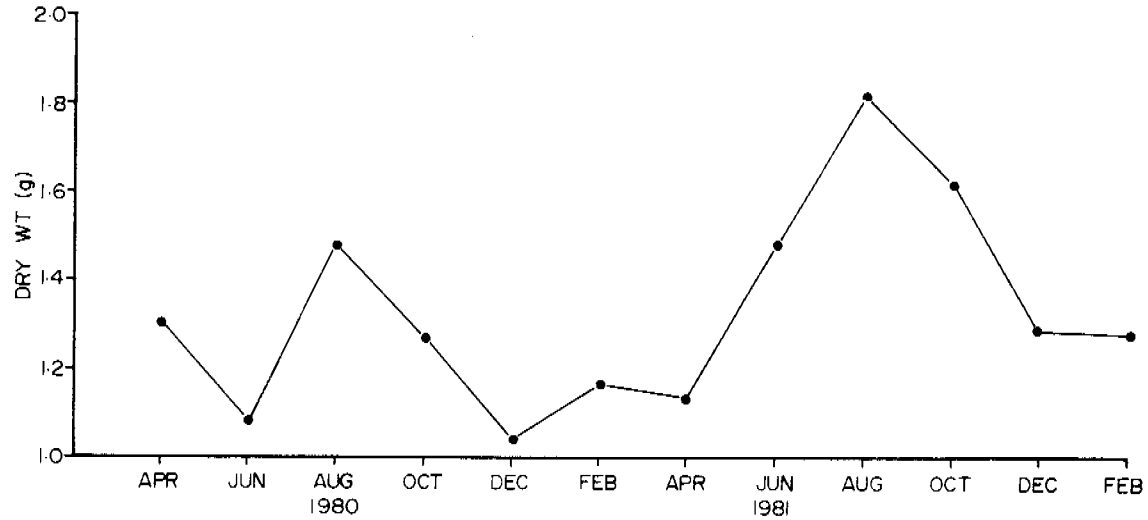


FIG. 3.5.1.29 MEAN DRY WEIGHT(g) OF MUSSELS OF LENGTH RANGE 61-65 MM FROM GEORGETOWN BETWEEN APRIL 1980 AND FEBRUARY 1982.

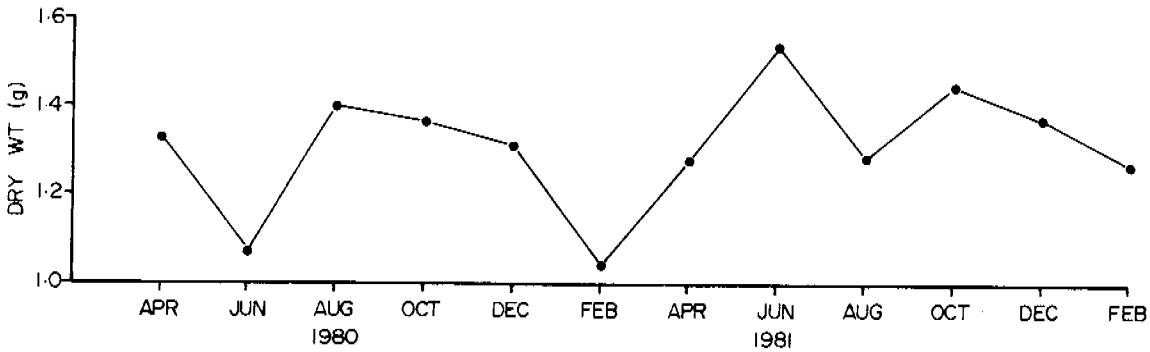


FIG. 3.5.1.30 MEAN DRY WEIGHT(g) OF MUSSELS OF LENGTH RANGE 61-65 MM FROM MUDGINBERRI BETWEEN APRIL 1980 AND FEBRUARY 1982.

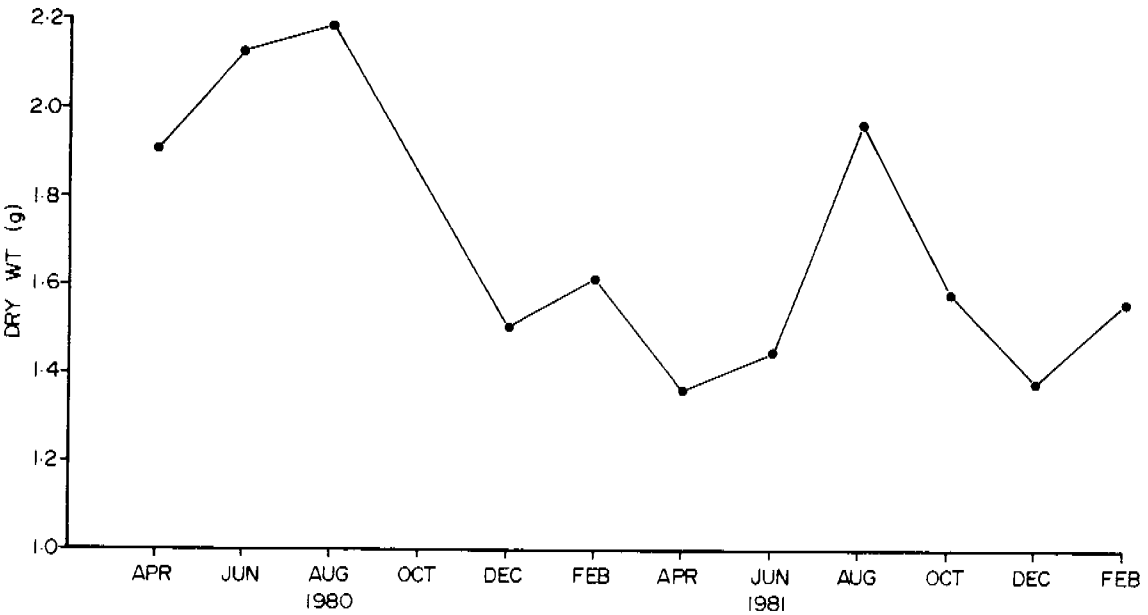


Figure A31. Mean dry weight of the soft parts of mussels of shell length range 61-65 mm from Georgetown, Mudginberri and Nankeen billabongs between April 1980 and February 1982

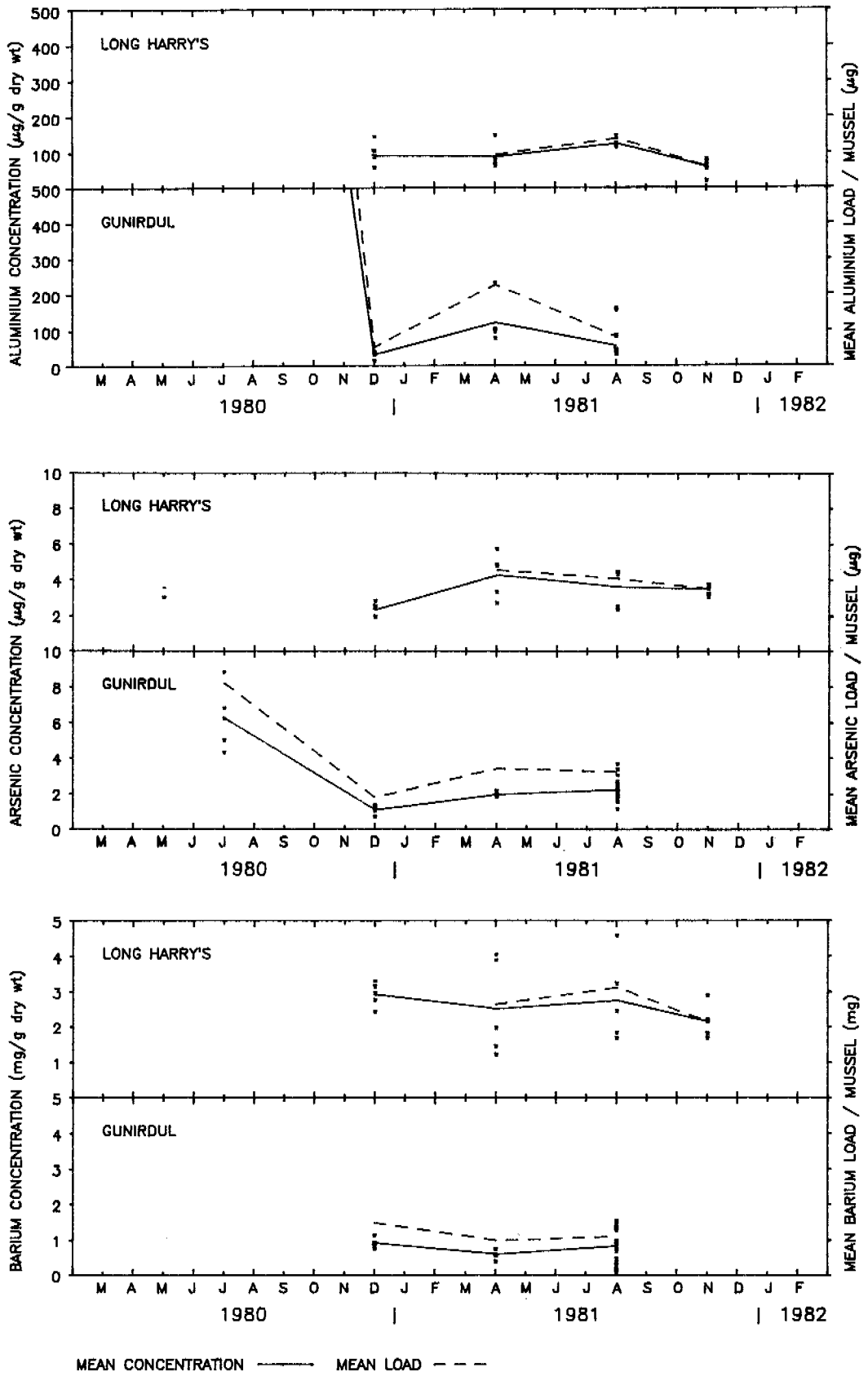


Figure A32. Concentration and mean load per mussel of Al, As and Ba in the soft parts of mussels from Long Harry's (Nourlangie Creek) and Gunirdul (Cooper Creek) Between March 1980 and February 1982
The scales for concentration and load on the Y-axes are the same

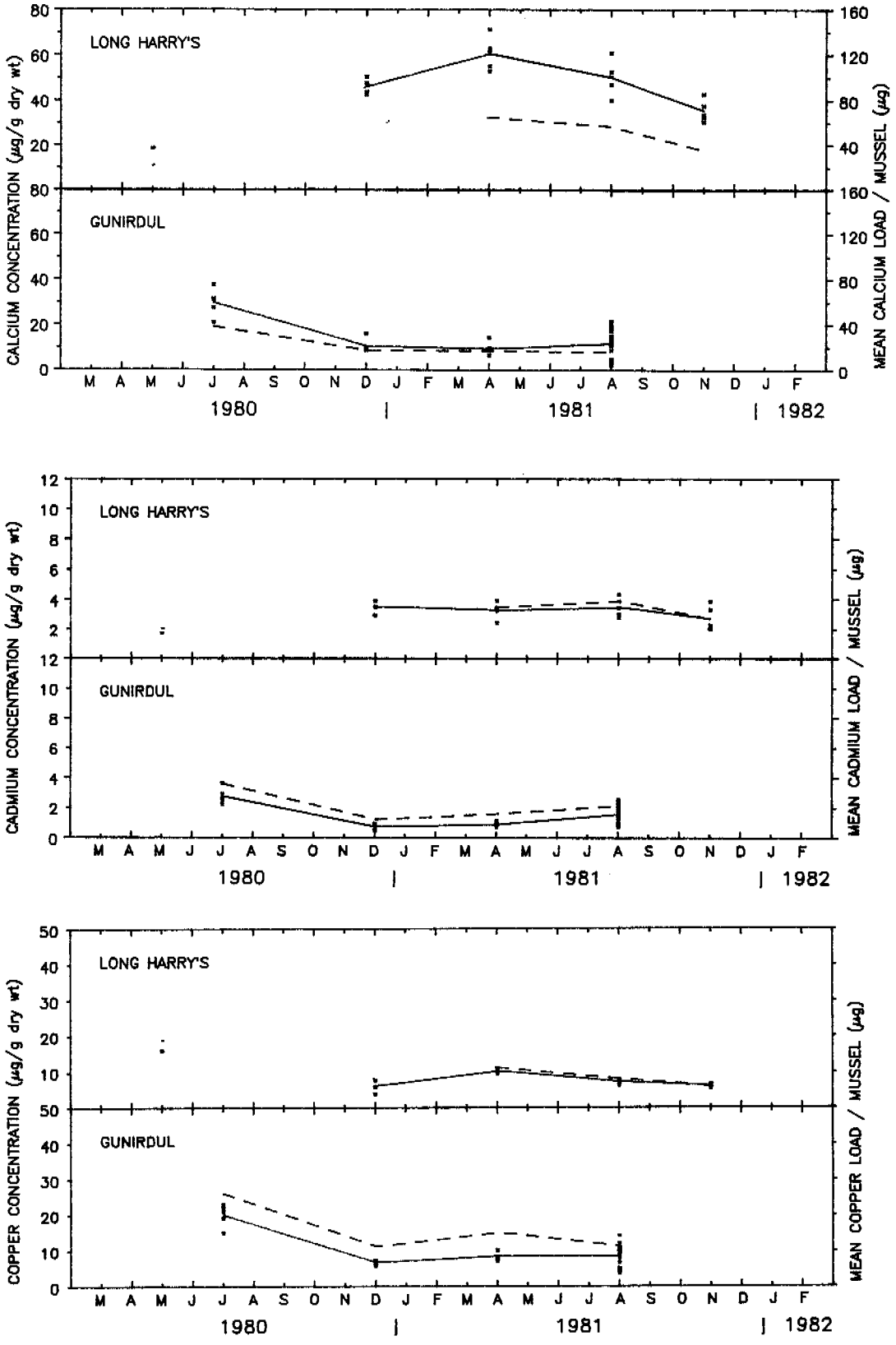


Figure A33. Concentration and mean load per mussel of Ca, Cd and Cu in the soft parts of mussels from Long Harry's (Nourlangie Creek) and Gunirdul (Cooper Creek) Between March 1980 and February 1982
The scales for concentration and load on the Y-axes are the same

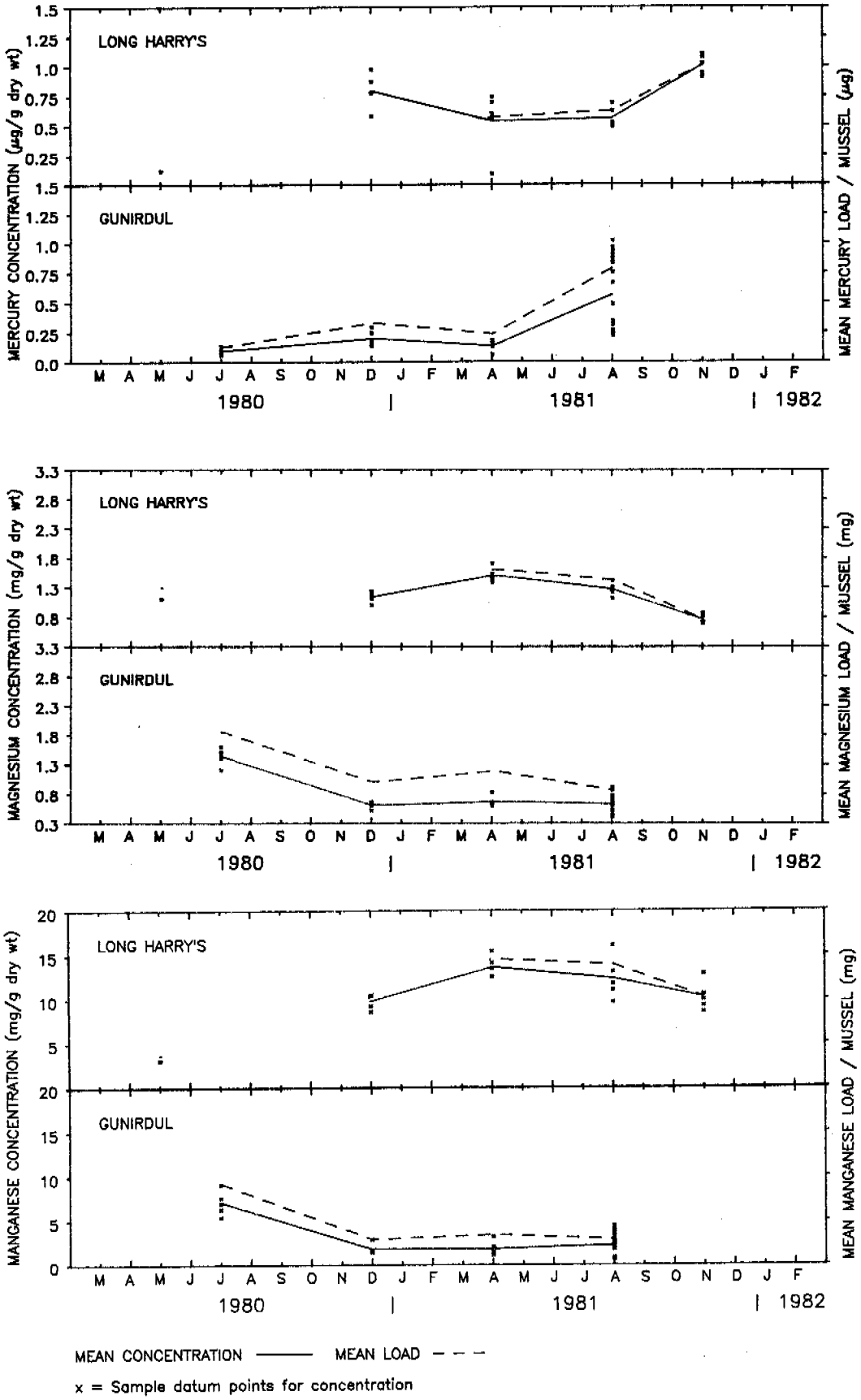


Figure A34.Concentration and mean load per mussel of Hg, Mg and Mn in the soft parts of mussels from Long Harry's (Nourlangie Creek) and Gunirdul (Cooper Creek) Between March 1980 and February 1982
The scales for concentration and load on the Y-axes are the same

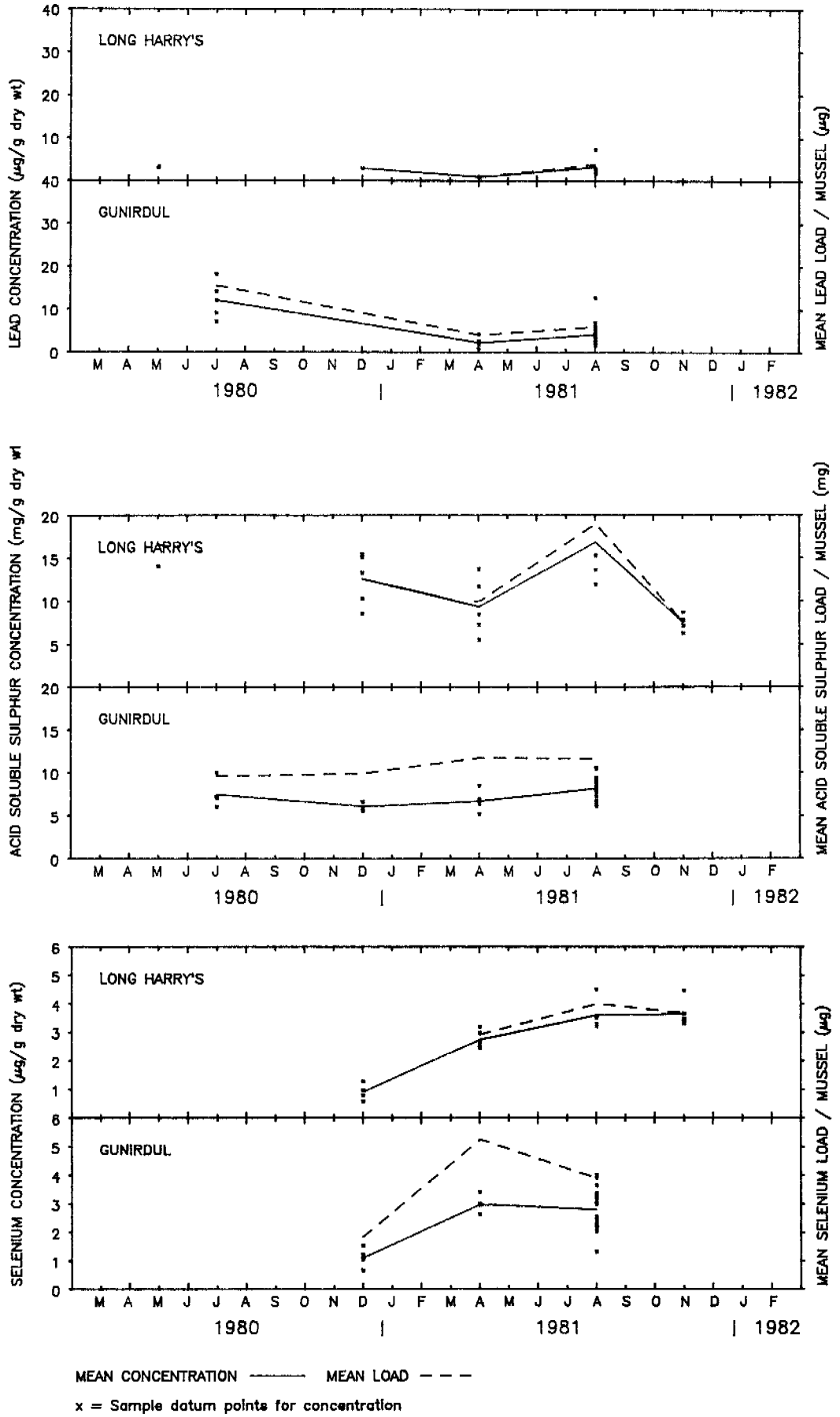


Figure A35. Concentration and mean load per mussel of Pb, S and Se in the soft parts of mussels from Long Harry's (Nourlangie Creek) and Gunirdul (Cooper Creek) Between March 1980 and February 1982
The scales for concentration and load on the Y-axes are the same

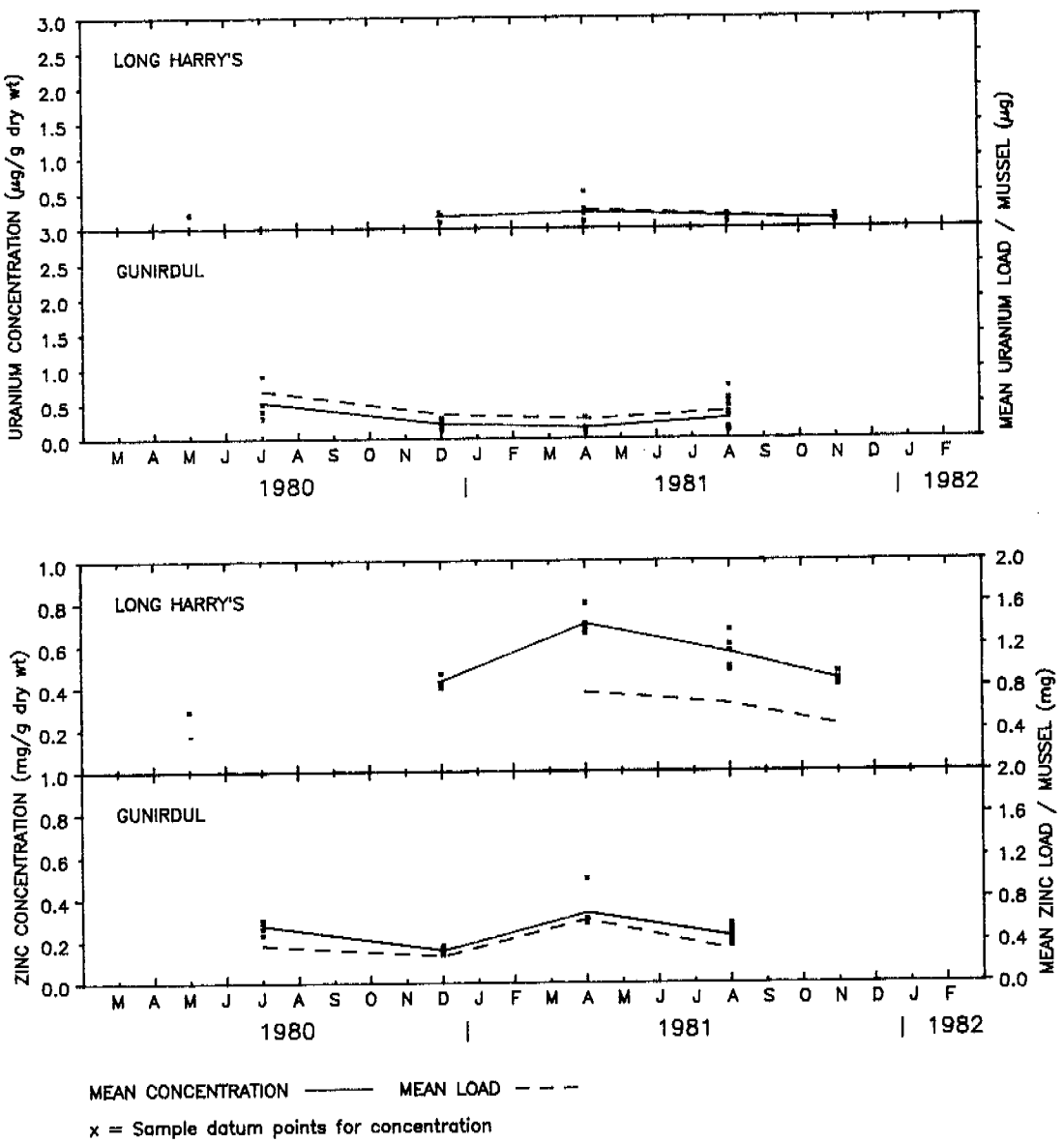


Figure A36. Concentration and mean load per mussel of U and Zn in the soft parts of mussels from Long Harry's (Nourlangie Creek) and Gunirdul (Cooper Creek) Between March 1980 and February 1982
The scales for concentration and load on the Y-axes are the same