FINAL REPORT TO THE FISHING INDUSTRY
RESEARCH COMMITTEE

FIRTA PROJECT 83/47

MEASURING THE FEEDING RANGE OF WESTERN
ROCK LOBSTERS AND THE EFFECTIVE
FISHING AREA OF A BAITED POT

CSIRO
Marine Laboratories

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MEASURING THE FEEDING RANGE OF WESTERN ROCK LOBSTERS

AND THE EFFECTIVE FISHING AREA OF A BAITED POT.

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PREFACE

This report has been kept to a minimum to make it easy to read and assimilate. The information and conclusions that it contains are relevant for fisheries management.

More detailed information including analyses and scientific discussion of data appear in appendices accompanying the master copy of this report. References to specific appendices within the report allow Committee members, if they wish, to investigate aspects of the project in greater detail. A list of the appendices is shown on the next page.

Appendix 7 consists of an 18 min. VHS video documentary of the project. This has been shown at Fish Expo in Adelaide during July, 1986 and also to Western rock lobster fishermen during the 1986 tour by the Rock Lobster Industry Advisory Committee of Western Australia.

APPENDICES OF THE MASTER COPY

Appendix Number	Title of Publication	Destination of Publication
1	Electromagnetic tracking of juvenile rock lobsters.	Australian Fisheries
2	How far do rock lobsters search for food ?	Australian Fisheries
3	The effective catching area of a commercial lobster trap and its influence on foraging behaviour of juvenile western rock lobsters.	Australian Journal of Marine and Freshwater Research
4	A quantitative study of nocturnal foraging distances of the West Australian rock lobster, **Panulirus cygnus**, George.	Journal of Experimental Marine Biology and Ecology
5	Foraging patterns and activity of juvenile rock lobsters, **Panulirus cygnus**, George.	Journal of Experimental Marine Biology and Ecology
6	An electromagnetic tracking system for use in shallow water.	CSIRO Technical Report
7	Electromagnetic tracking of western rock lobsters.	VHS Video Documentary Film (18 minutes)

CONCLUSIONS

1)   The idea that the growth and survival of juvenile western rock lobsters is limited by the relative shortage of food possibly due to small foraging ranges (Chittleborough 1974, 1975, Chittleborough and Phillips 1975) was not supported by the present study.

2)   Foraging patterns and activity of juvenile lobsters suggest that in nursery reefs, beds of *Heterozostera* and *Halophila* seagrasses are more heavily foraged than other areas. Because lobsters are very numerous, their influence on prey within these areas is very important.

3)   The effective fishing area of a baited pot was approximately 120 m. If pots are set closer than 120 m, competition between pots may occur. The maximum distance that lobsters are attracted to a pot is, however, variable because of large variations in the responses of individual lobsters to the baited pot and also due the influence of water currents.

INTRODUCTION

Chittleborough and Phillips (1975) concluded that food is a primary factor affecting the growth and survival of juvenile western rock lobsters in nursery areas. Determining how far juveniles travel when searching for food is essential in determining the size of area foraged and how much food is potentially available to them. Knowledge of foraging patterns and feeding activity of juvenile western rock lobsters are, therefore, required to understand their ecology.

Studies on natural foraging activity of rock lobsters are difficult. The animals feed at night and it is only possible for divers to observe a few animals. In addition, the natural behaviour of rock lobsters is affected by the presence of divers. The lobsters hide from the divers in the seagrass beds instead of foraging.

Phillips et al. (1984) developed a method of remotely tracking juvenile western rock lobsters using electromagnetic tags. Natural foraging distances and activity can be determined by this method, enabling researchers to monitor the position of the tagged lobsters throughout the night.

Apart form a strategic benefit to the Fishing Industry, remote tracking of rock lobsters has tactical applications. All catch-per-unit effort data currently used in analysis of commercial catch data relies on the hypotheses that the effective fishing area of a

commercial pot is constant with different baits. In addition, there is a second assumption, that they do not overlap i.e., there is no fishing competition between pots. Both have been identified by Hancock (1980), in his review of research for management of the western rock lobster fishery, as items for which no data are available but needed for standardizing units of fishing effort. The electromagnetic tracking system can be used to provide data towards answering both of these questions.

The objectives of this project as originally proposed were to:

    a. determine the foraging range of rock lobsters.

    b. assess the effective fishing area of a commercial pot.

    c. examine the effects of different baits in the pot on its fishing area.

MATERIALS AND METHODS

Study Site

The study site was at Seven Mile Beach in Western Australia. It is approximately 360 km. north of Perth and 60 km. south of Geraldton and lies approximately in the middle of the range of _Panulirus_ _cygnus_. The area is typical of the shallow water (<10 m.) nursery sites where juvenile rock lobsters are found.

Four major habitat types were present within the tracking area. They were sand, reefs and the two types of seagrass beds, 1) _Amphibolis_ spp. and 2) _Heterozostera_ and _Halophila_. _Amphibolis_ spp. form dense canopies (30 cm. high) with an average biomass of 700 g dry wt m^{-2} while _Heterozostera_ and _Halophila_ is much sparser (av. biomass is 100 g dry wt m^{-2}) and is usually less than 8 cm high.

Tracking Methods

A more detailed description of the method can be found in Phillips _et_ _al_. (1984) and in appendix 6 at the back of this report. Briefly, self contained tags (approximately 4 x 3 x 2 cm) emit periodic magnetic fields. These fields are picked up by a network of aerials laid on the sea bed. A heavy duty Telecom cable relayed signals from the sea bed to a land based tracking system.

Tagged rock lobsters were originally tracked using an oscilloscope to manually decode signals from the tags (Phillips _et_ _al_. 1984).

While information on the position of lobsters can be obtained using this method, it has several drawbacks. Firstly, lobsters can only be tracked at night (due to manpower limitations) and thus no information was available on what proportion of lobsters if any foraged during the daytime. Secondly, and more importantly, only a few individuals could be tracked at any one time. If foraging behaviour of **P. cygnus** is variable then data on many individuals are required to get an accurate idea of normal foraging behaviour.

An automatic computerized tracking system was developed during the project to overcome the limitations of using the manual system (appendix 6). The computerized system could track up to 14 tagged lobsters simultaneously (each tag has a unique signal). It was battery operated and solar powered enabling data on the position of tagged lobsters to be collected until the batteries in the tags expired (21 days).

Capture and tagging of lobsters

Because the behaviour of lobsters may change with age or moult stage (Kanciruk, 1980; Lipcius and Herrnkind, 1982) the study was confined to 4 year old juveniles in an intermoult condition. These animals (55 - 68 mm. carapace length) were the oldest juveniles in the nursery areas that do not migrate as a cohort to deeper water during Spring.

Animals were caught during 8 field trips (Table 1, appendix 4)

between 0900 - 1300 hrs in baited pots placed on Reefs IV and I (Fig. 1, appendix 5). Tags were glued to the cephalothorax using an epoxy resin that set under water (Phillips et al. 1984). Lobsters were returned to their site of capture, left in the pots for an hour to readjust and for the glue to harden, and then released.

Preliminary experiments demonstrated that the tags did not significantly affect the behaviour of tagged lobsters (appendix 4). This means that results on tagged juveniles from the present study can be applied to natural untagged populations of animals.

Information on the physical environment

Data on water temperatures and currents and the amount of underwater light (sunlight and moonlight) were collected to determine if these variables influenced foraging behaviour. These data were collected with automatically recording loggers.

Experiments of the catching area of a baited pot

The study was conducted using a standard wooden western rock lobster batten pot. The single escape gap (305 x 54mm) was closed so that the only way tagged juveniles could escape was through the entrance. Bait used during the study consisted of cowhide and herring (Arripsis georgianus).

A single pot was placed for up to 5 consecutive nights within 6 days of the new moon. This was repeated during November 1984,

January 1985, April 1985, September 1985 and November 1985. The pot was set on a total of 18 nights during the study (Table 1, appendix 3).

Some additional studies were carried out to see if lobsters were capable of escaping from the rock lobster pots. In these studies tagged animals were placed into pots without escape gaps. In addition, the behaviour of animals in and around another pot was documented.

The influence of different baits on the catching area of the pot

The results of the project demonstrated that it was impossible to adequately design such an experiment within the tracking study. This was due to the variable behaviour of lobsters and the problems of standardizing the position of more than one pot relative to the direction of water currents. This problem is discussed in more detail in the discussion section.

RESULTS

Number of lobsters tracked

Lobsters tagged during the first 2 fieldtrips (February and April,
1984) were not tracked due to electronic breakdowns. Out of 80
tagged lobsters released during the remaining 6 fieldtrips, 58% were
tracked for at least 1 night. The fate of the remaining 42% remains
a mystery. A few were not tracked due to tag-loss and malfunction
(appendix 4). Others may have moved outside the tracking area
because several tagged lobsters were caught outside the tracking area
by professional fishermen (the furthest was caught 9.3 km north of
the tracking area after 2 weeks).

Lobsters were tracked from between 1 to 23 nights during a sampling
period (i.e. a fieldtrip). A total of 460 lobster-nights (data on 1
lobster for 1 night) were recorded during the study. Lobsters did
not forage on 48 nights.

Nocturnal foraging distances

Distances traveled by 95% of the tagged population of rock lobsters
ranged between 72.5 and 585 m. per night. The greatest distance
moved by a lobster in a single night was 810 m. and half of the
population moved at least 310 m. per night.

In general, there was no significant difference in distances moved
between sexes, sampling times and there was no detectable short term

effect on distance traveled of capture and handling the tagged lobsters (appendix 4).

Activity patterns

Most lobsters started foraging when the amount of light had declined to very low levels (i.e. dusk). Animals returned from foraging around dawn when light levels increased (appendix 5). Activity was not influenced by diurnal changes in temperature or water currents (appendix 5).

Lobsters remained active throughout the night and there was no significant difference in activity levels between sexes and/or sampling times.

Rates of movement

Lobsters moved at an average speed of about 1 m min^{-1} during a night's foraging. The maximum speed that lobsters were observed to walk over open sand was 18 m min^{-1}.

Foraging patterns

Although foraging patterns varied between individuals, 3 general patterns were observed: 1) small circular areas usually within 20 m of the home den; 2) long straight paths; 3) long circuitous routes (Fig 3, appendix 5).

Foraging direction was never random. Lobsters tended to go to the same general area for at least several nights.

Some lobsters visited dens on other reefs during a night's foraging before returning to their own home den at dawn. Sometimes lobsters changed their home den onto another reef during a sampling period (appendix 5).

Habitat utilized during foraging

Lobsters foraged in the two structural types of seagrass but not on open sand. Although animals stopped just as frequently within the Amphibolis, and Heterozostera and Halophila, they spent longer within the Heterozostera and Halophila beds (appendix 5). On average this pattern was consistent between sexes and sampling times.

Introducing a baited lobster pot into the study area

An average of 6 tagged lobsters were tracked each night when the pot was present within the tracking area. However, an average of only 2 tagged animals were caught in the pot per 5 nights, although twice this number of tagged lobsters visited the pot during the same period. Additional experiments and observations suggest that the lobsters that visited the pot entered it but escaped by morning (appendix 3).

Analyses of water currents data revealed that current flow within the tracking area was unidirectional, from south to north, parallel

to the shore. Hence, the influence of direction of water currents on the detection of bait was examined.

The maximum distance that lobsters detected the scent of bait and followed it to the pot varied depending on whether lobsters were up or down current from the bait. The furthest distance that a lobster was attracted down current from the bait was 120m. Some lobsters at closer distances down current from the bait foraged but made no attempt to visit the pot. Some lobsters passed within 10m up current from the bait and either did not detect the scent or did not choose to go to the pot. Other lobsters up current from the pot visited it but previous foraging history of these individuals suggest that these animals foraged normally and encountered the pot within their usual foraging range. Thus the response of lobsters to the pot was variable (appendix 3).

DISCUSSION

Foraging distances

The results of this project demonstrated that 95% of tagged juvenile P. cygnus traveled between 72.5 m and 545 m per night, and half of the population traveled at least 310 m during nocturnal foraging. This distance (approximately 150 m radius out from the den) was much larger than the home (foraging) range proposed for P. cygnus by Chittleborough (1974). Chittleborough used baited pots to capture tagged animals. He concluded that home ranges of juvenile P.cygnus were 15 m away from the home den although the maximum distance that traps were set from home dens was between approximately 15 m and 20 m. Thus Chittleborough's results may have been an artifact of the trapping method i.e. lobsters were caught in the first trap they encountered and thus were only recorded as moving that far. Chittleborough's study was at Garden Island where P. cygnus perhaps forage over smaller distances, although he suggested that foraging distances may be up to 50 m at Seven Mile Beach. The results of the present study suggest that nocturnal foraging distances of P. cygnus may be an order of magnitude greater, and are comparable to those of the Florida spiny lobster P. argus (Herrnkind et al. 1975).

Chittleborough (1976) suggested that limited food supply resulted in differences in growth between age/sex classes in natural field situations. This hypothesis was not supported by Joll and Phillips (1984) in a study examining the natural diet and growth of P.cygnus.

The idea that the growth and survival of juvenile P. cygnus was limited by the relative shortage of food due to small foraging ranges (Chittleborough 1974,1975; Chittleborough and Phillips 1975) is not supported by the present study.

Nocturnal foraging patterns

Laboratory studies on activity and commercial catch data suggest that P. cygnus are less active around the period of full moon (Morgan 1978). Results of the present study could detect no significant difference in distances moved by lobsters with increasing moonlight levels. It is possible that during this period lobsters remain active but do not enter pots. Alternatively, the small amount of data available on lobsters foraging outside the new moon period was too small for significant trends to be apparent.

Panulirus cygnus foraged in both structural types of seagrass beds. Although on average, lobsters stopped a similar number of times in Amphibolis, and Heterozostera and Halophila beds, the results suggested that they stayed longer in the Heterozostera and Halophila beds. These seagrasses support a greater biomass of infaunal prey than do Amphibolis beds (V. Wadley CSIRO Marine Laboratories pers. communication).

In a study of the natural diet of Panulirus cygnus, Joll and Phillips (1984) found pieces of Amphibolis, coralline algae and other organisms associated with Amphibolis beds in the stomach contents of juvenile rock lobsters. However, most of their observations on

foraging activity and analyses of stomach contents support the conclusions of the present study that most foraging occurs in the *Heterozostera* and *Halophila* beds.

The foraging patterns and feeding activity of juvenile *P. cygnus* suggests that particular sites within algal beds may be foraged repeatedly by individuals on successive nights. Certain areas and habitats are more heavily foraged than others. The fact that lobsters are an extremely numerous organism within the shallow water community of Western Australia suggest that they play an important role in influencing the abundance and diversity of infaunal prey associated with these seagrass communities.

The catching area of a commercial pot

Large variations in the response of tagged rock lobsters to the commercial pot is probably typical and normal for *P. cygnus* because natural foraging patterns and activity are also highly variable. Varied responses and low recapture rates of other marine crustaceans have also been reported in scientific literature (e.g. Williams and Hill 1982; Brethes *et al.* 1985).

It was not possible to examine the effects of different baits in the pot on its fishing area for several reasons: Firstly, because the response of lobsters to a single bait combination (cow hide and herring) was so variable, it would not have been possible within the tracking study to distinguish between the effects of different baits. Secondly, only 1 pot (i.e. 1 bait combination) could be used within

the tracking area during a single night. If more pots (with different combinations of bait) were placed in the area, the position of the pots relative to the proximity of the lobsters' home reefs and also to water currents could not be standardized.

Nevertheless, the results of the present study have revealed information on the natural foraging response of lobsters when exposed to baited pots. The direction of water currents was shown to be very important in influencing the catching area of a baited pot. Lobsters down current from the bait were attracted over greater distances than animals up current from the pot. In addition, many lobsters that visited a pot apparently entered and escaped through the entrance before sunrise. The escape of adult P. cygnus from commercial pots is also known to occur (R. Brown, Western Australian Fisheries Department, pers. communication) as is the escape of Jasus lalandii (J.McKoy, New Zealand Fisheries Department, pers. communication).

The results of this project have important implications for research on spiny lobsters using pot-recapture techniques. The use of pots to estimate densities of P. cygnus on patch reefs (e.g. Chittleborough 1974) may be invalid due to the ability of the pot to draw individuals of neighbouring reefs thus leading to overestimates of natural densities.

A basic assumption made when collecting commercial catch statistics on P. cygnus is that there is no fishing competition between pots (Hancock 1980). Results of the present study suggest that if pots are set closer than 120 m together, competition between pots may

occur. This result is dependent upon the influence of water currents and a multitude of other factors. The area of a pot can and does vary.

Some assumptions of fisheries management (e.g. competition between pots) may never be able to be tested successfully under a range of conditions experienced in the field. Thus the general applicability of results may be restricted. The present study does, however, provide an indication of the likely range of effects as a first approximation.

REFERENCES

Chittleborough R.G. (1974) Home range, homing, and dominance in juvenile western rock lobsters. Aust. J. Mar. Freshw. Res., Vol. 25, pp. 227-234.

Chittleborough R.G. (1975) Environmental factors affecting growth and survival of juvenile western rock lobsters Panulirus longipes (Milne-Edwards). Aust. J. Mar. Freshw. Res., Vol. 26, pp. 177-196.

Chittleborough R.G. (1976) Growth of Panulirus longipes cygnus George on coastal reefs compared with those reared under optimal environmental conditions. Aust. J. Mar. Freshw. Res., Vol. 27, pp. 279-295.

Chittleborough R.G. and B.F. Phillips (1975). Fluctuations of year-class strength and recruitment in the western rock lobster Panulirus longipes (Milne-Edwards). Aust. J. Mar. Freshw. Res., Vol. 26, pp. 317-328.

Hancock D.A. (1980). Research for management of the rock lobster fishery of Western Australia. Proc. 33rd Ann. Gulf and Caribbean Fish. Inst., Vol. 33, pp. 207-229.

Herrnkind W.F., J. VanderWalker and L. Barr (1975). Population dynamics, ecology and behaviour of spiny lobster Panulirus argus of St. John, U.S. Virgin Islands: Habitation and pattern of movements. Results of the Tektite Program, Vol. 2 Sci. Bull. Nat. Hist. Mus. Los Angeles Cty., Vol. 20, pp. 31-45.

Joll L.M. and B.F. Phillips (1984). Natural diet and growth of juvenile western rock lobsters Panulirus cygnus George. J. Exp. Mar. Biol. Ecol., Vol. 75, pp. 145-169.

Kanciruk P. (1980). Ecology of juvenile and adult Palinuridae (spiny lobsters), In: The Biology and Management of Lobsters, Vol. 11. Edited by J.S. Cobb and B.F. Phillips. Academic press, New York, pp. 59-96.

Lipcius R.N. and W.F. Herrnkind (1985). Photoperiodic regulation and daily timing of spiny lobster mating behaviour. J. Exp. Mar. Biol. Ecol., Vol. 89, pp. 191-204.

Phillips B.F., Joll L.M. and D.C. Ramm (1984). An electromagnetic tracking system for studying the movements of rock (spiny) lobsters. J. Exp. Mar. Biol. Ecol., Vol. 79, pp. 9-18.

APPENDIX 1

Electromagnetic tracking of
juvenile rock lobsters.

Australian
Fisheries

Tuna Catches
—South Australia
—Indian Ocean

Electromagnetic tracking of juvenile rock lobsters

by Dr P. Jernakoff and Dr B. F. Phillips

THE western rock lobster fishery is Australia's most valuable single species fishery. The 1986-87 catch for example is expected to be worth $110.4 million. Obviously, the more we know about the life history and ecology of the western rock lobster, *Panulirus cygnus*, the better we can manage and develop the fishery.

The feeding activities of the juveniles is the focus of the latest research project to be undertaken by CSIRO Division of Fisheries Research funded in part by the Fishing Industry Research Trust Account.

Juvenile western rock lobsters live in shallow coastal nursery areas before moving, at about four years old, to the deeper waters where they are fished commercially.

The reason for the study is that the growth and possibly survival of the recruiting juvenile stocks are believed to be controlled by the availability of food. One of the steps in examining this hypothesis is to find out the extent of foraging so that we can estimate how much food is potentially available to them.

In addition to information on how far *P. cygnus* will travel to natural food supplies, the question of how far rock lobsters will be attracted and travel to a baited pot is also of great interest and relevant to the management of the fishing industry. This is because when commercial catch statistics are collected, it is assumed that there is no fishing competition
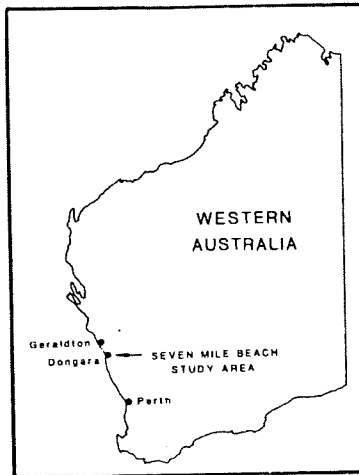

Figure 1. Location of study area.

between pots — that is, two adjacent pots do not attract the same rock lobster. Information from the present study can be used to examine the validity of this assumption.

The foraging movements of juvenile rock lobsters in their natural environment can, in theory, be studied by divers observing them underwater. But this is logistically impossible if they must observe more than a few animals, and must observe them for longer than the 30 to 90 minutes that the air in a scuba tank lasts. And as *P. cygnus* is a nocturnal feeder, all diving would have to be done at night.

A better method — and the one that CSIRO is using — is to track the movements of the lobsters with a transmitting tag.

Wild animals are usually tracked by either radio or ultrasonic methods. Radio telemetry is only useful for tracking animals on or above the surface of the ocean, because the high conductivity of seawater attenuates radio signals under the sea.

Ultrasonic telemetry has worked well with fish and lobsters (such as the spiny American rock lobster) that live in open habitats. Unfortunately, *P. cygnus* lives in patch reefs and seagrass, which interfere with the sonic signals released by the tags.

A third method of tracking uses electromagnetic signals. This method, which was first used to study the den positions of the southern rock lobster, *Jasus novaehollandiae*, has been modified and tested by the CSIRO. A pilot study in 1981 confirmed the feasibility of this method for tracking the foraging movements of juvenile *P. cygnus*.

In the electromagnetic method of tracking, signals put out by the tags on the lobsters are picked up by aerials placed in a regular pattern on the seabed. Over 16,000 m² of seabed are covered by 50 (12 m x 12 m) aerials at the study area at Seven Mile Beach (360 km north of Perth) (see Fig. 1). Signals picked up by the aerials are relayed by a heavy-duty Telecom cable from the seabed to a caravan housing the electronics on shore.

An oscilloscope was originally used to decode these signals from

the tags (each tag has a unique pulse), but this proved a tedious procedure, because the nocturnal habits of the rock lobsters meant that CSIRO personnel had to stay up all night to operate the oscilloscope and decode the information (see Fig. 2).

Instead, a computerised tracking system was developed (Fig. 3).

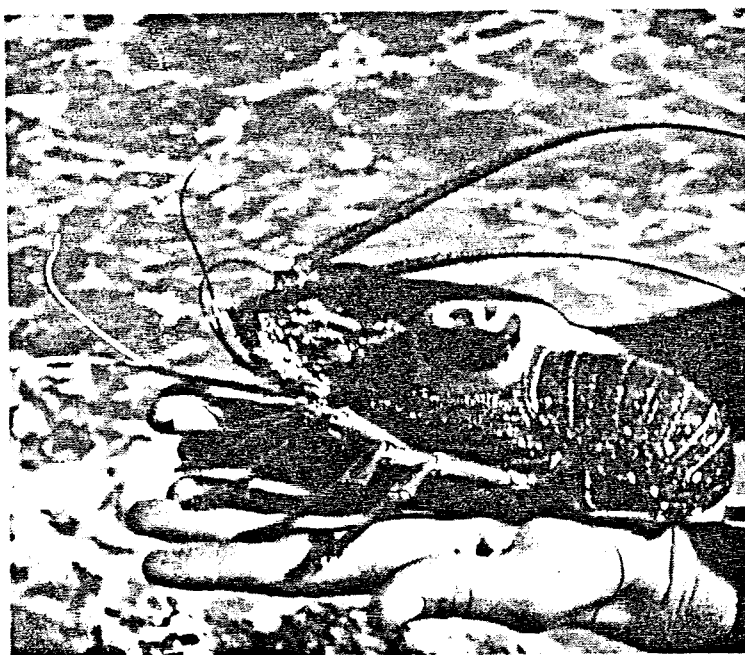Figure 2. Technical assistant, Kevin Smith, decoding signals on the oscilloscope.

Figure 4. Western rock lobster with electromagnetic tag glued to its carapace.

Among its many advantages is that it can track and identify more rock lobsters faster and more efficiently than the manual method, and it operates 24 hours a day. Because the system is powered by a bank of solar panels, it can be used in remote locations away from conventional power sources, saving the information for later analyses.

The tags for this project were specially designed. They are neutrally bouyant and shaped to fit the carapace of the rock lobster, onto which they are glued with an epoxy resin that sets underwater (Fig. 4). Once the transmitter is activated by a magnetic switch it operates continuously for about three weeks, emitting periodic magnetic pulses, which are picked up by the aerials. When the lobster eventually moults, the tag is discarded along with the old shell.

At the beginning of the project, we carried out experiments to determine whether the tags influenced the behaviour of the rock lobsters. The animals might be affected by the capture and the tagging process itself, by the physical presence of the tags on the carapace, or by the electromagnetic signal emitted by the tags.

The ideal way to test for the behavioural effects of capturing and tagging the animals would be to compare the behaviour of tagged and untagged individuals, but it is impossible in the field to identify untagged individuals. However the effect of the physical presence of the tags can be tested by comparing the behaviour of rock lobsters marked with a dab of coloured epoxy resin on the carapace with that of animals with the same mark and a non-transmitting tag. Any differences in the behaviour of these two groups can only be attributed to the physical presence of the tag.

To test whether the signal produced by the tag affects behaviour, we compared the

behaviour of animals with non-transmitting tags to those with transmitting tags. In neither test did the presence of tags or the transmission of signals produce a detectable change in the foraging behaviour of the rock lobsters.

Marked and unmarked individuals were caught in baited pots in the same proportions.

From these experiments, we can reasonably conclude that the foraging patterns of tagged rock lobsters in the tracking study are representative of natural foraging patterns and are not due to the behavioural effect of the tags.

The study is still underway and analyses are therefore incomplete. However several trends are apparent. Many rock lobsters appear to follow set foraging paths, even visiting dens in other reefs more than 100 m away during a night's foraging (Fig. 5).

The distances they travel are much greater than had been previously thought; one lobster travelled over 700 m in a single night.

Preliminary results on the fishing area of a commercial pot suggest that rock lobsters can be attracted to a pot at least 80 m away from their home reef.

The project will end in June 1986. The information on foraging patterns, which is essential to understanding the ecology of juvenile rock lobsters, will assist in the long-term protection of this valuable resource and in the management of the fishery.
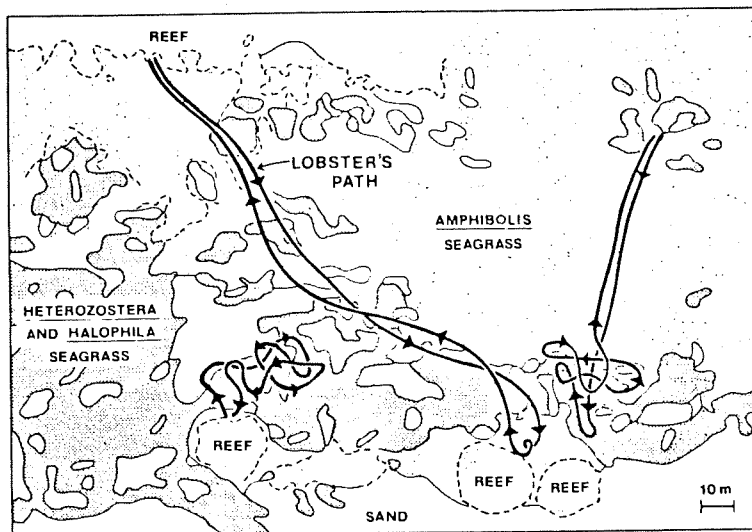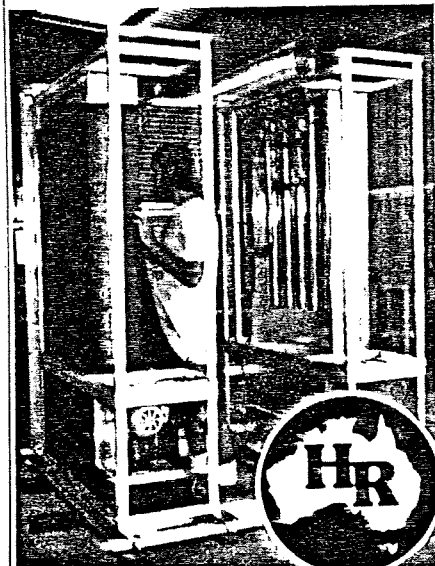

Figure 5. Nocturnal foraging paths of tagged western rock lobsters.

APPENDIX 2

How far do rock lobsters
search for food?

This paper is in preparation to be
submitted to Australian Fisheries

APPENDIX 3

The effective catching area of a commercial lobster
trap and its influence on foraging behaviour
of juvenile western rock lobsters.

This manuscript is to be submitted
to the Australian Journal of Marine
and Freshwater Research

THE EFFECTIVE CATCHING AREA OF A COMMERCIAL LOBSTER TRAP AND ITS INFLUENCE ON

FORAGING OF JUVENILE WESTERN ROCK LOBSTERS

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ABSTRACT

The influence of a commercial trap on the foraging of juvenile _Panulirus cygnus_ was determined by tracking animals to which electromagnetic tags had been attached. Catch rates were low. On 14 occasions, tagged lobsters were not caught, but visited the trap, stayed for up to several hours during the night and left again by morning. The greatest distance lobsters that lobsters were attracted to the baited trap was 120 m, when the animals were downcurrent. On 19 occasions lobsters upcurrent from the trap passed as close as 20 m without apparently detecting the trap. Other lobsters as far away as 75 m upcurrent visited the trap. From previous records of the foraging ranges of individuals that foraged upcurrent, it seems their visit may have been due to the location of the trap within their foraging range rather than to detection of the bait.

Present trapping techniques used to estimate the densities of juvenile lobsters on individual patch reefs may be biased because lobsters on neighbouring reefs as far away as 120 m could be attracted to the baited trap. The results of the present study also suggest that traps set closer than 120 m apart may fish competitively for the same rock lobster.

INTRODUCTION

The western rock lobster, _Panulirus cygnus_, George, is found off the coast of Western Australia between North West Cape (21°45'S) and Cape Leeuwin (34°22'S). The fishery based on the lobster is worth over $A100 million per annum and is Australia's most valuable single species-fishery.

Juvenile western rock lobsters are nocturnal foragers. Foraging usually starts after sunset and continues until around dawn (Cobb 1981, Phillips _et al._, 1984). Foraging juveniles may travel up to 800 m during a single night (Jernakoff _et al._, in prep.) making numerous stops and visits to areas in search of food (Jernakoff in prep.). They forage on a variety of plant and animal material found in the seagrass beds of the shallow coastal areas of Western Australia (Joll and Phillips 1984). The animals forage by searching and probing the substratum and seagrass with their first and second pereiopods for prey which is passed by the maxillipeds to the mandibles. Foraging stops when food is found and recommences after it is eaten (pers. obs.).

Although _Panulirus cygnus_ eats chiefly live prey, they are also opportunistic scavengers, and are commercially caught in traps baited with, for example, fish and cowhide. Although the fishery is based on the capture of adult lobsters (carapace length $>$ 76 mm), juvenile lobsters are also caught, which suggests that their foraging is affected by the presence of a trap.

The aim of the present study is to examine changes in the natural foraging of juvenile lobsters in the field in the presence of a commercial lobster trap. In addition, the area of effect of a trap was assessed to examine a potential bias in catch statistics. Such statistics are based on the assumption that traps do not "compete" for the same lobster, as the traps are set some distance apart. The need to examine such biases has been

recognised in attempting to standardize units for fishing effort (Hancock 1980, 1981).

MATERIALS AND METHODS

The study area at Seven Mile Beach in Western Australia (29°08'S 114°54'E) is typical of the shallow, coastal nursery areas of juvenile western rock lobsters. The study site had previously been used for electromagnetic tracking of juvenile rock lobsters (Phillips et al. 1984) and the tracking area covers approximately 16,000 m² (Jernakoff et al., in prep.).

Rock lobsters estimated to be 4 years old (55-68 mm carapace length; Phillips unpubl. data) were chosen for this study because they are the largest juveniles that do not migrate as a cohort from nursery areas to deeper water during spring. Only intermoult lobsters with 8 or more legs were used as moultstage can affect foraging (Lipcius and Herrnkind 1985) as may loss of legs.

Lobsters were tagged with electromagnetic tags, released at their site of capture and left for at least a week before trapping experiments were started. A single commercial trap was placed within the study area for up to five consecutive nights within six days of the new moon. This was repeated during November 1984, January 1985, April 1985, September 1985 and November 1985 to give a total of 18 nights (Table 1). All lobsters caught in the trap overnight were released the following morning.

A single wooden batten trap (Bowen 1980) was baited with the normal combination of baits used in the commercial fishery (Australian herring; Arripsis georgianus and cowhide). Standard lobster traps have an escape gap (305 x 54 mm) for undersized lobsters (Hancock 1980); in the present study it was closed. To determine if tagged lobsters could still escape (through the

entrance) six tagged lobsters were placed in an unbaited commercial lobster trap (no escape gap) during September 1985 and again in November 1985. Traps were unbaited, providing lobsters with no reason to stay and feed.

A pilot study was conducted to determine whether lobsters tagged with electromagnetic tags had the same probability of capture as untagged animals. This formed part of an experiment on the effects of the tags on the natural foraging of juvenile P. cygnus and will be presented elsewhere (Jernakoff et al. in prep.). Neither the presence of tags nor sex of the lobsters, affected the frequence with which they were caught (analyses of variance p > 0.25). Thus the results obtained in the present study could be applied to natural, untagged populations of western rock lobsters. Measurements made of the water temperature, the amount of light and the speed and direction of the water current, all of which might influence catchability, will be presented elsewhere (Jernakoff in prep.).

To check whether lobsters were entering the trap, feeding and escaping (i.e. only visiting; see Results), a boat was moored over a commercial trap within the tracking area for two nights in September 1985. The top wooden battens were replaced with clear perspex battens. A viewing chamber and underwater white lights were used to count the number of lobsters at the commercial trap every half an hour during the night. The lights were turned on for a maximum of 5 s every half an hour as the lighting increased the activity of the lobsters, although those on the outside or near the traps did not leave as long as the lights were on for less than 10 s.

RESULTS

An average of six tagged rock lobsters per night were tracked on each of the 18 nights of the study. A maximum of two tagged animals per night (mean 0.44) were caught by the trap, while up to six tagged lobsters (mean 0.78)

visited the trap each night but left by morning (Table 1). Four tagged animals were caught once while two were caught on 2 successive nights. Two tagged lobsters that were caught in the baited trap left the test area on the following night. However, the other four animals continued to forage within the test area on subsequent nights.

Untagged P cygnus were also attracted to the trap. An average of 22.7 animals per night was caught during the 18 nights of sampling.

The maximum distance from which lobsters detected bait in the trap varied depending upon whether animals were up- or downcurrent from the bait. On 19 occasions, lobsters upcurrent from the bait passed within 20 m of the trap and did not go to it. However, on eight occasions, lobsters upcurrent from the bait visited the trap but it was inside their usual foraging area (Jernakoff in prep.); these lobsters presumably had not been attracted to the trap by the bait. On 10 occasions, lobsters in dens at an average distance of 75.48 m (s.e. 8.66 m) downcurrent from the bait were observed to leave their usual foraging ranges to visit the trap. The mean time between their beginning to forage and their arriving at the trap was 2.84 h (s.e. 0.55 h). The greatest straight line distance that two lobsters were recorded to track the bait to the trap (and were caught) was 120 m. These two lobsters travelled from the boundary of the tracking area to the trap (e.g. see lobster G, Fig. 1). On 12 occasions foraging lobsters closer than 75 m downcurrent from the bait did not visit the trap (e.g. see lobster C, Fig. 1).

Tagged lobsters that visited, but were not caught by the lobster trap spent an average of 3.82 h (s.e. 0.75 h; range 9.03 to 0.42 h) at the trap before leaving. It was not possible to determine whether these animals entered, fed and escaped from the trap, or whether they just remained on the outside of the trap. They could not have fed on the bait from the outside of

the trap because the bait bags were beyond reach, tied to the centre of the floor.

During September (1985), lobsters in and around the trap were counted every half hour throughout the night for two nights. Only one tagged lobster entered the trap and it was caught. No other tagged lobsters were seen at the trap. This was confirmed from the results of the tracking study. On both nights very few animals were recorded on the outside of the trap after 0230 hrs (Table 2). Judging from the difference in sizes, these lobsters were not the same individuals throughout the night. Of the tagged lobsters tracked visiting and then leaving (a total of 14 visits) half left after 0230 h (between 0300 h and 0652 h) and the other half visited and left between 1852 h and 0230 h.

Of six tagged lobsters placed in an unbaited trap during September 1985, only five were present after one day and only one was left in the trap after three days (together with an octopus and the eaten remains of a single tagged lobster). When the experiment was repeated in November 1985, there was an extra (untagged) lobster in the pot after one night. An octopus entered the trap during the following night and killed and ate three of the tagged lobsters. The experiment was stopped at this time.

DISCUSSION

Little pattern in the response of tagged rock lobsters and low recapture rates by the commercial trap necessitated qualitative analyses of the results, and conclusions are drawn accordingly. Both the foraging distances and ranges of juvenile P. cygnus are variable for different rock lobsters on the same night and by the same individuals on different nights (Jernakoff in prep., Jernakoff et al., in prep.). Hence their varied response to the presence of a

trap is probably typical and normal for P. cygnus.

The influence of water currents on foraging of rock lobsters has been noted in review articles by Bowen (1980) Hancock (1980) Herrnkind (1980) and Kanciruk (1980). Because of the logistical problems in measuring water currents and flow, field studies on the attraction of lobsters to bait have typically assumed that the scent is uniformly diluted (e.g. Zimmer-Faust & Case (1983), Brethes et al. 1985). Jernakoff (in prep.) found that the current flowed through the study area and was only in one direction, from south to north, parallel to the shoreline. This information, and previously obtained data on the natural foraging patterns of individual lobsters (Jernakoff in prep.) suggested an explanation for some of the results of the present study. A few lobsters up to 75 m upcurrent from the bait visited the trap. Their foraging paths, however, were typical for those individuals hence their arrival at the trap was probably not because they detected the bait. Other lobsters passed to within 20 m up current from the trap without apparently detecting the bait. But two tagged lobsters that had previously left the tracking area were attracted back to the tracking area to the trap from 120 m downcurrent.

While water currents may affect the lobster's response to the trap, other influences are less clear. Water temperature, lunar-cycles, and moult stage can all have an effect (Bowen 1980) but they do not explain why lobsters at the same moult stage, the same distance from the trap and on the same night respond differently to the trap.

The effective fishing area of traps for crustaceans has not been intensively studied. Most work has been on the catchability of crabs (e.g. Williams and Hill 1982; Brethes et al. 1985). In a series of trap spacing trials Williams and Hill (1982) found that traps set 50 m apart fished

competitively for <u>Scylla serrata</u>, unlike traps set 100 m and 200 m apart. The effective fishing area of their traps was therefore apparently around 100 m. Catchability was also influenced by water temperature and the moult-stage of <u>S</u>. <u>serrata</u>. Williams and Hill (1982) reported that recaptures of tagged <u>S</u>. <u>serrata</u> varied between days and also months, even though traps were placed at the same site each day of the experiment. <u>Panulirus cygnus</u> behaved similarly in the present study. Differential catch success was also reported for the snow crab, <u>Chionoectes opilio</u>, by Brethes <u>et al</u>. (1985). They reported an effective fishing area of about 50-70 m radius. Low recapture rates and variable captures led them to suggest that biological factors may interfere with the theoretical bait stimulus-response.

The remote tracking of rock lobsters in the present study revealed that many lobsters visited a commercial trap, apparently entered it and then escaped before sunrise. The disappearance of some lobsters from an unbaited commercial trap with no escape gap, suggests that they can escape through the entrance. The fact that the same individuals did not remain on the outside of the trap during the night and also that only one individual remained outside after 0230 h is further evidence that tagged lobsters that visited the trap, did not stay on the outside, but entered the trap, fed, and then escaped. Commercial sized adult <u>P</u>. <u>cygnus</u> (C.L. $\geqslant$ 76 mm) are also known to escape from commercial lobster traps (R. Brown, Western Australian Marine Research laboratories, unpubl. data) Escape from commercial traps has also been demonstrated for <u>Jasus lalandii</u> (J. McKoy, NZ Fisheries Department, unpubl. data).

The results of the present study may have important implications for rock lobster research that use trap-capture techniques. The use of traps to estimate densities of <u>P</u>. <u>cygnus</u> on patch reefs (e.g. Chittleborough 1970) may

be invalid as traps were found to attract lobsters from as far away as 120 m, which would lead to natural densities being overestimated.

Commercial catch statistics on P. cygnus, are based on the assumption that there is no fishing competition between traps (Hancock 1980, 1981). The distance between commercial western rock lobster traps is usually 100 m (R. Brown, Western Australian Marine Research Laboratories, pers. comm.). The results of the present study suggest that if traps are set closer together than 120 m, competition between traps may occur, although other factors especially water currents affect the area over which a trap is effective.

REFERENCES

Bowen, B.K. (1980). Spiny lobster fisheries management. In "The Biology and Management of Lobsters. Vol. 2". (Eds J.S. Cobb and B.F. Phillips.) pp. 243-264. (Academic Press: New York.)

Brethes, J.C., Bouchard, R., and Desrosiers, G. (1985). Determination of the area prospected by a baited trap from a tagging and recapture experiment with snow crabs (Chionoectes opilio). J. NorthWest Atl. Fish. Sci. 6, 37-42.

Chittleborough, R.G. (1970). Studies on recruitment in the Western Australian rock lobster Panulirus longipes cygnus George: Density and natural mortality of juveniles. Aust. J. Mar. Freshw. Res. 21, 131-143.

Cobb, J.S.(1981). Behaviour of the Western Australian spiny lobster, Panulirus cygnus George, in the field and laboratory. Aust. J. Mar. Freshwat. Res. 32: 399-409.

Hancock, D.A. (1980). Introduction to Part 2, Management. In "The Biology and Management of Lobsters. Vol. 2". (Eds J.S. Cobb and B.F. Phillips.) pp. 181-188. (Academic Press: New York.)

Hancock, D.A. (1981). Research for management of the rock lobster fishery of Western Australia. Proc. 33rd Ann. Gulf and Caribbean Fish. Inst. 33, 207-229.

Herrnkind, W.F. (1980). Spiny lobsters: patterns of movement. In "The Biology and Management of Lobsters. Vol. 1". (Eds Cobb, J.S. and B.F. Phillips.). pp. 349-401. (Academic Press: New York.)

Jernakoff, P. (in prep.). Foraging patterns and activity of juvenile spiny

    rock lobsters, Panulirus cygnus, George.

Jernakoff, P., Phillips, B.F., and R.A. Maller. (in prep.). A quantitative

    study of nocturnal foraging distances of the West Australian Rock Lobster,

    Panulirus cygnus George.

Joll, L.M., and Phillips, B.F. (1984). Natural diet and growth of juvenile

    western rock lobsters Panulirus cygnus George. J. Exp. Mar. Biol. Ecol.,

    75, 145-169.

Kanciruk, P. (1980). Ecology of juvenile and adult Palinuridae (spiny

    lobsters). In "The Biology and Management of Lobsters. Vol. II". (Eds

    Cobb, J.S. and B.F. Phillips.) pp. 59-96. (Academic Press: New York.)

Lipcius, R.N., and Herrnkind, W.F. (1985). Photoperiodic regulation and daily

    timing of spiny lobster mating behaviour. J. Exp. Mar. Biol. Ecol. 89,

    191-204.

Phillips, B.F., Joll, L.M., and Ramm, D.C. (1984). An electromagnetic

    tracking system for studying the movements of rock (spiny) lobsters. J.

    Exp. Mar. Biol. Ecol. 79, 9-18.

Williams, M.J., and Hill, B.J. (1982). Factors influencing pot catches and

    population estimates of the portunid crab Scylla serrata. Mar. Biol. 71,

    187-192.

Zimmer-Faust, R.K., and Case, J.F. (1983). A proposed dual odor in foraging

    by the Californian spiny lobster Panulirus interruptus (Randall). Biol.

    Bull. 164, 341-353.

FIGURE CAPTIONS

Figure 1. An example of foraging patterns of (electromagnetically) tagged

rock lobsters. Data taken from nocturnal foraging excursions of 21

January 1985.

Lobsters A,B,C do not go to the trap; lobsters D and E visit the

trap and leave; lobsters F and G go to the trap and are caught.
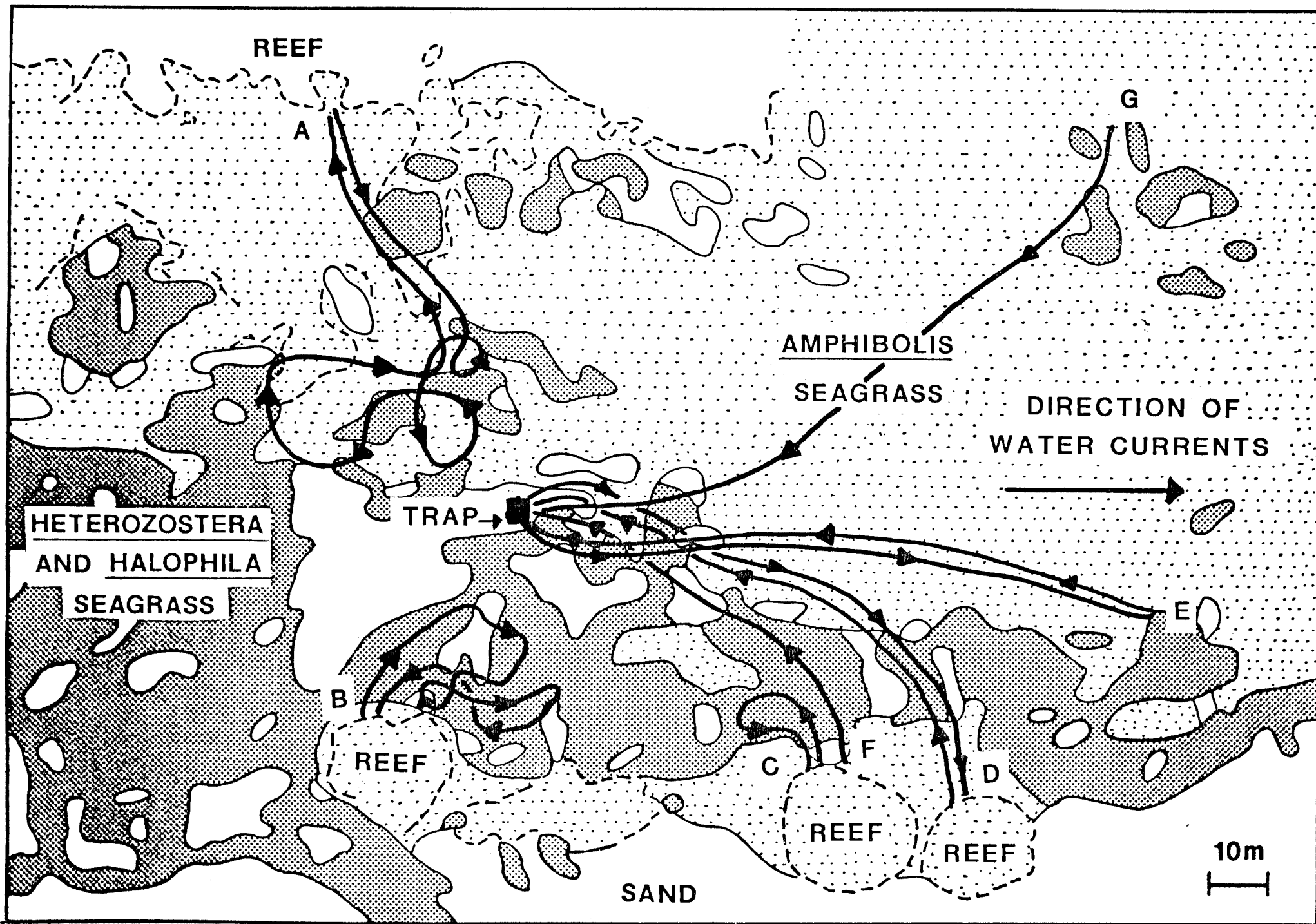
i

Figure 1 (Draft)

REEF

A

G

AMPHIBOLIS

SEAGRASS

DIRECTION OF
WATER CURRENTS

TRAP →

HETEROZOSTERA
AND HALOPHILA
SEAGRASS

E

B

REEF

C

F

D

REEF

REEF

SAND

10m

TABLE 1

Numbers of P. cygnus tracked, caught, and visiting a commercial trap.

| Date | Tagged Lobsters | | | Untagged lobsters caught in trap |
| | Tracked | Caught in trap | Visiting trap | |
	(n)	(n)	(n)	(n)
28.11.1984	7	1	6	15
21.01.1985	7	2	2	29
22.01.1985	6	2	1	29
23.01.1985	6	1	0	16
23.04.1985	4	0	0	20
24.04.1985	4	0	0	8
25.04.1985	4	0	0	22
26.04.1985	4	1	0	40
27.04.1985	3	0	2	20
16.09.1985	6	1	0	37
17.09.1985	6	0	0	39
18.09.1985	5	0	0	31
19.09.1985	4	0	0	34
11.11.1985	9	0	1	18
12.11.1985	9	0	1	14
13.11.1985	9	0	0	12
14.11.1985	9	0	1	11
15.11.1985	9	0	0	3
Mean	6.17	0.44	0.78	22.11
Standard Error	0.50	0.20	0.35	2.63

TABLE 2

Lobsters observed in and around the commercial trap. Twenty lobsters in a
trap was the maximum number that could be counted accurately from the boat.

	16 September 1985		17 September 1985	
Time	Lobsters in trap	Lobsters on outside of trap	Lobsters in trap	Lobsters on outside of trap
1800	0	0	0	2
1830	0	0	0	3
1900	0	0	0	5
1930	4	6	3	6
2000	6	5	10	7
2030	10	2	20	8
2100	17	5	>20	0
2130	17	4	>20	0
2200	20	3	>20	1
2230	20	3	>20	0
2300	20	4	>20	2
2330	>25	0	>25	0
0000	>25	3	>25	0
0030	>25	3	>25	0
0100	>25	1	>30	0
0130	>25	3	>30	0
0200	>25	3	>30	0
0230	>25	1	>30	0
0300	>25	1	>30	0
0330	>25	1	>30	0
0400	>25	1	>30	0
0430	>25	0	>30	0
0500	>25	0	>30	0
0530	>25	0	>30	0
0600	>25	0	>30	0
0630	>25	0	>30	0
0700	>25	0	>30	0

APPENDIX 4

A quantitative study of nocturnal foraging
distances of the West Australian rock
lobster, **Panulirus cygnus**, George.

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to the Journal of Experimental
Marine Biology and Ecology

A QUANTITATIVE STUDY OF NOCTURNAL FORAGING DISTANCES OF THE WEST AUSTRALIAN

ROCK LOBSTER, PANULIRUS CYGNUS, GEORGE

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Running Headline: Foraging distances of western rock lobsters.

ABSTRACT

An electromagnetic tracking device was used to study the nocturnal foraging distances of juvenile western rock lobsters. An automatic tracking system was developed that enabled continuous tracking of up to 14 tagged lobsters for periods of up to three weeks.

A total of 460 lobster-nights (data on one lobster for one night) were recorded during the study. Of these, there were 48 lobster nights when lobsters did not forage. Approximately half of the remaining data were incomplete or "censored". A Weibull distribution showed an extremely close fit to the data after adjustment for the bias of censoring. Analyses of deviance enabled comparisons of the effect of sampling time, sex, time since tagging and variability in movements within and between lobsters to be examined in a way which was analagous to analysis of variance.

The results of the study indicate that nocturnal foraging distances are variable with 95% of the population travelling between 72.5 m and 585 m per night. Distances moved by P. cygnus were much greater than previously reported providing the animals with a foraging area far greater than had been expected. Thus the effect on survival of P. cygnus of limited food supply due to small foraging distances (Chittleborough 1974) may not be as important as previously believed.

INTRODUCTION

Movements of Palinurid crustaceans can be divided into three basic types; migration, nomadism and homing (Herrnkind, 1980). Migration involves movements over large distances and is often associated with movements to breeding grounds (see Table I of Herrnkind, 1980 for a review of available knowledge). Nomadism is wandering of individuals over large areas without any clear start or endpoint (e.g. P. argus, Buesa Mas, 1965; N. edwardsii, Annala, 1981; P. cygnus George, 1957) while homing involves periodic movements from a home den or shelter to a foraging area and subsequent return to the original or near by den (e.g. P. argus, Herrnkind & McLean, 1971; Herrnkind & Redig, 1975; Herrnkind et al. 1975; Andree, 1981); P. cygnus Chittleborough, 1974; Phillips et al. 1984; P. interruptus Lindberg, 1955; J. lalandii, Heydorn, 1969).

Most methods of estimating the movements of lobsters use mark and recaptures which have logistical difficulties as well as problems with interpretation of data (as reviewed by Herrnkind, 1980). Large numbers of animals must be tagged (e.g. Heydorn, 1969; Booth, 1985; McKoy, 1984; Phillips, 1983) only a small fraction are ever caught again and only the minimum (straight line) distance from marking and recapture can be estimated. It is impossible to examine repeated daily and short term movements by this method. Remote tracking of lobsters by ultrasonic (Herrnkind & McLean (1971) and electromagnetic (Ramm, 1980; Phillips et al. 1984) means have provided data on short term and periodic (foraging) movements. Investigations using these methods are somewhat restricted because of the logistics of continuously tracking animals over long periods of time and space. Nevertheless, remote tracking of spiny lobsters has produced relevant and important information on homing and nomadism within the species (Herrnkind, 1980).

The West Australian spiny lobster, _Panulirus cygnus_, George, spends 4-6
years within shallow (< 10m) coastal nursery areas before migrating offshore
(Chittleborough & Phillips, 1975).

Chittleborough (1974) reported that within the nursery areas there was
minimal exchange of juveniles (< 5 years old) between reefs, and individuals
foraged over small areas or home ranges. These areas did not exceed a radius
of 15 m on uncrowded reefs although some individuals on more crowded reefs
travelled 50 m. Lobsters left their dens around sunset, foraged in
surrounding seagrass beds, and returned from foraging around dawn (Cobb 1981).

The lack of movement and small home range (Chittleborough 1974) and
studies on the growth rates and survival of juvenile lobsters (Chittleborough
1975; Chittleborough & Phillips 1975) have led to the hypothesis that the
growth rates and survival of lobsters during their stay within the nursery
reefs was limited by the food supply and possibly shelter.

Phillips _et al._ (1984) developed an electromagnetic method of tracking
the movements of juvenile _Panulirus cygnus_. Although the study was
preliminary, and primarily tested the suitability of the tracking method,
their results suggested that juvenile lobsters were foraging over distances
greater than that found by Chittleborough (1974).

The aim of the present study was to determine the extent of nocturnal
foraging distances of juvenile _Panulirus cygnus_. The assumption that juvenile
western rock lobsters foraged over small distances was re-examined by
determining the variation in movements between individuals, sexes, seasons and
years.

MATERIALS AND METHODS

Study Site

The study was done in Western Australia at Seven Mile Beach
(29°08'S;114°54'E) which lies approximately in the centre of the range of P.
cygnus. This area is reserved for research under state legislation and thus
closed to both amateur and professional fishing.

The habitat consists of numerous limestone patch reefs separated by sand
and seagrasses which are ideal nursery sites for juvenile animals
(Chittleborough & Phillips 1979). The particular tracking site included
several patch reefs lying in a lagoon like environment bordered by the shore
and an outer limestone reef approximately 400 m offshore. Water depth within
the area was 2-3 m. Holes and ledges at the base of the limestone reefs
provided shelter for juvenile lobsters during the day.

Tracking Equipment

Rock lobsters were tracked using the electromagnetic method (Phillips et
al 1984). This method was selected because the location of tagged animals
could be determined more accurately than by sonic methods (e.g. Herrnkind et
al 1971) because sonic signals would be blocked by the numerous patch reefs
and the abundant seagrass within the rock lobsters environment. In addition,
the shallowness of the exposed study area (1-5m) and associated acoustical
noise from wave action would interfere with sonic reception.

Tag circuitry and components were described by Phillips et al. (1984).
Briefly, the sealed tags emitted periodic magnetic fields of between 1.2 and
3.2 s duration at a frequency of 31 kHz for up to about 3 wk. Looped antennae
used to receive signals from the tags were composed of 24 strand (0.20 mm
diameter strands) copper wire in PVC insulation (see Phillips et al. 1984).
This wire subsequently was found to be unsuitable for extended use because the

insulation was easily damaged by abrasion and salt water leakage, thus shorting out the signals. It was replaced by a double (PVC) insulated multi stranded building wire (1.5 mm^2; 7 strands). Damaged aerials were replaced by twisting the ends of the replacement aerial to the old twisted wire pair (out of water) and embedding the connections in 5 ml hypodermic syringes filled with 5 minute "Araldite" (Ciba-Geigy Ltd.). The new aerial was relaid on the seabed and held in position with steel tent pegs which did not interfere with signal reception. Fifty aerials were laid over approximately 16000 m^2 of seabed to cover an area of approximately 100 m x 160 m (Fig. 1).

Twisted pairs of wires from each aerial were connected in a junction box to a 50 pair heavy duty cable that ran from the seabed to a caravan on shore. This cable was disconnected via an underwater plug between field trips because prolonged exposure to wave action on shore was sufficient to sever the cable.

Signals from the tags during September 1984 were originally manually decoded using an oscilloscope (Phillips et al. 1984). This method was tedious and precluded gathering of comprehensive data gathering on more than a few tags. Due to logistical constraints, it could only operate between 1800-0600 hrs when the majority of lobsters were out foraging and thus no information was obtained on lobsters that may have foraged outside those hours.

A computerized tracking system was used to automatically record and decode information from up to 14 tags at once. The tracking system sequentially scanned each of the 50 aerials every 10 min and signals from the tags were identified by a Hewellet Packard 71B computer. Data were both saved for later analyses and printed to provide real time plots of the location of tagged lobsters. The system was battery operated and solar powered and is described elsewhere (Jernakoff in prep.).

Lobsters

Animals estimated to be 4 yrs old (55-68 mm carapace-length) were trapped between approximately 0900-1300 hrs in baited pots placed adjacent to two reefs (Reef IV and Reef I; see Fig. 1) Only rock lobsters with eight or more legs were used in the study.

Tags were glued with an epoxy resin ("Vepox", Vessey Chemicals Ltd.) to the dorsal surface of the cephalothorax of rock lobsters (Phillips et al. 1984). The lobsters were then held for about 1 hr in a trap on the seabed at their site of capture to allow recovery from the effects of handling and for the glue to harden. The number of male and female lobsters tagged during the study is shown in Table 1.

Tagging Artifacts

Preliminary experiments to determine whether the electromagnetic tags influenced the natural behaviour of rock lobsters were carried out during February 1984, November 1984 and January 1985. Control animals were used to determine how the physical presence of the tags and signals affected lobster behaviour. All rock lobsters were individually marked by writing numbers onto their carapace with "Vepox". Males and females were distinguished by different coloured glue. Treatments consisted of either

1) animals marked with glue,

2) animals marked with glue and a non transmitting tag; and

3) animals marked with glue and a transmitting tag (see Fig. 2).

Comparison of the behaviour of Transmitter control (mark only) and Signal control (mark plus nontransmitting tag) tested for the effect of the physical presence of the tag on the rock lobster, whilst comparison of Signal control animals with Experimental (mark plus transmitting tag) animals tested for the influence of electromagnetic pulses on normal behaviour. Equal numbers of

male and female lobsters were released in each of the 3 treatments (N=7; Total = 42 in February 1984, N=6 in November 1984 and N=6 in January 1985.

Rock lobsters were tagged and left undisturbed for one week to adjust to the tagging and handling. After this time, data on location, habitat and activity of individually marked rock lobsters within the study site were obtained by diving on 14 days and 11 nights. Two divers swam 8 regularly spaced non overlapping 100 m transects (4 per diver). The entire study site including the patch reefs was censussed in one dive.

It was not possible in the above experiment to directly control for the effects of capture and handling on foraging distance because lobsters have to be caught and handled to be tagged. However, if it is assumed that lobsters have recovered from any effects of capture and handling after 1 wk, foraging distances travelled within the first week can be compared with distances moved at later times to determine the effects of capture and handling.

Statistical Methods

Some lobsters moved outside the tracking area during nightly foraging excursions. Some of these lobsters were absent for short periods (< 1 hr) while others were absent for almost a complete night (Jernakoff unpubl. data). Such incomplete data is said to be "censored", and often occurs in biomedical or reliability applications, where failure has not occurred by a boundary condition such as a time interval (e.g. Elandt-Johnson & Johnson 1980).

Censored distances were calculated as the total distance travelled within the tracking area. In most cases, lobsters re-entered the area at their approximate exit locations except when animals moved to/from aerial 49 (Fig. 1). In this case, the minimum straight line distance between aerial 49 and

the entry/exit location within the main tracking area was added to the observed distance travelled.

Ignoring the censored observations can bias estimates of the distribution of distance travelled. A descriptive method of examining the distribution of the distance travelled is given by the Kaplan-Meier nonparametric distribution function (Kalbfleisch & Prentice, 1980). This produces an unbiased estimate of the empirical distribution function of distance travelled from the censored and uncensored observations, by assuming that lobsters travel independently (confirmed by tracking data and observation) and that the distance travelled by the "censored" lobsters has the same distribution as that of uncensored lobsters. If the distribution is not the same i.e. "censored" lobsters travel further, the analysis will underestimate distances moved. Inspection of the Kaplan-Meier distribution or transformations of it may suggest a parametric form for the distribution; often in reliability contexts the exponential or Weibull distributions have been found to provide reasonable fits to data (see e.g. Johnson & Kotz, 1970). In the present study, the distance travelled by a lobster can be quite closely modelled by a Weibull distribution, having the following functional form:

$$F(t) = 1 - \exp(-\gamma t^{\alpha}) \qquad\qquad (1)$$

$$f(t) = \gamma \alpha t^{\alpha-1} \exp(-\gamma t^{\alpha}) \qquad\qquad (2)$$

where F is the cumulative distribution, f is its density, $\alpha > 0$, $\gamma > 0$ are parameters, and $t > 0$ is the distance travelled.

Aitkin and Clayton (1980) give a method of not only fitting the Weibull (and other failure rate distributions) to censored data, but of testing hypotheses on data collected from complex experimental designs, possibly with covariates. They rewrite the model (1) for censored data in a form in which the model fitting technique of the statistical package GLIM (Baker & Nelder, 1978) can be used. The result is a maximum likelihood fit of models of the form (1) closely related to the methods of fitting generalised linear models as expounded by McCullough & Nelder (1983). "Deviance differences" obtained from GLIM are equivalent to likelihood ratio tests on hypotheses of interest (such as, in the present context, no differences in distribution of distance travelled due to sex, etc.). Asymptotic statistical theory permits testing of the deviance differences as χ^2 random variables with appropriate degrees of freedom. A model fitted might be, for example,

$$\lambda(t) = \lambda_o(t)e^{\beta x}$$

where $\lambda(t) = f(t) [(1-F(t))]^{-1}$ is the "hazard", $\lambda_o(t) = \gamma \alpha t^{\alpha-1}$ is the "baseline" hazard due to the underlying Weibull, and β and $x = 1,2$ are the coefficient and explanatory variable for sex (male = 1, female = 2). That is, the hazards are proportional for each sex.

The Weibull distribution is a skew distribution defined only for positive values, so statistical methods different to methods used for normal distributions are necessary. The distribution of distance travelled for the data reported here is not greatly asymmetrical (Fig. 3) However, the censoring is important (approximately 50% of the observations were censored) and so the above described methods are essential. Due to the asymetry, the median rather than the mean is often used as a description of the location of the Weibull distribution and quantiles are used in preference to variances.

Censoring of data

To assess the effect of the heavy censoring on the data, an analysis was done only on the 213 uncensored data. The Weibull distribution fitted the data less well, and led to an estimate of the median distance moved, which was 60 metres less than that obtained by the correct analysis.

RESULTS

Effects of tags on lobster behaviour

Data from all three time periods (February 1984, November 1984, January 1985) were pooled. Of 114 lobsters released, information was recorded on 20 lobsters during day and 21 during night sampling. Lobsters seen during daytime were sheltering in dens whilst lobsters at night were in most cases foraging away from shelters.

Neither the physical presence of the tags nor the signals produced affected the number of animals sheltering during the day or foraging at night. (Daytime: equal numbers of treatment animals observed; night counts, no significant differences χ^2; 2df, $\underline{P} > 0.25$). The behaviour of lobsters in all 3 treatments appeared identical to that of unmarked populations of lobsters seen during sampling.

Number of lobsters remaining within the study area

Breakdown of electronic equipment during the first two field trips (February and April 1984) precluded tracking of tagged lobsters (Table 1). Of the 80 lobsters tagged and released during the remaining 6 sampling times (Table 1) 58% were tracked for at least one night.

There was no significant difference in the number of male to female lobsters that remained and were tracked within the study area (Males χ^2;5df, P > 0.90; Females: χ^2;5df, P > 0.99).

The fate of the remaining 42% of tagged lobsters remains unknown. A few of the lobsters remained within the tracking area but were not tracked due to malfunctioning of tags and tag loss. Other lobsters moved away from the study area and several were caught within 2 wk outside the tracking area by professional fisherman (1 at 1.9 km, 2 at 2.8 km and 1 at 9.3 km).

Distribution of distances travelled

The number of nights that individual lobsters were tracked ranged from 1 to 23 (Fig. 4). A total of 460 lobster-nights (data on one lobster for 1 night) were recorded during the study. Of these, lobsters did not leave dens to forage on 48 lobster nights and of the remaining 412 there were 199 nights when lobsters moved out of the tracking area for part of the night. These data were thus incomplete or censored.

The Weibull distribution showed an extremely close fit to the observed data when lobsters travelling zero distance were removed. Estimates of parameters in equations (1) and (2) were:

α = 2.36

γ = 13.93

The corresponding fitted probability density from equation (2) is plotted in Figure 3.

The Weibull distribution of distances travelled is shown in Fig. 5. The results suggested that the median distanced moved was 310 metres per night, with 95% of all foraging distances of the population being between 72.5 and 585 metres per night. The greatest distance moved on a single night by a lobster was 803 metres (Figs. 3 and 5).

Analyses of deviance showed no difference between the total distances moved by lobsters between the first and subsequent weeks since tagging (χ^2; $\underline{P} > 0.05$) and there was no significant trend in the distance moved each night with time since tagging. Thus there appeared to be no short term (within the first week) effects of initial capture/handling of the lobsters.

The median distance moved by lobsters was significantly greater in the first than in subsequent sampling periods (September 1984; analysis of deviance, $\underline{P} < 0.001$) while there was no significant difference between other sampling periods; (analysis of deviance $\underline{P} > 0.05$). There was no significant difference in the median distance moved between sexes (Main Effect; $\underline{P} > 0.05$) although there was a significant interaction between sex and time (analysis of deviance $\underline{P} < 0.05$). For males, there was no significant difference in median distance travelled over sampling times whereas females travelled further in September 1984 than at other times.

A loglinear analysis showed that there was no significant difference between sampling period, sexes and week since tagging in the number of lobsters not foraging ($\underline{P} > 0.05$).

Levels of variability

Analyses of deviance demonstrated that the levels of variability in the distance moved each night between different lobsters was not significantly greater than the levels of variability in distance moved by an individual lobster on different nights (Table 2).

A separate analysis was done on the maximum straight line distance travelled (i.e. radius) from the den. The data were censored and again the Weibull distribution provided a good fit. The variability in distance moved from the den, between individual lobsters was no greater than within individuals on different nights (analysis of deviance $P > 0.05$).

DISCUSSION

In this work, neither the physical presence of the tags nor the electromagnetic signals appeared to significantly influenced behaviour of the animals. Sonic tags (e.g. Chapman et al. 1975; Herrnkind et al., 1975) have been assumed to have no influence on lobster behaviour although tests of this assumption have not been reported in the literature. In the present study such tests were believed to be important especially because of the influence of the periodic magnetic fields produced by the tags. Lohmann (1984) detected in the spiny lobster P. argus aligned magnetic remanence which could potentially play a role in navigation, although Walton & Herrnkind (1977) found that experimentally distorting the magnetic field around P. argus had no noticeable affect on its behaviour. In the present study, superimposition of magnetic fields produced no observable affect on behaviour or navigation.

Although no short term effect of capture and handling the lobsters could be detected (i.e. distances moved within the first week days were no different from later times), most lobsters that disappeared from the area did so within the first few nights. While these lobsters may have been transients sensu Herrnkind (1980), their disappearance so soon after tagging suggests an immediate response to disturbance. While the majority of tagged lobsters that disappeared were not seen again, other animals were captured by professional fishermen, the furthest being 9.3 km north of the site of tagging.

Lobsters that remained within the study area were found to travel a median distance of 310 m during a night's foraging. This distance (approximately 150 m radius out from the den) was much larger than the home range proposed for P. cygnus by Chittleborough (1974). Chittleborough used baited traps to capture tagged animals. He concluded that home ranges of juvenile P. cygnus were between 15 and 20 m away from the home den, although the maximum distance that pots were set away from home dens was 20 m. It is likely that Chittleborough's results were an artifact of the trapping method i.e. lobsters were caught in the first trap they encountered. Chittleborough's study was also at a different site, Garden Island in Western Australia, where lobsters perhaps forage over a smaller distance, although he suggested that foraging distances may be up to 50 m at Seven Mile Beach. Phillips et al. (1984) suggested that foraging (home) ranges at Seven Mile Beach may be greater than 50 m because one of their two tagged lobsters was found 105 m away from the home reef during the following day. The results of the present study suggest that foraging distances for P. cygnus are large and very variable with 25% of foraging distances being between 400 m and 800 m, and this is similar to findings on P. argus (Herrnkind et al. 1975).

Many factors are believed to influence non migratory movements. Examples include ambient light levels (e.g. Fielder, 1965; Morgan, 1978; Reneke, 1982; Kanciruk & Herrnkind (1973); Herrnkind & McLean (1971) moult stage (e.g. Lipcius & Herrnkind, 1982), temperature (e.g. Morgan, 1978) hydrodynamic influences (e.g. Herrnkind & McLean, 1971) and density and food supply (Chittleborough, 1975).

It is not known why foraging distances on the first field trip (September 1984) were slightly greater for females. The lack of any significant difference in distances travelled during the other 13 months suggests that any seasonal variations in potential factors influencing foraging e.g.

temperature, photoperiod or food supply did not significantly influence the distances travelled. Such field studies of seasonal changes (or lack thereof) in foraging distance have not been reported in the literature.

Both laboratory studies on activity and commercial catch data suggest that P. cygnus are less active with increasing light levels (i.e. around the period of full moon; Morgan 1978). Lobsters in the present study were usually tagged around 8 days prior to the new moon and thus the influence of increasing moon light levels would be discerned 1-16 days later. No significant difference could be detected in the distances moved as full moon approached (i.e. time since tagging). This result may be due to the small data set (N=7) on lobsters foraging consecutively for periods greater than 16 days i.e. there was not enough significant trends to be apparent.

The results of the present study have demonstrated that juvenile P. cygnus can move distances of an order of magnitude greater than those reported by Chittleborough (1974). Such extensive movements provide these animals with a far greater foraging area. In a study examining the natural diet and growth of juvenile P. cygnus Joll & Phillips (1984) found no evidence to support the hypothesis of Chittleborough (1976) that limited food supply resulted in differences in growth between age/sex class groups in natural field situations. The idea that the growth and survival of juvenile P. cygnus is directly related to small foraging ranges (Chittleborough 1974, 1975; Chittleborough & Phillips 1975) is not supported by the present study.

Electromagnetic tracking rock lobsters has enabled a re-evaluation of current ideas on the nocturnal foraging movements of juvenile P. cygnus and the size of area that is foraged. Foraging distances are similar to those reported for P. argus (Herrnkind et al 1975). Distances travelled can, however, be quite variable among the population and between individuals on

different nights.   Large numbers of field measurements on P. cygnus are
necessary for descriptions of foraging movements to be made.

References

Aitken, M., & D. Clayton, 1980. The fitting of exponential Weibull
distributions and extreme value distributions to complex censored survival
data using GLIM. Applied Stat., Vol. 29, pp. 156-163.

Andree, S.N., 1981. Locomotory activity patterns and food items of benthic
postlarval spiny lobsters, Panulirus argus. Ph.D. Thesis. University of
Southern California, 50 pp.

Annala, J.H., 1981. Movements of rock lobsters (Jasus edwardsii) tagged near
Gisborne, New Zealand. N.Z. J. Mar. freshwat. Res., Vol. 15(4), pp. 437-
443.

Baker, R.J. & J.A. Nelder, 1978. General Linear Interactive Modelling
(GLIM). Release 3.77. Numerical Algorithms Group, Oxford.

Booth, J., 1985. Movements of packhorse rock lobsters (Jasus verreauxi)
tagged along the eastern coast of the North Island, New Zealand. N.Z. J.
Mar. Freshwat. Res., Vol. 18, pp. 275-282.

Buesa Mas. R.J., 1965. Biologia de la langosta. Panulirus argus (Latreille,
1804. Crustacea Decapoda, Reptantia) en Cuba, p. 230. Inst. Nac. de la
Pesca, Cuba.

Chapman, C.J., A.D.F. Johnstone & A.L. Rice, 1975. The behavior and ecology
of the Norway lobster, Nephrops norvegicus (L.) Proc. Eur. Mar. Biol.
Symp., 9th, pp. 59-74.

Chittleborough, R.G., 1974. Home range, homing, and dominance in juvenile
Western rock lobsters. Aust. J. Mar. Freshwat. Res., Vol. 25, pp. 227-
234.

Chittleborough, R.G., 1975. Environmental factors affecting growth and survival of juvenile western rock lobsters Panulirus longipes (Milne-Edwards). Aust. J. Mar. Freshwat. Res., Vol. 26, pp. 177-196.

Chittleborough, R.G., 1976. Growth of juvenile Panulirus longipes cygnus George on coastal reefs compared with those reared under optimal environmenal conditions. Aust. J. Mar. Freshwat. Res., Vol. 27, pp. 279-295.

Chittleborough, R.G., & B. F. Phillips, 1975. Fluctuations of year-class strength and recruitment in the western rock lobster Panulirus longipes (Milne-Edwards). Aust. J. Mar. Freshwat. Res., Vol. 26, pp. 317-328.

Chittleborough, R.G., & B.F. Phillips, 1979. Recruitment to the catchable stock of the western rock lobster Panulirus longipes cygnus George. Rapp. P-v. Reun. Cons. int. Explor. Mer., Vol. 175, pp. 139-142.

Cobb, J.S., 1981. Behaviour of the Western Australian spiny lobster, Panulirus cygnus George, in the field and laboratory. Aust. J. Mar. Freshwat. Res., Vol. 32, pp. 399-409.

Elandt-Johnson, R.C., & N.L. Johnson, 1980. Survival Models and Data Analysis. 457 pp. Wiley New York.

Fielder, D.R., 1965. The spiny lobster, Jasus lalandei (H. Milne Edwards) in South Australia. III. Food, feeding and locomotor activity. Aust. J. Mar. Freshwat. Res., Vol. 16, pp. 351-367.

George, R.W., 1957. Continuous crayfishing tests: Pelsart group, Houtman Abrolhos, Western Australia. Aust. J. Mar. Freshwat. Res., Vol. 8, pp. 476-490.

Herrnkind, W.F., 1980. Spiny lobsters: patterns of movement pp. 349-401. In: The Biology and Management of Lobsters. Cobb, J.S., and B.F. Phillips (Eds.) Vol. 1. Academic Press, New York.

Herrnkind, W.F., & R.B. McLean, 1971. Field studies of homing, mass

   emigration and orientation in the spiny lobster, _Panulirus argus_. _Ann._

   _N.Y._ _Acad._ _Sci._, Vol. 188, pp. 359-377.

Herrnkind, W.F., and M.X. Redig, 1975. Preliminary study of establishment or

   den residency by spiny lobster, _Panulirus argus_, at Grand Bahama Island.

   Hydro-Lab. _J._, Vol. 3, pp. 6-101.

Herrnkind, W.F., J. VanderWalker, & L. Barr, 1975. Population dynamics,

   ecology and behavior of spiny lobster, _Panulirus argus_ of St. John, U.S.

   Virgin Islands: Habitation and pattern of movements. Results of the

   Tektite Program, Vol. 2. _Sci._ _Bull._ _Nat._ _Hist._ _Mus._ _Los_ _Angeles_ _Cty._,

   Vol. 20, pp. 31-45.

Heydorn, A.E.F., 1969. The rock lobster of the South African West Coast _Jasus_

   lalandii (H. Milne-Edwards) 2. Populations Studies. Behavior,

   reproduction, moulting, growth and migration. _S._ _Afr._ _Div._ _Sea._ _Fish._,

   Invest. _Rep._, 71, pp. 1-52.

Johnson, N.L., & S. Kotz, 1970. Continuous univariate distributions. Horton.

   New York.

Joll, L.M., & B.F. Phillips, 1984. Natural diet and growth of juvenile

   western rock lobsters _Panulirus cygnus_ George. _J._ _Exp._ _Mar._ _Biol._ _Ecol._,

   Vol. 75, pp. 145-169.

Kalbfleisch, J.D., & R.L. Prentice, 1980. Statistical analysis and failure

   time data. 321 pp. Wiley, New York.

Kanciruk, P., and W.F. Herrnkind, 1973. Preliminary investigations of the

   daily and seasonal locomotor activity rhythms of the spiny lobster

   Panulirus argus. _Mar._ _Behav._ _Physiol._ Vol. I, pp. 351-359.

Lindberg, R.G., 1955. Growth, population dynamics and field behavior in the spiny lobster, _Panulirus interruptus_. _Univ. Calif. Berkeley, Publ. Zool._, Vol. 59, pp. 157-248.

Lipcius, R.N., & W.F. Herrnkind, 1982. Moult cycle alterations in behaviour, feeding and diel rhythms of a decapod crustacean, the spiny lobster, _Panulirus argus_. _Mar. Biol._, Vol. 64, pp.241-252.

Lohmann, K.J., 1984. Magnetic remanence in the Western Atlantic spiny lobster, _Panulirus argus_. _J. Exp. Biol._, Vol. 113, pp. 29-41.

McCullough, P., & J.A. Nelder, 1983. Generalized linear models. 261 pp. Chapman & Hall, University Press, Cambridge.

McKoy, J.L., 1984. Movements of rock lobsters, _Jasus edwardsii_ (Decapoda:Palinuridae) tagged near Stewart Island, New Zealand. _N.Z.J. Mar. Freshw. Res._, Vol. 17, pp. 357-366.

Morgan, G.R., 1978. Locomotor activity in the western rock lobster _Panulirus longipes cygnus_. _Aust. J. Mar. Freshwat. Res._, Vol. 29, pp. 169-174.

Phillips, B.F., 1983. Migrations of pre-adult western rock lobsters, _Panulirus cygnus_ in Western Australia. _Mar. Biol._, Vol. 76, pp. 311-318.

Phillips, B.F., L.M. Joll, & D.C. Ramm, 1984. An electromagnetic tracking system for studying the movements of rock (spiny) lobsters. _J. Exp. Mar. Biol. Ecol._, Vol. 79, pp. 9-18.

Ramm, D.C., 1980. Electromagnetic tracking of rock lobsters (_Jasus novaehollandiae_). _Aust. J. Mar. Freshwat. Res._, Vol. 31, pp. 263-269.

Reneke, F.W., 1982. The effect of light intensiy on the activity of spiny lobsters (_Panulirus interruptus_) during the lunar cycle. A proposal presented to the faculty of the Graduate School, San Diego State University, 35 pp.

Walton, A.S., & W.F. Herrnkind, 1977. Hydrodynamic orientation of spiny

    lobster, _Panulirus argus_ (Crustacea:Palinuridae): Wave surge and

    unidirectional currents. Memorial University of Newfoundland, Marine

    Science Research Lab., Technical Report 20, pp. 184-211.

TABLE 1

Numbers of tagged lobsters released and tracked during the study

Date	Number of lobsters released		Number of lobsters tracked	
	Males	Females	Males	Females
February 1984	7	7	0	0
April 1984	7	7	0	0
September 1984	7	7	5	2
November 1984	6	6	4	5
January 1985	6	6	4	3
April 1985	7	7	3	5
September 1985	7	7	1	5
November 1985	7	7	5	5
	54	54	22	25

TABLE 2

Analysis of deviance of the distances travelled by lobsters. Analysis of
April 1985 data was not possible due to heavy censoring of those data. See
text for explanation of Weibull α.

Field Trip	Source of Variation	Degrees of Freedom	Deviance	Dev/DF	Weibull α
1984					
September	Between lobsters	6	8.94	1.49	1.24
	Within lobsters	13	168.49	12.96	
	Total	19	177.43		
November	Between lobsters	8	14.21	1.82	2.77
	Within lobsters	42	354.00	8.42	
	Total	50	368.21		
1985					
January	Between lobsters	6	44.25	7.38	2.20
	Within lobsters	54	378.62	7.01	
	Total	60	422.87		
September	Between lobsters	5	6.26	1.25	2.24
	Within lobsters	66	250.80	3.80	
	Total	71	257.06		
November	Between lobsters	9	19.30	2.10	2.85
	Within lobsters	119	865.90	7.30	
	Total	128	885.23		

FIGURE CAPTIONS

Figure 1   Position of the aerials on the sea floor.
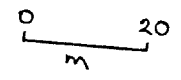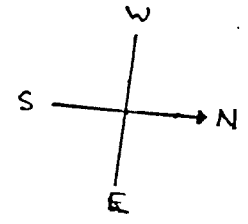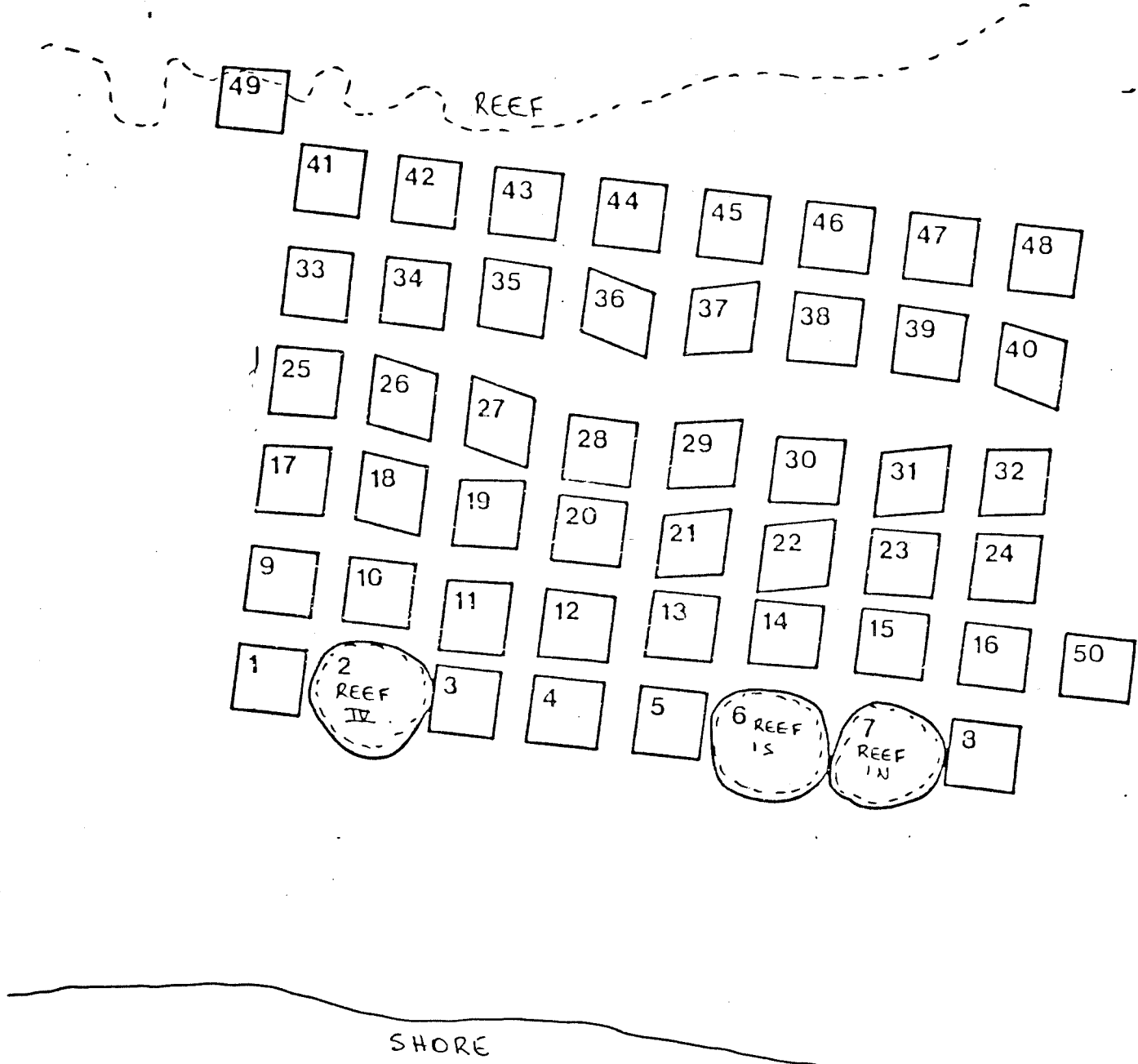
Figure 2   Controls for electromagnetic tagging.

Figure 3   The fitted probability distribution of distances travelled.

Figure 4   Number of lobsters tracked each night in the course of the
            experiment. ● September 1984, ▲ November 1984, ■ January 1985,
            ◆ April 1985, O September 1985, △ November 1985.

Figure 5   The cumulative distribution of distances travelled. Solid line =
            actual data; dashed line = the fitted Weibull distribution.

Fig 1 draft

REEF

49

41 42 43 44 45 46 47 48

33 34 35 36 37 38 39 40

25 26 27 28 29 30 31 32

17 18 19 20 21 22 23 24

9 10 11 12 13 14 15 16 50

1 2 REEF IV 3 4 5 6 REEF IS 7 REEF IN 3

SHORE

S — N
E — W

0 — 20
m

CONTROLS FOR ELECTROMAGNETIC TAGGING

FIG 2

TREATMENT 1
TRANSMITTER CONTROL

+ MARK
− TRANSMITTER
− SIGNAL

TREATMENT 2
SIGNAL CONTROL

+ MARK
+ TRANSMITTER
− SIGNAL

TREATMENT 3
EXPERIMENTAL ANIMAL

+ MARK
+ TRANSMITTER
+ SIGNAL

TRANSMITTER

SIGNAL
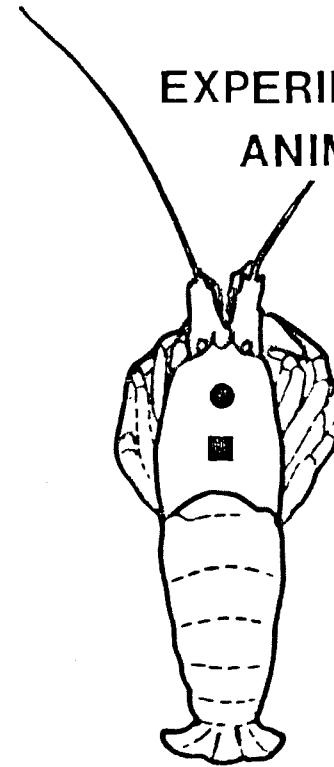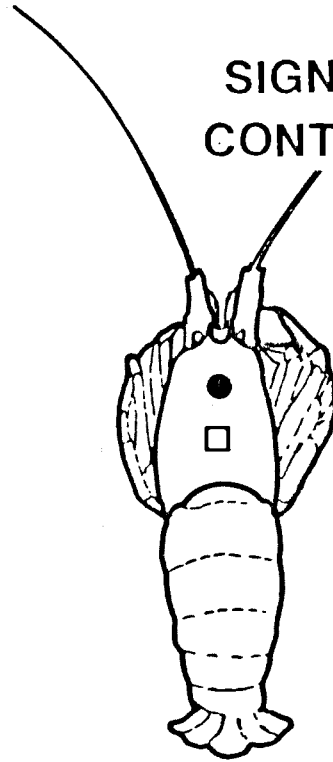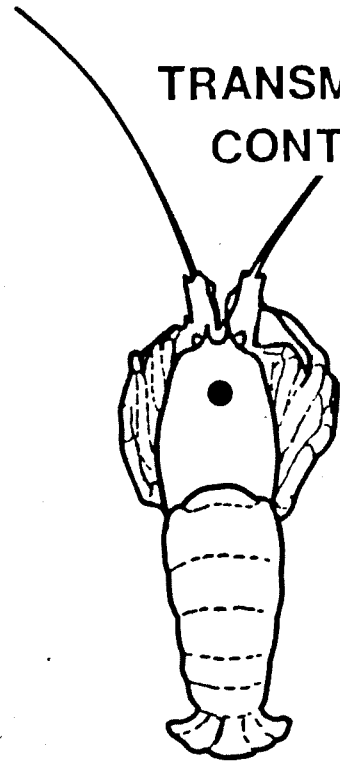
Fig 4
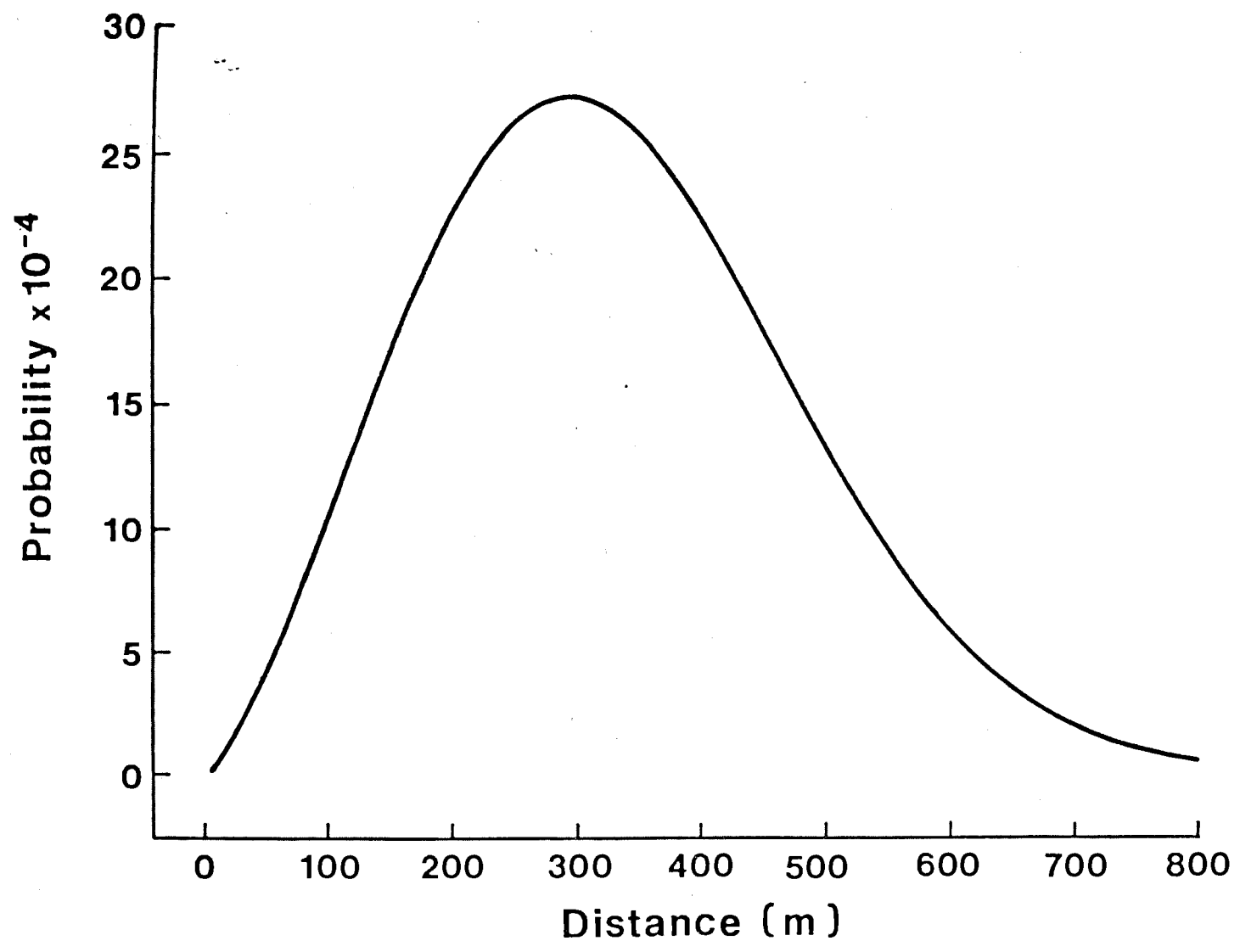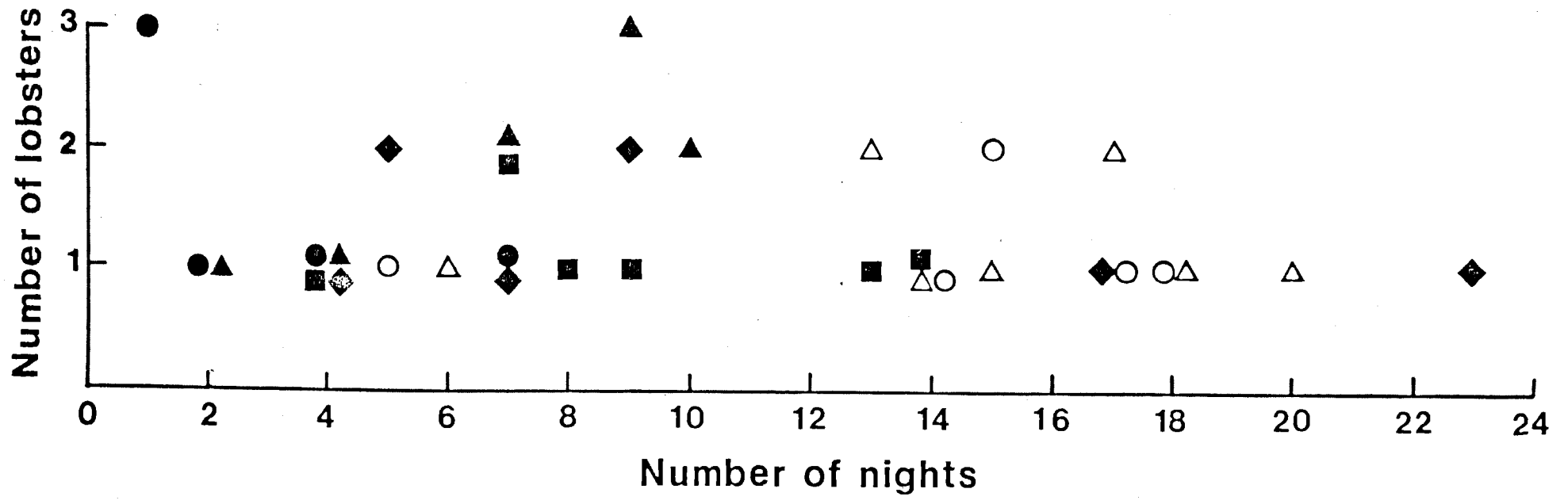
P. JEI
Fig. 1

Figure 5
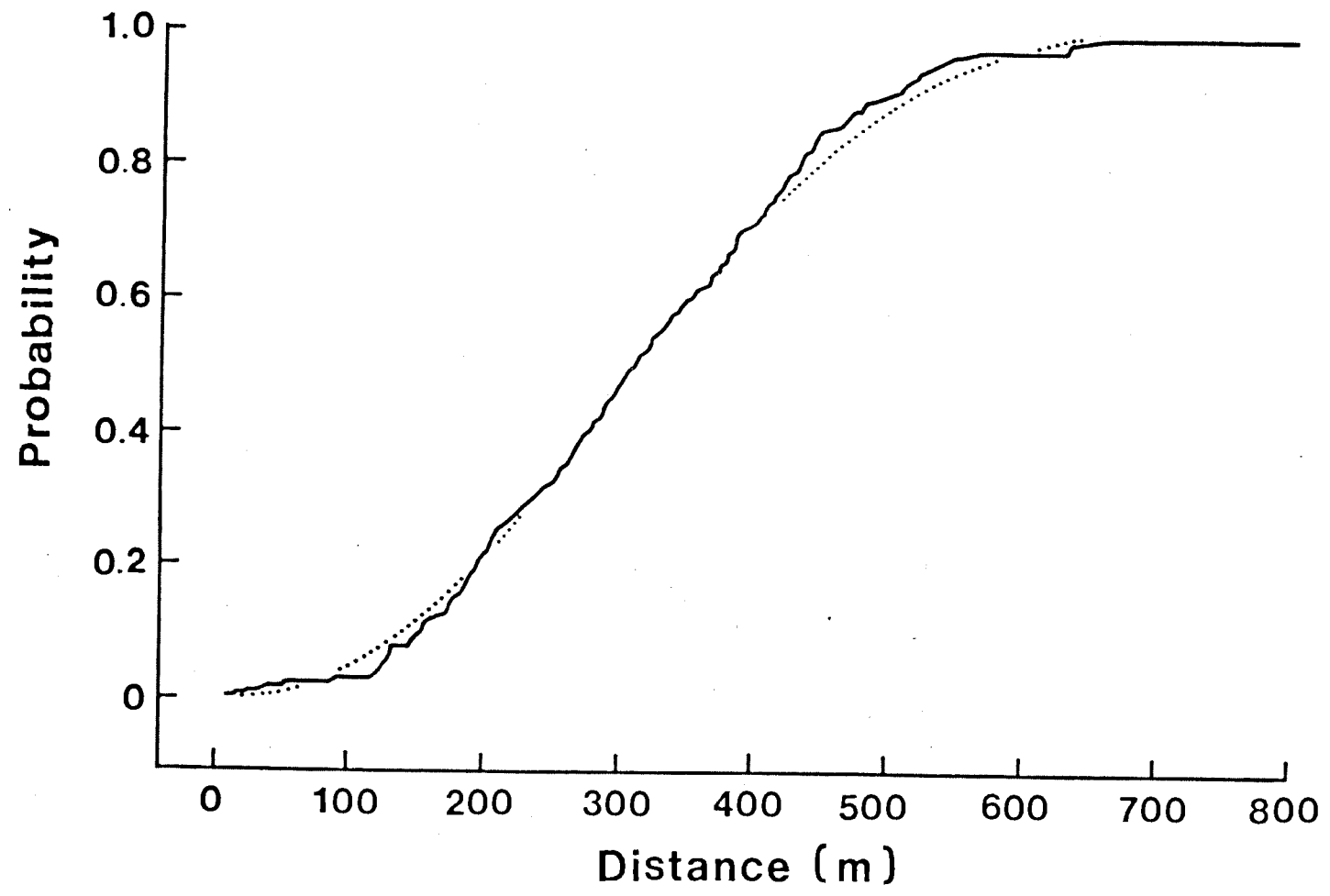
APPENDIX 5

Foraging patterns and activity of juvenile
rock lobsters, **Panulirus cygnus**, George.

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Marine Biology and Ecology

FORAGING PATTERNS AND ACTIVITY OF JUVENILE SPINY ROCK LOBSTERS, PANULIRUS

CYGNUS, GEORGE.

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Running Headline: Foraging patterns of Western Rock Lobsters.

ABSTRACT

Foraging patterns and activity of juvenile western rock lobsters were investigated in the field by tracking lobsters with electromagnetic tags. A tracking system automatically recorded information on the movements of lobsters for periods up to three weeks.

Results of the study suggested that most foraging activity is initiated at very low light levels and not in response to diurnal changes in water temperature or currents. A similar pattern occurs when lobsters return from foraging as light levels increase above 1 log μ E m^{-2}s^{-1}. Foraging activity was constant throughout the night and female lobsters were more active than males. Lobsters usually moved at a rate of about 1 m min^{-1} at night although sometimes they were observed to travel up to 18 m min^{-1} when walking over bare sand. Some lobsters utilised several dens on different reefs during the three week periods of observation. They would often live on one reef but travel to forage on seagrass beds in front of another reef, sometimes visiting a den on that reef. Although lobsters foraged in both of the two main structural varieties of seagrass beds, Amphibolis and Heterozostera with Halophila spp., they foraged for longer periods in the latter beds. Foraging ranges varied within and between individuals although an individual lobster would forage in the same general area night after night for periods ranging from a few nights up to several weeks. Thus certain areas and habitats were more heavily foraged than others.

INTRODUCTION

Understanding the feeding ecology of an organism requires an understanding of the spatial and temporal patterns of foraging activity. There have been few quantitative field studies on foraging behaviour of large marine crustaceans because they are are difficult to observe in their natural habitat and this is particularly true for spiny and clawed lobsters (Herrnkind 1980; Kanciruk 1980; Atema & Cobb 1980).

Panulirus cygnus George, is a numerous rock (spiny) lobster inhabiting subtidal coastal regions of Western Australia (Chittleborough 1970, 1974). Lobsters reside during the daytime in dens or ledges within the reefs (Cobb 1981) and forage at night within seagrass beds (Cobb 1981, Phillips *et al.* 1984, Joll & Phillips 1984, Jernakoff *et al.* in prep.). *P. cygnus* is believed to be an important predator structuring the benthic community within these areas (Joll & Phillips 1984).

The feeding ecology of *P. cygnus* is also important because the rate of growth and survival of juvenile lobsters (1-5 yrs old) are believed to be limited by the availability and quality of food (Chittleborough 1974, 1975; Chittleborough & Phillips 1975). Chittleborough (1974) reported that *P. cygnus* foraged over small areas, usually within a 20m radius of its den, although animals may forage up to 50 m away. Recent studies by Phillips *et al.* (1984) and Jernakoff *et al.* (in prep.) suggest that foraging occurs over a larger area.

The aim of the present paper is to document natural patterns of foraging activity of juvenile *P. cygnus*. The type of foraging ranges, extent of foraging within a range and the direction of foraging were determined. Times when the majority of lobsters commenced and finished foraging, rates of movement, and the type of habitat where foraging occurred was recorded. In

addition, the effects of changes in water temperature and currents were examined as potential stimuli for foraging activity.

MATERIALS AND METHODS

Study Site

The study site was at Seven Mile Beach in Western Australia (29°08'S 114°54'E). The area is typical of the shallow water (< 10 m) nursery sites where juvenile rock lobsters occur. The habitat consists of limestone patch reefs separated by sand and seagrass beds.

Two main structural forms of seagrass are found within the study site. One type, composed mainly of Amphibolis antarctica (Labill.) Sond & Asch. ex Asch. and A. griffithii (Black) den Hartog, forms dense thick canopies 30 cm high with average biomass of approximately 700 g dry wt. m^{-2} (H. Kirkman, CSIRO Marine Laboratories, pers. comm.). The second structural type of seagrass bed is composed predominantly of Heterozostera tasmanica (Martens ex Asch.) Den Hartog and Halophila ovalis (Brown) Hooker. Heterozostera and Halophila is much sparser (average biomass 100 g dry wt. m^{-2}; H. Kirkman pers. comm.) and is usually less than 8 cm high. Infaunal biomass is greater in the Heterozostera and Halophila beds than in Amphibolis (V. Wadley, CSIRO Marine Laboratories, pers. comm.) while the abundance of epifaunal material is greater in Amphibolis beds (C. Edgar, CSIRO Marine Laboratories, pers. comm.).

Major habitat features of the study site were interpreted from aerial photographs and by mapping the area from scuba surveys. Four major habitats were recognised. These were sand, reefs and the two types of seagrass beds; Amphibolis and Heterozostera and Halophila (Fig. 1). The tracking area was made up of 47.6% Amphibolis, 27.6% Heterozostera and Halophila and 24.8% sand. The amount of each of these habitats remained relatively constant throughout the study.

Capture and tagging of lobsters

The study was restricted to a single size cohort of lobsters (between 55-68 mm carapace length) in intermoult condition because the behaviour of lobsters may change with size/age or moult stage (Kanciruk 1980, Lipcius & Herrnkind 1982).

Lobsters were caught in baited pots placed next to Reefs IV and I (Fig. 1) between 0900-1300 hrs. Only lobsters with 8 or more legs were tagged and the sex ratio of tagged lobsters was equal. Tags were glued to the cephalothorax using an epoxy resin that set underwater (Phillips et al. 1984). Tagged animals were held in pots at their site of capture for an hour to readjust and then released.

Tracking Methods

A description of the theory of electromagnetic tracking can be found in Ramm (1980) and designs of tags and receiving aerials used in this study are described by Phillips et al. (1984) and Jernakoff et al. (in prep.). A solar powered automatic tracking system that could simultaneously track up to 14 (unique) tag signals was used to plot the position of tagged lobsters. The system is described by Jernakoff (in prep.).

Night observations

Because the tracking system could not determine the exact location or activity of tagged lobsters, a series of night observations were made on both tagged and untagged animals. Diving commenced just after sunset and lasted for approximately one hour. The approximate position of tagged lobsters was determined by the tracking system and then their exact position was determined using a directional underwater hand held receiver.

This receiver was designed by the electronics section of the CSIRO Marine Laboratories. When one or more tags were within 6 m, a series of light emitting diodes were illuminated on the receiver's display. The number of diodes illuminated (maximum = 8) was proportional to the distance from the tags. Once located, tagged lobsters' activity and behaviour were observed using muted underwater lights.

To quantify the extent of foraging by untagged lobsters within Amphibolis, and Heterozostera and Halophila beds, two different nocturnal sampling strategies were undertaken. In the first strategy, the number and activity of lobsters were recorded in each type of seagrass within 22 aerials that enclosed a mixture of both structural types. In the second strategy, 9 randomly stratified 50 m transects (± 1.5 m each diver; width censussed = 6 m) were swum in both Amphibolis and in Heterozostera and Halophila habitat. The number and activity of all rock lobsters was recorded.

Environmenal Variables

Information was collected on some environmental variables that may have influenced foraging movements. The amount of light (sunlight and moonlight) was recorded by a light meter positioned 0.5 m above the substratum in the centre of the study site. The sensor was connected via a cable to a recorder in a caravan on shore. This meter was sensitive to infra red wavelengths, and light readings at 2 m depth ranged from 2,500 μ E m^{-2} s^{-1} during midday (clear skies) to 0.013 μ E m^{-2} s^{-1} on moonless nights. The velocity and direction of water movement was measured by a "Marsh McBernie" current meter. This meter measured changes in electrical conductivity on N-S and E-W axes. The sensor head of the meter was mounted 0.5 m above the substratum and data averaged over 60 s were continuously collected at 5 or 10 min intervals and recorded as

millivolts onto automatically recording dataloggers. Water temperatures were recorded at 5 min. intervals by a self-contained logger.

RESULTS

The influence of physical variables on activity

Most lobsters started foraging at very low light levels (Fig. 2a). 57% of foraging excursions commenced after the start of sunset (i.e. < 3 log μ E m^{-2} s^{-1}), 32% commenced within 1.5 hrs of sunset (i.e. between 3 and 6.5 log μ E m^{-2} s^{-1}) and 11% of activity commenced at other times of the day. A similar trend occurred when lobsters returned from nocturnal excursions (Fig. 2b). 54% of foraging excursions ended by the end of sunrise (i.e. < 3 log μ E m^{-2} s^{-1}), 31% ended within 1.5 hrs after sunrise (i.e. between 3 and 6.5 log μ E m^{-2} s^{-1}) and 15% of activity ended at later times of the day.

There was no apparent association between changes in either water temperatures or currents and lobster activity. Diurnal variation in temperature was generally around 2°C for all sampling periods when temperatures were successfully recorded. Average temperatures were 18.5° in September 1985, 20°C in September 1984 and 21°C during April 1985 and November 1984 and 1985.

Water currents through the area were always from the south to the north. Average velocities were 7.6 cm s^{-1} in September 1984; 10.9 cm s^{-1} in November; 8.6 cm s^{-1} in January 1985; 6.7 cm s^{-1} in April 1985 and 6.9 cm s^{-1} in November 1985. There was very little east-west component of current. The maximum velocity occurred in November 1985 (0.42 cm s^{-1} towards the east).

Activity Patterns

The number of times lobsters passed from one aerial to another was used as an index of activity. Differences in activity was examined between sexes of lobsters, field trips and the time of day. The time of day was divided into 8 three hr time blocks; (day blocks: 0600-0900 hrs; 0900-1200 hrs; 1200-1500 hrs; 1500-1800 hrs; and night blocks: 1800-2100 hrs; 2100-0000 hrs; 0000-0300 hrs and 0300-0600 hrs).

The activity of lobsters was not significantly different between sexes or field trips although there was a significant interaction between these factors and there was also significant variability between lobsters (Table 2a). There was a highly significant difference in the activity of lobsters with time of day (Table 2a).

Interactions between field trips and time of day, sexes and time of day, and between field trips, sexes and time of day were all significant (Table 2a). Results of a Student-Newman-Keuls analysis on the interaction between field trips, sexes and time of day were complex but several trends were apparent and some are indicated in Table 2b. Activity within day blocks (0600-1800 hrs) and within night blocks (1800-0600 hrs) was not significantly different ($P > 0.05$). Activity during daytime was much less than during the night on all field trips (Table 2b). Although there was no significant difference in activity between sexes during the day, ($P > 0.05$) female lobsters, on average, were more active than males at night during all field trips except April 1985 (Table 2b). Lobsters (males and females combined) were most active during November in 1984 and 1985 (Table 2b).

Rates of Movement

Although the tags themselves did not affect the foraging behaviour and activity of P. cygnus (Jernakoff et al. in prep.) it was felt that the capture and handling of the lobsters to attach the tags may have influenced their behaviour during the first week after tagging. Data on activity were therefore separated into two categories; within the first week after tagging and more than one week after being tagged. Data were analysed by a split-plot anaylsis of variance (Snedecor & Cochran 1976) for differences in the rate of movement between sexes, field trips, time of day and whether rate of movements of lobsters differed in the first week of being tagged compared with later times (i.e. a handling effect).

The results of the analysis suggested that relative to the variation among lobsters, there were no significant effects of sex or field trip (Table 3a). The level of variation among lobsters in their movements was highly significant ($P < 0.001$). Most of this reflects the behaviour of an individual lobster, whose rate of movement was 3.71 m min^{-1} compared with the other 44 lobsters whose rate was close to 1.0 m min^{-1}. Although there was a significant interaction between sexes, field trips and weeks there was no significant difference in the rates of movements between sexes or weeks of sampling in three out of the six field trips (Student-Newman-Keuls analysis, Table 3b). In September 1985 the rate of movement by females was greater during the first week while in the other two field trips (September 1984 and November 1984), results varied and were the opposite for each field trip (Table 3b).

A Student-Newman-Keuls test on the other important significant interaction between field trips and time of day revealed that in three of the field trips (January, April and November 1984) there was no significant

difference in rates of movement with time of day. In the other three field trips movements were faster early in the morning (0300-0600 hrs) in September 1984, faster in the early evening (1800-2100 hrs) during November 1984 and faster in both the early evening and morning during September 1985 ($\underline{P}$ < 0.05).

Foraging Patterns

Foraging ranges varied among lobsters although three general patterns were observed; foraging over a small circular area; foraging over long straight paths, and foraging on a more circuitous route (Fig. 3).

Foraging patterns also varied within individuals on different nights. A typical sequence can be seen in Figure 4. While the total distance travelled, and the straight line distance from the home den varied, (Jernakoff et al. in prep.) lobsters tended to go to the same general area for at least a few nights in succession.

The foraging direction of lobsters was never random. Lobsters repeatedly foraged around the same seagrass beds night after night (Fig. 4). Twenty four of the animals tagged on Reef IV and Reef I moved from their original den to one or more dens in the south west corner of the tracking area. They foraged in seagrass beds in front of Reefs IV and I returning to the dens in the south west corner by sunrise. On 57 occasions during 29 nights, ten of these lobsters visited dens on Reefs IV and Reef I before returning to their current den (south west corner of the study area) as light levels increased. On 12 occasions a single visit was made to a den, on 10 occasions 2 visits were made, on 5 occasions 3 visits were made, on 1 occasion 4 visits were made and on 1 occasion a tagged animal visited a den 6 times during the night. Visits lasted from 8 min to 198 min with an average time of 47 min (S.E. = 6 min, N = 57). Ten lobsters changed their homing back to the original reef and four of

those lobsters had made previous visits to the new dens. The maximum number of dens on different reefs that a lobster was observed to shelter in during the daytime in a single field trip (up to 23 nights) was three.

Habitat Utilized During Foraging

The 50 12 m x 12 m aerials used to track lobsters, enclosed seagrass habitat composed of either <u>Amphibolis</u>, <u>Heterozostera</u> and <u>Halophila</u> or a combination of both structural forms. By determining the amount of time spent in each aerial and the seagrass habitat within that aerial, a measure of the amount of time that lobsters spent in the two structural types of seagrass could be determined. No lobsters were observed to forage in bare sand. All home dens were on reefs covered with <u>Amphibolis</u>. Because some lobsters did not forage every night or returned from foraging early, aerials covering these reefs (and dens; aerials 49, 2, 6, 7) were excluded from statistical analyses. The duration of stay of foraging lobsters within aerials was examined for differences between sexes, field trips, time since tagging, and habitat.

The results of the analysis (see Table 4a) demonstrated that relative to between lobster variation, there was no significant difference in the amount of time spent within an aerial between sexes and/or field trips. There was however, significant variation between lobsters.

There was a very significant effect of habitat and significant interactions between field trips and habitats, and sexes, field trips and habitats ($\underline{P} < 0.05$). Because the interpretation of the three way interaction was unclear, and because of the highly non significant influence of the main effect of sex (P > 0.25) a Student-Newman-Keuls analysis on only the interaction of field trips and habitat is presented in Table 4. The results

indicate that lobsters spent significantly less time foraging in aerials enclosing Amphibolis than in aerials enclosing Heterozostera and Halophila or a mixture between the two seagrass types in September 1984, April 1985 and September 1985. There was no significant difference in time spent within each of the habitat types during the other three field trips. While the time spent foraging in aerials of mixed seagrass habitat was similar at all times of the year, the analysis was unable to distinguish clear differences in the amount of time spent in either Amphibolis or Heterozostera and Halophila during the 6 field trips (Table 4b). A Student-Newman-Keuls analysis on the main effect of habitat (i.e. pooling the effect of field trips and sexes) demonstrated that lobsters foraged less in Amphibolis (untransformed mean = 22 min.) than either in Heterozostera and Halophila (untransformed mean = 32 min.) or aerials of both seagrass types (untransformed mean = 32 min. as well; $P < 0.05$).

The number of stops made by lobsters within aerials were analysed for differences between sexes, field trips and habitat. The results suggested that relative to between lobster variation there were significant differences between sexes (Table 5a). There was a very significant habitat effect as well as an interaction between sexes and field trips and the major interaction between sexes, habitats and field trips (Table 5a). The results of a Student-Newman-Keuls analysis on this 3 way interaction are presented in Table 5b. There was no significant difference in the number of stops between sexes in either aerials enclosing Amphibolis or Heterozostera and Halophila except during April 1985 when females made more stops in Heterozostera and Halophila. In aerials with mixed habitat, there was no difference between sexes on four occasions while in September 1984 females made more stops than males although the opposite trend occurred during April 1985 (Table 5b). There was no significant difference in the number of stops by males between

habitats in four field trips while in January and April 1985 males made more stops in aerials of mixed habitat. Females made more stops in aerials of mixed habitat in all field trips except for September 1985 (Table 5b).

The exact position of lobsters in aerials enclosing both types of seagrass could not be determined by the tracking system (i.e. lobsters could have been either in Heterozostera and Halophila beds or in Amphibolis areas with those aerials). To determine what habitat (i.e. Heterozostera and Halophila or Amphibolis) was being used by the tagged lobsters, a series of night dives were carried out when tagged lobsters moved into these aerials. Unfortunately, the behaviour of lobsters changed in response to the divers' presence after about 30 seconds of observation. Thus only instantaneous readings could be obtained before the animals hid from the divers in the Amphibolis beds. The instantaneous observations suggested that lobsters were foraging in the Heterozostera and Halophila beds. This conclusion is supported by results from diving observations on untagged lobsters in aerials of mixed habitat and also from transects within the two types of algal beds (Table 6).

DISCUSSION

Light levels have often been cited as providing the stimulus for the start and the finish of activity in spiny and clawed lobsters (e.g. Lindberg 1955; Fielder 1965; Kanciruk & Herrnkind 1973; Chapman et al., 1975; Herrnkind et al., 1975). Some laboratory studies have examined the sensitivity and absorbance of visual pigments of lobsters (e.g. Kubo & Ishiwata 1964) and have concluded that the maximum scotopic absorbance is around the range of light levels experienced around twilight (Ache & Macmilian 1980). Results of the present study indicate that P. cygnus responds rapidly to very small changes

at very low light intensities (< 1 μ E m^{-2} s^{-1}) experienced around dawn and dusk. <u>Panulirus argus</u> has also been reported to respond to light intensities as low as 1.5 μ E m^{-2} s^{-1} (Herrnkind 1980). The start of diurnal activity of <u>P. cygnus</u> prior to 1.5 hrs before dusk (i.e. during the main part of the day: > 6 log μ E m^{-2}s^{-1}; Fig. 2a) was in most cases not a foraging excursion but due to lobsters moving out to the entrance of the den where the signal from their tag was picked up by surrounding aerials, thus indicating small movements. A similar trend occurred for the end of activity (Fig. 2b). The frequencies of these movements were far less than when the bulk of lobsters began foraging around dusk and finished around dawn, regardless of the time of year. Similar starts and ends of activity in response to light levels for <u>P. cygnus</u> have been demonstrated in the laboratory (Morgan 1978) and reported in the field (e.g. Cobb 1981; Phillips <u>et al</u>., 1984).

Changes in waterflow has been reported to influence activity of clawed lobsters (Howard & Nunny, 1983). In the present study, activity patterns of <u>P. cygnus</u> were not correlated with changes in water currents nor with diurnal temperature changes. Thus in natural field situations, changing light levels are the major physical factor influencing the start and end of foraging activity.

Results of the present study suggest that lobsters remain active throughout the night and continue to forage until dawn. Females are more active foragers than males and lobsters are most active during November. Increased activity during November was not correlated with changes in water temperature compared with other sampling dates. Greater activity during November may be associated with seasonal moulting of the animals' exoskeleton and the migration of the older juveniles to deeper water. Some laboratory studies of activity have reported crepuscular peaks in activity (e.g. Kubo &

Ishiwata 1964; Morgan 1978; Andree 1981). Kanciruk & Herrnkind (1973)

reported that, depending upon water temperature, P. argus exhibited two

different kinds of activity patterns in the laboratory. During winter,

activity of animals peaked after sunset then declined whereas in spring,

activity began around sunset and was maintained throughout the night; a

similar pattern to that exhibited by P. cygnus in the field during the present

study.

Rates of movement during foraging of P. cygnus tended to be relatively

constant between times of year and sexes. In general, animals tended to move

at a rate of 1 m min^{-1} (1.7 cm s^{-1}), although some were observed during night

dives to move across sand at an approximate rate of 30 cm s^{-1}. This is in the

range of speeds observed by Lindberg (1955) for P. interruptus (30-60 cm

sec^{-1}) and within the capabilities for P. argus (Herrnkind & McLean 1971).

Foraging patterns of P. cygnus were usually consistent for individual

lobsters although patterns could vary between individuals. Foraging never

occurred at random. Excursions generally fell into three categories;

circuitous routes repeatedly visiting the same algal bed, long straight paths

to an algal bed then return via the same route, and finally a small circular

path close to the home den. Approximately half of the lobsters changed their

home reef and den during the 2-3 week periods of observation. Similar

activity has been also described for P. argus (Herrnkind et al., 1975). While

the majority of P. cygnus foraged each night, there were occasions when

individuals did not forage during the night. The reason is unknown, but a

similar behaviour is shown by P. argus where night time den residency was

shown in 7% of all observations (Herrnkind et al., 1975). Some P. cygnus

visited dens during the night on neighbouring reefs where they had previously

held residence. A possible explanation is that such dens are alternative

homes within an individual's foraging range and periodic visits are made prior to moving to another den.

The small home range and fidelity to the same patch of reef reported for _P. cygnus_ by Chittleborough (1974) was not apparent in the present study. Chittleborough's conclusions were based on the results of mark recapture techniques using baited traps. These were set along a single test reef. It is possible that some of the marked individuals in his study were attracted away from current dens on other reefs by the presence of bait in the trap (Jernakoff & Phillips in prep.). Chittleborough's study was also done at Garden Island. Jernakoff _et al._, (in prep.) found that at Seven Mile Beach, approximately half of an electromagnetically tagged population of rock lobsters left the area. Some of the lobsters were discovered several kilometres away within two weeks after being tagged. These lobsters would appear to be either nomads or transients rather than homing (_sensu_ Herrnkind 1980) at that particular stage in their juvenile life cycle.

Panulirus cygnus was demonstrated to forage in both structural types of seagrass beds. On average, it stopped less often in _Amphibolis_ than in _Heterozostera_ and _Halophila_ beds, and its duration of stay between foraging movements was longer in _Heterozostera_ and _Halophila_ beds than in _Amphibolis_. A possible explanation is that although animals preferred foraging in _Heterozostera_ and _Halophila_ beds, they also preferred to be near the shelter of _Amphibolis_ where they could quickly hide from predators. Thus aerials of mixed habitat were preferred because they offered both types of habitat. Results of the present study show that the average time spent in these beds before moving again was approximately 22 min. Many tagged lobsters had to travel through _Amphibolis_ beds to reach _Heterozostera_ and _Halophila_ seagrasses. Hence, some of the time spent in _Amphibolis_ may be attributed to

travelling through the beds to better foraging grounds. In a study on the natural diet of P. cygnus, Joll & Phillips (1984) found pieces of Amphibolis, coralline algae and other organisms associated with Amphibolis beds in the guts of lobsters. Most of their observations on foraging activity and analyses of stomach contents, however, support the conclusions of the present study, that most foraging by 4 yr old P. cygnus occurs in Heterozostera and Halophila beds.

The foraging patterns and feeding activity of juvenile P. cygnus suggest that particular sites within algal beds may be foraged by individuals repeatedly over successive nights, thus some areas and habitats were more heavily foraged than others.

REFERENCES

Ache, B.W. & D.L. Macmillan, 1980. Neurobiology. In, The Biology and
Management of Lobsters, Vol. I, edited by J.S. Cobb & B.F. Phillips,
Academic Press, New York, pp. 165-213

Andree, S.W., 1981. Locomotory activity patterns and food items of benthic
post-larval spiny lobsters, Panulirus argus. Ph.D. thesis, University of
Southern California, 50 pp.

Atema, J. & J.S. Cobb, 1980. Social Behaviour. In, The Biology and
Management of Lobsters, Vol. I, edited by J.S. Cobb & B.F. Phillips,
Academic Press, New York, pp. 409-450.

Chapman, C.J., A.D.F. Johnstone & A.L. Rice, 1975. The behaviour and ecology
of the Norway lobster, Nephrops norvegicus (L.) Proc. Eur. Mar. Biol.
Symp., 9th, pp. 59-74.

Chittleborough, R.G., 1970. Studies on recruitment in the Western Australian
rock lobster Panulirus longipes cygnus George: density and natural
mortality of juveniles. Aust. J. Mar. Freshwater Res., Vol. 21, pp. 131-
148.

Chittleborough, R.G., 1974. Home range, homing, and dominance in juvenile
Western rock lobsters. Aust. J. Mar Freshwat. Res., Vol. 25, pp. 227-234.

Chittleborough, R.G., 1975. Environmental factors affecting growth and
survival of juvenile western rock lobsters Panulirus longipes (Milne-
Edwards). Aust. J. Mar. Freshwat. Res., Vol. 26, pp. 177-196.

Chittleborough, R.G. & B.F. Phillips, 1975. Fluctuations of year-class
strength and recruitment in the western rock lobster Panulirus longipes
(Milne-Edwards). Aust. J. Mar. Freshwat. Res., Vol. 26, pp. 317-328.

Cobb, J.S., 1981. Behaviour of the Western Australian spiny lobster, Panulirus cygnus George, in the field and the laboratory. Aust. J. Mar. Freshwat. Res., Vol. 32, pp. 399-409.

Fielder, D.R., 1965. The spiny lobster, Jasus lalandei (H. Milne Edwards) in South Australia. III. Food, feeding and locomotor activity. Aust. J. Mar. Freshwat. Res., 16, pp. 351-367.

Herrnkind, W.F. & R.B. McLean, 1971. Field studies of homing, mass emigration and orientation in the spiny lobster, Panulirus argus. Ann. N.Y. Acad. Sci., Vol. 188, pp. 359-377.

Herrnkind, W.F., J. VanderWalker & L. Barr, 1975. Population, dynamics, ecology and behaviour of spiny lobster, Panulirus argus of St. John, U.S. Virgin Islands: Habitation and pattern of movements. Results of the Tektite Program, Vol. 2. Sci. Bull. Nat. Hist. Mus. Los Angeles Cty., Vol. 20, pp. 31-45.

Herrnkind, W.F., 1980. Spiny lobsters: patterns of movement. In, The Biology and Management of Lobsters, Vol. I, edited by J.S. Cobb & B.F. Phillips, Academic Press, New York, pp. 349-401.

Howard, A.E. & R.S. Nunny, 1983. Effects of nearbed current speed on the distribution and behaviour of the lobster Homarus gammarus (L.). J. Exp. Mar. Biol. Ecol., Vol. 71, pp. 27-42.

Joll, L.M. & B.F. Phillips, 1984. Natural diet and growth of juvenile western rock lobsters Panulirus cygnus George. J. Exp. Mar. Biol. Ecol., Vol. 75, pp. 145-169.

Kanciruk, P., 1980. Ecology of juvenile and adult Palinuridae (spiny lobsters), In, The Biology and Management of Lobsters, Vol. II, edited by J.S. Cobb & B.F. Phillips, Academic Press, New York, pp. 59-96.

Kubo, I. & N. Ishiwata, 1964. On the relationship between Japanese spiny

 lobster and light intensity. Bull. Sci. Fish., Vol. 30, pp. 884-888.

Lindberg, R.G., 1955. Growth, population dynamics and field behavior in the

 spiny lobster, Panulirus interruptus. Univ. Calif. Berkeley, Publ. Zool.,

 Vol. 59, pp. 157-248.

Lipcius, R.N., & W.F. Herrnkind., 1982. Moult cycle alterations in behaviour,

 feeding and diel rhythms of a decapod crustacean, the spiny lobster

 Panulirus arqus. Mar. Biol., Vol. 64, pp. 241-252.

Morgan, G.R., 1978. Locomotor activity in the western rock lobster Panulirus

 longipes cygnus. Aust. J. Mar. Freshwat. Res., Vol. 29, pp. 169-174.

Phillips, B.F., L.M. Joll & D.C. Ramm, 1984. An electromagnetic tracking

 system for studying the movements of rock (spiny) lobsters. J. Exp. Mar.

 Biol. Ecol., Vol. 79, pp. 9-18.

Ramm, D.C., 1980. Electromagnetic tracking of rock lobsters (Jasus

 novaehollandiae) Aust. J. Mar. Freshwat. Res., Vol. 31, pp. 263-269.

Snedecor, G.W., & W.G. Cochran, 1976. Statistical Methods. Iowa State

 University Press. Ames, Iowa, U.S.A. 593 pp.

FIGURE CAPTIONS

Figure 1:   Habitat features within the study site at Seven Mile Beach,
             Western Australia. Reefs IV and I are approximately 50 m due
             west of the shore line.

Figure 2:   Activity of lobsters and light levels experienced in the
             field. Sunset (Fig. 2a) and sunrise (Fig. 2b) are between
             approximately 1.5 to 3 log μ E m^{-2}s^{-1}. Data have been pooled
             over sexes and field trips.

             a: Start of activity - beginning of foraging.

             b: End of activity - end of foraging.

Figure 3:   Examples of 3 general foraging patterns of <u>Panulirus cygnus</u> at
             Seven Mile Beach. A: long circuitous route; B: long straight
             path; C: small circuitous route.

Figure 4:   An example of nocturnal foraging paths of 2 individual <u>Panulirus</u>
             <u>cygnus</u> on successive nights: A,B,C,D.

             ------ Lobster path, January 1985.

             ...... Lobster path, April 1985. This lobster changes den on
             night D. Arrows indicate direction of movement.

Fig 1 (Draft)

Figure 2

a. Start of activity

b. End of activity

Number of lobsters

Light levels [log microeinsteins] [log $\mu E \, m^{-2} s^{-1}$]

REEF

AMPHIBOLIS

SEAGRASS

HETEROZOSTERA

AND HALOPHILA

SEAGRASS

A

B

C

REEF
IV

REEF

REEF

SAND

10m

Fig 3

Fig 4

A — REEF

REEF IV   REEF III   REEF II

Is. D

B

C

D
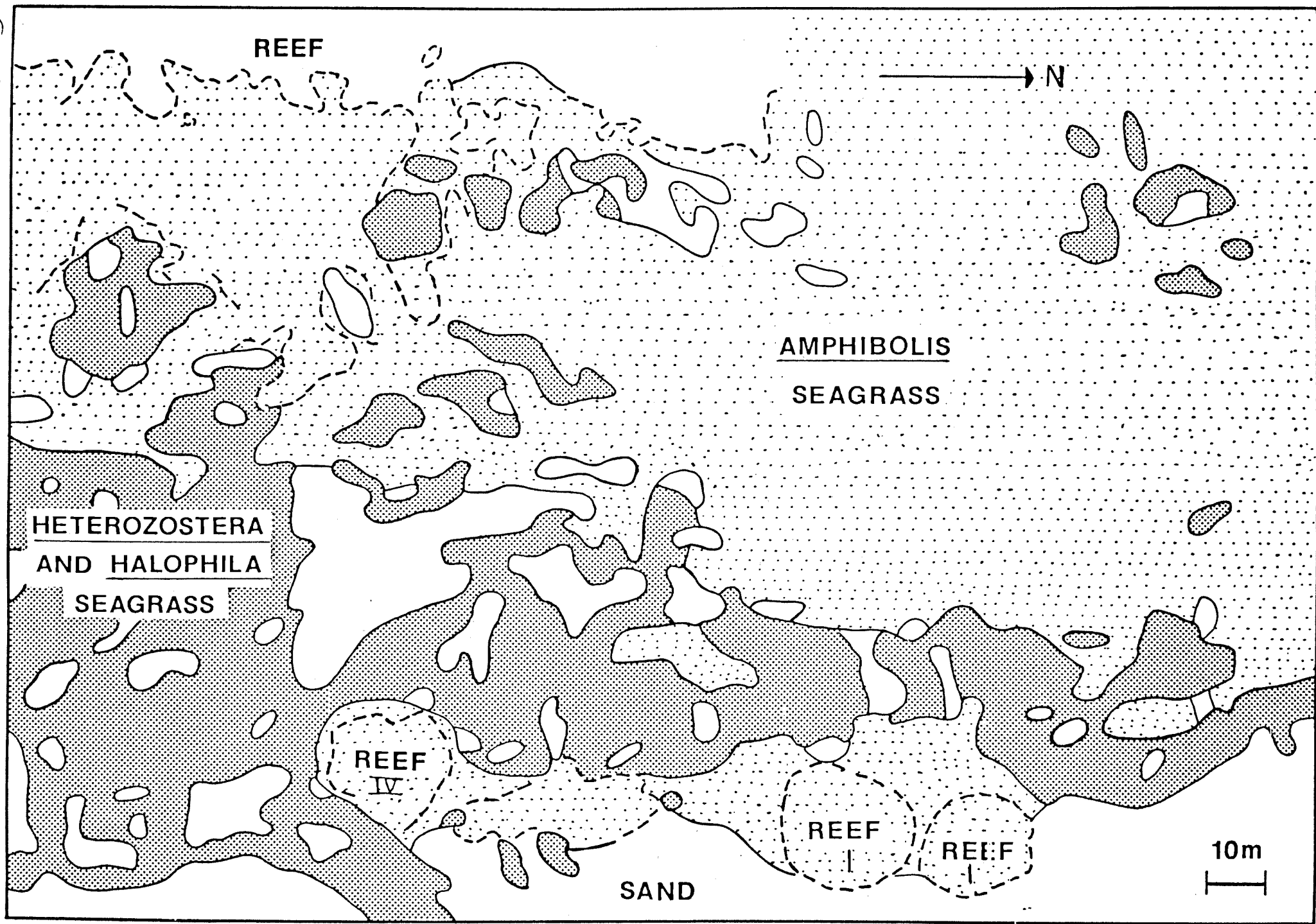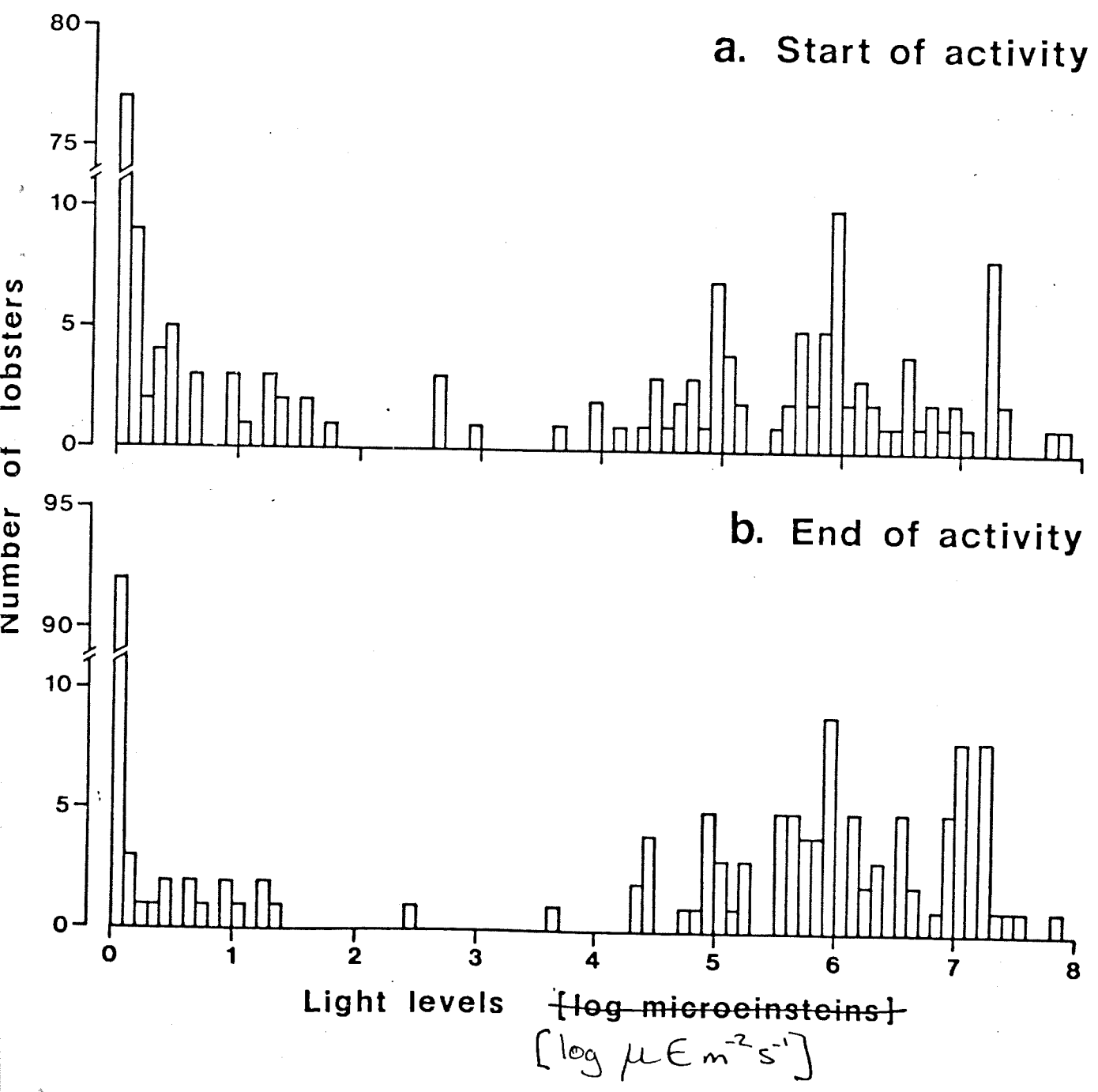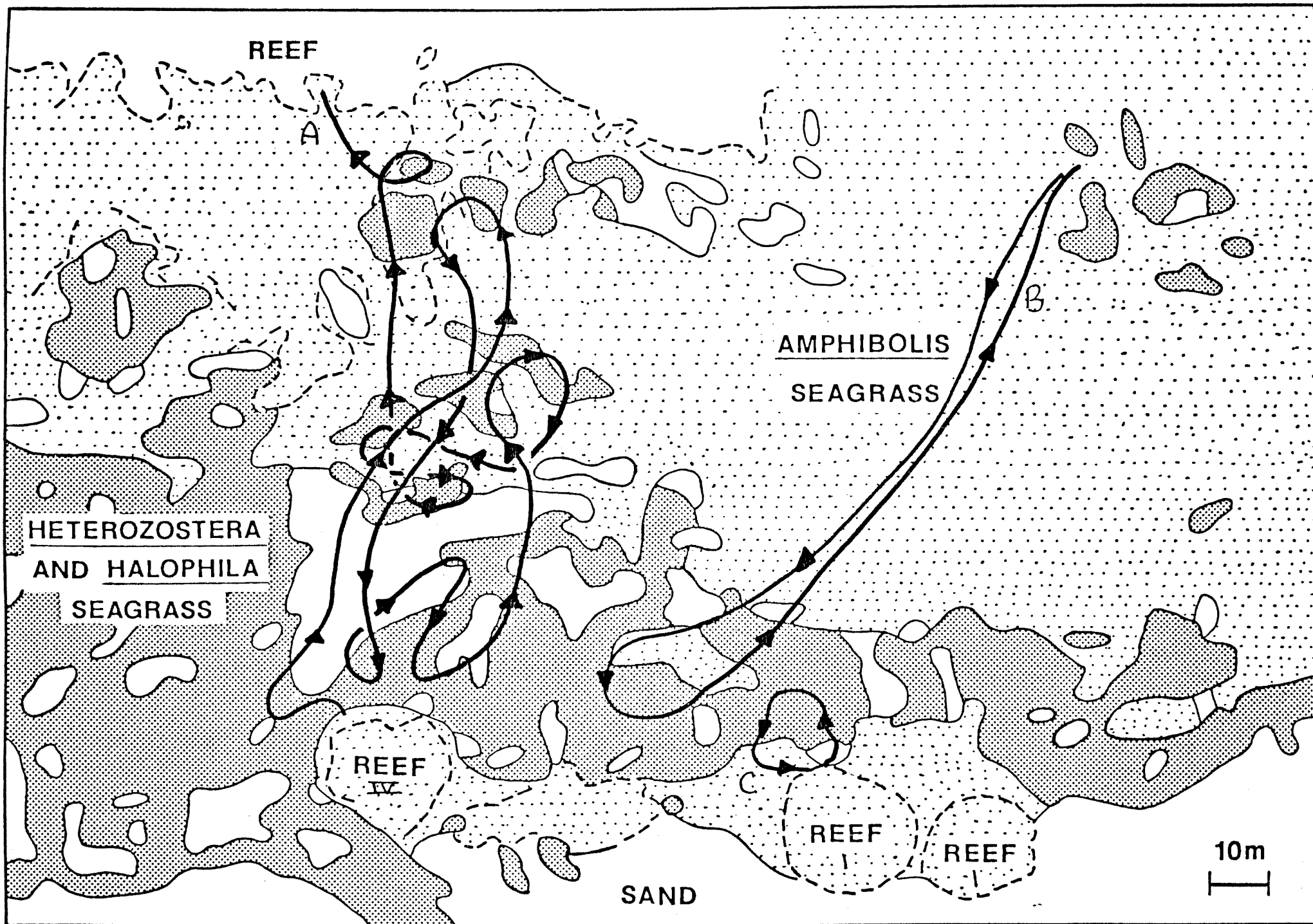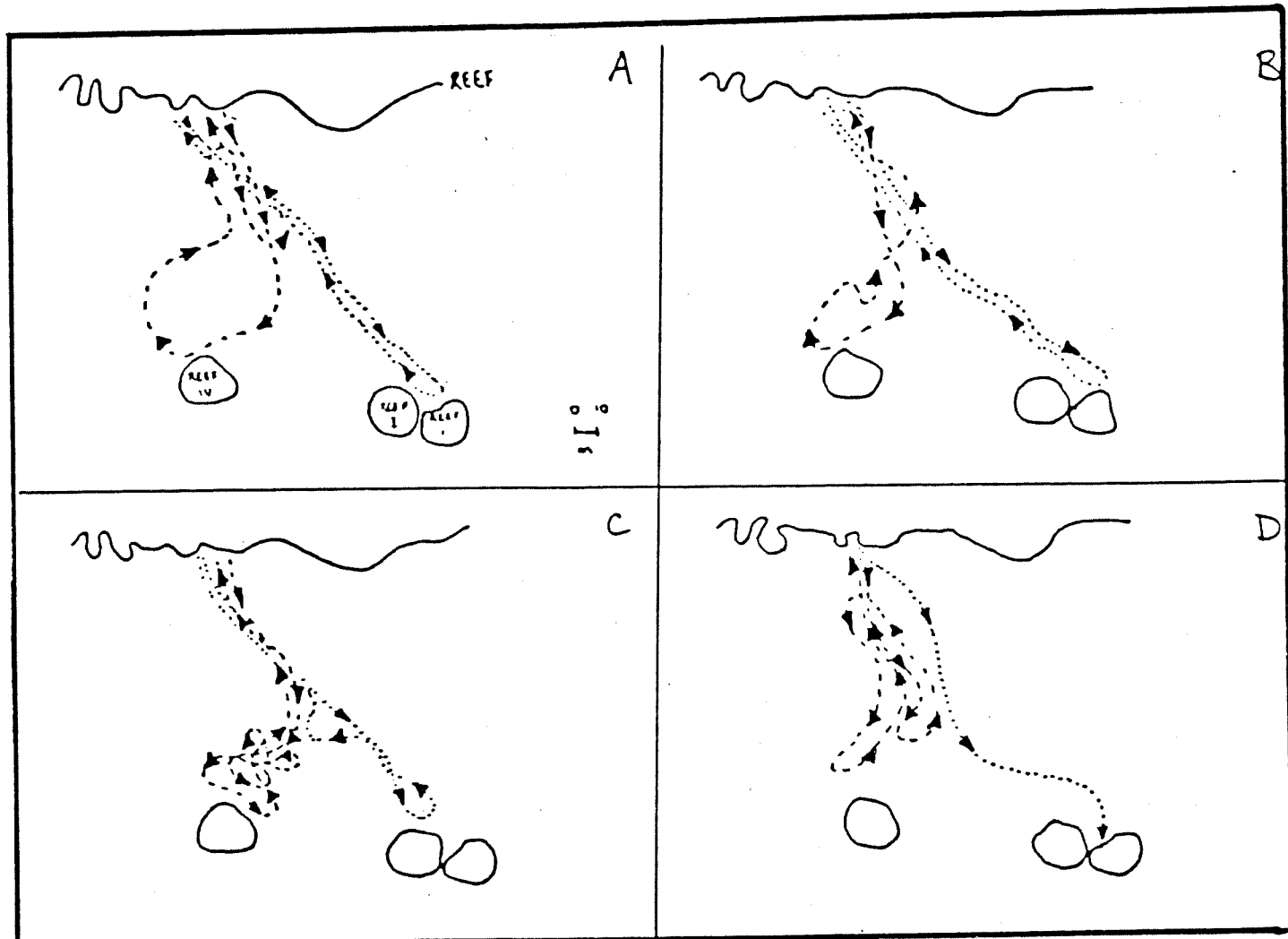
TABLE 1. Numbers of tagged rock lobsters.

Field Trip	Numbers of Tagged Lobsters	
	Male	Female
September 1984	7	7
November 1984	6	6
January 1985	6	6
April 1985	7	7
September 1985	7	7
November 1985	7	7
Total:	40	40

TABLE 2a. Split-plot analysis of variance on the effects of Field trip, Sex,
           and Time of Day on the number of rate movements of rock lobsters.
           Data are transformed (square root).

Source of Variation	Degrees of Freedom	Mean Square	F Ratio	Probability Value
Field trip	5	4.45	1.85	> 0.10
Sex	1	7.25	3.01	> 0.05
F/trip x Sex	5	8.70	3.61	< 0.01
Lobsters (F/trip x Sex)	36	2.41	4.02	< 0.001
Time of Day	7	40.09	66.82	< 0.001
F/trip x Time of Day	35	1.67	2.87	< 0.001
Sex x Time of Day	7	1.33	2.22	< 0.05
F/trip x Sex x Time of Day	35	1.95	3.25	< 0.001
Residual	252	0.60		
Total	383			

TABLE 2b. Summarised data from a Student-Newman-Keuls analysis on the interaction between Fieldtrips, Sexes and Time of Day. Data are untransformed mean number of rate movements per 12 hr (ie day or night) period.

Field Trip	Day Blocks 0600-1800 hrs	Night Blocks 1800-0600 hrs		
	Both Sexes	Both Sexes	Males	Females
September 1984	Not recorded	15.64	9.00	22.28
November 1984	1.36	40.17	20.25	60.06
January 1985	2.36	34.96	22.46	47.47
April 1985	1.17	32.76	34.69	30.82
September 1985	0.14	27.82	0.13	55.50
November 1985	10.21	43.40	36.12	50.69

TABLE 3a. Split-plot analysis of variance on the effects of sex, field trip, week (time since tagging) and time of day, on rates of movement of rock lobsters. Data have been log transformed.

Source of Variation	Degrees of Freedom	Mean Square	F Ratio	Probability Value
Sex	1	5.69	1.27	> 0.25
Field trip	5	5.18	1.16	> 0.25
Sex x Field trip	5	4.54	1.02	> 0.25
Lobsters (Sex x F/trip)	33	4.47	6.77	< 0.001
Week	1	2.58	3.91	< 0.05
Sex x Week	1	6.22	9.42	< 0.005
F/trip x Week	5	5.87	8.89	< 0.001
Sex x F/trip x Week	4	2.52	3.82	< 0.01
Time of Day	7	5.66	8.58	< 0.001
Sex x Time of Day	7	0.97	1.47	> 0.25
F/trip x Time of Day	31	2.55	3.86	< 0.001
Residual	5301	0.66		
Total	5392			

TABLE 3b. Results of a Student-Newman-Keuls analysis on the Sex x Field trip x Week interaction ($\underline{P}$ = 0.05). Untransformed means are shown in brackets.

Field Trip	Sex	Week 1		Week 2,3
September 1984	Male	(3.71)	>	(1.02)
	Female	(2.05)	>	(1.30)
November 1984	Males	(0.82)	<	(1.00)
	Females	(0.80)	<	(1.11)
January 1985	Males	(1.13)	=	(1.11)
	Females	(0.86)	=	(0.91)
April 1985	Males	(0.89)	=	(0.94)
	Females	(0.95)	=	(1.05)
September 1985	Males	(1.17)	=	(1.14)
	Females	(1.60)	>	(1.29)
November 1985	Males	(0.85)	=	(1.02)
	Females	(0.97)	=	(0.91)

TABLE 4a. Split plot analysis of variance on the effects of Fieldtrips, Sexes,
Weeks (time since tagging) and Habitat on the duration of a stay of
rock lobsters.

Sums of squares and degrees of freedom have been adjusted for
missing cells. Data are transformed (log).

Source of Variation	Degrees of Freedom	Mean Square	F Ratio	Probability Value
Field trip	5	5.66	1.66	> 0.10
Sex	1	0.30	0.09	> 0.25
Field trip x Sex	5	2.90	0.85	> 0.25
Lobsters (F/trip x Sex)	32	3.40	3.40	< 0.001
Week	1	0.60	0.60	> 0.25
F/trip x Week	4	3.70	3.70	< 0.01
Sex x Week	1	0.40	0.40	> 0.25
F/trip x Sex x Week	3	1.30	1.30	> 0.25
Habitat	3	5.40	5.40	< 0.005
F/trip x Habitat	11	2.20	2.20	< 0.05
Sex x Habitat	2	2.80	2.80	> 0.05
F/trip x Sex x Habitat	9	2.40	2.40	< 0.05
Residual	1409	1.00		
Total	1486			

TABLE 4b. Results of Student-Newman-Keuls analysis on the duration of stay
of the Field trips x Habitats interaction from analysis of variance
on transformed data. Untransformed means (minutes) are given in
brackets).

Amph. refers to aerials of only Amphibolis, H&H refers to
aerials only of Heterozostera and Halophila and Mixed refers to
aerials with a mixture of both types of seagrasses.

Field Trips	Habitats		
September 1984 :	Amph. (12.94) <	Mixed (34.81) =	H&H (46.06)
November 1984 :	Amph. (25.79) =	Mixed (25.53) =	H&H (30.57)
January 1984 :	Amph. (22.2) =	Mixed (28.5) =	H&H (22.2)
April 1985 :	Amph. (13.87) <	Mixed (26.84) =	H&H (27.11)
September 1985 :	Amph. (17.12) <	Mixed (41.68) =	H&H (37.71)
November 1985 :	Amph. (40.85) =	Mixed (33.45) =	H&H (29.96)

Habitats	Field trips					
Amphibolis :	Sept. 84	Ap. 85	Jan. 85	Sep. 85	Nov. 84	Nov. 85
Mixed :	Jan. 85 =	Ap. 85 =	Nov. 84 =	Nov. 85 =	Sept. 84 =	Sept. 85
H&H :	Jan. 85	Ap. 85	Nov. 85	Nov. 84	Sept. 85	Sept. 84

TABLE 5a. Split-plot analysis of variance on the effects of Field trips, Sexes and Habitats on the number of stops of rock lobsters per night. Data are transformed (square root).

Source of Variation	Degrees of Freedom	Mean Square	F Ratio	Probability Value
Field trip	5	1.36	2.47	> 0.10
Sex	1	4.98	9.05	< 0.01
F/trip x Sex	5	1.10	2.00	> 0.10
Lobsters (F/trip x Sex)	35	0.55	0.59	> 0.25
Habitat	3	39.67	42.66	< 0.001
F/trip x Habitat	15	2.14	2.30	< 0.01
Sex x Habitat	3	1.88	2.02	> 0.10
F/trip x Sex x Habitat	15	2.16	2.32	< 0.01
Residual	105	0.93		
Total	187			

TABLE 5b. Results of the Student-Newman-Keuls analysis on the interaction
between Field trips, Sexes and Habitats, on transformed data
(P = 0.05). One of the habitats (sand) has been deleted from
the analysis because it was rarely utilised by lobsters. Numbers
shown are the untransformed mean numbers of stops per night.
Amph. refers to Amphibolis and H&H refers to Heterozostera and
Halophila.

Field Trip	Habitat	Males		Females	Sex
September 1984	Amph.	0.42	=	0.48	Male : Amph.= H&H = Mixed
	H&H	0.30	=	0.01	Female: Amph.= H&H < Mixed
	Mixed	1.44	<	8.35	
November 1984	Amph.	0.22	=	0.01	Male : Amph. = H&H = Mixed
	H&H	0.92	=	6.15	Female: Amph. H&H Mixed
	Mixed	3.92	=	3.46	
January 1985	Amph.	0.01	=	0.85	Male : Amph. H&H Mixed
	H&H	0.41	=	1.59	Female: Amph. = H&H < Mixed
	Mixed	4.37	<	27.14	
April 1985	Amph.	0.02	=	0.01	Male : Amph. = H&H < Mixed
	H&H	0.05	<	4.93	Female: Amph. = Mixed < H&H
	Mixed	8.58	>	0.59	
September 1985	Amph.	0.25	=	0.02	Male : Amph. = H&H = Mixed
	H&H	0.25	=	3.42	Female: Amph. = H&H = Mixed
	Mixed	0.00	=	2.69	
November 1985	Amph.	0.01	=	0.02	Male : Amph. = H&H < Mixed
	H&H	0.14	=	0.26	Female: Amph. = H&H < Mixed
	Mixed	4.41	=	6.25	

TABLE 6. Number and activity of lobsters.

A) Censussing aerials enclosing both types of habitat.

Numbers of rock lobsters	Activity	Habitat
11	Feeding	Heterozostera and Halophila
4	Moving	Heterozostera and Halophila
1	Feeding	Amphibolis
1	Moving	Amphibolis

B) Random stratified sampling

Numbers of rock lobsters	Activity	Habitat
87	Feeding	Heterozostera and Halophila
1	Moving	Heterozostera and Halophila
2	Feeding	Amphibolis
2	Moving	Amphibolis

APPENDIX 6

An electromagnetic tracking device
for use in shallow water

This manuscript is to be submitted
to the CSIRO Division of Fisheries
Research as a Technical Report

AN ELECTROMAGNETIC TRACKING

SYSTEM FOR USE IN

SHALLOW WATER

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C.S.I.R.O.

Division of Fisheries Research

ABSTRACT

Modifications to an electromagnetic method of tracking juvenile western rock lobsters (Panulirus cygnus) are documented. Major improvements include a more robust type of receiving aerial enabling long term use, and the development of an automated tracking system. The system collects continuous and quantitative information on the location of up to 14 tagged lobsters simultaneously.

INTRODUCTION

Phillips et al. (1984) described an electromagnetic method of tracking western rock lobsters. Tags emitted periodic pulses of electromagnetic energy that were picked up by aerials laid on the seabed. Signals were relayed via a heavy duty multi-core cable to a receiver and monitored on an oscilloscope in a shore station where they were manually decoded and identified (see Phillips et al., 1984 for details).

On the basis of the method described by Phillips et al. (1984), a study was undertaken on the feeding and foraging ranges of western rock lobsters (see Jernakoff, in prep; Jernakoff and Phillips, in prep; Jernakoff et al., in prep). During the study, several modifications to the original method of Phillips et al. (1984) were developed including an automated tracking system. This report documents these modifications to provide future users a streamlined and effective procedure.

METHODS AND RESULTS

1) STUDY AREA

Tracking was carried out at Seven Mile Beach in Western Australia (29° 08'S : 114° 54'E) The tracking area was bounded between the beach and a limestone barrier reef approximately 400 m offshore, forming a lagoon-like environment. The area (< 3 m. deep) was relatively protected from oceanic swell by the outer reef at low tide but was exposed at high tide. More detailed descriptions of the area can be found in Phillips et al. (1984), Jernakoff (in prep.) and Jernakoff et al. (in prep.)

2) RECEIVING AERIALS

a) Composition

Initially, the wire used to make the aerials was identical to that used by Phillips et al. (1984). It was 24 strand (0.2 mm diameter strands) copper wire covered in grey PVC insulation ("Cable Makers Australia" 24/0.20 CCB 01 PAA). However, after 6 wk of submersion in the field, 24 of the 50 aerials had broken and/or the outer PVC sheath was damaged allowing electrical contact with the seawater. Thus although the wire used by Phillips et al.,(1984) was suitable for short term use (< 1 wk) it was unsuitable for extended exposure.

A heavy duty double PVC insulated multistranded building wire was used to replace the original aerials. The copper wire was composed of 7 strands, each of 0.5 mm diameter, with an orange PVC

outer sheath ("GEC Australia" 7/0.50)

b) Size

Phillips et al. (1984) reported that reception distance of the tags was 6 m. Aerials to pick up signals were 12 m x 12 m and separated by a 6 m gap. Thus if a lobster was within an aerial, its signal was picked up by at least 1 side of the aerial, and if it was between aerials, its signal was picked up by both aerials. This arrangement was used during the study.

c) Layout

Fifty aerials were laid on the seabed in a regular pattern within the study site (Fig. 1). The most efficient way to lay the aerials was by compass bearings. Two star pickets were placed on shore at both the southern and northern ends of the study area to enable an east-west bearing to be sighted by divers from the water (Fig. 2). Star pickets were then placed using these bearings along the southern and northern margins of the study site at distances 12 m apart with a 6 m gap in between pairs of pickets (Fig. 2). A wire cable (marked in intervals of 12 m followed by a interval of 6 m) was connected to the most shoreward picket in the water at the southern end and to the most shoreward picket at the northern end of the study site. Another cable was connected in a similar manner to the next set of pickets at either end of the study site (Fig. 2). Eight aerials were then laid by divers along this north-south transect. The cables were then moved out to the next set of star pickets and the procedure was repeated until 6 rows had been laid. The 49th aerial was laid on the south-western corner of the area and the 50th

aerial was laid near the north-eastern corner (Fig. 2). Aerials were also laid around Reefs IV, I south and I north (Fig. 2).

Aerials were held in place by steel tent pegs placed at the corners of each aerial and at 4 m intervals along the sides. The twisted wire pairs from each aerial (see Phillips et al., 1984) were unrolled back to the junction box position (in the middle of the study site; Fig. 2). Twisted pairs of wires were run between rows of aerials, tied together with PVC tape and pegged to the substratum.

d) Connections

Each of the 50 twisted pairs of wires associated with each aerial was connected in a junction box (out of water) to wires of a heavy duty shielded cable ("Telecom Australia"). The connections were waterproofed and insulated by embedding them in a cold setting elastomer compound (Sylgard 174, "Dow Corning Corp. USA"). The Sylgard in the junction box was left to set overnight in a dinghy and the next day, the junction box was secured on the seabed.

e) Replacement of individual aerials

On many occasions individual aerials failed to receive signals correctly and had to be replaced. The most common cause of the breakdown was partial or complete fracturing of one or all of the multistranded wires within the PVC insulation. In most cases, there was no physical damage to the outer sheath and the only evidence of breakdown was an internal electrical resistance of > 30 ohms (the resistance of intact functional aerials is between 20-30 ohms). Breakage of the aerials was due to metal fatigue of the wires when

part of the aerial was moved continuously by wave action or surge.

A common location of breaks was at the join of the aerials with the twisted-pair wires. Because there was no physical damage to the aerial, the exact position of the break could not be determined. Thus, the entire aerial had to be replaced. The twisted-pair was cut approximately 1 m from the aerial and the landward side of the wires brought to the surface. The ends were dried and then the wires were connected to those from the new aerial and the connections embedded in 5 ml hypodermic syringes filled with an epoxy glue (5 Minute Araldite, "Ciber-Geigy Australia"). Once the Araldite had dried (approximately 15 min.) the new aerial was laid on the seabed.

3)   MODIFICATIONS TO THE TELECOM CABLE

The cable was originally connected from the underwater junction box to a land-station (Phillips et al., 1984). Although the cable was buried to a depth of 1 m in the sand on the beach to protect it from wave action, it was uncovered during storms and was broken by bending due to waves within 6 wk of deployment.

To eliminate the problem of long term exposure of the cable, a plug was designed so that the cable could be disconnected between field trips (Fig. 3). The cable was connected by dragging out the landward side of the cable to the site of the junction box and then lifting the sealed off seaward side of the cable onto a dinghy. The 50 pairs of wires in the cable were reconnected by 5 pairs of 25-pin "D" connectors, commonly used in RS232 communications applications (each clip connected 10 pairs of wires). The two sides

of the plug were then bolted together and the plug was filled with a silicon oil (Repco silicon clutch fluid, "Repco Australia") so that no potential saltwater leaks could corrode the connector pins or short out the wires. At the end of each field trip, the oil was drained and the plug disconnected. The sealed off seaward side of the cable was tied down to the seabed and the landward side was dragged back to shore.

4) AUTOMATIC TRACKING SYSTEM

a) General description

The method of tracking described by Phillips _et al._ (1984) required personnel to manually decode and identify signals from the tags. The system was manned only between approximately 1800-0600 hrs. due to logistic constraints. In addition, only about 4 tagged lobsters could be tracked simultaneously and if more than 2 animals were in one aerial, identification of individual tags was almost impossible.

An automated tracking system was developed to overcome these limitations. The system (designed by ProLink Ltd.) can simultaneously track up to a maximum of 14 (unique) tag signals and it can identify up to 6 tagged lobsters within a single aerial.

Components of the system comprise a Hewlett-Packard 71B computer, Hewlett-Packard 225A thinkjet printer, Hewlett-Packard 82161A digital cassette drive, Hewlett-Packard 82166A IL converter, Hewlett-Packard 3468A voltmeter, a CSIRO designed receiving unit and

multiplexer, solar panels and 12 V battery (Fig. 4).

The multiplexer allows each of the 50 aerials to be connected to the input of the receiver via reed-relay switches. By this means, the Hewlett-Packard 71B can select any one of the aerials scanning sequentially from 1 to 50 on a repetitive basis. Scanning speed is programmed to rescan the entire network of aerials every 10 min.

The receiver unit was tuned to a frequency of 30.0 kHz and has a gain of 69 db. It provides a digital pulse to interrupt the Hewlett-Packard 71B when a signal is received. In addition an analogue voltage is produced by the receiver that represents the strength of the incoming signals. This voltage, monitored by the Hewlett-Packard 34684 voltmeter, is transferred to the Hewlett-Packard 71B via an Hewlett-Packard IL link. When requested by the programme, the voltage reading is transferred to the memory of the Hewlett-Packard 71B. The programme also controls the access and recognition of signals from the receiver.

Once the validity and identification of signals has been established, the time, date, aerial number, signal value and strength are stored in the Hewlett-Packard 71B memory. Data collected in memory are dumped as sequential ASCII files to the Hewlett-Packard 82161A cassette drive every 2 hrs. The Hewlett-Packard 2225A printer provided (on software command) printouts of data saved on cassette and/or as maps showing the instantaneous location of tagged lobsters within the area. Data tapes in the Hewlett-Packard 82161A cassette

drive require replacement every 2 to 4 days depending upon the number of tagged lobsters within the tracking area (i.e. the amount of information obtained).

The entire tracking system was powered by a 120 A hr, 12 V battery and the system used approximately 24 W.hr. During daylight hours, a series of solar panels provided enough power to recharge the battery and operate the system (48 W.hr).

b) Operations guide

The operations guide was written by ProLink (Ltd). It contains instructions for operating the automated tracking system and includes a list of all software programmes. Copies of the operations guide are available from the CSIRO Marine Laboratories, Perth, Western Australia.

5) PROBLEMS WITH INTERPRETATION OF SIGNALS

a) Location of tagged lobsters

Phillips et al. (1984) reported that the approximate position of a tagged lobster could be determined from its signal received by a particular (or group of adjacent) aerials. A more accurate position could then be determined because the signal strength of the tag (i.e. its voltage) was proportional to the distance of the tag from an aerial.

However, it was found that the signal strength of a tag

is dependent upon the age of battery in the tag, vertical orientation of the tag relative to the aerial and burial of the aerial by sand. Thus signal strength could not be used to determine the exact tag location.

b)   False signals

There were two known sources of false signals. The first source was when strands of wire within aerials broke due to bending of the aerials by wave surge. The friction of the broken wires rubbing against each other caused electromagnetic signals. The second source of false signals within the tracking area could only be ascribed to "demonic intrusion" (see Table 1 of Hurlbert 1984). Certain areas within the tracking area appeared to produce electrical noise and/or echo replica signals at random times of the day and night.

These signals were within the expected range of tag signals (1-4 s; see Phillips et al., 1984) thus the automated tracking system was unable to filter them out. Consequently, they were interpreted as being valid. On a few occasions, these signals represented approximately 30% of all signals received.

All data underwent a series of 7 checks during processing for analyses, to ensure their authenticity. In cases where there was a reasonable doubt about the validity of information, the suspect data were deleted from the records.

DISCUSSION

The modifications described in this report enable continuous collection of information on the location of up to a maximum of 14 tagged lobsters to be collected. The restrictions on data collection are imposed primarily by the battery life of the tags (approximately 3 wk), the resilience of the total aerial network (in operation for 15 mo) and the movement of tagged lobsters outside the tracking area (Jernakoff et al., in prep).

The development of an automated tracking system has enabled a quantitative study on foraging movements of tagged lobsters (e.g. Jernakoff et al., in prep.). Because personnel were freed from the necessity of manually tracking, they were able to spend their time repairing aerials and also to directly observe lobsters whilst the animals were out foraging at night.

The design of a waterproof plug for the main Telecom cable enabled the cable to be connected only during field trips, vastly prolonging its life. However, even with the plug, the cable was snapped in a storm during a field trip in April 1985. Transmission of the tag signals from the aerial to the shore by radio signals may be a practical alternative to a cable in shallow water environments although wave action and surge associated with these areas may create unforeseen problems with transmitting devices.

There are still drawbacks with the method. Firstly, the small reception range of the signals requires many aerials to cover the sea floor. Fifty aerials in the present study covered about 16,000 m^2 (100 m x 160 m) and required approximately 11.5 km of wire (3 km of single cable for the aerials and 4.25 km of twisted-pair cable - 9 km single cable twisted together, 7 twists per m.).

Secondly, maintenance of aerials was a major ongoing task. There were always aerials to be replaced at the start of field trips culminating with 40% needing replacement by September 1985 (13 mo after the aerial network had been re-laid). The major cause of breakdown was due to wave action in the study area. If aerials were encased in a protective electrical conduit, they would be protected from movement by wave action. However, the protected aerials would not be able to follow the undulations of an uneven sea floor and this would create other problems in securing the aerials to the substratum and therefore problems with their stability.

In conclusion, the necessity for the presence of an aerial network and main Telecom cable and their susceptibility to wave action suggest that electromagnetic tracking is suitable only in calm and shallow environments.

ACKNOWLEDGMENTS

REFERENCES

Hurlbert, S.H.   (1984)   Pseudoreplication and the design of
        ecological field experiments.   Ecolog. Monogr. 54: 187-211.

Jernakoff, P.   (in Prep.)   Foraging patterns and activity of juvenile
        spiny rock lobsters, Panulirus cygnus, George.   To be
        submitted to J. Exp. Mar. Biol. Ecol.

Jernakoff, P., B.F. Phillips.   (in prep.)   The effective catching
        area of a commercial lobster pot and its influence on
        foraging behaviour of juvenile western rock lobsters.   To
        be submitted to Aust. J. Mar. Freshw. Res.

Jernakoff, P., B.F. Phillips, R.A. Maller.   (in prep.)   A
        quantitative study of nocturnal foraging distances of the
        Western Australian rock lobster, Panulirus cygnus, George.
        To be submitted to J. Exp. Mar. Biol. Ecol.

Phillips, B.F., L.M. Joll, D.C. Ramm.   (1984)   An electromagnetic
        tracking system for studying the movements of rock (spiny)
        lobsters.   J. Exp. Mar. Biol. Ecol. 79: 9-18.

ProLink Ltd. (1984) Operations guide for the Dongara lobster
        tracking project. 41 pp.
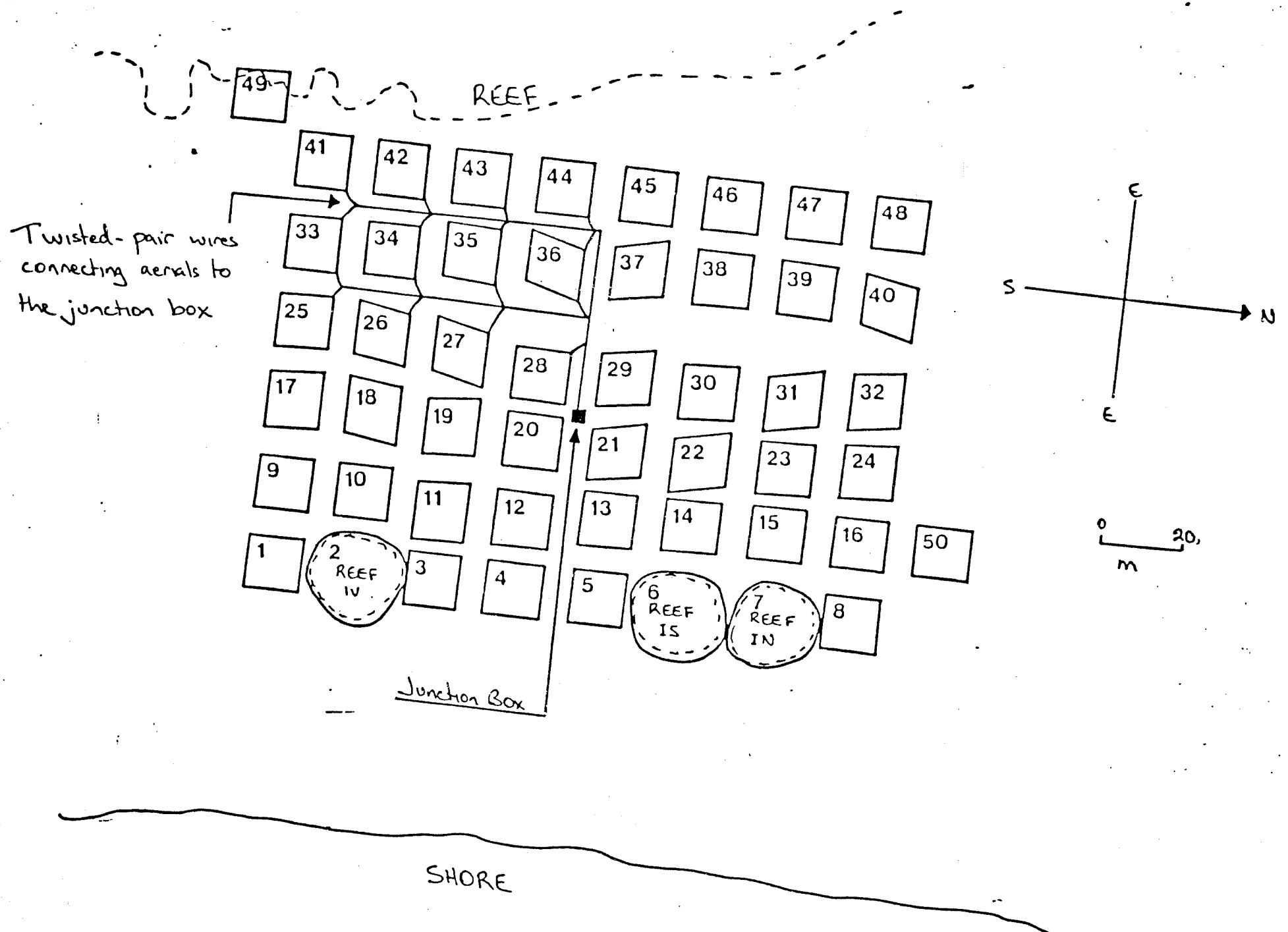
FIGURE CAPTIONS

Figure 1. Layout of the aerial network.

Figure 2. Method of laying out the aerials.

Figure 3. The design of the waterproof, heavy duty PVC plastic plug.

Figure 4. Layout of the automatic tracking system.

Fig 1 (draft)

REEF

49

41 42 43 44 45 46 47 48

33 34 35 36 37 38 39 40

Twisted-pair wires
connecting aerials to
the junction box

25 26 27 28 29 30 31 32

17 18 19 20 21 22 23 24

9 10 11 12 13 14 15 16

1 2 REEF IV 3 4 5 6 REEF IS 7 REEF IN 8 50

Junction Box

SHORE

E
S — N
E

0 |___| 20,
m

Fig # 2
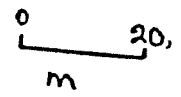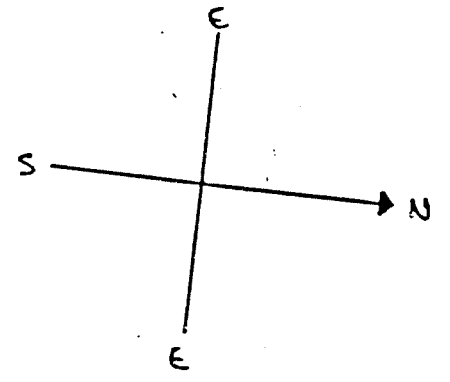
MAJOR FEATURES OF LAYING OUT AERIALS

Aerials

Cables divided into 12 m and 6 m intervals

REEF IV

REEF 1 SOUTH

REEF 1 NORTH

W · S — N · E

SEA

SHORE LINE

Star Pickets

LAND

Fig 3

RS232C "D"
connectors

Heat-shrink
seal

stainless steel bolts

Oil drain plug

260mm

160mm

Brace for
Telecom Cable

O ring Seal

Telecom Cable

JUNCTION
BOX

Groups of twisted-pair
cables

To Caravan

Figure 4

Receiving aerials

Tagged Rock Lobsters

Junction box

UNDER WATER

Plug

Twisted pair wire

Telecom cable

HP 3468A Multimeter

HP 82161A Cassette drive

HP 2225A Printer

HP 82166A HP-IL Converter

Power distribution board

HP 71B Computer

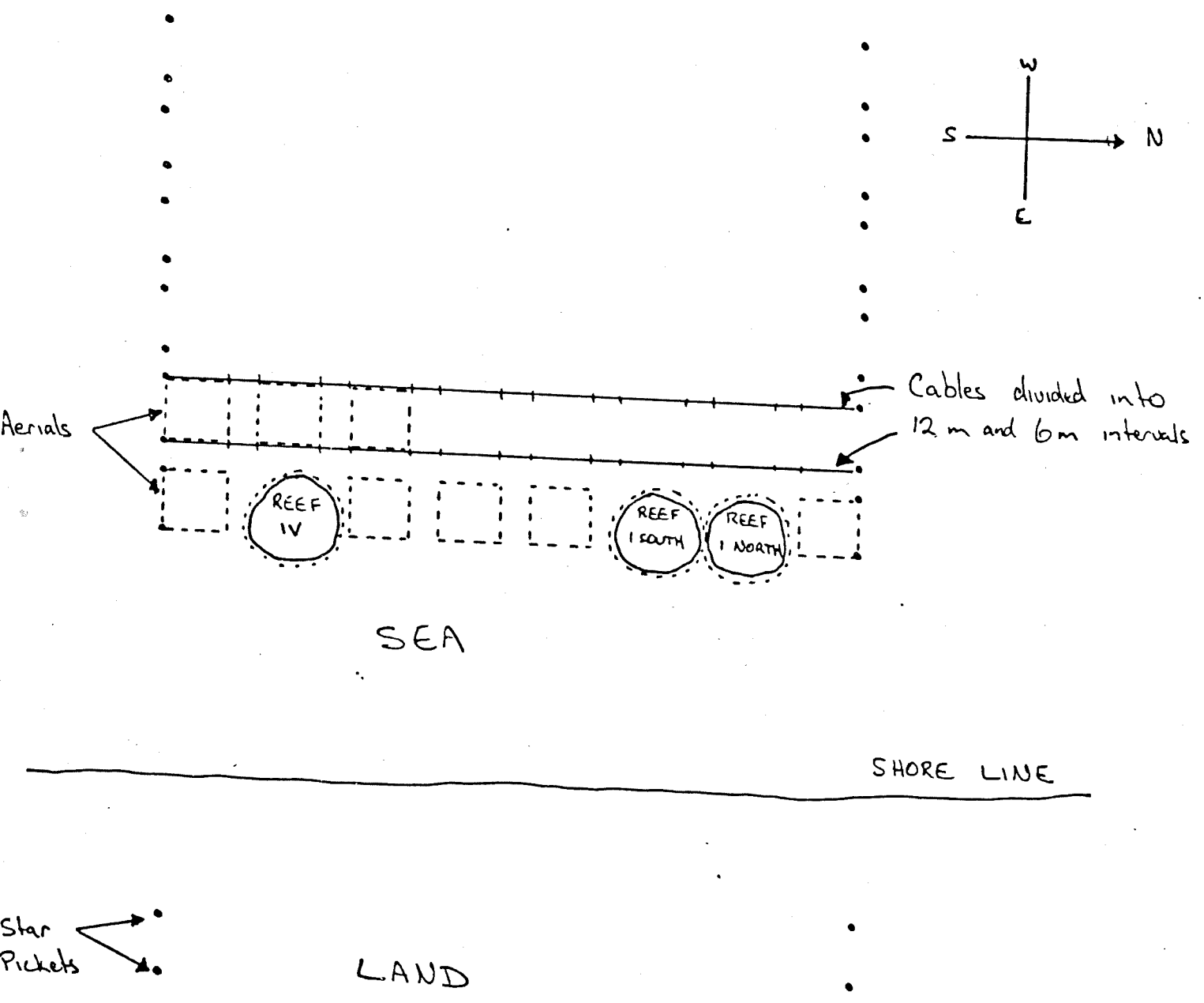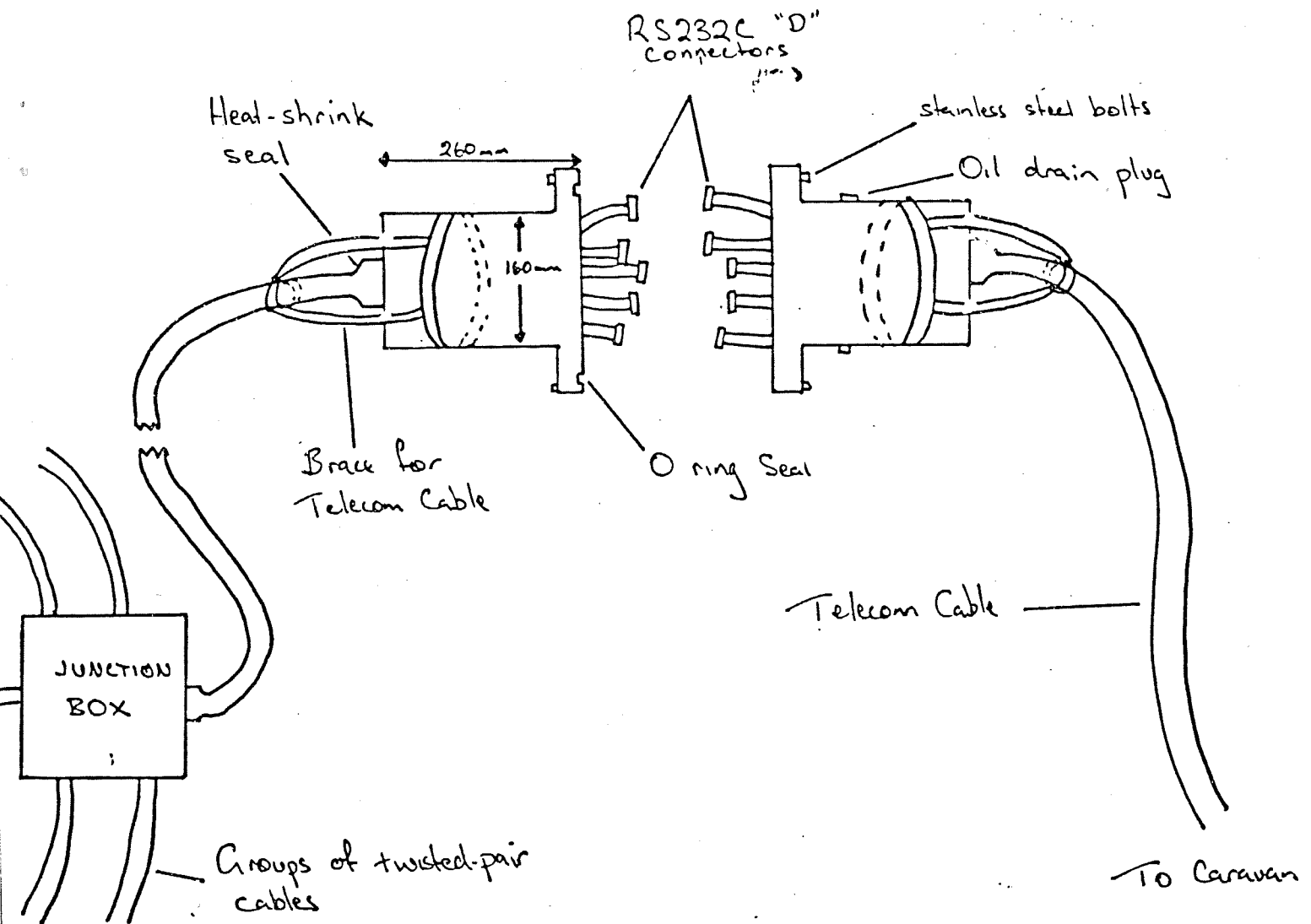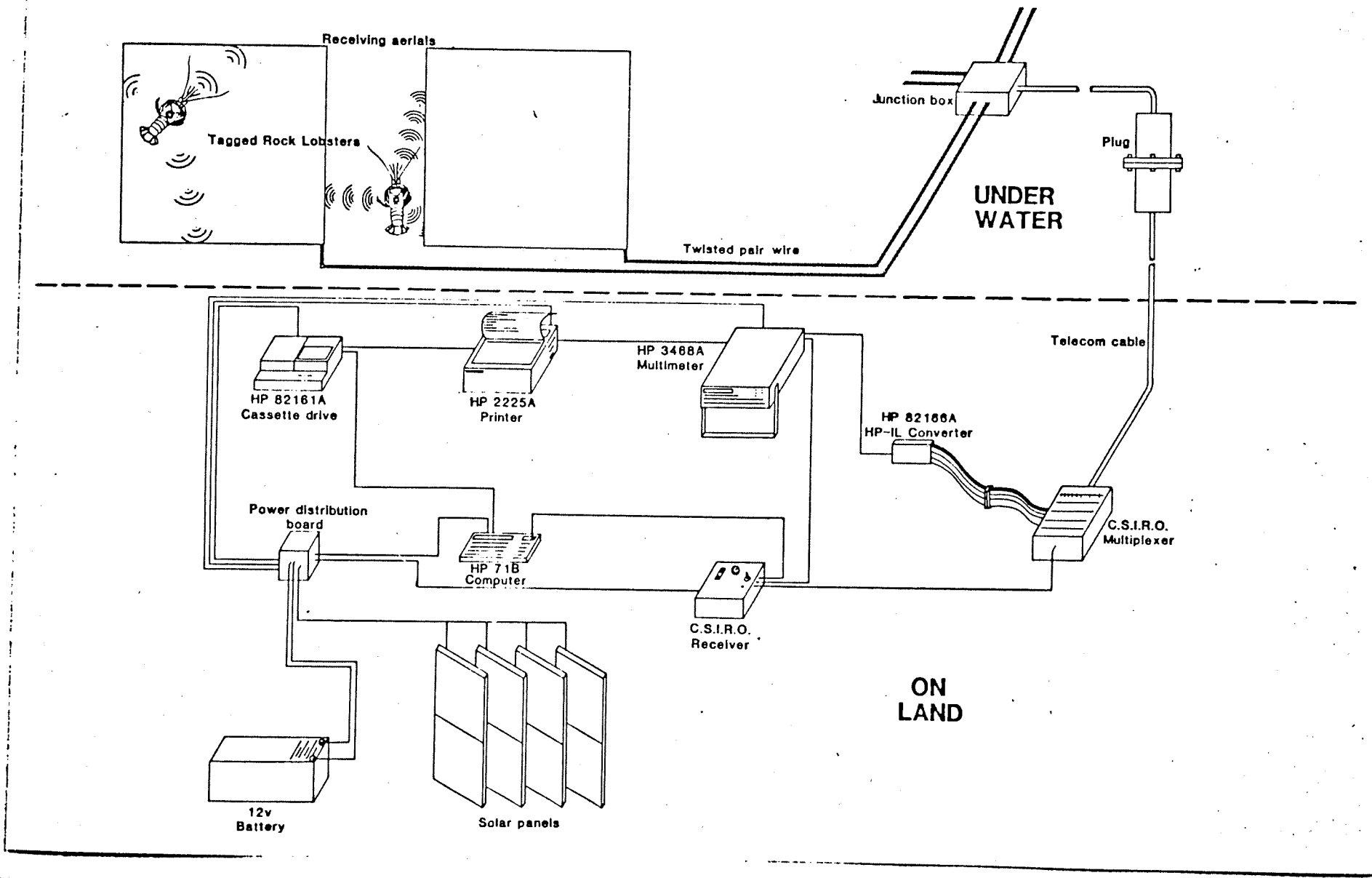C.S.I.R.O. Multiplexer

C.S.I.R.O. Receiver

ON LAND

12v Battery

Solar panels

APPENDIX 7

Electromagnetic tracking of western rock lobsters.
An 18 minute VHS Video Documentary Film

Copies lodged with Dr M. Walker, Executive Officer of FIRC,
and with the CSIRO Division of Fisheries Research
Laboratories in Hobart and Perth