



**NEW TECHNOLOGY FOR THE
ASSESSMENT OF LARVAL FISH STOCKS:
DEVELOPMENT OF SUBMERSIBLE,
AUTOMATED LIGHT-TRAPS**

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Cover

A diver checks the operation of the latest generation of submersible light-trap; automated devices developed for monitoring the larval replenishment of tropical marine fish populations.

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EXECUTIVE SUMMARY

Submersible automated light-traps are indicated as an alternative to conventional towed plankton nets for ichthyoplankton surveys, especially where there is an interest in developing a recruitment index or surveying complex spatial phenomena. This is because light attracts large pelagic juveniles that have high potential for net avoidance and because automation allows the mass production and simultaneous deployment of multiple traps.

Prior to 1987, I had developed a working prototype of a light-trap for oceanic deployment and shown that such devices could sample temporal pulsing in the larval supply of a broad range of species. Funds were sought from FRDC to develop this technology into a reliable and robust sampling tool with demonstrated relevance to fisheries research.

A small number of comparisons with alternative designs showed that performance can be influenced by the physical characteristics of the trap. Consequently, there was no attempt at a radical redesign, especially since the original prototypes were productive, albeit clumsy. Most of the development effort was devoted to making the traps more user-friendly, more reliable, and more robust.

Overall size was reduced dramatically, while keeping similar internal dimensions and performance, by switching to fibreglass monocoque construction and injection moulding of complex shapes. Identified weak points subject to stress fracture and seal failure were completely redesigned and/or eliminated. Electronic circuit was redesigned to a substantially more complex but reliable state. Enhancements like warning lights and test switches were incorporated to improve productivity from limited field time. Power supply was augmented, simplified and made more reliable by choosing disposable alkaline cells over rechargeable alternatives. The period between battery changes was increased from two days to two weeks, which greatly reduced exposure of the electronics to saltwater and lessened deterioration of the equipment.

More than 50 of these traps have been mass-produced in the AIMS workshop at a materials cost of around \$1000 per trap. Subsequent experience has shown that with reasonable care such equipment can be expected to operate for approximately five years based on usage of 50-100 days per year.

This inventory of light-traps has been used extensively over six summers since the end of the development period and three representative sampling programs are described. The reliability and utility of the traps has been tested with >10,000 hours of operations in water up to 100 m deep.

Relevance to the fishing industry has been demonstrated through two projects also partially supported by FRDC funds. The first project (89/28) involved cross-shelf, depth-stratified sampling off Townsville spanning fish habitats from the shallow turbid waters near the coast to the deep clear waters of the Coral Sea. This project identified the seasonal appearance, spatial distributions, and ontogenetic migrations of a number of exploited species with special emphasis on mackerels. The second project (90/18) involved the first monitoring of the larval replenishment of populations of the common coral trout, which is the single most important fish taken from the Great Barrier Reef. More than 500 pelagic juveniles of this species were caught over three seasons and some were maintained in captivity by QDPI for over a year, indicating the potential of this technique to supply live individuals for experimental growout.

Finally, the influence of the light-trap technology is traced through more than 20 scientific publications, nine student dissertations, scientific collaborations, and attendant publicity. Future directions are briefly discussed.

INTRODUCTION

JUSTIFICATION

Few harvest fisheries from the sea are without uncertainty over matters like the definition of the stock unit, changes in stock size, and the impact of fishing (Walters 1984). Historically, a great deal of this information has been sought from catch statistics, which is why little is known about the early life history of most species (Rothschild 1986). Young stages are deliberately not retained by fishing gear and few fin fisheries can justify expensive fishery-independent research.

Despite the lack of research, variable recruitment of new individuals into a fishery is one of the most common sources of uncertainty about catches and sustained recruitment failure has been implicated in the decline of some substantial stocks (Sissenwine 1984, Fogarty *et al.* 1991). Uncertain recruitment increases the risk of overfishing and forces conservative harvest strategies upon industry (Hilborn 1987, Walters 1984). The ultimate challenge then is to understand why reproduction fails to deliver consistent replenishment, bearing in mind that this is a common and natural attribute of populations of marine organisms that reproduce themselves as pelagic larvae (Houde 1987).

Egg and larval surveys can reveal spawning patterns but are not very useful for forecasting recruitment. In contrast, surveys of juveniles perform much better (Bradford 1992). One of the best examples is the use of static collectors in Western Australia to monitor the return of the puerulus larvae of rock lobsters from the Indian Ocean (Phillips 1986). These counts predict the relative size of recruitment entering the fishery four years forward, supporting a widely held view that the most important part of population regulation occurs before the end of the larval period (Rothschild *et al.* 1989).

One of the reasons why conventional ichthyoplankton surveys are not good estimators of recruitment is that towed plankton nets are not good at catching the survivors from this phase of intense mortality (Choat *et al.* 1993). Once all their fins are formed, larval fish become very efficient at detecting and evading towed gear. Alternative techniques are necessary to sample these fully-formed nektonic stages, which are more properly designated as pelagic juveniles.

Traditional fishers have long known that small pelagic fish can be drawn to artificial light during the night. Surveys of the tuna baitfishing industry have shown that fish attracted include the pelagic juveniles of a wide range of species as well as the adults of small pelagic species sought for bait (Rawlinson 1990). The basis of this project was to capitalise on this known photopositive behaviour to produce a robust sampling tool that might be deployed in the assessment of recruitment indices for tropical fish stocks.

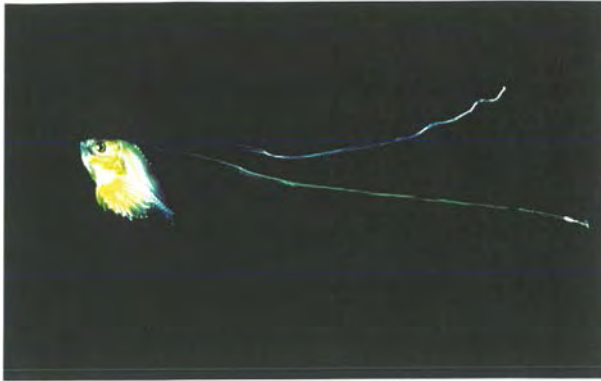
BACKGROUND

Small inexpensive light-traps have been used to sample larval fish in restricted situations (e.g. in shallow weed beds, under polar ice) where it is impossible to tow plankton nets (Gregory and Powles 1985, Kawaguchi *et al.* 1986). Doherty (1987) published the first design for a large automated light-trap specifically designed for use in the ocean. Preliminary trials on the northern Great Barrier Reef, prior to my application to FIRDC in 1987, showed that such devices could sample pelagic juvenile fish and detect strong temporal pulsing in this fauna. Desirable attributes of these sampling devices included the:

- (1) capture of stages poorly sampled by conventional techniques (Fig. 1a,b)
- (2) precise taxonomy allowed by the maturity of the specimens (Fig. 1c,d)
- (3) retention of live material allowing growout to confirm identifications
- (4) broad diversity of the catches (Fig. 1e,f)
- (5) fish of value to commercial and recreational fisheries (Fig. 1g,h)
- (6) simultaneous sampling allowed by automation of the traps
- (7) relatively quick processing of samples due to the size of the retained fishes

Immediately prior to proposing further development of this technology, the performance of light-traps relative to other gear types was tested by sampling the same water with traps, three different towed nets and a large plankton-mesh purse seine (Choat *et al.* 1993). These simultaneous comparisons showed that all gears are selective; however, light provided a powerful attractant to large pelagic juveniles that were apparently able to escape the towed nets. Consequently, only those gears using light (traps, purse seines with light) were able to detect temporal changes among nights in the relative abundance of this component of the ichthyoplankton community. Comparisons between the traps and the purse seine closed around submerged lights showed that the traps retained a representative sample of the taxa attracted to light.

Figure 1. (a,b) Light-traps attract ichthyoplankton that have well-formed fins and good swimming ability as shown by the smallest and largest captures of the yellow emperor, *Diploprion bifasciatum*. (c,d) At full development, pelagic juveniles may closely resemble their benthic stages (e.g. cowfish - *Lactoria cornuta*) or have diagnostic pigmentation (e.g. damselfish - *Pomacentrus bankanensis*) that enables identification. (e,f) Fish with both benthic (e.g. squirrelfish - *Neoniphon sammara*) and pelagic (e.g. herring - *Amblygaster sirm*) adults can be sampled together only at this stage in their lifecycles. (g,h) Species with cryptic juveniles after settlement (e.g. common coral trout - *Plectropomus leopardus*) or highly mobile juveniles (e.g. Pacific sailfish - *Istiophorus platypterus*) are included among the catches and could not be assessed by other means.



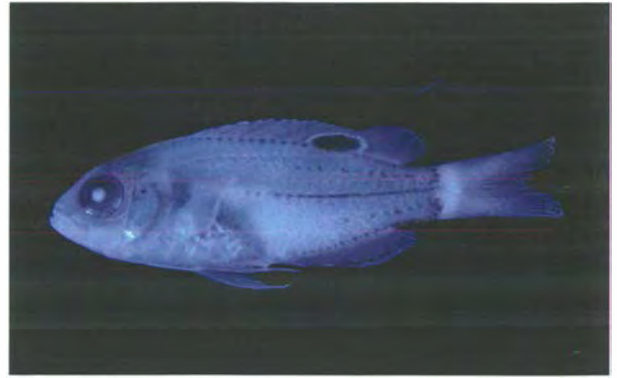
a. *Diploprion bifasciatum*



b. *Diploprion bifasciatum*



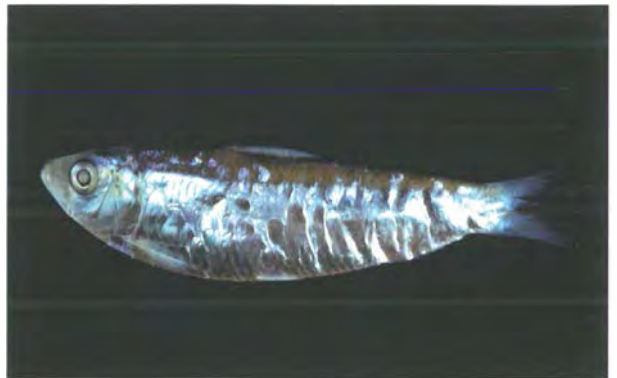
c. *Lactoria cornuta*



d. *Pomacentrus bankanensis*



e. *Neoniphon sammara*



f. *Amblygaster sirm*



g. *Plectropomus leopardus*



h. *Istiophorus platypterus*

In addition to these sampling characteristics, the automation of the traps makes them particularly suitable for the extended sampling required to monitor larval supply (Milicich 1988). Furthermore, automation allows simultaneous deployments in arrays where the resolution of complex spatial phenomena is limited only by the density of traps. With these features, light-traps have potential to overcome another of the other great limitations inherent in conventional plankton surveys, which is the inability to sample at more than one place at the same time and thus a poor ability to resolve synoptic pattern in plankton communities.

The potential of light-traps was clearly evident by 1987 but the devices in use at that time were still crude prototypes; adequate for research but clearly in need of refinement (Fig.2). Such development was the major purpose of my request for industry support.

OBJECTIVES

- (1) Optimise trap design
- (2) Develop robust prototypes suitable for mass production
- (3) Test the new design for application to exploited species.

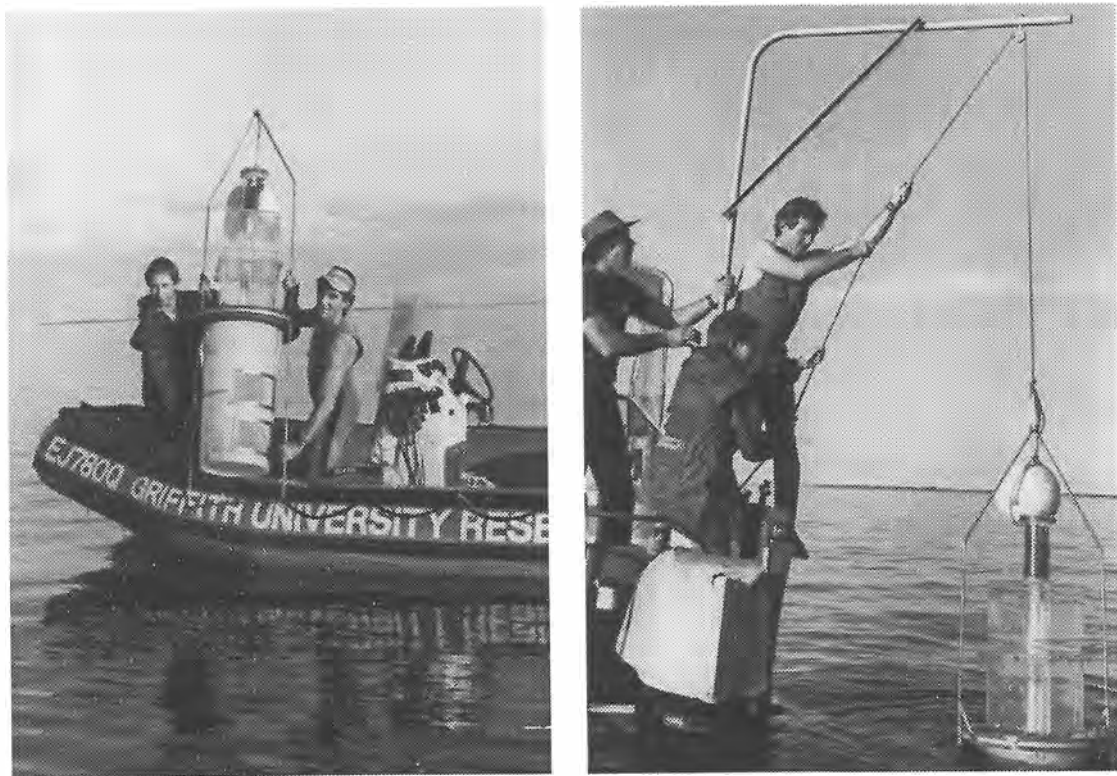


Figure 2. Compact enough to deploy from small boats but fragile and difficult to recover.

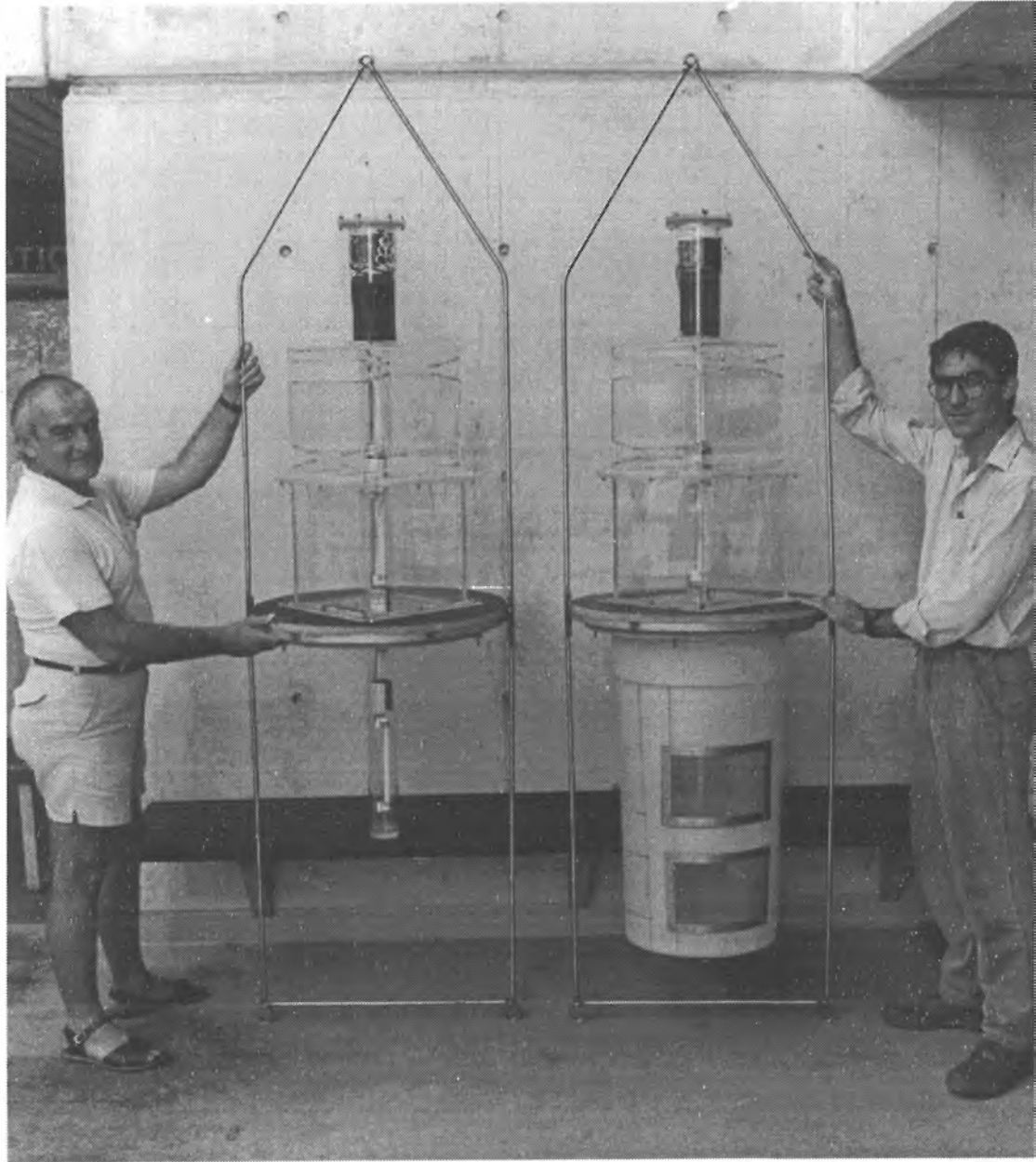


Figure 3. Shows the original prototypes that were in use in 1987.

RESULTS

ORIGINAL DESIGN

Fig.3 shows the trap design that was developed in 1984 and subsequently used as the template for development. Since the modifications have been evolutionary rather than revolutionary, the construction and operation of components that have not changed among versions may be described generically in the present tense.

There are no moving parts in the light-trap, in order to get the greatest reliability under continuous operation in the sea. The essential trap consists of three interconnected chambers with a white fluorescent light at the centre of each. Early prototypes used a bulky rechargeable lead-acid battery to power the 24 hr mechanical clock that determines the start and end of each fishing period. Once activated, the simple circuit described in Doherty (1987) controlled the action of the lights, which alternate in a sequence designed to draw larvae into and through the various chambers.

The two upper chambers were fabricated from clear perspex to allow the greatest emission of light into the surrounding water. Photopositive nekton drawn to the trap enter the top chamber through horizontal slits, previously of adjustable width, when the light in that chamber is on. After a fixed time period, this light is extinguished and the one in the middle chamber is switched on instead. Larvae migrate downwards within the trap, following this light, while new organisms continue to be attracted to the vicinity of the trap. After another cycle, the middle light is extinguished and the top one relit to begin the capture process again. At the same time, larvae in the middle chamber migrate to the third and deepest chamber in response to a light that is lit continuously while the trap is fishing. When the preset fishing period is completed, all lights are extinguished and the catch remains in the bottom of the trap until recovered. The lack of a closing mechanism means that there is nothing to prevent fish escaping but large numbers of fish are retained in the trap even when left uncollected for most of the following day. For this reason, the original design included a large 90 litre drum at the bottom to avoid oxygen demand problems and stagnation of the water when large biomass is attracted into the trap.

ALTERNATIVES

Since the initial prototypes were field-tested in 1984/85, there have been several attempts to construct smaller, simpler traps that would be cheaper as well as easier to make and handle. In an extreme reduction, Williams (1988) made very basic traps from pipe of 10-15cm diameter that was divided into two chambers by a baffle and had a constant light

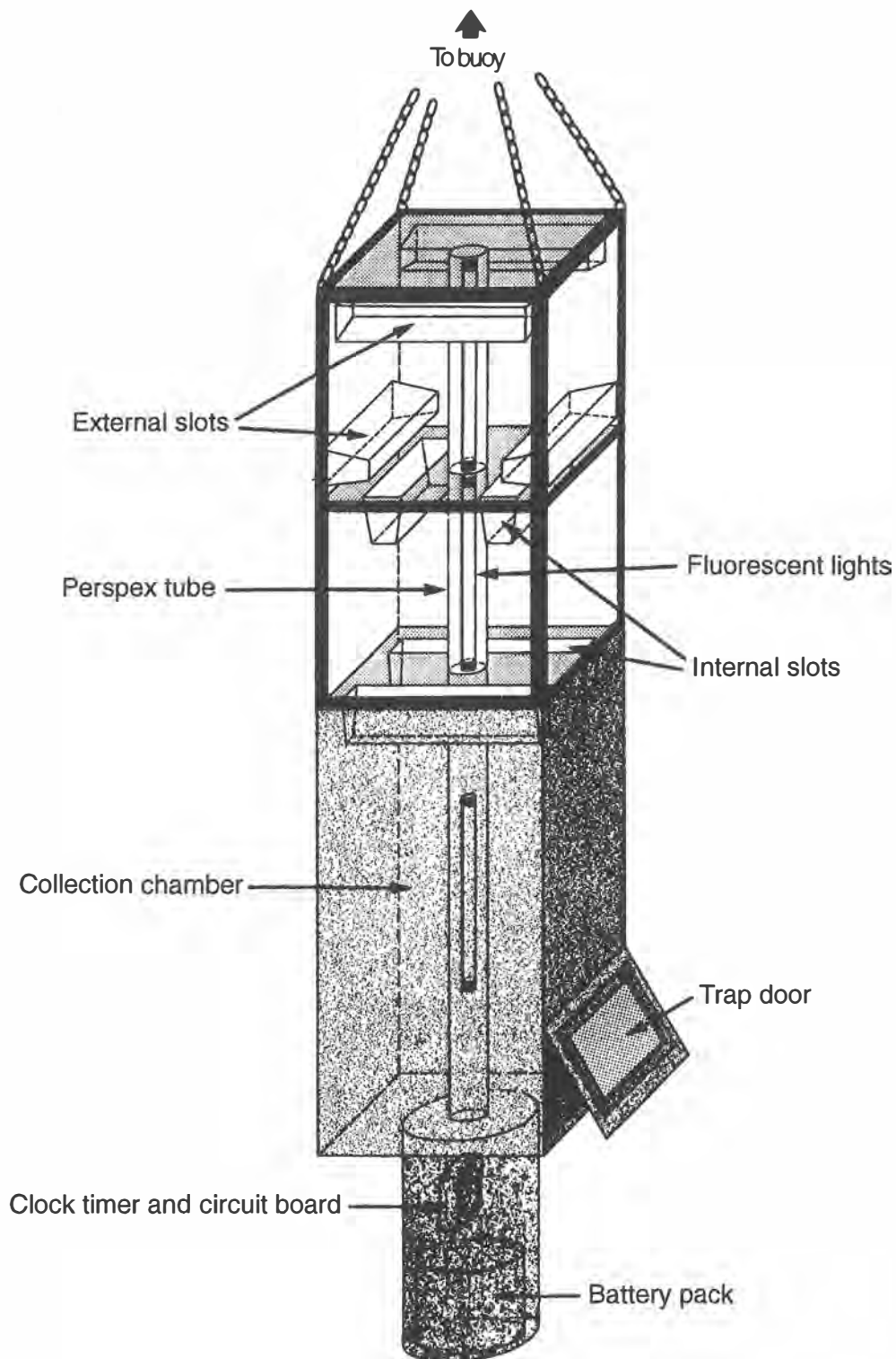


Figure 4. An alternative design built at AIMS in 1988, based on the principle of Doherty (1987), and used in drifting mode adjacent to Townsville (redrawn from Thorrold 1993a).

source (a diving torch) located in the bottom of the trap. Light was directed up through the trap and reflected to the outside by silver tape inside the top of the upper chamber. Replicate traps based on this design were deployed in the lagoon behind Ningaloo Reef, north Western Australia. Although Williams was able to collect pelagic juveniles from 13 families, the catch was dominated by gobies and the average nightly catch was less than impressive; fewer than two individuals per trap.

In 1986, I also built a substantially smaller light-trap by deleting the middle chamber, using 30 cm pipe for the collecting chamber and a quatrefoil design for entrances to the top chamber (Floyd *et al.* 1984). When deployed beside one of my original traps, this version performed very poorly by comparison, with catches typically <1% of those in the larger trap. It is not clear whether this poor performance was because entry was more difficult (unlikely with the more open quatrefoil entrances) or whether escape was easier. Regardless, both examples above showed that performance can be sensitive to the physical characteristics of the trap, which caused me to abandon thoughts of radical redesign.

Other alternatives can be found in various publications (e.g. Floyd *et al.* 1984, Gregory and Powles 1985, Kawaguchi *et al.* 1986, Brogan 1994) but all are smaller and appear to lack the sampling performance of those described in Doherty (1987). The nearest in performance terms was a modified version of my original three-chamber trap that was built by the AIMS workshop for use by a student who sampled fish and invertebrates from the Great Barrier Reef Lagoon in 1988/89 (Fig.4). This design was never tested explicitly against my larger traps but Thorrold's catches were generally low when compared with our own sampling in the same region between 1990/93 (c.f. Thorrold 1992, 1993a, Doherty 1995). The smaller trap offered the usual advantages of cheaper construction (sides were simply screwed to a metal frame of angled stainless steel) and easier handling. The most innovative aspect was the idea of inverting the light-tube so that the weight of the batteries was deployed most effectively at the bottom of the trap to produce a low centre of gravity (Fig.4). However, for regular sampling, this was also considered to be a weak point when recovering and processing traps in rough seas. Furthermore, Thorrold's design was never anchored and left overnight; a situation in which escapement may be very important (Doherty 1995).

Since the prototypes were known to be very productive, as indicated by large catches during extensive trials in the northern Great Barrier Reef, most of the development effort done under this project went into making traps easier and cheaper to produce, easier to handle in the field, more reliable, and more robust, without deviating too far from the principles embodied by the original design (Doherty 1987).

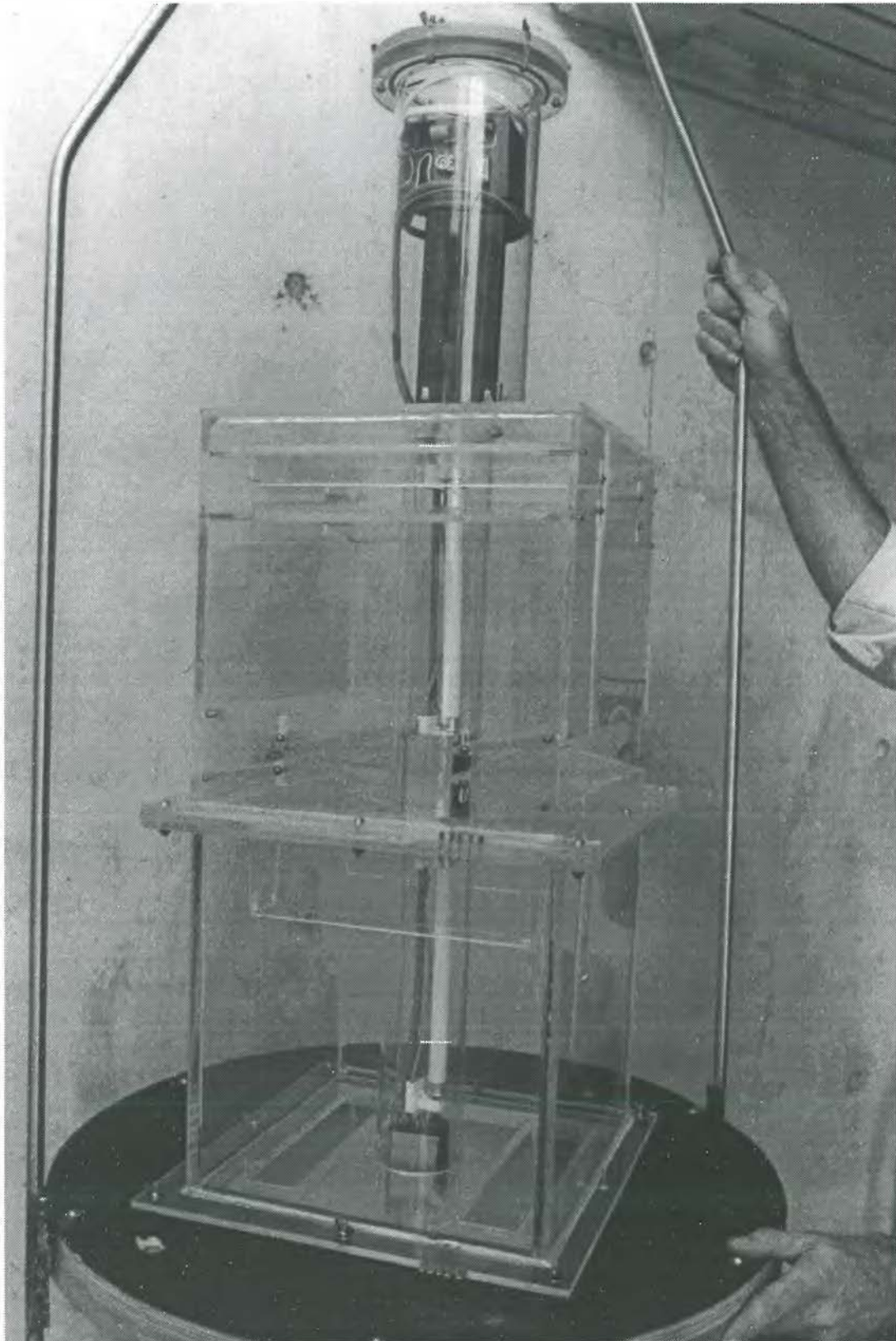


Figure 5. Close up of the upper chambers in the prototype trap, each with its own fluorescent light controlled by the circuitry seen at the top of the trap on the back of the mechanical timer, which was seated on top of a rechargeable battery.

CRITICAL ANALYSIS

Specific weaknesses in the prototypes shown in Figs 2,3,4 were identified as follows:

- (a) Although the traps could be handled by two persons and deployed from small boats (Fig.2a), recovery was more difficult and required a hoist with high clearance due to the overall length of the frame protecting the trap (Fig.2b). Except in smooth seas, it was difficult to control the trap while in the air during recovery, especially since it was necessary to lift the trap high enough to be able to remove pendulous weights from the bottom of the frame, which contributed vertical stability to the trap while in the water. The large size of the bottom drum and the substantial volume of retained water also made lifting difficult without the assistance of a block and tackle.
- (b) The housing for the sensitive electronic components was a particularly vulnerable area that had a high cost associated with failure. Originally, all parts were placed in a single container to minimise the number of pressure seals and to avoid electrical contacts exposed to saltwater. The extruded acrylic tube used to house the lights had a fairly low resistance to pressure, and deteriorated on exposure to strong sunlight. High internal stress apparently caused by the extrusion process was revealed by extensive crazing, which increased the failure rate. The glue joint between the two tubes of different diameter was easily fractured, especially because of the weight of the battery extending above the trap (Fig.5). Failure at any point in this housing was usually very costly with immersion causing total loss of all electronic components.
- (c) The electronic circuit was very simple (Doherty 1987) and consequently unstable. The main weakness was an inability to regulate the flashing sequence with precision, despite the inclusion of potentiometers for this purpose. Consequently, replicate traps were frequently flashing at different frequency with unknown effects on their fishing efficiency.
- (d) The rechargeable lead-acid battery was a liability in several ways. Power output was poor relative to the bulk of these batteries. The usual fishing protocol was for lights to be turned on for three widely-spaced periods, each of an hour, during the night and the working circuit drew 1-1.5 amps per hour. Contrary to the published specifications, batteries had to be changed every third day. This added a costly overhead to the handling time and increased the deterioration of the electronic components. Even without the ever present risk of seal failure after each opening, increased exposure to salt spray was inevitable as the changeovers were made in small boats. This led to corrosion and electronic failure.
- (e) The clear perspex chambers in the upper part of the trap were ideal for light emission but costly to fabricate since each contained many glued joints and fasteners (Fig.5). The variable width slits were particularly fiddly to construct and superfluous since trials established that catch rates were similar for all apertures between 1-2 cm.

DESIGN IMPROVEMENTS

Fig.6 contrasts the cross-sectional profiles of a prototype trap with the final design considered robust enough for most applications and suited to mass production. Essential improvements are as follows:

- (a) A change to fibreglass monocoque construction eliminates the need for an external protective frame and greatly reduces the height of the trap while retaining similar internal volumes in all but the lowest chamber. The reduction in size of the holding chamber by about 50% is compensated by larger mesh screens (0.5 mm) to allow for adequate ventilation and no decrease has been observed in the proportion of the catch that is taken alive. Initially, the fibreglass bodies were moulded as a single continuous taper; currently, the mould includes two steps and a flared lip. The latter provides anchorage for a steel band around the top of the trap which supports a swinging handle. The stability of the trap when suspended from this bridle has been improved by “glassing” a 5 kg flat sheet of lead into the bottom of the trap. The additional thickness of the floor makes the traps unbreakable with even moderately rough treatment on steel decks.
- (b) The fibreglass body is cast over a standard mould as a single solid piece. Apertures are cut on three sides into the top two chambers to allow the emission of light. One whole side of the trap body is deliberately left smooth which allows the trap to be pulled over the side of an inflatable boat and means that they can be recovered, if required, by a single person. The internal steps incorporated into the moulded shape provides adequate ledging to support the internal partitions that divide the three chambers. These partitions and those covering the holes cut into the fibreglass walls are all manufactured by vacuum moulding suitable shapes from sheet perspex. The partitions communicating between the chambers (i.e. the floors inside the trap) and all those in the top chamber, which communicate with the outside, have tapering slits of fixed width included in the moulded shapes. This moulding of complex shapes greatly reduces assembly time, as does avoiding steel fasteners (i.e. screws, nuts and bolts) wherever possible. Currently, the side panels of perspex are all attached to the smooth gel coat inside the trap by using a special double-sided tape obtained from 3M™. These panels when in place are adequate to secure the internal horizontal partitions without further fastening.
- (c) The perspex panels on the front of the trap are secured by wingnuts on stainless steel studs tapped into the trap body. This exception to the use of the double-sided tape used elsewhere allows removal of the front panels, which are mounted on the outside of the trap for this reason. Independent, easy access to each or all of the internal chambers is useful for removing fish and difficult invertebrates like cephalopods that can be seen inside but not washed through the trap.

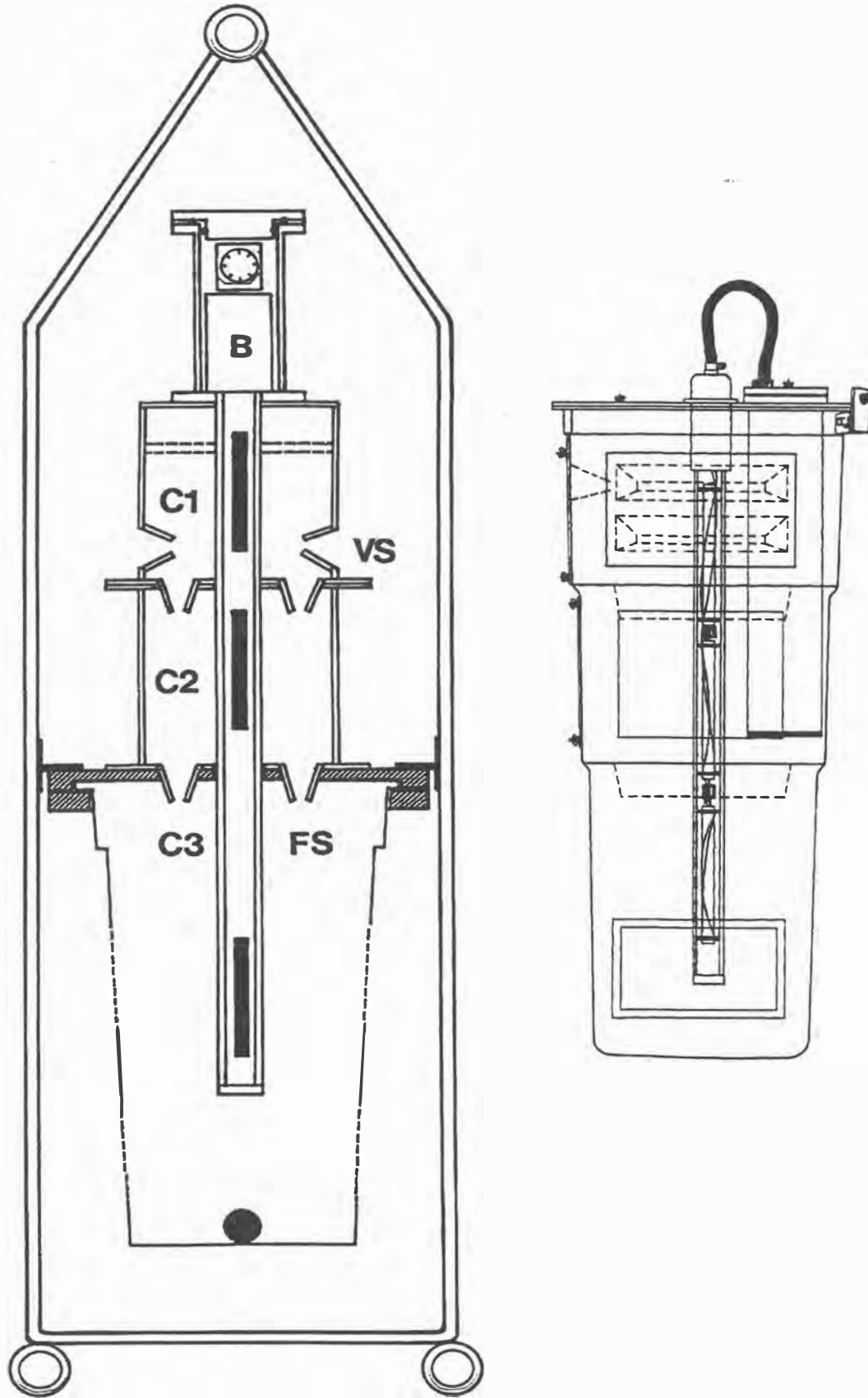


Figure 6. Initial and final versions of the submersible light-trap drawn to scale.

- (d) The electronics were redesigned completely by the AIMS workshop. The new circuit is substantially more complex (Fig.7) but utterly more reliable. To facilitate mass production, all components are mounted on printed circuit boards manufactured to our design. A large effort went into exploring alternative lighting, since the technology of fluorescents is very demanding. Trials were made with several incandescent designs but these did not produce adequate light nor the “white” light of the 6 Watt fluorescent tubes. Despite attempts to build the complete circuits, there was no method more cost-effective than cannibalising the necessary parts, particularly the electronic ballast, from Eveready Shed Lights™.
- (e) Power supply was enhanced by choosing disposable alkaline D-cells over rechargeable alternatives. The latter were investigated first and a large quantity of high quality, deep-cycling batteries were imported from the USA. These large batteries had relatively low storage and high failure rates after a small number of recharges. By comparison, the disposable cells store 10 Amps, which is released at 1.5 Volts. By placing four batteries in series, the output voltage was boosted to a maximum of 7.5 Volts. This slight over-voltage ensures good delivery of the full-rated power and no adverse effects have been noted on any of the circuitry, despite being designed for a nominal 6 Volts. By manufacturing a battery container that consists of four tubes, each containing four batteries in series, connected in parallel, an operator has the choice of filling some or all of the tubes to produce 10, 20, 30 or 40 Amp capacity. Since the enhanced circuitry still draws around 1 amp per hour of operation, the standard sampling protocol (3 hr per night) allows almost two weeks of operation between battery changes when all cylinders are filled. This means that batteries rarely have to be changed under poorly protected conditions with a consequent improvement in the life of the equipment.
- (f) The housing for the lights and power was redesigned. The lights are accommodated now in a separate tube from that containing the power supply, clock and circuit. The two tubes are connected by a flexible conduit sealed by hose clamps onto specially milled spigots. The separation into two parts has a practical benefit; small floods are much less costly, especially since they rarely breach the larger container which also holds the most expensive components. The lights are enclosed in cast not extruded acrylic tube, which has less internal tension, better pressure resistance, and is more stable under UV. The top of this tube is threaded so that it can be screwed into a female coupling milled from a solid PVC block and sealed with an internal O-ring. This allows easy access to the lights and fluorescent starters when replacing tubes or tracing faults, although care has to be taken that the wires do not compromise the O-ring seal when screwing the components together. The large container for the more expensive circuitry, clock and batteries, was made from blue pressure pipe with a machined acrylic lid sealed by twin O-rings. This design has been used extensively at 100 m depth without a single failure.

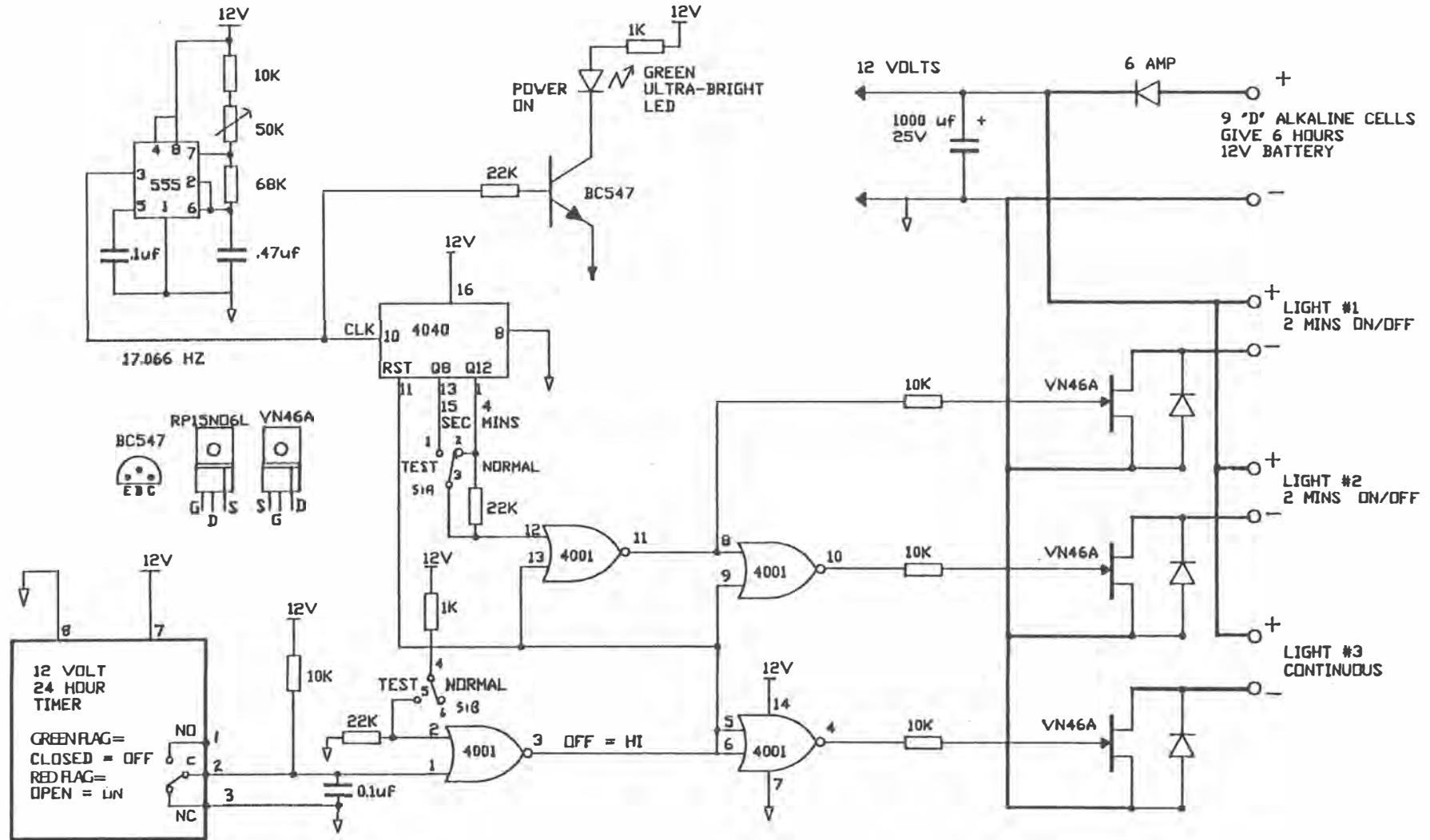


Figure 7. Circuit for control of the flashing lights. Unlike this version, the current design uses up to 20 alkaline cells which provides almost 40 hrs of continuous operation.

- (g) Unlike the original prototype, the container housing the power source and circuitry has been located inside the trap hard against the blank rear wall that emits no light. While the separation of the two containers eliminates the weak joint that existed when the two tubes were one, the internal placement of the battery container also lowers the centre of gravity of the trap. Despite their favourable power/weight ratio, the weight of 20 D-cells is considerable. This weight is placed at the bottom of the battery container where it is close to the centre of the trap. In addition, it provides a pedestal on which the circuit and then the clock sits. This allows the clock face to be seen through the clear lid, so that its time-keeping can be checked on every occasion that the trap is sampled.
- (h) Additional features were built into the new circuit. One consisted of a bright LED that is visible beside the clock and indicates whether adequate power is reaching the circuit. This light is checked every time that the trap is cleared and simple faults (like loose connections or bad batteries) are usually identified in this manner without a lost sampling opportunity. The second, more important, development has been the addition of a test switch. Once power is connected to the circuit, holding the test switch “on” overrides the clock, forces the lights on, and drives the circuit (i.e. the flashing sequence) at about 10 times the normal speed. In test mode, the full operation can be simulated at any time and is done both before and after every deployment. As a result, faulty gear is not committed to the water. Likewise, a pass on this test at the conclusion of sampling (typically 10 or more days) gives great confidence that the trap has operated correctly during the whole period.

RESEARCH APPLICATIONS

The development of the traps to the state described above was completed in 1989, shortly after I transferred from Griffith University to AIMS. Much of the physical redevelopment had been done at the University although the electronic circuit was completely redesigned by technical staff in the AIMS electronic workshop. On arrival, the resources of the AIMS mechanical workshop were used to mass produce around 50 traps (Fig.8). My decision to leave the University was largely motivated by a desire to use the unique resources of AIMS, especially its vessels, to exploit this new technology to its fullest potential and to evaluate the ability of light-traps to contribute novel solutions to practical problems in tropical fisheries.

In 1989/90, concentric rings of traps were deployed at distances ranging from 100 m to 6 km around one small coral reef (Helix) located 60 km offshore from Townsville. This array was sampled over five consecutive new moons encompassing the full spawning season for most reef fishes. Traps were anchored at different depths in the water column (Fig.9) and this showed that most species are in the surface layers at night.



Figure 8. Mass production of the new light-traps in the AIMS mechanical workshop.

The far- and near-field comparisons around Helix showed that the larvae of reef fishes are transported between reefs, which has implications for the management of reef resources; in the absence of self-recruitment, “sustainability” must be considered at a regional scale rather than a local one. The catches also showed that pelagic juveniles apparently detect reefs at some distance and migrate to them across the mainstream current. This behaviour results in high concentrations of presettlement fish in the near-field, which are maintained until the fish are competent to colonise benthic habitat. Evidence that this orientation is active (rather than a reflection of hydrodynamics) is indicated by the inverse pattern in some holoplanktonic species (e.g. nomeids) that appear to avoid near-reef water.

In 1990/91, light-traps were deployed for the first time in an untethered mode (exactly as Fig.9 except with lighted buoys replacing anchors). Using a ship with 24 hr capabilities, drifting traps were deployed at 15 stations along a 160 km cross-shelf transect that covered open-water habitats from the coast to the Coral Sea (Doherty 1992, 1995). Simultaneous sampling was done with traps anchored in the lee of four small reefs of similar size but different cross-shelf position on the outer half of the shelf. The purpose of this cross-shelf monitoring was to identify the nursery grounds of a range of taxa including exploited species. In 1991/92, the continuous improvement in water proofing allowed sampling near the bottom to a maximum depth of 100 m, as well as at the surface, which revealed some additional species as well as ontogenetic migrations in others. These surveys received marginal but critical funding from a second FIRDC grant (89/28); their outcomes are described in more detail in a separate report (Doherty 1995).

In 1992/93, a third project was undertaken with support from FRDC as part of a multi-institutional investigation into the dominant food fishes of the Great Barrier Reef (Project 90/18). As part of this large project, extensive monitoring of larval supply was done for three consecutive seasons off Arlington and Green Reefs in the Cairns Section of the Marine Park with special emphasis on the common coral trout, which is the single most valuable fish extracted from the GBR. Like other serranids, this species has cryptic juveniles that cannot be counted until they are almost 6 months of age. Over the three seasons, our sampling collected >500 pelagic juveniles of this fish and their replenishment was described for the first time (Appendix 1: Doherty *et al.* 1994). The length of pelagic development, early growth rates and links with reproduction were also established. The latter showed that recruitment among years was much more variable than reproduction and strong recruitment signals have since been detected in the age structure of trout populations off Townsville (Brown *et al.* 1994). Currently, I am analysing the other components of the catch from these years looking for evidence of changes correlated with environment.

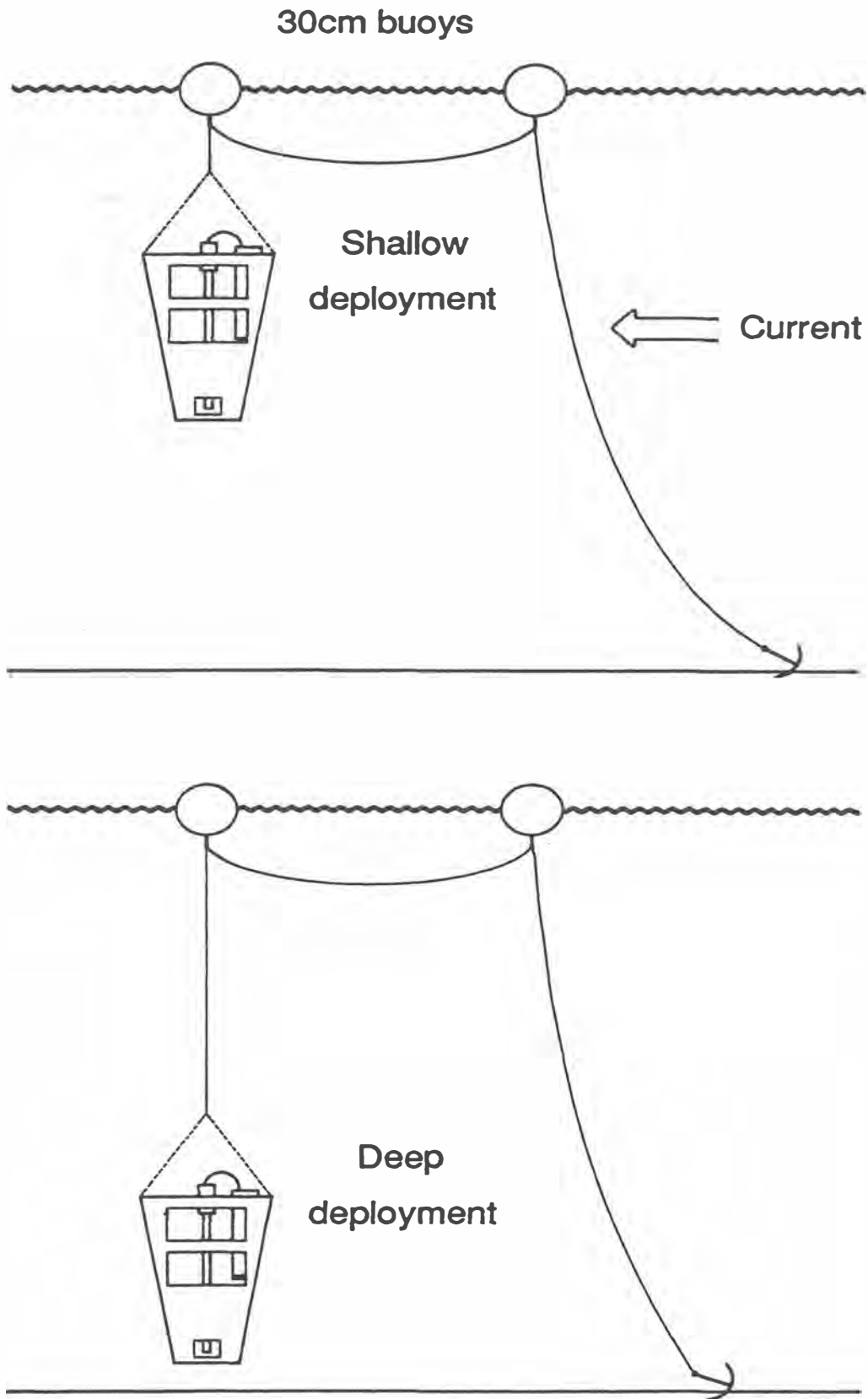


Figure 9. Typical deployments for anchored traps fishing at different depths in the water column. Drifting deployments look very similar except that the anchors are replaced by marker buoys with lights and flags.

In addition to monitoring larval supply, there were several transfers of live pelagic juveniles to the Northern Fisheries Centre (QDPI) where some coral trout were maintained in captivity for over a year. This contrasted with a complete failure at NFC to obtain juveniles from spawning captive broodstock and allowed some experience to be gained of serranid culture without first having to close the lifecycle.

The three projects described above are given as examples of the type of strategic basic research that has been done at AIMS using light-traps in order to understand the early life histories of tropical marine fishes, especially those of commercial importance (Objective 3). More detail of the research outcomes can be found in two reports (Brown *et al.* 1994, Doherty 1995) and a large number of scientific publications listed below.

FUTURE DIRECTIONS

In addition to these applied projects, there has been other research with more fundamental objectives such as predicting the dispersal trajectories of larval fish given data on oceanographic circulation. In an archipelagic system like the Great Barrier Reef, understanding the larval exchanges (connectivities) among reefs is crucial to understanding the large-scale dynamics of fish stocks and their resilience to fishing. Although this will certainly be a long-term project, its solution will be just as applicable to important exploited species like coral trout as to the rest of the reef fish community. Currently, light-traps are playing a pivotal role in this type of research by providing the feedstock of data for the hydrodynamic modelling. Eventually, they will be the tool of choice for large-scale empirical tests of the model predictions.

Further development of the light-trap technology is also continuing, albeit by way of slow refinement, to a well-tested and proven design. The major change under investigation at the moment concerns a completely new approach to the control of the lights. Greater use will be made of IC technology to replace some functions (e.g. the DC mechanical clocks) and to upgrade others. Onboard memory will be used to monitor the performance of the trap during its operations and to report on several conditions (e.g. low power, faulty lights, etc). Instructions to the controller and interrogation will be done through a standard RS-232 interface and laptop computer. The most significant effect will be the possibility to instruct the chipset to vary the daily routine during a single deployment, which will for the first time allow the trap to track the tidal cycle, potentially reducing another source of variation on the catches. At a more practical level, the downloading of a standard program to all traps will overcome the small level of operator error that occurs inevitably when a small team is trying to get a large number of traps into the water in a short period of time.

EXTENSION

While I don't anticipate that the data sets collected since 1989 will be fully published for several years, this does not mean that there has not been substantial output along the way. Reproduced below is an incomplete list of more than 20 scientific publications by myself, my students, or those whose research has been influenced directly by our progress since 1987. To date, there have been nine student theses based wholly or in part on this technique and more are in progress. Several of these involve students or collaborators outside Australia.

In 1990, the Australian Research Council conducted an external review of the effectiveness of their funding of ecological research in Australia and that panel ranked our work as some of the most influential in the world, responsible for a new perspective on tropical fish population dynamics (this review is available on request). As the technology has spread, so the applications have progressed beyond simple monitoring. One student project has used traps to recover live pelagic juveniles for laboratory trials of swimming performance (Stobutzki and Bellwood 1994). Last summer, another team went further and released live juveniles back into the ocean, where they were tracked by divers to establish their behaviour (Leis *et al.* in press). Finally, light-traps are being used at this time by an ARC-funded research team from James Cook University to collect large numbers of pelagic juvenile reef fish in the hope of finding some that were chemically tagged as embryos in order to quantify the relative importance of local recruitment.

Extension to industry and/or community has also been strong. To date, we have collaborated on short-term projects with the CSIRO Division of Fisheries, South Pacific Commission, Japanese Far Seas Fisheries Laboratory, InterAmerican Tropical Tuna Commission, and the Sydney Water Board. The possibilities for using light-traps in aquaculture and reef enhancement are being pursued in conjunction with the International Centre for Living Aquatic Resource Management (Doherty 1994). In July this year, representatives from seven Asian and Pacific nations met at AIMS to plan a coordinated multilateral study into the seasonality of fish recruitment throughout this region. The sampling tool of choice for most participants was the light-trap because of its broad taxonomic coverage, including exploited species, and the standardisation of effort.

Finally, the light-traps have had considerable exposure in the media and through public participation events (e.g. Open Days at both institutions, Townsville Fishermen's Fair). At AIMS, they have become part of a permanent display in the public area and demonstrated to many visitors (Fig.10). In all of these promotions, the support of the Corporation and its predecessor (FIRC) has been gratefully acknowledged as assisting the development of this technology.

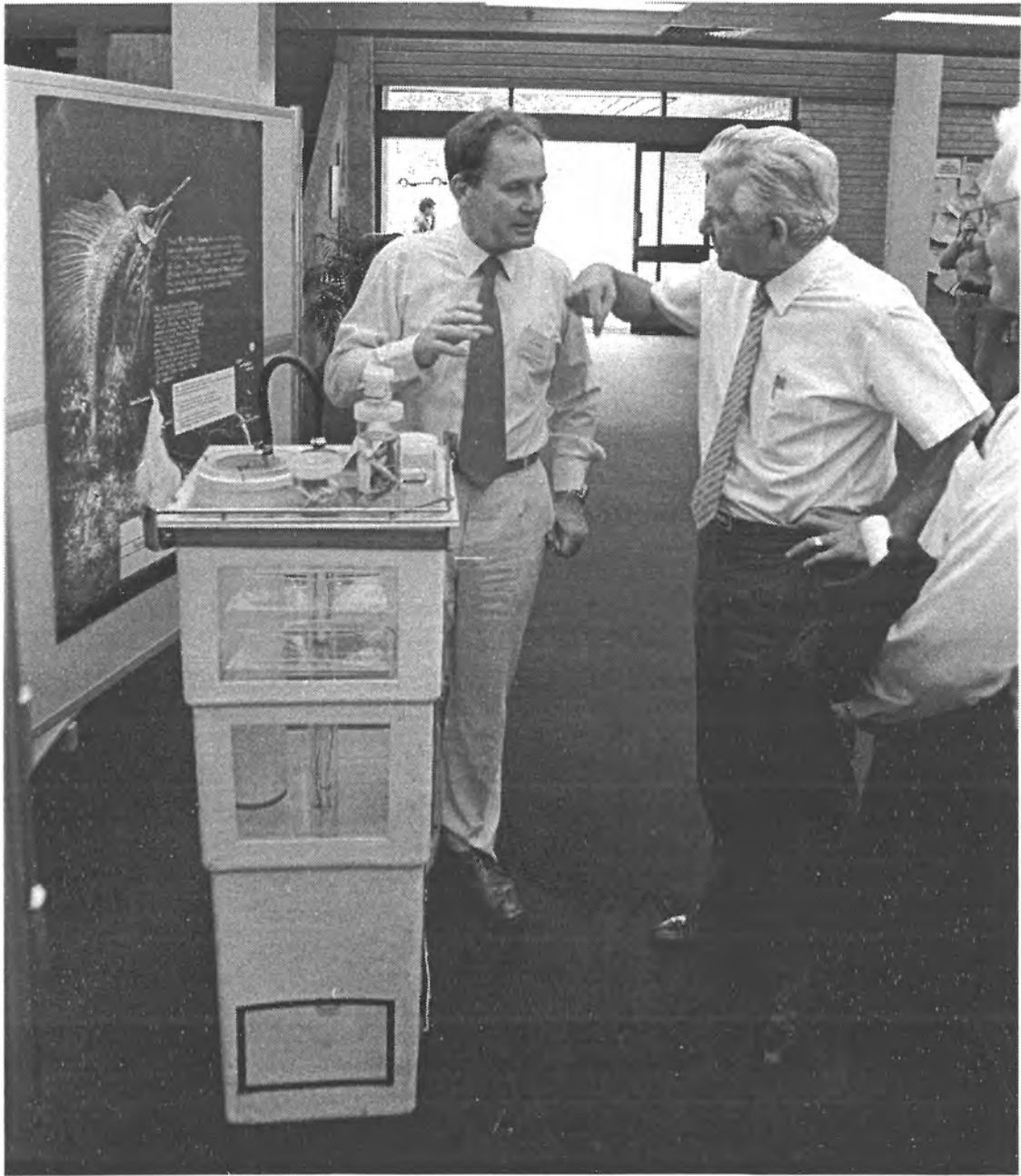


Figure 10. Dr J.T. Baker, Director of AIMS, and the Prime Minister of Australia, Rt. Hon. R.L.J. Hawke, discuss light-traps.

SELECTED OUTPUTS

SCIENTIFIC PUBLICATIONS AND REPORTS

While the following list of scientific publications and reports is not claimed to be a direct result of the FIRDC funding of this project, those that are not were nonetheless influenced by the developments laid down in this report.

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- Leis, J.M., Sweatman, H.P.A. and S. Reader (in press) Field studies of behaviour in coral reef fish larvae. *Mar. Freshwater Res.*

- Leis, J.M., Trnski, T., Doherty, P.J. and V. Dufour (in press) Maintenance and replenishment of coral reef fish populations in the enclosed lagoon of Taiaro Atoll, Tuamotu Islands: evidence from the fish eggs and larvae. *Coral Reefs*
- Meekan, M.G., Milicich, M.M. and P.J. Doherty (1993) Larval production drives temporal patterns of larval supply and recruitment of a coral reef damselfish. *Mar. Ecol. Prog. Ser.* 93: 217-225
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- Moltschaniwskyj, N.A. and P.J. Doherty (1995) Cross-shelf distributions of tropical juvenile cephalopods sampled by light-traps. *Mar. Freshwater Res.* 46: 707-714
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- Thorrold, S.R. (1992) Evaluating the performance of light-traps for sampling small fish and squid in open waters of the central Great Barrier Reef Lagoon. *Mar. Ecol. Prog. Ser.* 89: 277-285
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Thorrold, S.R. and M.J. Milicich (1990) Comparison of the larval duration and pre- and post-settlement growth in two species of damselfish, *Chromis atripectoralis* and *Pomacentrus coelestis* (Pisces: Pomacentridae) from the Great Barrier Reef. Mar. Biol. 105: 375-384

Thorrold, S.R. and D.McB. Williams (in press) Meso-scale distribution patterns of larval and juvenile fishes in the central Great Barrier Reef Lagoon. Mar. Ecol. Prog. Ser.

Wolanski, E. and P.J. Doherty (1995) Fate of coral eggs and fish larvae around coral reefs. ICES Statutory meeting

RELEVANT STUDENT THESES

All of these theses have been based on research done with light-traps after Doherty (1987) or on material collected from these devices.

Michael Brogan PhD (Seattle)
Phillip Light PhD (James Cook)
Mark Meekan PhD (Griffith)
Maria Milicich PhD (Griffith)
Julie Murdoch MSc (James Cook)
Kylie Pitt BSc(Hons) (James Cook)
Christine Schmit BSc(Hons) (Munster)
Ilona Stobutzki BSc(Hons), PhD (James Cook)
Simon Thorrold PhD (James Cook)

SELECTED PRESENTATIONS

For reasons of space, this list is restricted to the author's contributions.

ACRS Annual Scientific Meeting, Sydney Uni, November 1987
Second National Workshop on the Ecology of Coral Reef Fishes, Sydney, Nov 1987
CSIRO Division of Fisheries, Marmion, December 1987
AMSA Regional Meeting, Brisbane, June 1988
Sixth International Coral Reef Symposium, Townsville, August 1988
ACRS Scientific Conference, Brisbane, July 1989.
ASFB Scientific Conference, Townsville, August 1989

Boden Conference, Thredbo, February 1990
42nd Tuna Conference, Lake Arrowhead, California, May 1991
Oregon State University, Zoology Department, May 1991
ASFB Larval Biology Workshop, Hobart, August 1991
Sydney University, Zoology Department, October 1991
ICLARM Workshop on Reef Resource Management, Townsville, March 1992
Seventh International Coral Reef Symposium, Guam, July 1992
Universite de Perpignan, June 1994
International Larval Fish Conference (2 talks), Sydney July 1995

ACKNOWLEDGMENTS

Many persons have supported this research during the life of the project, particularly the staff of the workshops at AES, Griffith University (N. Allaway, R. McPhee, B. Pollock) and AIMS (I. Ashworth, J. Collingwood, E. Gill, J. Small, R. Smith) for making and maintaining the light-traps; the Marine Operations Section of AIMS and crews of the RV LADY BASTEN, HARRY MESSEL and SIRIUS for providing excellent and safe working conditions under conditions that were frequently hazardous; the numerous volunteers who helped to collect and/or process the samples. In addition, I thank J. Carleton for all aspects of our collaboration; H. Sturney for training and supervising the sorting team; K. Kavanagh and K. Handley for photography; S. Clarke and T. Simmonds for graphics; C. Cansfield-Smith and L. Howlett for production assistance. Thank you all.

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LIGHT-TRAPS: SELECTIVE BUT USEFUL DEVICES FOR QUANTIFYING THE DISTRIBUTIONS AND ABUNDANCES OF LARVAL FISHES

Peter J. Doherty

ABSTRACT

An inexpensive automated light-trap has shown great potential as a tool for quantifying spatial and temporal patchiness in assemblages of larval fishes. Automation means that *simultaneous* samples can be collected within narrow time-windows from multiple locations. With the right sampling design, synoptic maps of larval abundance can be produced with a resolution equivalent to the density of traps. Because the traps do not kill like other techniques, it is far easier to resolve the distributions of individual species and the live larvae can be used for further experimentation. Some data from Lizard Island, northern Great Barrier Reef, are reported to demonstrate the utility and the limitations of this technique.

In a companion paper in this volume (Doherty, 1987), I hypothesized that larvae of coral reef fishes are distributed in the sea in meso-scale patches with dimensions between 1-100 km. This hypothesis was formulated after studying the patterns of spatial and temporal variability shown by newly-recruited fishes. My desire to test the hypothesis of meso-scale patchiness in pelagic assemblages led to interest in developing light-traps as an alternative to traditional sampling methods.

There were three reasons why I did not wish to sample pelagic assemblages at this scale using the conventional techniques of either towed plankton nets or plankton pumps. First, because few programs can justify multiple ships, there has to be an undesirable choice about the distribution of sampling effort. Given that it takes time to sample one location and steam to another, it is rarely possible to resolve large and small scale pattern in the same sampling program. Most programs have to choose between a few widely-spaced samples with minimal resolution of fine-scale pattern or more closely-spaced samples with minimal resolution of large-scale pattern. The logistics of sampling with shipborne devices generally preclude simultaneous resolution of pattern at both scales. Second, the logistics of sorting and identifying plankton samples impose severe limits on the total number of samples that can be processed. Third, it takes highly skilled personnel to identify the larval stages of marine fishes and identifications often have to be truncated at familial or generic levels with a corresponding loss of information. These problems are compounded in tropical environments because of the great species richness of reef fishes and the scarcity of taxonomic treatises on tropical larval fishes.

When seeking an alternative sampling strategy, I started with the knowledge that fish larvae can be attracted to lights at night (Doherty, 1983; Leis and Rennis, 1983; Thresher, 1984; Victor, 1986). Usually, this is done by netting larvae from around a light suspended at the surface but may include netting around submerged lights (Smith et al., 1987). These techniques are no more suited to resolving spatial pattern than pumps or towed nets because a platform and an operator is still required at each sampling location. My aim was to construct an inexpensive automated trap capable of giving reliable estimates of the relative abundance of larvae among different places and times. In this paper, I report on my first attempt to produce such a device.

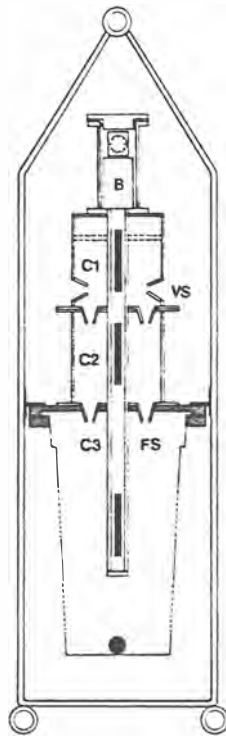


Figure 1. Longitudinal section of a light-trap showing the three stacked chambers (C1–C3) and the central core containing lights (solid bars). The upper part of the core contains a battery (B) and a clock/timer. Fish enter through horizontal slits of variable width (VS) and two sets of vertical slits of fixed width (FS). The diagram is drawn to scale and the top chambers are each 30 × 30 cm.

MATERIALS AND METHODS

Figure 1 shows a cut away view of the prototype design. This device consists of three vertically-stacked chambers which are connected internally by tapered slits. The upper two are made of clear plexiglass; the third is a 90-liter PVC drum which acts as a final reservoir for the sample. The lights and control mechanisms are encased within a central vertical core produced from a cylinder of plexiglass. At appropriate positions within this tube, there are three fluorescent tubes (6-W) each of which casts a white light into one of the three chambers. The upper part of the central core is wider and contains a rechargeable lead-acid battery (12-V, 6.5-A.h), a 12-V DC mechanical timer and a small circuit board which controls the operation of individual lights.

The mechanical timer consists of a 24-h clock which is run by a 12-V DC stepping motor and can be set to real time. Around the dial of the clockface is a serrated rim on which pegs can be inserted to toggle a mechanical switch. The closest spacing permitted by the graduations on this rim corresponds to a 15-min interval between opening and closing of the switch.

On the back of the timer there are two input terminals (E, F) which deliver power to the clock and three other terminals (X, Y, Z). The time switch alternately closes the circuit between X-Y and Y-Z. When X-Y is closed, power is delivered directly to the bottom light and indirectly (through the printed circuit) to the other lights (Fig. 2). Terminal Z is not used so that when the time switch closes Y-Z, the lights and circuit board are disconnected. Fishing begins when X-Y is closed again and power is restored to the lights.

The circuit board contains a small IC chip with an astable output at pin 3 (Fig. 2) which toggles a relay switch. Depending on its position, the relay directs power either to the light in the top chamber or to the light in the middle chamber. Both cannot be on at the same time. The frequency of switching depends on the values of several resistors and capacitors in the circuit and this can be regulated to some extent by the variable potentiometer (R3). The circuit shown in Figure 2 allows the top and middle lights to alternate on a frequency ranging from 3–8 min. The bottom light is lit whenever X-Y is closed.

At the start of a hypothetical fishing period, the top and bottom lights are lit. The top light shines through the transparent walls of the upper chamber and casts a pool of light of at least 5 m radius around the trap. Photopositive organisms approach the light and enter the trap through four hori-

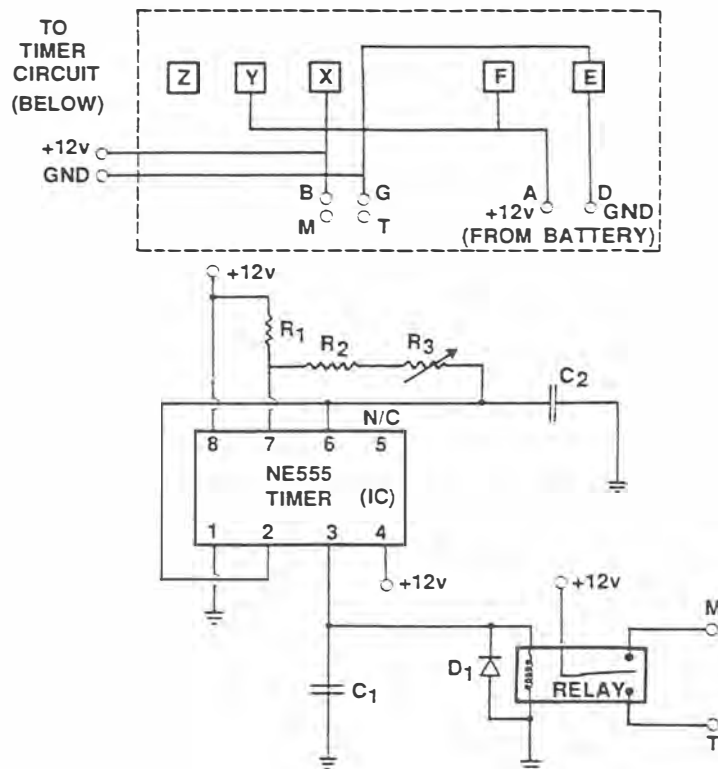


Figure 2. A circuit diagram for control of the (T)op, (M)iddle and (B)ottom lights. The values of R1–R3 (all 0.25-watt) and C1–C2 were 10 KOhm, 3.3 MOhm, 2 MOhm, 47 KpF and 100 μ F respectively. The relay was rated at 1 amp. See text for all operational details.

zontally positioned slits. The width of these tapered slits is fixed at any given time but can be altered from 0–5 cm. After a fixed period, the circuit switches power from the top light to the middle one. Organisms in the upper chamber can follow this by passing through tapered slits of fixed width (2 cm) let into the floor of the upper chamber. The middle light serves two purposes; it draws organisms deeper into the trap and it continues to advertise the trap to passing organisms which explains why it is also transparent. When power is directed again to the top light, new organisms enter the upper chamber and those in the middle chamber migrate to the lower one through another set of tapered slits. In this way, organisms gradually accumulate in the lower chamber until the timer switches off all lights.

After the lights are extinguished, the trap remains open. No satisfactory way of closing the trap has been invented that would not involve a considerable increase in the complexity, cost and unreliability of the trap. The effective retention of organisms in the lower chamber depends on (1) the difficulty of returning through three sets of tapered slits without light, and (2) the relatively large volume of the lower chamber compared with the size and position of the exits. The sides of this chamber contain four holes (each approximately 600 cm²) covered by 500- μ M stainless steel mesh which permits considerable flushing of the water in the lower chamber. The water quality in this chamber is important since with the right conditions captured organisms can be kept alive until the trap is recovered during the following day.

The three chambers are surrounded with a rigid frame of 10 mm stainless steel rod which provides secure points of attachment above and below the trap. The former allows the trap to be suspended from a 300-mm polystyrene float. The latter allows weights to be suspended below the trap providing a measure of vertical stability. These weights were adjusted so that the whole rig was just positively buoyant. The advantage of near neutral buoyancy is that the motion of the trap is less violent in a heavy sea. This was considered important since the initial sampling was done near the surface with the slits in the upper chamber positioned at approximately 1-m depth.

Each trap was attached by a 5-m rope to another surface float which was anchored to the bottom. On the trap end, the rope was connected to the steel frame by a stainless steel snap shackle which allowed the trap to be disconnected quickly from its mooring and lifted aboard the boat. This arrangement for mooring had another advantage in that the shackle fell under its own weight to a position

Table 1. Comparison of catches of fish larvae from light-traps on two sides of Lizard Island (data presented in order of decreasing abundance at the windward site)

Families	Windward site		Leeward site	
	Species	Individuals	Species	Individuals
Pomacentridae	15	1,274	11	80
Gobiidae	1	24		
Syngnathidae	1	19	1	3
Lethrinidae	2	18		
Apogonidae	5	16	2	9
Scorpaenidae	1	16	1	1
Blennidae	2	14	2	3
Carangidae	2	12		
Monocanthidae	1	12		
Holocentridae	2	11		
Scomberidae	1	5		
Chaetodontidae	2	3	1	1
Mullidae	2	3	2	2
Sphyraenidae	1	3		
Balistidae	2	2		
Muraenidae	1	1		
Nemipteridae	1	1		
Tetraodontidae			1	2
Unidentified (includes 20 pre-flexion larvae)	?	13	?	11
Totals	42	1,447	21	112

about halfway down the steel frame. With the horizontal pull being applied at this point, the trap maintained a vertical orientation regardless of the speed of the surrounding water.

The complete device was light enough to pull from the water using a small davit mounted on the side of a 6-m vessel. The large openings in the lower chamber allowed water to drain instantly from the trap as it was being lifted leaving a residual volume of 5 liters. Once swung inboard, organisms were removed from the lower chamber through a 35-mm aperture that was stoppered with a cork.

Field Tests.—Four prototypes built to the design above were tested in the field at Lizard Island (14°14'S; 145°27'E), northern Great Barrier Reef. This is a relatively large and high continental island which interrupts the mainstream currents (Leis, 1986). Pairs of light-traps were anchored at the surface approximately 1 km offshore on the windward and leeward sides of the island where the water columns were 20-m and 12-m deep, respectively.

Because there was no way to predict how catches might be affected by the time of night or the tidal state, each trap was programed to fish several times a night (2100–2200 h, 2400–0100 h, 0300–0400 h). Thus, the nightly catches represent the total accumulation of organisms caught during these three periods and there is no way of distinguishing among the contributions of individual periods. This lack of resolution was considered acceptable in the pilot experiment since the most important test was whether the traps would catch any larval fishes at all.

Each trap was serviced daily for 25 days during January 1986. On most days, this simply required that the trap be visited and emptied, taking <10 min at each trap site. Every third day, the batteries were exchanged for fresh ones and this added a further 10 min to the time spent handling each trap.

RESULTS

The pilot experiment showed that light-traps sample both fish larvae and invertebrate zooplankton. In 25 days, the traps captured 1,559 fish larvae of which >98% were identified subsequently to 46 species (Table 1).

While the ability to identify most of the catch compares positively with other techniques, this was possible only because light-traps are selective. Most of the fishes caught with this method were either competent or near-competent to settle into reef habitats when removed from the traps. In other words, the catches were

dominated by relatively old, mature larvae. Because they were alive when removed from the trap, it was an easy matter to transfer unknown forms to aquaria and grow them up to recognizable juveniles.

During this relatively brief trial, the traps caught 46 species of fishes belonging to 18 families (Table 1). The catches included slender elongate individuals (Sygnathids), squat forms (Tetraodontids), pelagic species (Scombrids, Carangids), benthic species (Pomacentrids, Chaetodontids), and commercially valuable species (Lethrinids). The traps also yielded a wide variety of invertebrate zooplankton including holo- and mero-planktonic forms (Fig. 3).

The total catch of pre-settlement fish from the windward site declined exponentially but steadily throughout January 1986 despite great variations in the prevailing physical conditions (tidal states, sea states, moon rise and cloud cover). There could be a number of explanations for this decline ranging from movement out of the area, settlement into benthic habitats or changing efficiency of the light-traps. The parallel changes recorded in the abundance and diversity of the invertebrate component of the catch support the first and last hypotheses.

The same pattern was not repeated in the catches from the leeward side of the island even though most of the species taken from there were common to both locations (Table 1). The total catch of fish larvae was an order of magnitude lower on the protected side (species richness was half) and the daily catches from there were so low that no temporal trends were discerned. These differences and species-specific patterns will be elaborated elsewhere.

DISCUSSION

Light-traps are not an original concept. Indeed, the literature on this subject is surprisingly large. While the entomological precedents are well established, light-traps of a variety of designs have been used also in aquatic habitats to sample invertebrates and larval fishes (reviewed by Faber, 1981; see also Gregory and Powles, 1985). My ignorance of this literature during the construction phase of this project explains why my traps turned out quite differently from previous designs.

From the outset, I imposed a number of conditions on the design of the light-traps. In descending order of importance, these were: (1) an ability to attract and retain a representative sample of larval fishes from the surrounding water, (2) an ability to operate without the need for human surveillance to enable concurrent sampling, (3) high reliability under a variety of conditions and over extended periods of use, and (4) the lowest possible cost per unit.

Each of these constraints defined one or more characteristics of the final product. After watching the behavior of larvae around lights, I decided that traps and trap entrances would have to be large and lights relatively bright. The desire to take samples simultaneously meant that automation was essential. The desire to resolve spatial pattern as accurately as possible from fixed locations meant that sampling had to be confined to narrow time windows and synchronized to real time. On the other hand, the competing desires to keep reliability high and costs low indicated a minimum of moving parts and waterproof seals. This was the reason for not having an opening/closing mechanism that could control access to the trap. The inability to close the trap led to the decision to draw individuals into a relatively large and complex trap from which escape would be difficult. The problem of waterproofing was simplified by housing all of the components "at risk" within a self-contained module that could be sealed with double O-rings at its one entrance.

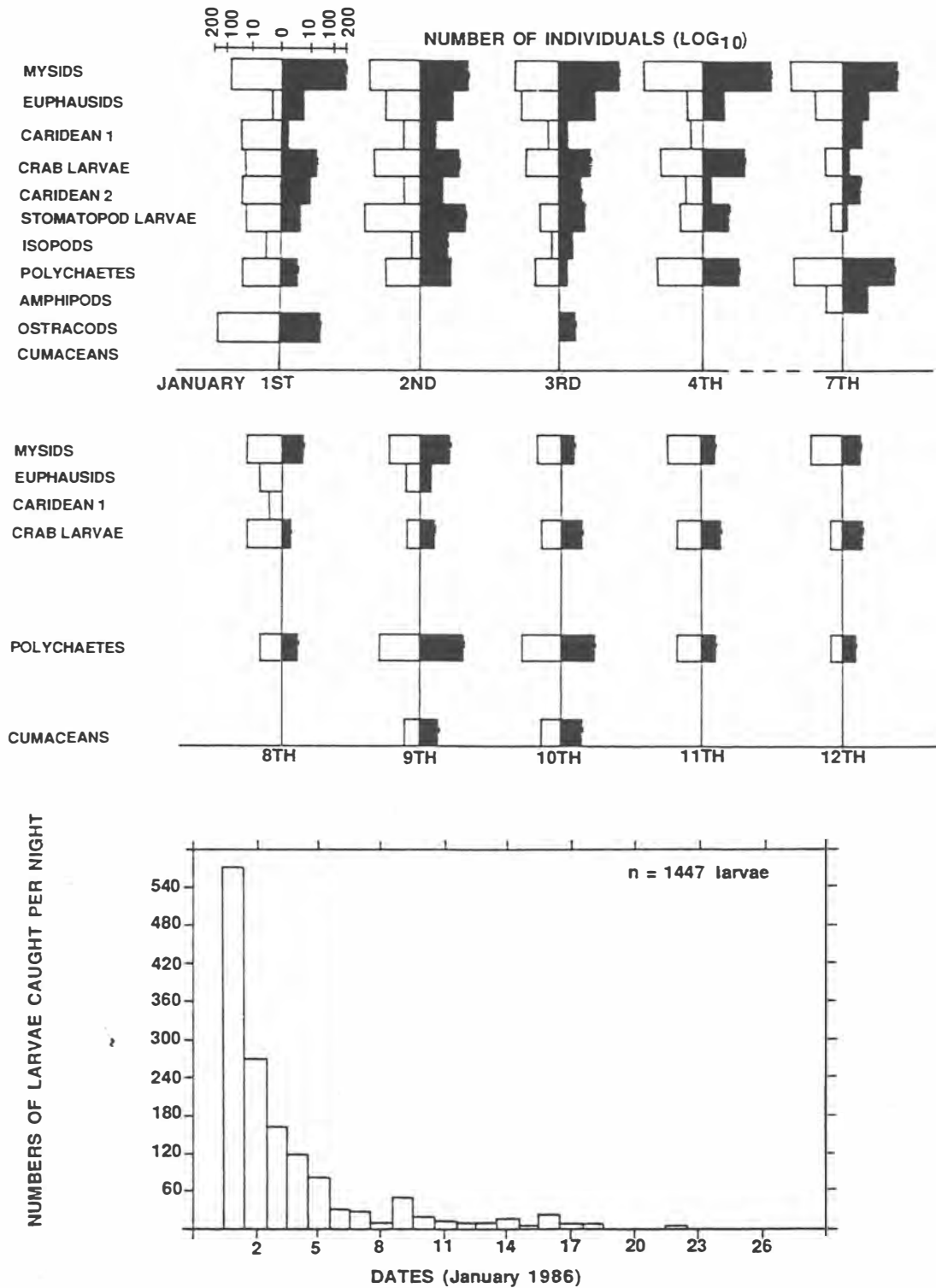


Figure 3. Nightly catches of photopositive invertebrates and ichthyoplankton from two light-traps anchored on the windward side of Lizard Island. The catches of invertebrates from the two replicate traps are shown separately (shaded vs. unshaded) but the catches of fish larvae have been pooled.

Thus the prototype described above is larger, more complex and more costly than other designs (Faber, 1981; 1984). Faber's two designs enclosed about 5 liters of water (against the present 144 liters), had essentially a single chamber (against three), had small entrances (1.5 mm against 10 mm), had a single relatively low power and diffuse light (against three bright fluorescent tubes) and was not automated (against real-time control). While Faber's traps were well suited to the particular task of sampling larvae within shallow weed beds (Faber, 1981; Gregory and Powles, 1985), such small traps would be unlikely to catch the same kinds of fish as those taken at Lizard Island. For a start, the small size of the entrances would exclude most of the forms caught in this study and may explain why Faber's catches were dominated by very young larvae whereas I caught mostly mature forms. I cannot explain why small forms appear to be under-represented in my catches because I have observed previously that newly-hatched larvae of at least some species are photopositive (Doherty, 1980).

While some of the performance characteristics of individual traps can be traced to design, all light-traps share common problems. It is not clear exactly why fish larvae and invertebrates should be attracted to lights (Verheijen, 1958) and this must be considered a fortuitous accident. Unfortunately, the effectiveness of a given light may vary among different species or different ages of the same species or in conditions of different water clarity or at different times of the lunar month (Gregory and Powles, 1985). These sources of error will be investigated in a planned comparison between light-trap samples and concurrent catches from two other gear types: larval purse seines (Kingsford and Choat, 1985) and conventional ichthyoplankton nets (Leis, 1986). These comparisons will show to what extent different species and ages of larvae respond differently to the lights and differ in their willingness to enter light-traps. They will reveal also whether larvae are more responsive at certain times of the night or lunar month. Until these sorts of questions are answered, I expect that light-traps will receive little serious consideration as alternative sampling devices. However, it is important to realize that all gear types are biased to some extent. For example, the pre-settlement fishes which dominate the catches from the light-traps probably are undersampled with standard nets. Thus, it may be that a balanced program requires a diversity of types of sampling gear.

Even if light-traps are found to be unalterably biased, there is still a class of question which can be answered best with these devices. This is the synoptic mapping of two- and three-dimensional abundance in larval assemblages. Even if such comparisons have to be limited to one species at a time (and perhaps one age class), the ability to take multiple samples at the same time over large areas will lead to improved resolution of spatial pattern.

The accuracy of this mapping will depend on a number of factors but one is of paramount importance. If sampling is carried out at fixed locations (with anchored traps), any differences in water current speed among the trap sites could bias the estimates of relative abundance among sites. Although current meters could be deployed on every mooring to calibrate the catches for differential flow, this would be a costly solution with present technology. Also, it is likely that this relationship will be complex and probably non-linear; i.e., catches may increase initially as faster currents mean that more water is sampled but then decline as current speed interferes with catchability. Such patterns are likely to be species-specific and highly dependent upon fish size. While current meters will help, it will be difficult to discern these relationships. Alternatively, sampling could be restricted to large open expanses of sea where mainstream currents are coherent and need to be measured at only one point within the region. This would be an unfortunate

restriction given that some of the most interesting questions involve larval abundance around objects like islands and coral reefs. Ultimately, if the problem of differential flow cannot be overcome, spatial pattern can be resolved with an array of traps which drift with the water mass under investigation. In this configuration, each light-trap will yield a point sample and traps can be spaced more closely without risk of interference or blurring of the pattern.

In fixed designs, the distance between neighboring traps should be considerably more than the expected water flow during the fishing interval. One possible response to higher current speeds is to shorten the fishing time but this must be traded off against the weaker statistical power of tests with small sample sizes.

The limited data presented here show that light-traps have considerable potential as an alternative and/or supplementary method for sampling pelagic communities. For example, the differential abundance of pre-settlement fishes detected on the two sides of Lizard Island are consistent with net tow data reported by Leis (1986). However, the light-traps provided the same answer in a fraction of the time, required less effort and gave improved taxonomic resolution.

During the review of this paper, one referee commented that the pattern of declining abundance in catches from the windward site looked like an effect of fishing down the local stock. Subsequent sampling by a graduate student (Maria Milicich) at the same site over 122 consecutive nights has shown that this is not the explanation. During four months of continuous sampling, catches showed a coherent pattern of variation, rising and falling through two and three orders of magnitude on several occasions with a different species composition each time. These variations in the abundance of pre-settlement fishes in nearshore waters provide a parsimonious explanation of the episodic recruitments observed in benthic populations over scales of kilometers (Doherty, 1987).

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Abstract. – We compared sampling performance of four nets and two aggregation devices for larval and pelagic juvenile coral-reef fishes. The six sampling devices were deployed simultaneously over three nights near a coral reef at Lizard Island, northern Great Barrier Reef, Australia. The resulting 83 samples captured 57,701 larval and pelagic juvenile fishes of 70 families (excluding clupeoids which were not considered in this analysis). The bongo net took the most families, and the light-trap the fewest. In all methods, a few families dominated the catch. Dominance was least in the Tucker trawl catches and greatest in light-trap catches, where pomacentrids constituted 93% of the catch. Composition of catches was similar for the four nets. Catches from the light-trap were markedly different from those taken by net; catches taken by light-seine showed similarities to those taken by both net and light-trap. For four abundant families (Apogonidae, Gobiidae, Lutjanidae, Pomacentridae), the bongo net gave the overall highest density estimates, although those from purse-seine were frequently equivalent to bongo-net estimates. The Tucker trawl provided the lowest density estimates in most cases. Catches of bongo, neuston, and seine nets were similar in size structure and were dominated by small larvae; overall, however, bongo nets collected the greatest size-range of fishes. The Tucker trawl did not collect small larvae well nor did it collect significantly greater densities of large larvae and pelagic juveniles than the bongo net. Fishes collected by aggregation devices were generally larger than those taken by net, and light-traps caught very few fish <5 mm. Light-traps collected greater numbers of large pomacentrids (>6 mm) than other methods. In an extended sampling period of five nights, both aggregation devices showed obvious peaks in the density of large pelagic pomacentrids and mullids; these patterns were not detected by the nets.

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A comparison of towed nets, purse seine, and light-aggregation devices for sampling larvae and pelagic juveniles of coral reef fishes*

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Almost all species of marine teleost fishes have a pelagic phase in the early part of their life history (Moser et al. 1984). Size, morphology, and behavior of larval and pelagic juvenile phases vary greatly (Moser 1981), and this makes accurate sampling of these fishes problematical (Murphy & Clutter 1972, Frank 1988, Suthers & Frank 1989, Brander & Thompson 1989). The problem is exaggerated in tropical waters due to high taxonomic and developmental diversity and the presence of many demersal species with extended pelagic phases (Leis & Rennis 1983, Leis & Trnski 1989, Leis 1991b). Studies of the pelagic phase can provide important information on population biology of reef fishes. Despite its brevity, the high mortality and dispersion characteristic of this phase can have important demographic consequences for many species (Victor 1986). There is now a widespread interest in the process of recruitment in coral reef fishes (Doherty & Wil-

liams 1988, Warner & Hughes 1989), and sampling techniques which cover the full size-range of the pelagic phase are needed.

A number of different methods are available to sample this complex assemblage of early-life-history stages, including towed nets, purse-seines, and various types of aggregation devices which attract fish into collection sites or traps. These methods differ in their method of deployment and capture, and each has its own set of advantages and disadvantages. All have biases in number, identity, and sizes of pelagic fishes collected (Clutter & Anraku 1968, Clarke 1983 and 1991). For the pelagic phase of reef fishes, there have been few attempts to evaluate the relative bias of different sampling methods. Recent studies have provided information on the comparative performance

*Contribution of the Lizard Island Research Station. Authorship alphabetical.

of nets and light-traps (Gregory & Powles 1988), nets and plankton pumps (Brander & Thompson 1989), and towed nets and purse-seines (Kingsford & Choat 1985), but have dealt with the less-diverse fauna of temperate waters.

The purpose of this study was to compare several types of towed and seine nets and an automated light-trap (Doherty 1987) in terms of taxa, numbers, and sizes of larvae and pelagic juveniles of coral reef fishes captured. These methods represent the range of sampling devices currently used to collect larval and pelagic juvenile fishes. For the towed nets, we used dimensions and mesh size normally employed to sample larval and pelagic juvenile fishes. We used designs of purse-seine and light-trap which had been subject to thorough field testing (Kingsford & Choat 1985 and 1986, Kingsford et al. 1991, Doherty 1987). For each sampling device we obtained the following information: (1) Taxonomic composition of samples at the level of family; (2) patterns of density and size structure in selected taxa; and (3) temporal patterns in the density of selected taxa over short time-periods. The program also provided information on the logistic constraints associated with each sampling method.

Our findings will be useful to those designing sampling programs for larval and pelagic juvenile stages of demersal fishes in tropical and other areas, and should have some generality because the taxa sampled included a wide variety of body shapes and swimming capabilities. Among the taxa studied are families of great importance in coral reef ecosystems as adults (Apogonidae, Atherinidae, Callionymidae, Gobiidae, Labridae, Pomacentridae), and several are also important in commercial, sport, or subsistence fisheries throughout the tropics (Carangidae, Lethrinidae, Lutjanidae, Mullidae, Nemipteridae, Platycephalidae, Scaridae). All are abundant in ichthyoplankton samples in tropical coastal areas, especially in the Indo-Pacific.

Materials and methods

Sampling and identification procedures

We sampled at 150–600 m off the fringing reefs at Watsons Bay on the NW side of Lizard Island in the lagoon of the northern Great Barrier Reef, Australia (145°26'E, 14°40'S). Water depth was 20–30 m over a sandy bottom (Fig. 1). This site was chosen for its proximity to the logistic support offered by the Lizard Island Research Station, a base for much work on the pelagic phase of coral reef fishes (Leis 1991b). Also, it offered relatively sheltered conditions from the 15–25 kn southeasterly winds present during the sampling

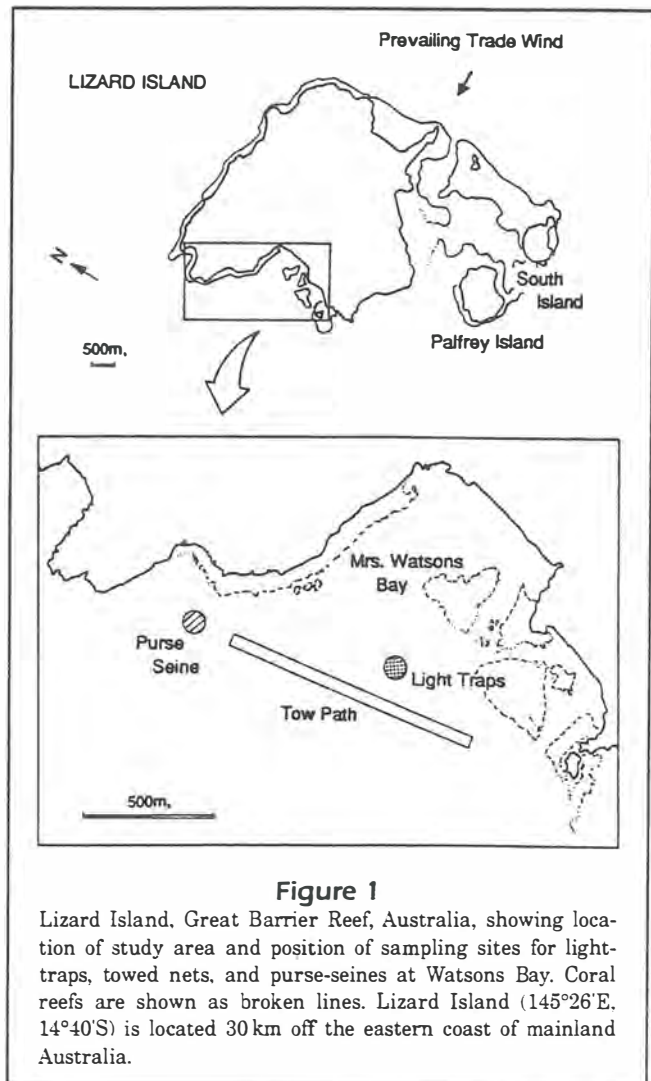


Figure 1

Lizard Island, Great Barrier Reef, Australia, showing location of study area and position of sampling sites for light-traps, towed nets, and purse-seines at Watsons Bay. Coral reefs are shown as broken lines. Lizard Island (145°26'E, 14°40'S) is located 30 km off the eastern coast of mainland Australia.

period. This was particularly important for the continuity of sampling over a number of nights.

We sampled on the nights of 2, 3, 5, 6, and 7 December 1986, starting at a minimum of 1.25 h after sunset. Sampling never continued past 0200 h. New moon was on 2 December 1986. Nocturnal sampling reduces potential bias due to vertical distribution because ichthyoplankton show little vertical stratification at night in the study area (Leis 1986, 1991a). In addition, the nets should operate at peak efficiency at night due to lessened visual avoidance. Finally, the aggregation devices are effective only at night because they depend on self-generated light to attract fishes.

We concentrated our analyses on data from 3, 5, and 6 December because we were able to take and process all planned samples from all gears only on these nights. For some gears, it was possible to examine temporal trends over the full sampling period.

Six different sampling devices were deployed each night. Three nets were towed from the 14 m catama-

ran RV *Sunbird* at 1 m/s along a fixed 1 km path. The towed nets were fitted with flowmeters and were washed with pumped seawater. Details of each collection device are as follows.

1 A neuston net of mouth dimensions 1.0×0.3 m with 0.5 mm mesh was rigged to sample water between the bows of the catamaran. Typically, the net sampled to a depth 0.1 m and filtered 187–312 m³/tow. Four tows were taken per night.

2 A bongo net (McGowan & Brown 1966) of 0.85 m mouth diameter per side, and with 0.5 mm mesh, was towed from an "A"-frame at the stern. The RV *Sunbird* draws 1 m, and the net was towed so its top was 1 m below surface and on the vessel's centerline in water which had not been disturbed by the passage of its twin hulls. The volume of water filtered for each side of the net was 498–673 m³/tow. Samples from only the port-side net were analyzed. Four tows were taken per night.

3 A Tucker trawl (Tucker 1951) with nominal mouth dimensions of 2×2 m and of 3 mm mesh was towed in the same position as the bongo net. At a towing speed of 1 m/s, a diver estimated that the bottom bar of the net trailed the top bar by ~0.5 m, so the effective mouth area was ~3.8 m². Between 3240 and 4570 m³ of water were filtered per tow. Four tows were taken per night. Both the bongo net and the Tucker trawl used the same depressor.

Time constraints and the logistics of rigging and deploying each net precluded randomising the order of bongo and Tucker trawl tows, so they were taken in blocks of four, with the order alternating from one night to the next. Neuston net samples were taken during the Tucker trawl tows.

4 A plankton mesh purse-seine of 14×2 m (Kingsford & Choat 1985) of 0.28 mm mesh was used to take samples of ~32 m³ each. This estimate was based on the ideal cylinder of water enclosed by the net at the beginning of pursing and made no allowance for herding of fishes during deployment or loss during pursing. There was no estimate of variation in the volume enclosed by the net sets. The net was deployed from a 4 m dinghy adjacent to the northern end of the tow path (Fig. 1). Wind conditions precluded effective deployment of this net at greater distances offshore. Two to four samples were taken per night.

5 Two automated light-traps (Doherty 1987) were deployed from an anchored boat adjacent to the center of the tow path and ~700 m from the purse-seine site. Traps were positioned at ~10 m apart. Entries into the trap were at 0.5–1 m below surface. The second trap began to sample 30 min after the first, and both traps sampled for hourly intervals, resulting in continuous sampling in overlapping, 1 h segments. The trap deployment was staggered to allow for clearing and pro-

cessing of each trap after the 1 h fishing period. Eight to nine 1 h light-trap samples were taken per night.

6 A battery-powered fluorescent light source identical to that in the trap (Doherty 1987) was deployed from a second boat anchored at the purse-seine site. After 1 h in the water, the light was set adrift and the water around it immediately sampled by the same purse-seine used in (4) above. Our estimates of what was attracted to the light included only those individuals that were within ~2 m (i.e., radius of the seine at pursing) of the light at the time of seining. Four to five light-seine samples were taken per night. Purse-seine (no light, (4) above) and light-seine samples were interspersed during the night.

Our goal was to sample simultaneously using six methods in the same location over several nights, so as to avoid confounding comparisons of methods with temporal or spatial variation. The purse-seine, light-seine, and light-trap samples were taken throughout the nightly sampling period. At the same time, the RV *Sunbird* sampled with the towed nets. Logistic problems required two compromises in this program. Bongo tows and Tucker trawl tows (and simultaneous neuston tows) were done in sequential blocks of four each night as discussed in (3) above. The purse-seine and light-trap samples were taken 700 m apart because it was not possible to duplicate these devices and thus randomize their positions. The RV *Sunbird* tow track covered the area between these two.

Fishes from the towed nets, purse-seines, and light-seines were immediately fixed in 10% formalin seawater. Samples from the light-traps were maintained alive until returned to the Research Station where they were subsequently fixed in 100% ethanol or 10% formalin seawater. All fish were transferred to 70% ethanol for at least a month prior to measurement.

For light-traps and light-seines, density is expressed as number per sample. Catches from the towed net and purse-seine collections were standardized to the number of fishes/1000 m³ on the basis of flowmeter records or purse-seine geometry.

All fishes were removed from samples and identified to family following Leis & Rennis (1983) and Leis & Trnski (1989). Standard lengths were measured to the nearest 0.1 mm using a Bioquant software package that allows for measurement of enlarged *camera lucida* images of fish and accommodates curvature of specimens. The accuracy of electronic measurement was monitored by measuring subsamples manually with calipers and eye-piece micrometers. In a few samples with very large numbers of certain taxa such as gobiids, the catch was subsampled and a minimum of 10% of the sample measured. For some analyses, fishes were divided into small (<6 mm) and large (≥6 mm) size-groups. This was done because, on the basis of results reported here, the light-

trap captures few larvae <6 mm, and we wished to compare density estimates among gears for the sizes of fishes captured by the light-trap. Damaged fish (~3% of total) were excluded from the length analysis.

The terminology of early-life-history stages of fishes is complex and ultimately arbitrary, whether based on morphological or ecological criteria (Kendall et al. 1984, Kingsford 1988, Leis 1991b). We were primarily interested in taxa of which the adults are benthic on coral reefs, but did not want to exclude semipelagic reef-associated taxa by use of an ecological term like 'presettlement', nor did we wish to exclude partially- or fully-transformed but still pelagic individuals of benthic taxa by the use of a morphological term like 'larva'. Therefore, we use the terms 'larvae' and 'pelagic juveniles' for the fishes collected during this study, or refer to them collectively as 'pelagic fishes'.

Larval, transforming, juvenile, and adult clupeoid fishes of several types (including *Spratelloides* spp., *Dussumeria* sp., *Stolephorus* sp., and probably *Herklotsichthys* sp.) were captured in large numbers, mainly by light attraction. These clupeoid fishes represented a distinct assemblage of fishes with a different age and size structure and adult habitat than the reef species of primary interest to us. These clupeoids are not considered here, but will be dealt with in a separate publication.

Reduction of data sets and analytical procedures

Sampling produced a data set comprising 70 families of fishes (exclusive of the Clupeidae and Engraulidae) collected from the sampling nights of 3, 5, and 6 December by six methods. For ease of analysis and unambiguous interpretation, it was necessary to reduce the number of families treated. We initially removed from consideration any family which did not constitute at least 1% of the catch of at least one method. The removal of taxa of this level of rarity would be unlikely to influence the outcome of the analyses (Green 1979). This excluded 51 families, leaving 19 (referred to as 'abundant families') for analysis beyond simple listing of numbers of families sampled (e.g., Table 1). Relative-abundance information obtained by all six sampling methods for the 19 abundant families was subjected to Principal Component Analysis (PCA) using the variance-covariance matrix. As a check, the same analysis was run incorporating the next 10 most-abundant families; this generated identical patterns. Reducing the data set from 29 to 19 families did not change the resulting pattern.

The PCA analysis identified patterns in the complex data set of 19 families sampled by six methods. Many of these 19 families were relatively rare and contrib-

uted little to the variation in the data set. A detailed examination of the factors contributing to these patterns required factorial analyses such as multivariate analysis-of-variance (MANOVA). These procedures are best carried out with a reduced number of variables, which allows a clearer interpretation of trends in the data. This called for a further reduction in the number of families analyzed.

To achieve this reduction, the data set of 19 families collected by nets was subjected to a PCA, which identified the taxa that contributed most substantially to the variation in the data set. This PCA identified apogonids, atherinids, gobiids, lethrinids, mullids, and pomacentrids as major contributors (95.2%) to the variation in the data set. These six taxa were used in a MANOVA. This design provided sufficient degrees of freedom for testing and interpreting the significance of method and night of sampling. The analysis was carried out on samples from nets only.

For graphic display of trends in sampling by nets, the eight most-important taxa from the PCA were depicted. These were apogonids, atherinids, gobiids, lethrinids, lutjanids, mullids, pomacentrids, and labrids. Labrids were included in this group at the expense of schindleriids, as they were an abundant reef-associated taxon of considerable interest to reef fish biologists. This substitution did not affect the cumulative variance accounted for by the eight families.

Unlike nets, aggregation devices did not allow for adjustment of fish densities to a common volume. Moreover, aggregation devices collected a different set of fishes. An additional PCA run on light-trap and light-seine data identified atherinids, gobiids, labrids, lethrinids, mullids, and pomacentrids as taxa, which explained over 90% of the variability in the data set. The families selected showed a strong relationship to the overall abundance ranking, although two relatively rare taxa (lethrinids and mullids) were included.

Aggregation devices sample an unknown volume of water. Because catches by aggregation devices could not be standardized to number of fish per unit volume, we made separate comparisons of nets and aggregation devices. The variables used were mean number/1000 m³ for nets, and mean number/sample for aggregation devices. A factorial analysis was designed to test for differences in sampling method (fixed) and time (random). For factorial analyses, residual analysis was performed (Snedecor & Cochran 1980) to check assumptions of normality and homogeneity of variance. Taylor's Power Law (Taylor 1961) was used to determine the appropriate transformation.

Canonical Discriminant Analysis and Tukey's Studentized Range Test (HSD) were used to display the differences detected. For MANOVA, the multivariate test statistic (Pillai's Trace) was used because it is

less likely to involve Type-I error and is more robust to heterogeneity of variance than comparable tests (Green 1979). All analyses were performed using SAS Version 6 (SAS 1987).

A more subjective procedure was used to select taxa for size-frequency measures. For meaningful comparisons, it was necessary to select taxa that were well represented in the collecting devices and that covered a reasonable size-range (>8 mm) within each method. Apogonids, gobiids, lutjanids, and pomacentrids met these criteria and also accounted for over 95% of the variation in the main data set from net sampling. Catches for nets and aggregation devices were analyzed separately. For net catches, density was expressed as mean number/1000 m³ within 2 mm size-classes among the different methods and compared by one-way ANOVAs. With aggregation devices, the variable was the number of fish per sample and comparisons were made by *t*-tests.

Results

The 83 samples contained a total of 57,701 fishes of 70 families, excluding clupeoids (Table 1). Table 2 lists families which constituted at least 1% of the individuals taken by any sampling method and records their

size-ranges by method. We refer to these as 'abundant families'.

Taxonomic composition and size structure of the samples

There were marked differences in taxonomic composition of the samples among methods. The bongo net collected the largest number of families overall (Table 1), including all of the abundant families and a wide size-range within most families (Table 2). The light-trap collected the fewest families overall and only

Table 1

Number of samples, total individuals, and numbers of families of fishes (clupeoids excluded) taken by six sampling methods on the nights of 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. Volume of water sampled by aggregation devices is unknown.

Sampling method	Number of samples	Number of fish	Volume of water sampled (m ³)	Number of families
Light-trap	26	7624	unknown	20
Seined light	14	2707	unknown	37
Purse-seine	7	812	224	25
Neuston net	12	2418	2861	31
Bongo net	12	43417	6833	63
Tucker trawl	12	723	47100	29
Total	83	57701	—	70

Table 2

Numbers and size ranges of the 19 families of fishes which made up >1% of the catch of at least one method on 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. Clupeoids are excluded. Size-range in mmSL, and total number of individuals within the taxon (*n*).

Family	Sampling method											
	Light-trap		Light-seine		Bongo net		Purse-seine		Neuston net		Tucker trawl	
	SL	<i>n</i>	SL	<i>n</i>	SL	<i>n</i>	SL	<i>n</i>	SL	<i>n</i>	SL	<i>n</i>
Apogonidae	5.4-9.3	4	1.6-9.8	211	1.6-15.5	10295	1.6-6.8	86	1.7-6.2	491	2.3-5.1	99
Atherinidae	6.7-19.1	20	7.6-61.7	135	6.0-25.2	14	6.8-24.7	2	16.0-56.3	110	15.2-39.3	36
Bothidae			3.2-5.3	3	1.4-7.7	76					3.0-10.0	10
Callionymidae			1.3-3.5	35	1.1-4.9	1003	1.3-2.9	11	1.6-3.9	94	1.9-4.5	6
Carangidae			1.9-57.4	19	1.8-7.6	1555	1.9-4.0	7	1.8-4.5	63	2.2-14.2	13
Ephippidae					1.7-8.7	81					5.3-7.5	14
Gobiidae	3.7-10.5	235	1.2-17.7	643	1.1-10.1	8386	1.4-8.6	487	1.4-20.3	1207	1.9-9.0	258
Labridae	5.1-8.8	48	1.5-13.1	47	1.6-6.0	876	1.7-5.9	21	2.0-5.3	27	2.2-4.1	9
Lethrinidae	8.4-16.6	45	1.9-18.0	24	1.8-4.7	380	2.6-3.3	3	1.9-4.4	17	2.6-11.3	9
Lutjanidae			2.1-5.2	76	1.8-6.6	2740	2.1-7.4	33	1.8-4.9	105	2.5-8.4	48
Microdesmidae			1.5-4.8	10	2.0-4.3	100	2.2-3.2	9	3.3-5.4	6	2.9-6.3	7
Monacanthidae	46.6	1	1.5-23.3	13	1.2-4.6	608	1.9-3.3	3	1.8-3.7	11	2.0-6.3	22
Mullidae	11.2-21.9	51	21.5-39.7	54	2.4-4.9	8	5.1-23.6	2	22.4-30.2	10		
Nemipteridae	6.4-9.3	28	1.8-12.3	42	1.5-5.6	1548	1.8-5.2	15	1.6-5.0	75	4.2-4.8	4
Pinguipedidae	2.0	1	1.4-6.5	30	1.3-5.6	2838	1.4-4.6	20	1.7-5.5	109	2.3-4.8	9
Platycephalidae			2.1-3.1	6	1.6-8.3	469	2.8-5.5	6	2.4-4.2	3		
Pomacentridae	5.3-14.9	7124	1.8-25.1	1248	1.0-14.6	496	1.9-9.4	22	1.8-11.7	30	6.4-14.6	68
Scaridae			1.6-4.4	30	1.7-4.6	136	2.2-4.0	34	2.5-7.7	10		
Schindleriidae					2.0-16.2	219	3.1-8.3	8	4.1-10.7	25	4.4-17.7	79

the larger individuals of most families. Analysis of the catch by method (Tables 1,2) suggests that the apparent selectivity of the light-trap reflects size-specific rather than taxonomic biases. The absence of certain taxa from the light-trap during the sampling period may mean that few large individuals were in the sampling area. Table 3 shows that, with the exception of bothids, schindleriids and carangids, taxa not caught by the light-trap were represented by relatively small individuals in the catch by other methods. Whether large carangids were present in more than trivial numbers is unclear. A single 57.4 mm carangid was taken by the light-seine, but the next-largest carangid taken by other methods was 14.2mm. The question of selectivity by light-traps must be resolved by more comprehensive sampling.

The light-seine and Tucker trawls captured most of the abundant families in all sizes. The neuston net and purse-seine captured the same abundant taxa, with size-ranges similar to one another. The exceptions were mullids, microdesmids, gobiids, and atherinids, for which the neuston net captured larger individuals. For the mullids and microdesmids, size distributions produced by the two methods overlapped slightly.

Catches by all methods were dominated by a few abundant families of fishes. The first five most-

abundant families listed in Table 2 accounted for 80% or more of the catch by all methods. The Tucker trawl was the most equitable in terms of abundance distributions, and the light-trap the least. However, the rank order of abundant families was not the same for all methods (Fig. 2). The dominant families for all towed nets and the purse-seine were gobiids and apogonids. For light-trap and light-seine the dominant families were pomacentrids, followed by gobiids. Small apogonids, although consistently abundant in net samples, were not captured by light-aggregation devices. In light-trap catches, a single family—the Pomacentridae—accounted for 93% of individuals collected.

For most collecting methods, there was a high degree of consistency among samples. Results of PCA (Fig. 3) showed that samples taken by light-trap were

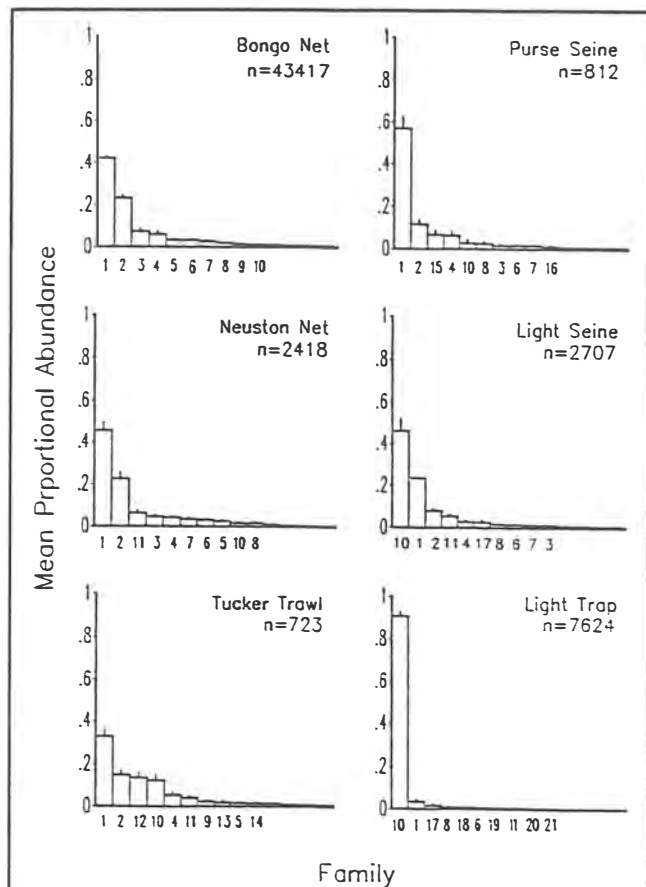


Figure 2

Mean proportional abundance (± 1 SE, vertical axis, shown only upward) and ranked taxonomic categories of fishes (clupeoids excluded) collected by six sampling methods off Lizard Island, Great Barrier Reef on 3, 5, and 6 December 1986. Other sample data are given in Table 1. Key to taxa: 1 Gobiidae, 2 Apogonidae, 3 Pinguipedidae, 4 Lutjanidae, 5 Carangidae, 6 Nemipteridae, 7 Callionymidae, 8 Labridae, 9 Monacanthidae, 10 Pomacentridae, 11 Atherinidae, 12 Schindleriidae, 13 Ehippididae, 14 Bothidae, 15 Scaridae, 16 Microdesmidae, 17 Mullidae, 18 Lethrinidae, 19 Synodontidae, 20 Scombridae, 21 Blenniidae.

Table 3

Comparison of maximum size of the 19 abundant taxa (Table 2). Maximum size captured by light-trap is compared with maximum size captured by five other methods tested on 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. Taxa listed in increasing order of maximum size captured by 'other methods' (maximum size captured by the next-best 'other method').

Taxon	Maximum size (mm) captured by	
	Light-trap	Other methods
Callionymidae	not caught	4.9(4.5)
Microdesmidae	not caught	6.3(5.4)
Pinguipedidae	2.0	6.5(5.6)
Scaridae	not caught	7.7(4.6)
Platycephalidae	not caught	8.3(5.5)
Lutjanidae	not caught	8.4(7.4)
Ehippididae	not caught	8.7(7.5)
Bothidae	not caught	10.0(7.7)
Nemipteridae	9.3	12.3(5.6)
Labridae	8.8	13.1(6.0)
Apogonidae	9.3	15.5(9.8)
Schindleriidae	not caught	17.7(16.2)
Lethrinidae	16.6	18.0(11.3)
Gobiidae	10.5	20.3(17.7)
Monacanthidae	46.6	23.3(6.3)
Pomacentridae	14.9	25.1(14.6)
Mullidae	21.9	39.7(30.2)
Carangidae	not caught	57.4(14.2)
Atherinidae	19.1	61.7(56.3)

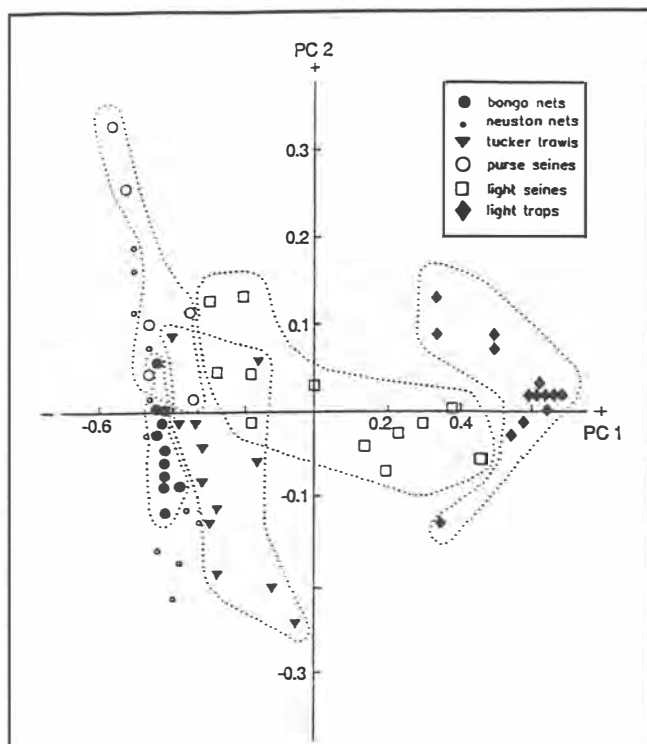


Figure 3

Results of Principal Components Analysis on proportional abundances of 19 families of fishes collected by six sampling methods on 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. Principal Components 1 and 2 are plotted. Differences between number of replicate samples and number of symbols for each method are due to overlap of some symbols.

distinct from net samples, and that samples taken by light-seine were intermediate between net and light-trap samples. Tucker trawl samples were almost completely distinct from bongo, neuston, and seine net samples. Bongo net samples formed a more discrete group than did the neuston and seine net samples.

The data sets for size analysis were heterogenous. Therefore, we attempted only to test for differences in density among methods within selected size-classes using single-factor ANOVA (df 3,39; $p < 0.05$). The power of these tests to detect differences among methods was low. For apogonids, gobiids, lutjanids, and pomacentrids, there were sufficient numbers for statistical comparisons across the first three size-classes (i.e., < 6 mm, Fig. 4). For all four families, density estimates provided by the bongo net were as high as, and in many cases higher than, those provided by the other nets. The Tucker trawl provided the lowest density estimates.

For the larger sizes (> 6 mm), low or zero catches in some size-classes precluded statistical tests in most cases. We compared the Tucker trawl, which is de-

signed to capture such large stages with the bongo net. The few tests that were possible show that in no instance did the Tucker trawl provide higher density estimates than the Bongo net (Fig. 4).

Two taxa, pomacentrids and gobiids, were sufficiently abundant to allow for comparisons of density by 2 mm size-classes between the aggregation devices. For pomacentrids we tested the 7–15 mm size-classes. Light-traps caught significantly higher numbers of pomacentrids in the 7, 9, and 11 mm size-classes than the light-seines (Fig. 4B). The two aggregation devices provided similar estimates of numbers for the 13 and 15 mm size-classes (Fig. 4B). The difference in overall density for pomacentrids sampled by light-traps and light-seines is due to the greater number of pomacentrids in the 7, 9, and 11 mm size-classes in the light-trap catches. Pomacentrid larvae > 14 mm were collected by the light-seine on one night only.

Although we did not statistically test the gobiid data, the light-seine appeared to collect greater numbers of smaller (< 4 mm), and the light-trap greater numbers of larger (> 8 mm), individuals (Fig. 4B). The light-seine collected few gobiids > 6 mm and the light-trap almost no gobiids < 6 mm. Sizes of apogonid and lutjanid fishes sampled by the light-seine were similar to those of the purse-seine (Fig. 4C). No lutjanids and only four apogonids were collected by the light-traps.

Results of pooled samples from three nights for eight taxa (Materials and methods) by the different nets (Fig. 5) reflect both entry of fish into nets and subsequent extrusion. Most of the fishes taken by all nets were small (Table 2, Fig. 4). Bongo nets consistently provided the highest estimates of density of small fishes, especially gobiids, apogonids, lutjanids, labrids, and lethrinids. This reflects both the low-avoidance and high-retention properties of this fine-mesh net. The purse-seine filtered only small volumes of water, but provided high estimates of density, especially for gobiids, apogonids, and lutjanids (Fig. 4). Extrusion is probably minimal, due to the passive mode of filtering and the very fine mesh of this seine. Neuston nets provided low estimates of density for all families except two that concentrate in the surface layer—atherinids and mullids (Leis 1991a). Density estimates from the Tucker trawl were low for all families, most probably due to the loss of smaller larvae through its large mesh. Both atherinids and mullids, which attained large size (Table 2), were also poorly represented in Tucker trawl catches, possibly because the Tucker trawl did not sample the neustonic habitat of these taxa.

For aggregation devices, we compared densities of the important families identified by PCA, excepting apogonids and lutjanids which were rare or absent from light-traps. Light-traps collect mainly large individuals, so the samples were subdivided by size

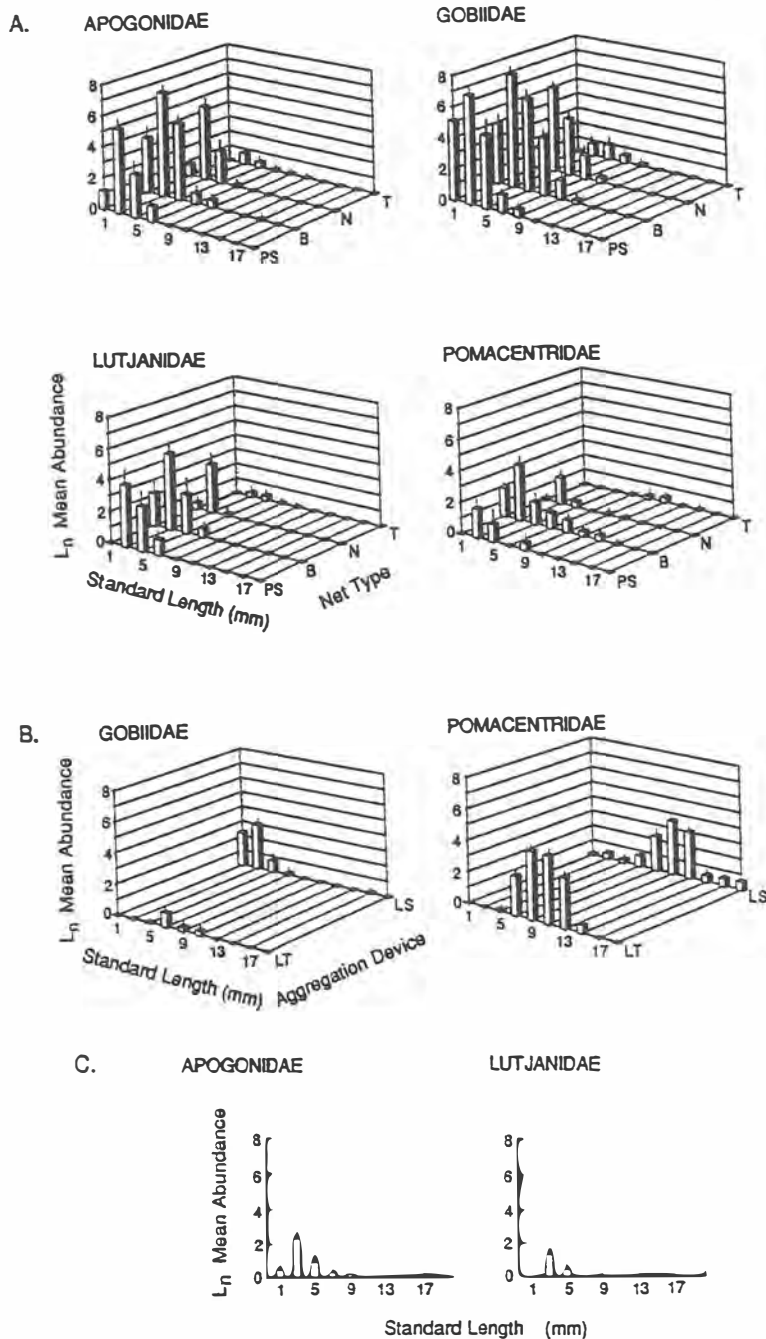


Figure 4

Analysis of size structure in selected families of fishes collected by six sampling methods on 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. (A) L_n mean density/1000 m³ (\pm SE) of four taxa in each of ten 2 mm size-classes collected by purse seine (PS), bongo net (B), neuston net (N), and Tucker trawl (T). (B) L_n mean density per sample (\pm SE) of gobiids and pomacentrids collected by light-trap (LT) and light-seine (LS). Size-classes as in (A). (C) L_n mean density per sample (\pm SE) of apogonids and lutjanids collected by light-seine. Size-classes as in (A).

(Table 4). Only three significant ($p < 0.05$) differences were detected by t -tests. The light-trap caught greater numbers of large pomacentrids, the light-seine greater numbers of large atherinids and small gobiids.

Among-night variation

Larval and pelagic juvenile fishes may vary in density at a particular location over short time-periods ranging from hours to days. We examined the among-night variation in two contexts. First, we used factorial analysis to examine the variation attributable to method of sampling and sampling period (nights) in the net collections. Second, we examined the ability of nets and aggregation devices to detect trends in density of large individuals of some families over a longer time-period (five nights).

A multivariate factorial analysis of variance was used to examine trends in mean density in six families: apogonids, atherinids, gobiids, lethrinids, mullids, and pomacentrids. Although both factors were significant (Table 5), the significant interaction between methods and nights (Pillai's Trace $F = 1.65$; $df = 36, 186$; $p < 0.01$) indicates that differences among methods were not consistent over nights.

Canonical Discriminant Analysis was used to display the relationship between methods and night of sampling. Canonical variates 1 and 2 explained 93% of the variation in the data set (Table 6). Figure 6 illustrates the main conclusions from this analysis. Tucker trawls, and neuston and bongo nets each sampled a distinct fish fauna with little among-night variation. Purse-seine samples overlapped with those of the bongo nets on two nights and were the most variable, both within and among nights, probably reflecting the influence of few samples of small volume. Tucker trawl samples were characterized by consistently low numbers of the

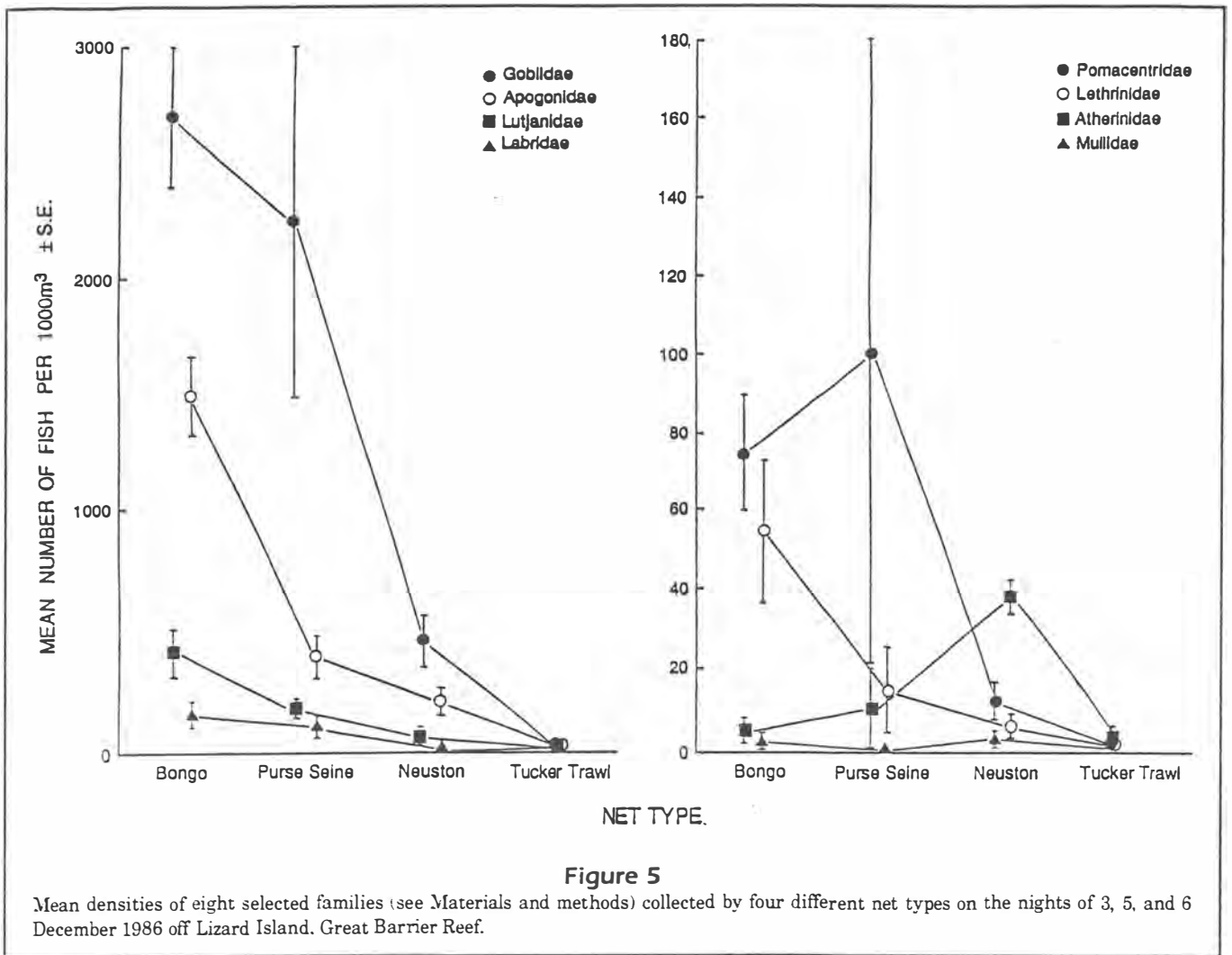


Table 4
 Density of six taxa of larval and juvenile fishes collected by aggregation devices on 3, 5, and 6 December 1986 off Lizard Island, Great Barrier Reef. Data are mean densities (with 1SE) of fish per sample pooled over three sampling nights. Fish are divided into two size-classes: <6 mmSL (Small) and >6 mmSL (Large). * 0.05>p>0.01; NS p>0.05.

Family	Size	Light-seine	Light-trap	p
Atherinidae	S	0.29± 0.22	0	
	L	9.36± 1.98	0.65± 0.25	*
Gobiidae	S	45.50±10.13	0.12± 0.08	*
	L	0.43± 0.23	3.92± 3.98	ns
Labridae	S	1.57± 0.62	0.04± 0.04	ns
	L	0.21± 0.11	1.54± 0.64	ns
Lethrinidae	S	0.43± 0.23	0	
	L	1.29± 0.34	1.38± 0.77	ns
Mullidae	S	0	0	
	L	3.86± 1.61	1.65± 0.68	ns
Pomacentridae	S	1.36± 0.52	0.27± 0.16	ns
	L	87.79 ±13.10	273.38±32.63	*

Table 5
 Multivariate analysis of variance of density data for apogonids, atherinids, gobiids, lethrinids, mullids, and pomacentrids (see Materials and methods) from off Lizard Island, Great Barrier Reef. Factors include sampling methods (purse-seine, bongo net, neuston net, Tucker trawl) and nights (3, 5, and 6 December 1986). Data are ln(x+1) transformed. Test statistic used is Pillai's trace. Significance levels: **0.01>p>0.001; ***p<0.001.

Source	F	Numerator df	Denominator df	p
Method	11.53	18	9	***
Night	4.05	12	54	***
Method×Night	1.65	36	186	**

dominant families; neuston, by higher numbers of atherinids, a neustonic group. The significant interaction is attributable largely to the purse-seine result.

Table 6

Standardized canonical coefficients from the Canonical Discriminant Analysis of density of fishes over each method by night combination, from samples taken off Lizard Island, Great Barrier Reef on 3, 5, and 6 December 1986. Data were $\ln(x+1)$ transformed.

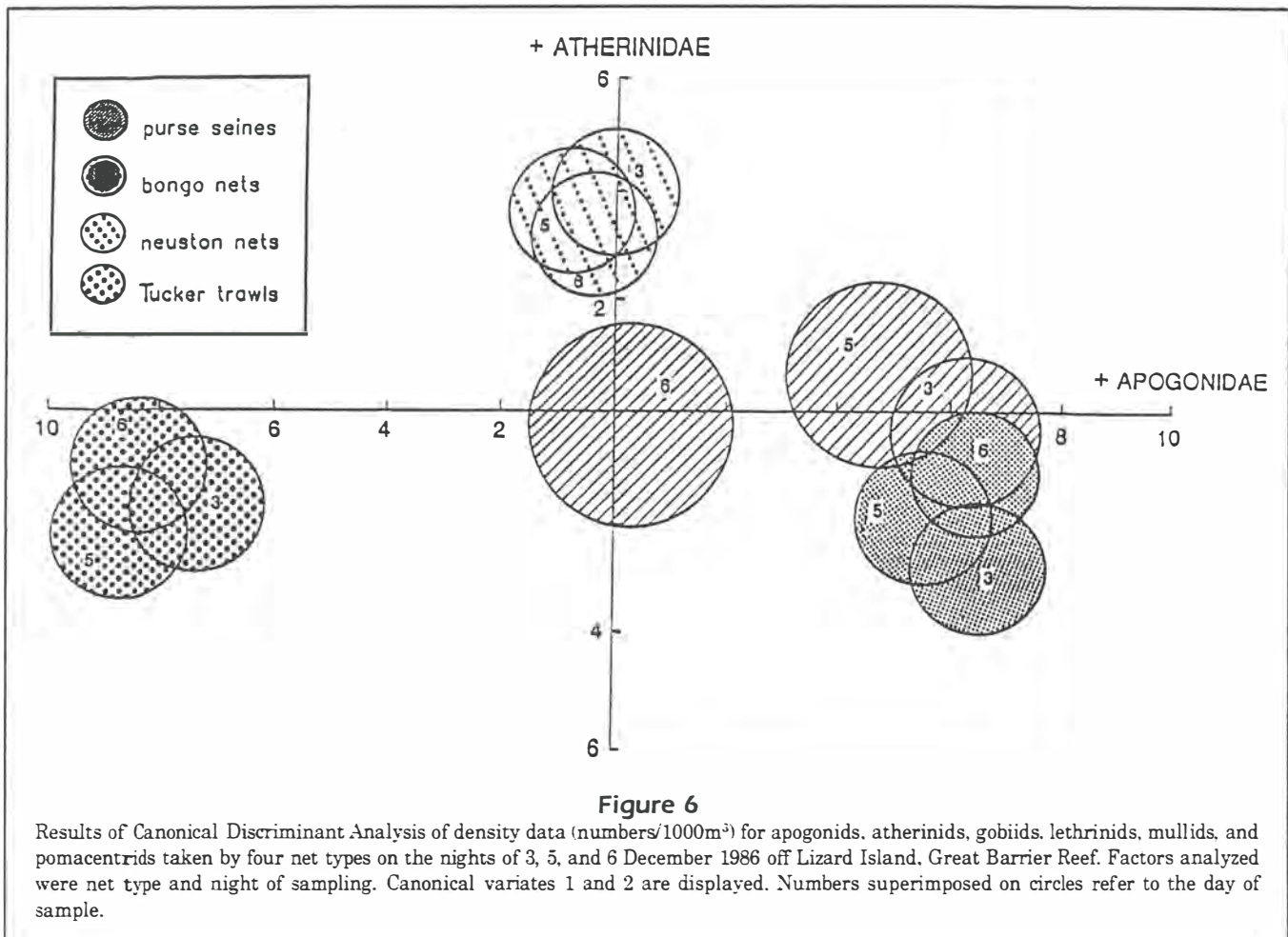
Family	CAN 1	CAN 2
Apogonidae	5.031*	0.675
Atherinidae	-1.129	1.961*
Gobiidae	1.463	0.585
Lethrinidae	-1.005	-1.279
Mullidae	0.177	0.595
Pomacentridae	0.184	-0.736

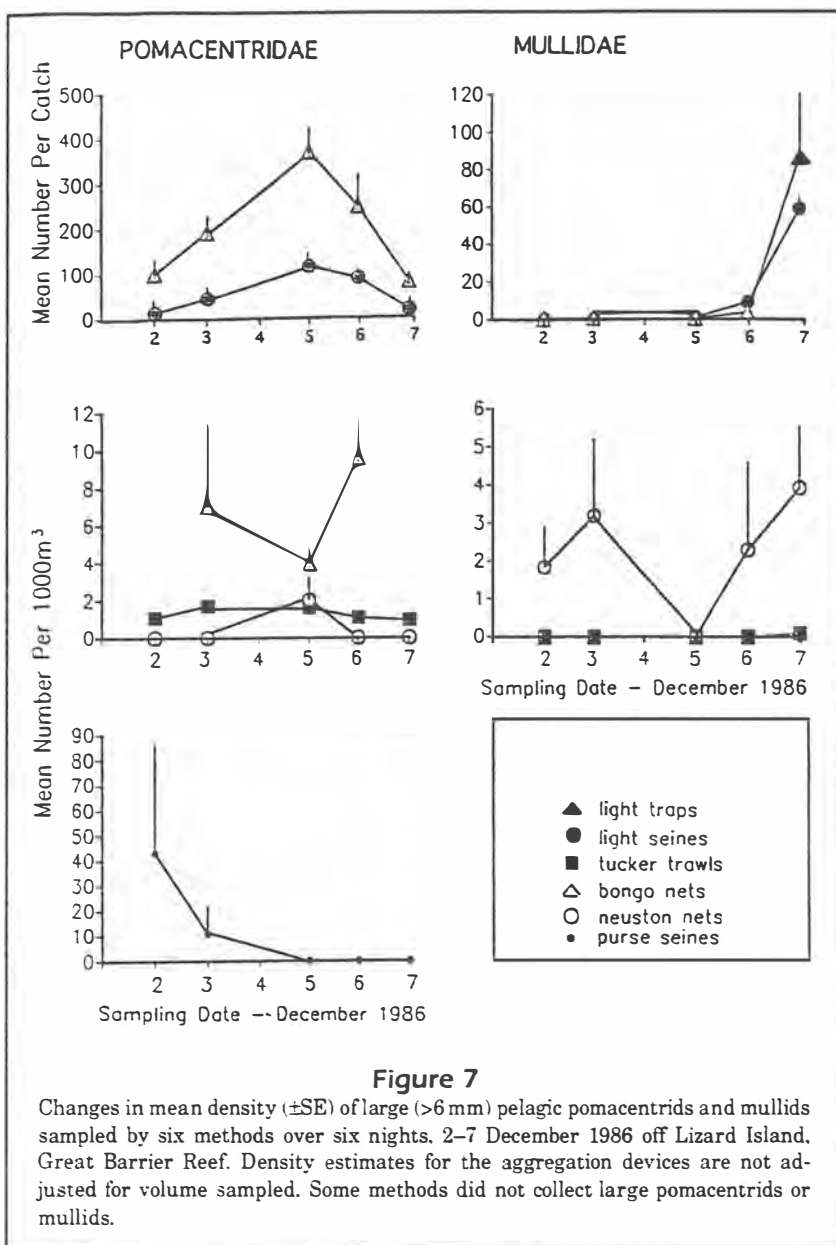
Canonical variate	Proportion	Cumulative
1	0.793	0.793
2	0.134	0.927

* Consistently high values in total, between and within canonical structure. These variables contribute significantly to the discriminatory power of the canonical variate.

Data from all five nights provided more information on patterns of temporal change for some taxa (Fig. 7). We focused on the comparative ability of the different methods to detect changes over time in numbers of the larger (>6 mm) individuals of some families because we wished to know the best methods for identifying temporal pulses of large larvae and pelagic juveniles of reef fishes. Large pomacentrids and mullids serve as appropriate examples. Although absolute numbers of fishes taken by nets and aggregation devices could not be directly compared, temporal changes in patterns of density could be evaluated among these methods. Comparisons were made using all methods, although bongo net data were available for the nights of 3, 5, and 6 December only.

Data from the two aggregation devices indicated that large pomacentrids increased in density from the 2nd to a peak on the 5th, and decreased over the 6th and 7th (Fig. 7). This pattern was not present in the data from nets, each of which provided a different temporal pattern of density.





The aggregation devices indicated that large mullids were rare or absent until the 5th, and increased greatly in density on the 7th (Fig. 7). This trend was not present in data from the nets. Only the neuston net caught large mullids, but in low and variable numbers.

Discussion

The taxonomic composition obtained when sampling for larval and pelagic fishes is highly method-dependent. The bongo net captured the largest number of families, many of which were rare in the samples.

Among abundant taxa, the four nets provided similar estimates of taxonomic composition. The light-trap, however, was more selective, and its catch differed in composition from that of the nets. Taxonomic composition of the light-seine samples was intermediate between the trap and nets, an expected result given its mode of operation.

Our results suggest that capture by the light-trap is dependent on fish size: larger pelagic stages are more likely to be attracted to the light and to swim into the trap than are small stages. However, trap performance may also be time-dependent. For example, apogonids, carangids, lutjanids, and scarids, which were rare or absent in light-trap catches during this study, have been captured during extended light-trap sampling around Lizard Island (M. Milicich, Griffith Univ., Nathan, Queensland, pers. commun.). The absence from light-traps at particular times may simply indicate that large or well-developed individuals of some families were not present at that time.

However, our study provides evidence that pelagic stages of some families may not be photopositive or enter traps, thus indicating some selectivity by the aggregation devices. Schindleriids were present in the net samples to adult size, yet were not captured with either of the light-aggregation methods. The net samples may have included the largest pelagic individuals of callionymids, and per-

haps platycephalids and bothids, because they leave the pelagic environment (i.e., settle) at a relatively small size (see Table 3). These families were not present in the light-trap catches.

The size-distribution and density estimates of pelagic fishes captured also differ among nets. The bongo net, neuston net, and purse-seine captured predominantly smaller fishes. For abundant families, density estimates by the bongo net and purse-seine were generally similar, neuston net estimates were somewhat lower, and the Tucker trawl provided still lower estimates. The bongo net provided the highest abundance estimates for most sizes of most families. The Tucker trawl

undersampled smaller individuals, but was no better than the bongo net at capturing larger larvae and pelagic juveniles. This is consistent with the results of Kendall et al. (1987) and Clarke (1991), who compared bongo nets and larger trawls. The light-seine captured a wide size-range of fishes because it combined the sampling characteristics of both a purse-seine and an aggregation device.

Mesh size is an important determinant of catch composition because extrusion varies with mesh size. For a given mesh size, extrusion is a function of body shape and pressure across the net mesh (Clarke 1983 and 1991, Gartner et al. 1989). Body shape is species-specific, which emphasizes the importance of taxon-specific factors in methodological studies. Our results cover a comprehensive range of body shapes, from slender (gobiids) to deep bodied (apogonids and pomacentrids) to moderately deep with elongate fin spines (lutjanids), and should have general application. Purse-seines appear to herd planktonic organisms, while towed nets actively filter, often under considerable pressure; thus extrusion will vary between these two gear types regardless of mesh size. As our primary interest was in comparing a series of sampling devices in their normal working configuration, we did not attempt to test the effects of different mesh sizes within gear types.

Although vertical stratification is minimal at night in the study area (Leis 1986, 1991a), vertical distribution of the fishes could have affected apparent performance of the samplers because each method sampled somewhat differently in the vertical plane. Towed nets were deployed at fixed depths. Experience elsewhere has suggested that light-traps draw their catch from a relatively narrow depth stratum, the upper 5 m (P.J. Doherty, unpubl.). However, only in the neuston net can we confidently attribute greater catches (especially of atherinids) to vertical stratification. For this study, we assumed that vertical distribution of the fishes did not affect our evaluation of the other methods.

Horizontal or temporal variations in density may also have confounded comparisons. A position effect was possible because the aggregation devices were operated at fixed positions about 700 m apart (Fig.1). A temporal effect is possible because the bongo net and Tucker trawl tows were run in blocks and not randomized during each night's sampling, although the order of blocks was alternated among nights.

Absolute sampling efficiency of the nets was not measured. Our estimates of sampling performance were relative, because we did not obtain unbiased estimates of the true densities of small pelagic fishes. We did not attempt to use the methods of Somerton & Kobayashi (1989) to correct our net catches because we felt some of the assumptions required, especially those relating to patch size and consistency through time, were not

appropriate in the case of our study. The smaller bongo net seemed to have equal or greater sampling efficiency than the larger Tucker trawl at night for large pomacentrids.

A comprehensive comparison of the six sampling methods would require two things. First, we would need to standardize all results as number of organisms per unit volume of water sampled. Second, we would require an estimate of the sampling precision of each device. For towed nets, both could be obtained because flowmeters provided estimates of the volume filtered for each tow. In the case of the purse-seine, it was not possible to obtain reliable estimates of the volume of water filtered during each deployment of the net. Minor variations in the deployment procedure can modify the dimensions of the volume enclosed by the net. At present, we have no reliable way of estimating this; therefore, for the purse-seine we have a general estimate of water filtered based on idealized dimensions of the deployed net.

Volumes sampled by aggregation devices cannot be estimated at this time, but preliminary calculations (below) suggest they may be large. The bongo net as operated in this study will sample ~4000 m³/h, the Tucker trawl ~14,000 m³/h, and we estimate the light-aggregation techniques could sample tens of thousands of m³/h. Therefore, light-aggregation techniques may be the best way to capture sufficient numbers of rarer, larger stages for useful analyses. Aggregation methods may offer considerable advantages in studies of settlement-stage reef fishes, but one must accommodate the characteristic taxonomic selectivity and unknown sample volume.

Two alternatives may explain the apparent disparity in numbers of larger pomacentrids estimated by the bongo net (average 6.9/1000 m³; Tucker trawl catches averaged 1.49/1000 m³) and the light-trap (average 273/h): (1) The bongo net undersamples these larger pelagic stages relative to the light-trap, or (2) the light-trap samples larger volumes of water. Assuming the two methods sample large pomacentrids with equal efficiency, the light-traps sample volumes on the order of 40,000 m³/h. This requires the trap to capture, with efficiency equal to that of the net, photopositive stages within a 7–50 m radius (to 5 m depth) of the trap, depending on the current speed (average in the area is 15 cm/s; Leis 1986) and geometry of the light field. It is not possible to choose between alternatives without a better measure of the effective volume swept by traps. Work in progress will help resolve this question.

Short-term temporal variation in the density of particular families was more obvious in the results of some methods than others. For the smaller size-classes, neuston, bongo, and Tucker nets gave consistent results

over short time-periods (Fig. 6). Catches from the purse-seine were more variable within a sampling period and showed greater variability among nights of sampling than did the towed nets. This reflects the localized sampling area and small sample volume of the purse-seine. For larger mullids and pomacentrids, similar trends in density over five nights were identified by the aggregation devices. These trends were not apparent in the data from the towed nets. Thus, the aggregation devices seem particularly suited to studies of short-term temporal variation in the larger (>6 mm) size-classes. The rapid and independent changes in density of the larger individuals of these two families suggest that larger pelagic stages are not present in the water at all times at a location. The alternative, that there are short-term taxon-specific changes in catchability due to changes in behavior of the fishes, seems less likely, but cannot be dismissed without further study.

A number of other studies have compared sampling methods for planktonic and pelagic assemblages. Purse-seines were found to be superior to towed nets for sampling larval anchovies (Murphy & Clutter 1972). Larger, faster, more-transparent nets may minimize net avoidance (Clutter & Anraku 1968). However, Smith & Richardson (1977) suggest that increased net size and towing speed may intensify the disturbance in front of the net and increase net avoidance. All towed nets in these cited studies employed towing bridles, which are a source of water disturbance and, thus, net avoidance by fishes. Towing bridles were not used in the present study, which may be why our conclusions differ from those of Clutter & Anraku (1968) and Murphy & Clutter (1972).

We agree, however, with Clarke (1991) who made detailed comparisons of the effectiveness of two types of bongo nets and a midwater trawl in capturing reef-fish larvae. He suggested that the bongo nets (0.7 m diameter with 0.183 mm mesh, and 1.25 m diameter

with 2.5 mm mesh) sampled larvae as well or better than a 3 m Issacs-Kidd trawl (6 mm mesh). Clarke concluded that when densities of larvae were high, 0.7 m and 1.25 m bongo nets were the most effective methods for sampling small and large larvae, respectively. Although larger nets are assumed to capture more and larger fishes due to lessened avoidance (Clarke 1983 and 1991, Methot 1988), this was not true in our study nor is it always true in other pelagic groups (Barnes & Tranter 1965, Sands 1978, Pillar 1984).

One other significant study compared catches from a light-trap with those from a towed net. Gregory & Powles (1988) investigated a relatively simple planktonic assemblage of freshwater fishes. Based on a comparison of taxonomic composition and size of fishes, they concluded that both sampling methods should be used to avoid selectivity biases. An interesting conclusion that differs from our results was that the light-trap provided a better representation of size-classes, including smaller individuals, than did the towed net. This emphasizes the taxon-specific and, perhaps, habitat-specific nature of gear-performance measures.

We agree with Omori & Hamner (1982) that the sampling device and program selected must be question-driven (Kingsford 1988). In order to assist in the choice of appropriate methods, we summarize the performance and sampling properties of the six methods employed in this study (Table 7). Surveys of larval fishes are best accomplished with a bongo net. This will cover a significant portion of the size-range in many important taxa, including larger individuals, at least at night. No extra benefits were apparent from using the larger Tucker trawl. A major advantage of bongo nets is the relative ease with which they may be deployed and retrieved. As expected, neuston nets focused on neustonic fishes.

Surprisingly, the purse-seine provided results comparable to the bongo net despite the small volumes sampled. Among-sample variances were predictably

Table 7

Sampling characteristics of six methods used to collect planktonic and pelagic fishes at the Lizard Island study site, Great Barrier Reef.

Performance criterion	Bongo net	Neuston net	Tucker trawl	Purse seine	Light-trap	Light-seine
Size selectivity	Wide size-range; modal values at lower size.	Samples larger individuals of some taxa; modal values at lower size.	Samples larger sizes; no more effective than bongo net at night.	Primarily small individuals.	Primarily large individuals.	Wide size-range.
Taxonomic selectivity	Least-selective.	Neustonic taxa only.	Slender taxa and small individuals extruded.	Captures only shallow living taxa; undersamples rare taxa.	Selective; dependent on taxon behavior.	Combines light selectivity with characteristics of purse-seine.

higher than those of towed nets. Sampling of local-scale surface features requires the degree of spatial precision and replication provided by small purse-seines (Kingsford & Choat 1985 and 1986, Kingsford et al. 1991), but purse-seines cannot sample deeper than the upper few meters of the water column, and are difficult to operate in any but the best conditions. Localized replicated sampling may also be obtained by free-fall plankton nets (Kobayashi 1989) which, however, obscure vertical patterns and also have a small volume sampled.

Investigation of the patch size of pelagic organisms requires the ability to sample simultaneously over several spatial scales. Large-scale deployment of arrays of automated light-traps will increase replication and allow investigation of phenomena at several spatial scales without risk of temporal confounding, provided the traps can be retrieved over the same time-period. Also, both light-traps and purse-seining with aggregation devices may detect temporal pulses in the density of larger larvae and pelagic juveniles with greater reliability and precision than towed nets.

In addition to the sampling properties of the different devices, there are a number of more pragmatic considerations. Sorting and identification of samples may be a major bottleneck. This will be influenced by the size of the sample, the amount of organic material included, and condition of the fishes themselves. In this context, large samples taken by finer-mesh nets may be particularly difficult to process. Smaller or more selective samples are more readily processed, and those from purse-seines and light-traps yield living fishes suitable for rearing and experimentation. Further, the smaller the larva the more difficult it is to identify; thus, methods like the light-trap, which samples larger fishes, simplify identification.

It is clear that studies of the biology of small pelagic fishes require the use of both nets and aggregation devices either separately or in combination, depending on the type of question posed. No single method can provide a comprehensive picture of the larval and pelagic juvenile fish fauna, and few programs could cover the expense and logistic effort of the simultaneous deployment of a variety of methods. The picture one obtains of the larval and pelagic juvenile fish fauna is highly method-dependent. Which picture or combination of pictures is suitable for answering a given question varies with the question, the taxon, and the size-range of the fishes.

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A Potential Role for Light-traps in Enhancement of Coral Reef Fisheries

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DOHERTY, P. 1994. A potential role for light-traps in enhancement of coral reef fisheries, p. 92-93. *In* J.L. Munro and P.E. Munro (eds.) *The management of coral reef resource systems*. ICLARM Conf. Proc. 44, 124 p.

Light-traps are automated samplers that use light attraction to collect live pelagic juvenile fish. These devices have now been extensively tested on the Great Barrier Reef with deployments of >20,000 trap hours over eight seasons at depths ranging from the surface to 100 m.

Although catches are strongly influenced by spatial factors (such as depth, distance across the continental shelf, proximity to reef), the general pattern is for highest catches around the new moon. On the GBR, greatest catches of reef fishes are obtained around midsummer, although certain commercially valuable targets are most abundant during winter/spring months. In addition to this seasonality, sampling of fixed sites has shown substantial interannual variability at all taxonomic levels; both results are consistent with the results of previous recruitment surveys.

Notwithstanding these sources of variability, light-traps have been found to capture a wide range of pelagic and demersal fishes, including reef and nonreef, commercial and noncommercial, taxa. Commercially valuable groups include lethrinids, lutjanids, scombrids, serranids and siganids. In the case of small noncommercial reef fish, we have shown that light-traps provide alternatives to

visual surveys for monitoring the replenishment of these stocks. In the case of high-value species, which often have mobile or cryptic juveniles, light-traps may offer the only cost-effective estimates of initial replenishment.

In addition to their use as monitoring tools, light-traps have potential to be applied to certain mariculture propositions, including experimental restocking of natural populations. This is because light-traps are size-selective, mainly capturing advanced pelagic juveniles which are generally inaccessible to conventional techniques. Furthermore, because these fish are merely trapped, not killed, they can be removed from the trap for controlled growout or released back into the environment.

In the long run, it would generally not be cost-effective, nor perhaps sustainable, to constantly harvest large numbers of wild juveniles for any form of mariculture. My proposal is that light-traps may offer a relatively cheap way of determining the feasibility of reef enhancement. In their current form, each trap represents a capital investment of approximately A\$1,500 with running costs of around A\$20 per month. At these levels and because of their automation, it is possible for a small operation to service quite a

large array of traps. Catches of target organisms from individual traps have been as high as hundreds or thousands in a single night.

Lethrinids and siganids are two taxa that seem particularly suitable for the proposed trials. Both share the following characteristics:

- reliable and abundant supply;
- robust to handling;
- easy to maintain in culture so that the effect of size at release could be easily manipulated;
- feed low or relatively low on the food chain and hence have mini-

mal impacts on species at high trophic levels;

- fast postsettlement growth, especially in the case of siganids; and
- appropriate habitat and ecological requirements, i.e., lagoonal species which offer some prospect for containment of the additional increment of productivity.

Positive results from this stage may provide the justification required for the more expensive proposition of closing the life cycles of suitable species in the laboratory, for the sustainable supply of juveniles.



MONITORING THE REPLENISHMENT OF CORAL TROUT (PISCES: SERRANIDAE) POPULATIONS

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David A. Harris*

ABSTRACT

The replenishment of coral trout populations was monitored by daily sampling for pelagic juveniles using automated light-traps anchored at three sites close to the crests of two reefs (Arlington, Green) in the Cairns Region of the Great Barrier Reef. The water depth at each site was approximately 25 m; traps were suspended at 1 m and 20 m. A total of 237 presettlement coral trout were captured during the 1990/1991 spawning season of which the majority were identified as *Plectropomus leopardus*. Four individuals were grown out to confirm generic identification. Pelagic juveniles were collected from both depths but were consistently more abundant at the surface. They were also consistently more abundant at Arlington than Green. Standard length was 16.8 ± 0.2 (95% CL) mm with no trends in size among depths, reefs, sites or time. All presettlement trout were caught during a 17 day time window centered around the new moon in November 1990. A similar pattern of replenishment was generated by back-calculating the settlement dates of 36 juveniles collected from the reef at the end of summer. These back-calculations also estimated pelagic larval duration as 25.2 ± 0.9 (95% CL) days, indicating birth dates near the previous new moon. This was consistent with systematic observations on trout spawning at Scott Reef, which lies 40 km downstream of Arlington. Since Scott was obviously not the source of the fish captured in our study, synchrony between spawning and recruitment at this scale suggests that reproduction may be regionally entrained, and that all replenishment in this season was sourced from one period of spawning lasting about 2 weeks.

Epinepheline serranids include many species that are large apex carnivores which are vulnerable to the spear and line fisheries imposed on coral reefs. Throughout the tropics, there is evidence that such fish are the first to be affected by fishing (Munro and Williams, 1985) and even recreational pressure can cause these attractive targets to become locally rare (Craik, 1989) with downstream effects on the rest of the community (Russ, 1991). Ironically, given the importance of large serranids to both economies and ecosystems, their life histories and demographics are not well described in quantitative terms relative to small non-commercial reef fishes.

Three characteristics of all large food fishes make them more difficult subjects for ecological study than damselfishes, which have received the majority of attention (Sale, 1991). First, densities are lower at all stages of the life cycle which increases the cost and effort associated with each observation. Second, adults are more likely to be mobile leading to unstable and patchy distributions, which further complicates the assessment of abundance. Third, juveniles may be cryptic after settlement or colonize inaccessible habitats, which means that they are not easily counted by divers. Collectively, these factors suggest that it will be costly, if not impossible, to monitor replenishment of these stocks using the simple visual protocols that have proven to be effective for small sedentary species (Doherty, 1991).

Despite the extra difficulty, there is no reason to believe that the population dynamics of large food fishes are qualitatively different from those of the small sessile species, which are greatly affected by spatial and temporal variations in replenishment (Victor, 1986; Doherty and Williams, 1988; Doherty, 1991). Nonetheless, these stocks are usually managed, in places where there is formal man-

agement, according to the predictions of mathematical models that assume constant recruitment (Gulland, 1983). Unfortunately, such models may permit overfishing when recruitment is highly variable (Munro and Williams, 1985). Only recently has the significance of variable recruitment begun to be addressed by fisheries managers (Hilborn and Walters, 1992) and one of the priorities for understanding the effect of fishing on reef fishes is the collection of empirical data on their recruitment.

The research described in this paper is a first attempt to find a way of monitoring the replenishment of coral trout. This common name is applied to seven species of grouper belonging to the Indo-Pacific genus *Plectropomus* (Randall and Hoese, 1986) of which three (*P. laevis*, *P. leopardus*, *P. maculatus*) are common on the Great Barrier Reef (GBR). Stocks of these species are segregated by distance across the continental shelf (Ayling and Ayling, 1986); *P. leopardus*, which is most common in the mid-shelf, is the most valuable fish exploited by both commercial and recreational fisheries on the GBR (Craik, 1989; Trainor, 1991).

In common with other groupers, the juveniles of these species are small and secretive after settlement. To date, no estimates of their settlement have been available. Ayling et al. (1992), using visual surveys, suggested that juveniles may be more common on reefs open to fishing, but they defined juveniles as fish <35 cm which includes individuals up to 2 years old (Ferreira and Russ, in press). These are pre-recruits to the fishery but clearly are not recently settled fish. To assess the management implications of these observations, it is necessary to have independent estimates of abundance closer to settlement to determine whether the differences detected among reefs are caused by variations in larval supply or by differential postsettlement mortality.

Doherty (1987) described an alternative technique to visual surveys for monitoring the replenishment of reef fish, based on fishing with light. He described an automated light-trap that attracts the pelagic juveniles of a broad range of reef fishes and that has been shown capable of monitoring spatial and temporal variations in the larval supply of three damselfishes (Milicich et al., 1992). Here we describe the first attempt to validate the use of light-traps as a tool for monitoring the replenishment of valuable fish stocks, which was funded as part of a multi-institutional investigation into the life history of coral trout.

MATERIALS AND METHODS

This study was part of a larger collaboration and therefore had several interlocking components. The questions asked here are (1) can the larval supply of coral trout be monitored using light-traps? (2) can temporal patterns in the trap catches be validated by an independent method; in this case, by back-calculating settlement based on the microstructure of otoliths from benthic juveniles? (3) can temporal trends in replenishment be explained by monitoring spawning effort?

Larval Supply.—Automated light-traps, identical functionally to those described by Doherty (1987), were anchored in two depths close to the crests of two reefs (Arlington, Green) in the Cairns Section of the Central GBR (Fig. 1). Dominant water flow over the continental shelf in this region is southerly under the influence of the poleward East Australian Current (Wolanski and Pickard, 1985).

Light-traps were anchored at three sites on each reef. Although their exact locations were arbitrary, the three sites on Arlington were all selected from the downstream side of that reef assuming a poleward base flow. This is because previous work with light-traps deployed in concentric rings around another reef showed that traps are more productive when fished in this position (Doherty and Carleton, unpubl. data). Two sites (G2, G3) were located in comparable downstream positions on nearby Green Reef, and a third site (G1) was located on the northern face of this reef to correlate catches across the narrow channel separating the two reefs (Fig. 1).

On both reefs, the profiles are sufficiently angled that traps could be located within 100 m horizontally of shallow water yet be in a 25-m water column. At each site, two traps were suspended from the surface so that one fished at 1 m and the other at 20 m. All traps were lit simultaneously over three

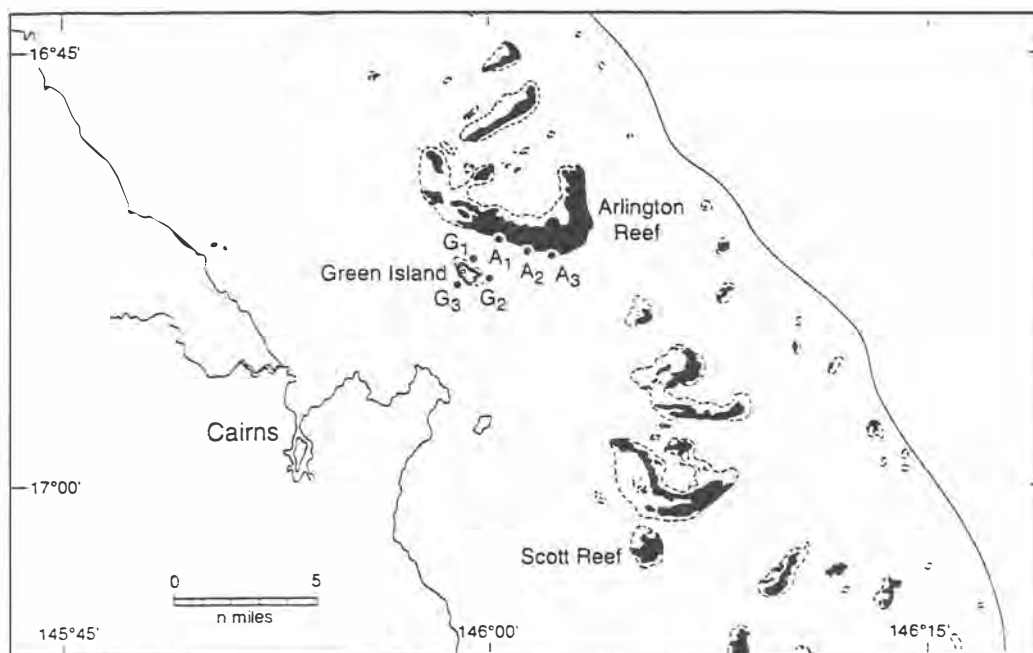


Figure 1. Location of light-traps at Arlington (A_n) and Green (G_n) Reefs, and Scott Reef where spawning of *Plectropomus leopardus* was monitored.

periods (2100–2200, 0000–0100, 0300–0400 Eastern Standard Time) during each night to ameliorate possible effects of time of night and/or tidal state on catch rates (Doherty, 1987). Each trap was cleared during the following day, usually in the morning.

Ideally, sampling would have been continuous over time but, for practical reasons, it was targeted at periods around the new moon when light-traps have proved most effective (Milicich, 1992). Sampling began on 25 September 1990 and ended on 23 January 1991. Within this period, trapping was done on 76 of the possible 121 days. A limit on the number of traps resulted in the design being unreplicated at the level of site within depth and reef. Although this limits the number of formal analyses possible, Milicich (1992) showed that replicated traps exhibit low variance relative to temporal trends at a sampling location. Nonetheless, without replication at each site, we have restricted our spatial comparisons to depth and reef.

Wind speed and direction was estimated daily by the field team; their observations agreed generally with instrumented wind records from various coastal weather stations maintained by the Australian Institute of Marine Science. Where appropriate, catch rates were compared with the records from the Cape Bowling Green station located near Townsville. Although this station is located several hundred kilometers south of Cairns, large scale wind patterns are quite coherent along the coast (Williams et al., 1984) and the use of an instrumented record seemed preferable because it could be averaged over the night.

Light-traps attract large pelagic juveniles (Choat et al., 1993) and maintain most of them in live state. Coral trout were readily identifiable from these catches by their orange-red coloration at the time of recovery. Most of the trout were picked from the samples while alive and some were transported to the mainland where they were grown out at the QDPI Northern Fisheries Centre to assist with identification of the catch.

Juveniles.—In late January 1991, 51 settled juveniles were collected from Arlington Reef to compare temporal trends in the light-trap catches with independent estimates of recruitment obtained by back-calculating their settlement dates from otolith microstructure. A further three fish were collected in early March. All these animals were collected by intensively searching the reef slope within 1 km of the three trap sites and attempting to spear every 0+ (young of the year) trout as it was encountered. While this method could be expected to be biased against the smallest individuals, our success rate was high and no size specific selection was evident to the spearmen. All fish were measured while fresh then preserved in ethanol until dissected for the removal of otoliths.

From each fish, both sagittae and lapilli were removed and cleaned by polishing them on a black rag. Initial trials showed similar counts from both sagittae and lapilli (Fowler, unpubl. data), but the latter being thinner and disc-like involved less preparation. Each lapillus was ground laterally on a

fingertip and polished using two grades of lapping film (10 μm , then 3 μm) to produce a thin polished section that was mounted on a glass slide in Euparal mounting medium and protected by a cover slip. After being left for several weeks for the otolith matrix to clear, the prepared lapilli were examined using a Leitz compound microscope (400 \times magnification) fitted with an Ikagami high resolution black and white video camera connected to a Commodore Amiga personal computer with a high resolution monitor. One lapillus from each juvenile was counted twice by the same experienced reader (AJF), but more often if there was any ambiguity in the interpretation of the microstructure. The most precise count was accepted as the most accurate.

The microstructure of a coral trout lapillus is similar to that of other coral reef fishes, displaying a presettlement region of relatively broad microincrements, surrounded by a postsettlement region of thinner increments, with the two regions demarcated by a "settlement mark" (Victor, 1982; Fowler, 1989; Wellington and Victor, 1989). Settlement dates were back-calculated by counting the postsettlement increments and working back from the date of collection. Approximate birth dates were calculated in a similar manner from the combined count of all microincrements, assuming that all increments are formed daily.

Three individuals that had interpretable otoliths did not display an unambiguous settlement mark and only a total count (i.e., birth date) was estimated for these fish.

Spawning.—This part of the study has been described in detail by Samoily and Squire (1994). Hence it is appropriate here to record only that Scott Reef (Fig. 1) was visited frequently between August and December 1990 to monitor the number of coral trout (*Plectropomus leopardus*) on a site known to aggregate spawners. It is assumed for the purpose of this comparison that the intensity of spawning from this aggregation was proportional to the abundance of fish on the monitored site.

The choice of Arlington and Green Reefs as sites for monitoring replenishment, and Scott Reef as the site for monitoring spawning, was dictated by several factors and is not to suggest that there is any connectivity between them. In fact, strong connectivity is unlikely because the dominant flow over the shelf in this region is poleward, from Arlington towards Scott. Instead, we assume that Arlington and Green provide larval sinks for unknown sources to the north and that any temporal correlation with the observations from Scott Reef represents regional synchrony in reproduction.

RESULTS

Larval Supply.—A total of 222 pelagic juvenile trout were identified by their red color and extracted in live state from the light-trap samples. Another 15 individuals were recovered when the preserved samples were sorted systematically.

Four juveniles metamorphosed into juvenile colors after grow out; three were *Plectropomus leopardus*, the fourth was *P. maculatus*, which is the second most common trout encountered on these reefs (Samoily, unpubl. data). Microscopic examination of approximately 100 preserved specimens failed to detect any other *P. maculatus*. This identification was based on the presence/absence of a pigment spot on the pelvic spine which Leis (1986) suggested was the best character for separating the two congeners. Pectoral ray counts were used to exclude the outer-shelf species, *P. laevis* (Randall and Hoese, 1986). We conclude that most of the pelagic juveniles were *Plectropomus leopardus* because it is by far the most common coral trout encountered in the mid-shelf of the GBR (Ayling and Ayling, 1986).

All 237 pelagic juveniles were caught during a 17 day time window centered on the new moon in November (Fig. 2B). Within this period, three nights yielded the majority of the catch (11 Nov: 105, 17 Nov: 39, 24 Nov: 32) and this timing was consistent among productive sites (Fig. 3). A possible explanation for this daily variation was revealed by the analysis of wind records (Fig. 4), which showed that highest catches were correlated with northerly winds even though these represented only one third of the wind records during the November fishing period.

Analysis of spatial patterns was limited by the lack of replication at sites; however, Table 1 shows that sampling effort was close to orthogonal between depths, reefs, and among sites within reefs. On the basis of this standardized effort, it is clear that catches were not distributed uniformly in space. More trout were caught at Arlington Reef (N = 226, CPUE = 1.82) than at Green (N = 11, CPUE = 0.10) and more were caught in shallow water (202, CPUE = 1.68) than in deep

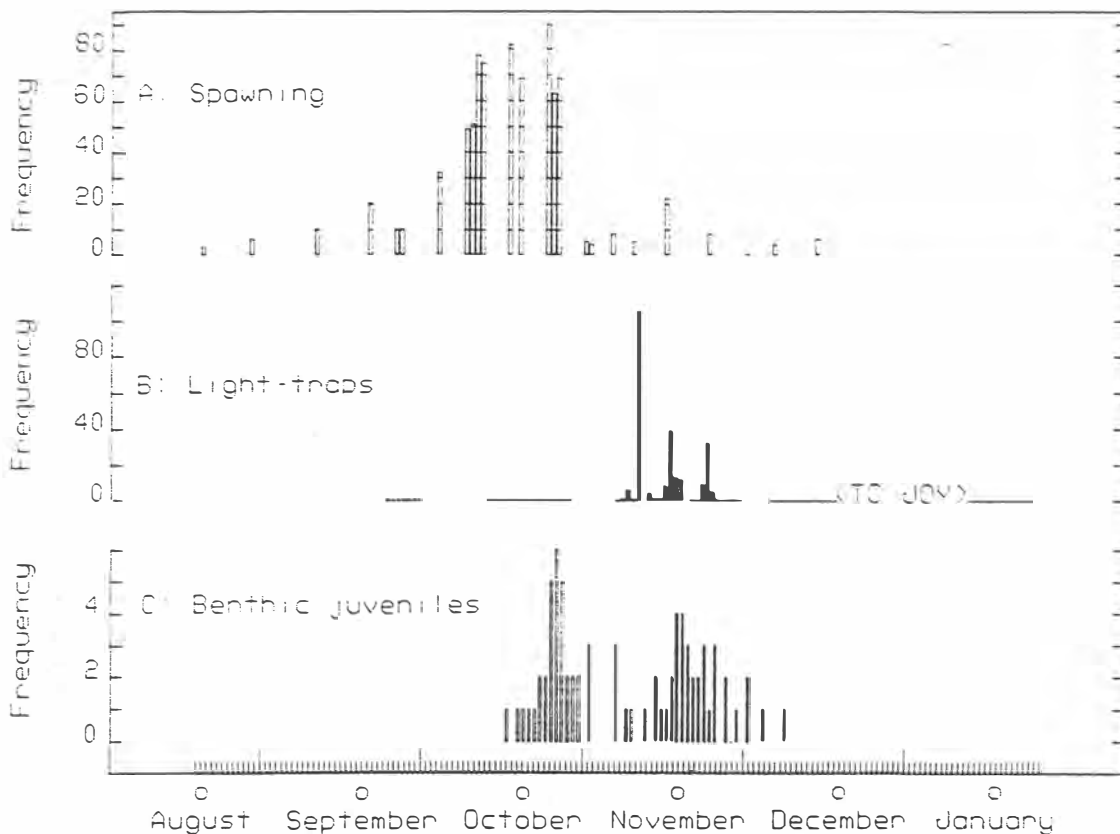


Figure 2. Timing and relative abundance of three life history stages of coral trout in 1990/1991: (A) number of *Plectropomus leopardus* on the aggregation site at Scott Reef; (B) pelagic juveniles of *Plectropomus* spp. in light-traps (TC JOY = tropical cyclone); (C) back-calculated birth (unfilled bars) and settlement (filled bars) dates of benthic juveniles of *Plectropomus leopardus* collected in late January from Arlington Reef.

($N = 35$, CPUE = 0.31). Most trout were collected from the three shallow traps at Arlington ($N = 191$, CPUE = 3.08) and catches increased towards the southeast corner of the reef (A1: 21, A2: 63, A3: 107); however, this trend must be considered in light of a single catch of 74 at A3. Catches in shallow and deep traps on the same sites at Arlington were correlated (Pearson's $r = 0.98$), albeit at different intensities, indicating a vertical coherence in the patchiness of the pelagic assemblages.

All of the trout collected in light-traps were of similar size and assumed to be competent to settle. Their average size was $16.8 \text{ mm} \pm 0.19$ (95% CL) with a range from 15–18.5 mm. Although not analysed formally, no pattern was evident in the distribution of fish size between depths or among reefs, sites, or days.

Juveniles.—The otoliths from 36 juveniles collected at the end of summer contained distinct settlement marks. The back-calculated settlement dates for these individuals showed reasonable agreement with the light-trap catches (Fig. 2C) with the modal date falling on the new moon in November. The coincidence was not perfect, however; there was no peak corresponding to the large catch on 11 November and some individuals were assigned ages that fell on dates when no trout were caught in the traps. While the general impression is of a slight lag between the two data sets, no formal correspondence analysis (e.g., cross-correlation) was considered appropriate because of the polymodal nature of the light-trap records and the unimodal nature of the back-calculated dates. The primary result must

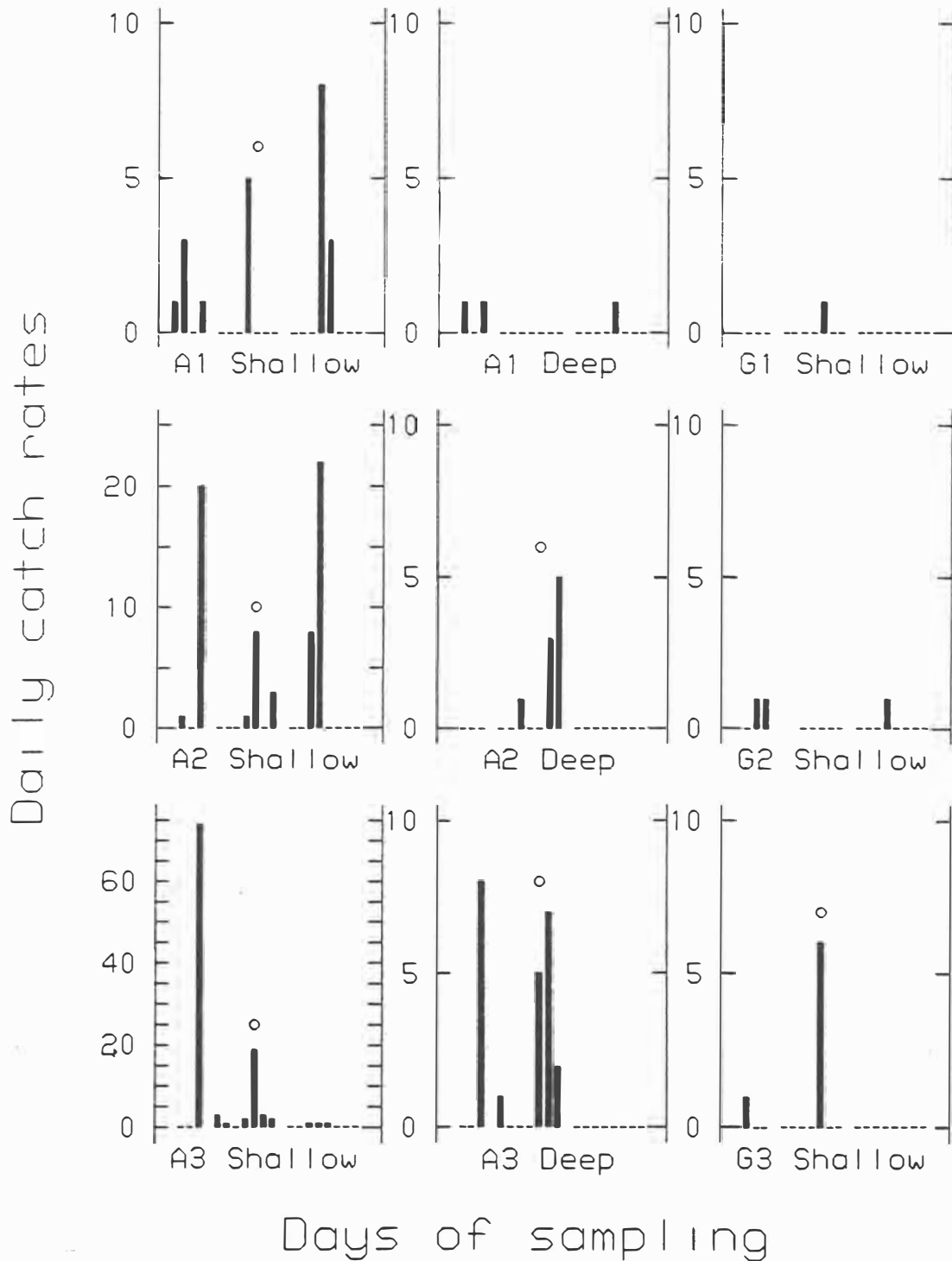


Figure 3. Daily catch records for the November sampling period of pelagic juveniles in shallow (-1 m) and deep (-20 m) light-traps at Arlington (A_n) and Green (G_n) Reefs (zero catch in all deep traps at Green). New moon (17 Nov) indicated by open circle.

be that we failed to detect any settlement on new moons from months other than November.

Analysis of the presettlement increments from these individuals revealed an average of 25.2 ± 0.9 (95% CL) presumptive daily increments with a range of

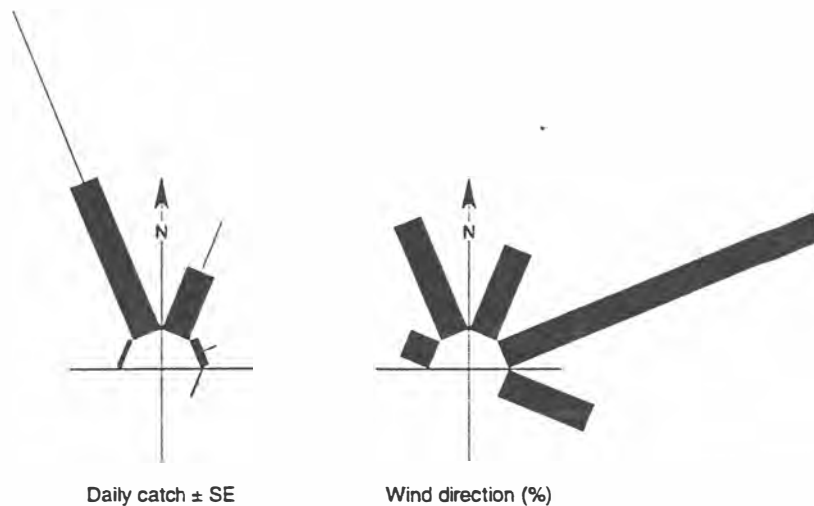


Figure 4. (Left) Mean daily catch of pelagic juveniles in light-traps during the November sampling period aligned with wind direction; (Right) Wind rose for the same period expressed as % of 22 days.

19–31. While this estimates minimum pelagic larval duration, it is almost certainly an underestimate because the first ring is unlikely to have been formed on the day of fertilisation.

Apart from the data on early life history, the juvenile collections also provided a record of postsettlement growth given that a discrete cohort was indicated by both light-traps and back-calculation. By the end of January, the size distribution of this cohort was skewed with a pronounced tail of smaller fish (Fig. 5). When analysed as size at age, however, most of these smaller juveniles were also found to be younger (Fig. 6). Since only two records are available for older fish, it is not clear whether growth should be modelled as linear or curvilinear over the whole period; hence, the temptation to fit a growth curve to these data has been resisted. Between November and January, however, the average daily growth of this cohort was 0.81 ± 0.04 (95% CL) $\text{mm} \cdot \text{day}^{-1}$.

Table 1. Catch and effort data from 12 light-traps deployed between 8–30 November 1990. Units of effort are nights of fishing during this period; catch is the total number of *Plectropomus* pooled across nights; CPUE = catch per unit effort. Reefs and sites can be located from Figure 1; CPUE in each cell (reef/depth combination) is in bold type.

	Trap depth					
	Shallow			Deep		
	Effort	Catch	CPUE	Effort	Catch	CPUE
Arlington Reef (124 trap-nights, 226 juveniles, CPUE 1.82)						
Site 1	21	21	1.00	21	3	0.14
Site 2	21	63	3.00	21	9	0.43
Site 3	20	107	5.35	20	23	1.15
Subtotal	62	191	3.08	62	35	0.56
Green Reef (109 trap-nights, 11 juveniles, CPUE 0.10)						
Site 1	21	1	0.05	19	0	0.00
Site 2	18	3	0.17	14	0	0.00
Site 3	19	7	0.37	18	0	0.00
Subtotal	58	11	0.19	51	0	0.00
Depth totals	120	202	1.68	113	35	0.31

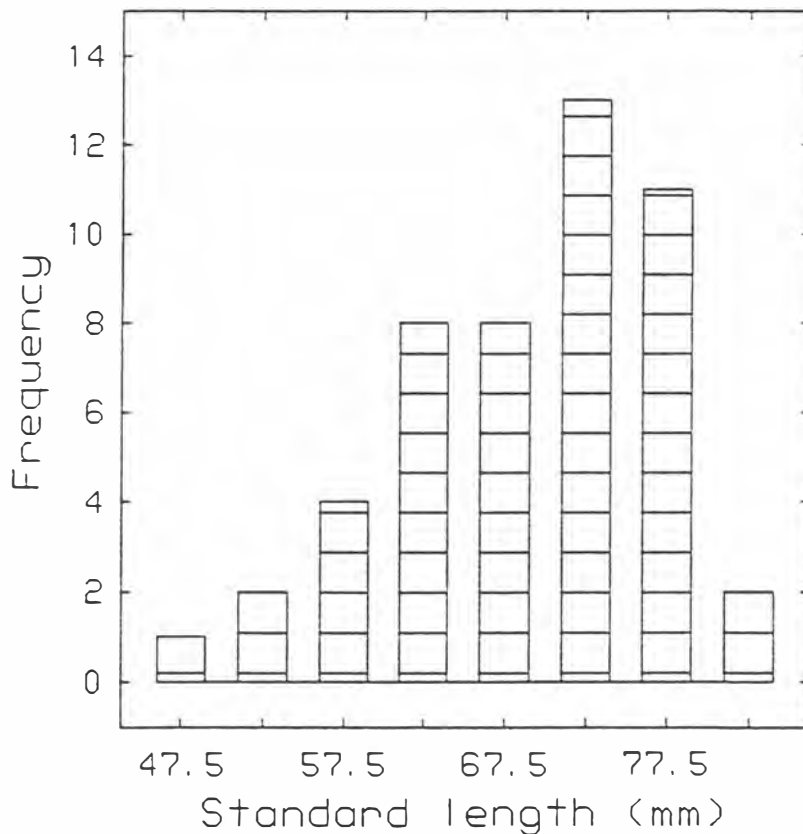


Figure 5. Size distribution of 49 intact juveniles of *Plectropomus leopardus* collected in late January from Arlington Reef.

Spawning.—The regular surveys of the aggregation site at Scott Reef showed just one major peak of spawning on that site (Fig. 2A), which lasted two weeks about the new moon in October. At this time, densities of trout counted on the spawning site were more than an order of magnitude higher than those observed during non spawning periods and gamete release was witnessed on several evenings (Samoilys and Squire, 1994).

The analysis of the microstructure of otoliths from speared juveniles collected in January yielded back-calculated birth dates that corresponded reasonably well with the observed spawning behavior, although the alignment was not perfect. However, the estimates of pelagic duration may have been underestimates (see above).

Samoilys and Squire (1994) also observed isolated spawnings on the new moon in November and inferred spawnings on the new moon in September. Our failure to detect recruitment at Arlington or Green from either of these spawning episodes (Fig. 2) may simply reflect the low level of activity at such times and the relatively small size of our sample of juveniles.

DISCUSSION

In a review of their early life histories, Leis (1987) argued that “larval studies of groupers were unlikely ever to contribute to stock assessment” but he noted the potential for unconventional plankton sampling gear to sample the larger pelagic stages. This refers to the tendency of catches from towed plankton nets to be biased towards very young larvae, which are poor indicators of recruitment,

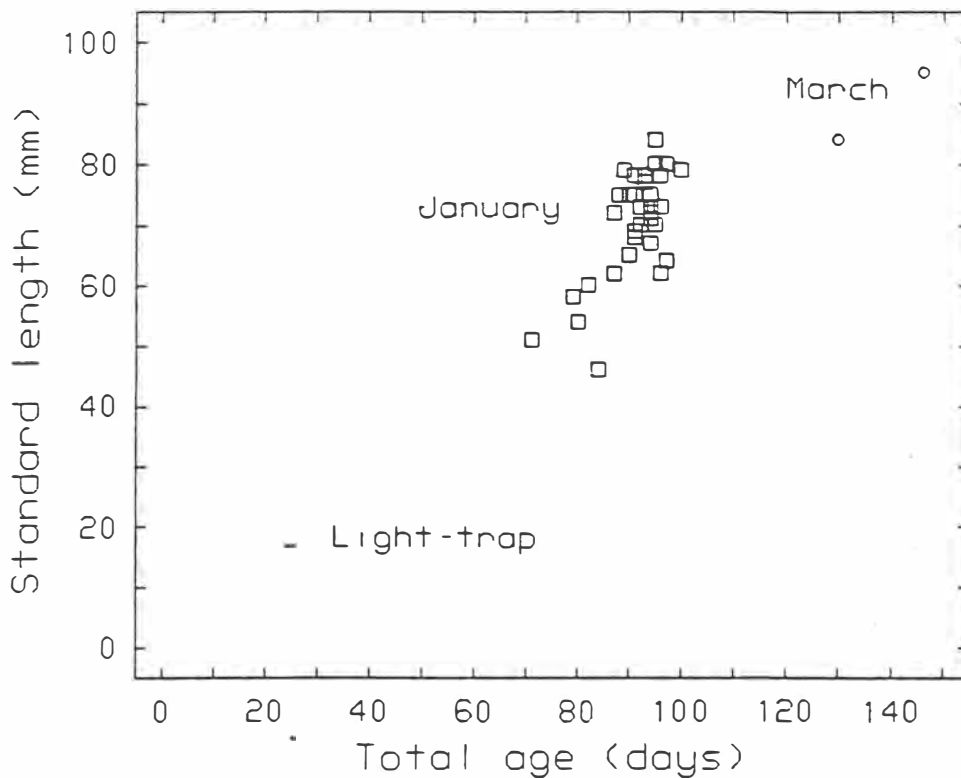


Figure 6. Standard length at age of (A) 84 pelagic juveniles from the light-traps, error bars = 95% confidence interval on size, age range (not shown) 19–31 days; (B) 36 intact benthic juveniles with interpretable otolith microstructure collected in January 1991; (C) two benthic juveniles collected in March 1991.

due to net avoidance by the older stages (Choat et al., 1993). Doherty (1987) suggested that the relative abundance of this agile nekton may be sampled through light attraction.

Since fishing with light, especially close to reefs, attracts pelagic juveniles that are competent or nearly competent to settle, it seems intuitive that light-trap catches should provide an index of colonisation. Milicich et al. (1992) demonstrated positive correlations between light-trap catches and settlement for three species of damselfish although these connections were expressed best at whole reef scales rather than fractional ones. Our paper shows for the first time that light-traps can be used to monitor the replenishment of other types of reef fish, where visual censuses may not be appropriate. In the case of coral trout, this is because young juveniles are cryptic for several months after settlement (Samoilys, unpubl. data).

In contrast to the limitations of visual censuses in such cases, we were able to monitor (and afterwards, independently confirm) the arrival of one cohort of coral trout to the study reefs, more or less simultaneously with settlement. On the basis of this preliminary data set, however, we claim only that light-traps are able to monitor temporal trends in the replenishment of coral trout; i.e., they can distinguish periods of settlement from non-settlement. We propose this caveat for three reasons. First, the volume of water sampled by a light-trap is unknown and therefore catches cannot be expressed other than in relative terms (Choat et al., 1993). Second, it is nearly impossible to estimate the densities of newly-settled coral trout in a complex habitat like the reef slope. Even with poisoning and habitat destruction, it is likely that such small fish would be undercollected which

is why we had to resort to an indirect method (back-calculation) to assess recruitment. Because of the difficulty of ensuring a representative sample of all ages by spearing, this method provides information on the timing of cohorts rather than their abundance. Third, there was apparently only one pulse of recruitment during the 1990/1991 season which, no matter how accurately measured, cannot test the reliability of any technique to monitor future variations in replenishment.

Given that sampling effort was nearly orthogonal across several factors in our design, the catch statistics show that pelagic juveniles of coral trout were not distributed homogeneously in either time or space. Despite sampling around five consecutive new moons, all trout caught by light-traps were taken around one: November. This pattern of replenishment was consistent with the back-calculation of settlement from juveniles collected from the reef at the end of summer. The congruence between these two data sets is the basis of our claim that light-traps are at least equally effective as monitoring tools and our claim that replenishment during the 1990/1991 season was limited to a single cohort.

We readily admit that alignment between the two data sets is not perfect: the time series from back-calculation lagged several days behind the catch records and daily variations in the latter were obviously smoothed. We offer two possible reasons for this. First, the simplest explanation is inaccuracy in the back-calculations which deteriorate as the period of extrapolation gets longer (Meekan, in press). Second, the light-traps collect fish of a range of ages which may not all be ready to settle on the night of capture. More attention needs to be given to the second problem in order to understand exactly what light-traps measure, although this will be done more easily with species that have abundant conspicuous recruits which can be sampled daily by simple independent methods.

The daily variations in the trap catches during November, although not confirmed by the second method due to its limited resolving power, seem to be more than sampling errors because of the coincidence of strong pulses among two or more traps and their correlation with the wind records. The CPUE on days after northerly winds far exceeded that of the dominant weather pattern, and no period of northerly wind was unproductive. Milicich (1992), who worked at another location, also found a correlation between light-trap catches and wind direction. In both cases, however, the correlations were derived from sampling a few fixed locations close to reef which means that it is not possible to know the scale of the process. A shift in wind direction may promote or retard the exchange of water between ocean and reef environments; or it may simply shift reef associated plankton into or out of the area being sampled with traps. Concurrent monitoring of hydrodynamics in the near- and far-fields will be necessary to distinguish between these alternatives.

Despite similar sampling effort at two depths, CPUE was much higher in shallow traps. At times and places where presettlement trout were caught in appreciable numbers at the surface, abundance was correlated but always lower in the deeper trap suggesting at least a nocturnal preference for the surface layers. This is not unusual as shallow light-traps consistently outfish deeper ones for most reef fish taxa, with the exception of a few groups like the Acanthuridae (Doherty and Carleton, unpubl. data). In contrast, Leis and Goldman (1987) working near Lizard Island, found more *Plectropomus* at depth compared with the surface. However, it must be emphasized that their results pertain to the daytime residence depth of net plankton which is dominated by larval stages that are smaller and younger than those collected by the light-traps.

Despite similar orientation with respect to mainstream currents and the wind,

traps around Arlington Reef consistently outfished those at Green. One possible explanation for this difference is that the larger reef casts a "hydrodynamic shadow" over its near neighbour, depleting its larval supply (Black, 1993). Such an effect would be exaggerated if presettlement fish actively orientated to the first reef encountered, assuming that they are transported from the north. We are cautious, however, about advocating any particular hypothesis to explain the fixed difference in catch rates between the reefs given the pseudo-replicated design of our study. In addition to the upstream/downstream difference between Arlington and Green with respect to longshore currents, Green is also located further inshore and the two reefs are of vastly different size. There is empirical evidence that cross-shelf position can influence the specific composition of ichthyoplankton assemblages (Young et al., 1986), recruitment patterns (Williams et al., 1986), and the relative abundance of closely related species (Anderson et al., 1981) including coral trouts (Ayling and Ayling, 1986). In addition, there is theoretical evidence from modelling studies that larger reefs should be more effective larval traps than smaller ones (Dight, 1992), retaining a higher proportion of propagules carried past by the mainstream flow. This proposition is supported by our sampling here and elsewhere, which has shown that rare taxa like coral trout are trapped more often behind large reefs than small ones (Doherty and Carleton, unpubl. data).

Whatever the reason, it appears that Arlington is an effective place to monitor the replenishment of coral trout. Since we believe that this reef derives its recruitment predominantly from upstream sources to the north, it is intriguing that the pattern of replenishment witnessed on these reefs should be correlated with the spawning effort of coral trout observed on Scott Reef which lies 40 km downstream. We attribute this synchrony to regional entrainment of spawning, probably by thermal and lunar cues (Samoilys and Squire, 1994). On this basis, it appears that coral trout populations in the Cairns region in 1990/1991 engaged in one major episode of spawning that resulted in one strong pulse of recruitment. Such circumscribed reproduction is unusual among tropical fishes (Thresher, 1984) although it may be more common among serranids that aggregate for spawning (Smith, 1972; Johannes, 1988; Fine, 1990).

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