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Biology of the Shortfinned Eel *Anguilla obscura* in Lake Te Rotonui, Mitiaro, Cook Islands[1]

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ABSTRACT: Lake Te Rotonui, a shallow depression lake in the center of Mitiaro Island, southern Cook Islands, contains freshwater eels despite having no surface connection to the sea. During a survey of the eel population in July 1988, all of the 287 eels captured using fyke nets and gaffs were *Anguilla obscura*, although it is possible that *A. megastoma* and perhaps *A. marmorata* also occur in small numbers. Ages of eels were found from burnt otoliths; it was assumed that otolith zones were formed annually, although this could not be validated. Growth rates were slower than those of other tropical eel species, being similar to those of temperate species. Eels fed exclusively on *Oreochromis mossambica*, which was abundant in the lake. The relatively slow growth in the presence of abundant food may be due to high and stressful summer water temperatures. From length and age frequency distributions, it is suggested that recruitment of glass-eels into the lake is intermittent and via submarine outfalls. A review of the limited larval information suggested that *A. obscura* spawns to the east of Tahiti, with larvae transported west and south by the South Equatorial Current.

ALTHOUGH THE TEMPERATE SPECIES of freshwater eels (genus *Anguilla*) have been widely studied, there have been few studies of the tropical species, especially those of the Pacific region. *Anguilla obscura* is a tropical shortfinned species that ranges from western New Guinea to Tahiti (Ege 1939). Biological data available for this species are limited larval information (Jespersen 1942, Castle 1963, Matsui et al. 1970), meristic features (Ege 1939, Beumer et al. 1981, Marquet and Lamarque 1986), distribution (Ege 1939, Castle 1968), and brief observations on some aspects of freshwater biology (Marquet and Lamarque 1986). The present study is the first that examines growth rates. It was carried out as part of a New Zealand Government Foreign Aid project to assess the eel population of Lake Te Rotonui and to advise on the commercial viability of the stock.

MATERIALS AND METHODS

Study Area

The island of Mitiaro (19° 1′ S, 157° 3′ W) is in the southern Cook Islands, ca. 230 km northeast of Rarotonga. Mitiaro is 2500 ha in area and saucer-shaped in cross section, with a raised coral limestone reef (*makatea*) surrounding a central depression (420 ha) occupied by swamps, lakes, and four small basalt "islands" (Figure 1). Cliffs around the outer margin of the island rise to a maximum height of 15 m above mean sea level (M.S.L.) and the lakes are ca. 2 m above M.S.L. The island has a human population of 250 living in villages adjacent to Omutu landing, an artificial gap in the fringing coral platform.

Lake Te Rotonui has a surface area of 70 ha at a water level of 2 m above M.S.L., although this may increase to 114 ha at maximum levels. The western margin is shallow and convoluted and the lake increases in depth to the east, with a maximum depth of 2–2.5 m to the south of the Parava Track. Because of the shallow and exposed nature

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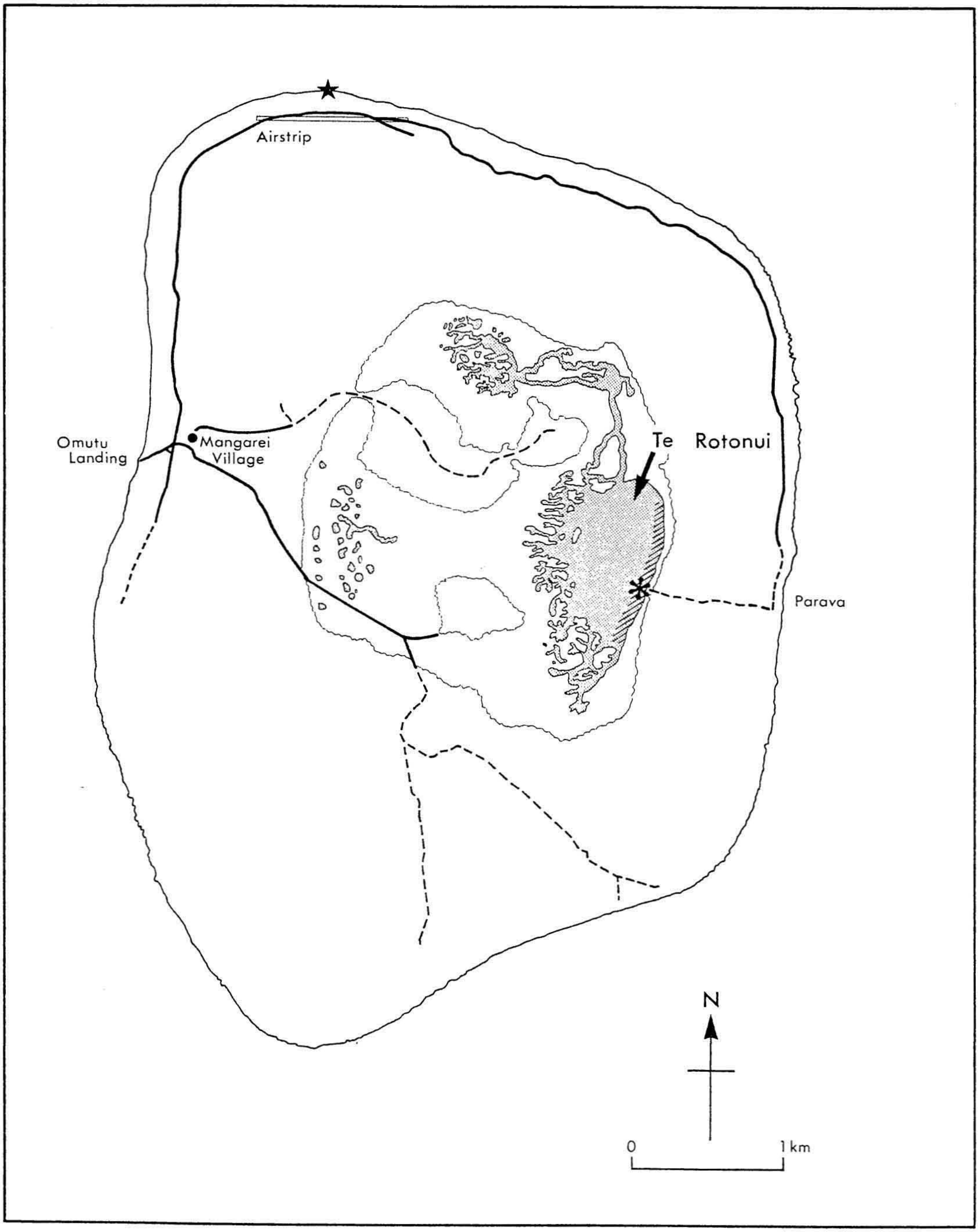

FIGURE 1. Mitiaro Island showing Lake Te Rotonui, the Parava work site (asterisk), the area fished (diagonal lines), and the location of the freshwater outfall (star).

of the lake and the presence of frequent sea breezes, it is unlikely that any thermal stratification would occur.

The lake does not have a surface outlet, and drainage is presumed to be via subterranean conduits through the porous *makatea*. The only observed outfall is a seepage area north of the airstrip (Figure 1) where flow was estimated at 4–5 liters/sec, although the islanders are aware of some seepage of similar rate at the Omutu landing. During the survey, 20–27 July 1988, the lake level fell at a rate of 10.8 mm/day. Evaporation from the lake calculated from air temperature data is estimated at 3.5 mm/day (I. Jowett, MAF, pers. comm.), meaning that the remaining fall (7.3 mm/day) must have been due to submarine outflow, equivalent to 59 liters/sec, less the seepage observed.

Between 20 and 27 July the midday surface water temperature fell from 30°C to 19.5°C. Conductivity of the lake water ranged from 267 to 285 mS/m. No aquatic macrophytes were seen in the lake, but the bottom was covered with a 0.5-m mat of blue-green algae and the decomposition products of this mat. The alga has been tentatively identified as *Coelospharerium* (Chroococcaceae). No aquatic invertebrates were seen in the lake, although adult damselflies (Odonata) were common.

Six species of fish were caught. Native species were the eel *Anguilla obscura* ("tuna") and the eleotrid *Eleotris fusca* ("kokopu"). Of the introduced species, guppies (*Poecilia reticulata*), mosquitofish (*Gambusia affinis*), and the cichlid *Oreochromis mossambica* were abundant around the shallow margins of the lake. Mosquitofish were introduced to the Cook Islands before 1948 (Krumholz 1948), probably from Hawaii. Together with guppies they provide a means of controlling mosquitoes. *Oreochromis mossambica* was introduced to several South Pacific islands during the mid- to late 1950s (Maciolek 1984). The population in Lake Te Rotonui was dense and stunted (author's unpublished data). Occasional milkfish, *Chanos chanos*, were seen; these fish resulted from a small trial stocking in 1984.

Capture and Handling Techniques

Eels were sampled using 12 unbaited, single-wing fyke nets (mesh size, 20 mm; leader, 2.9 m). Each net was numbered, set at right angles to the shore, and its location recorded. Nets were lifted and reset each morning and eels were taken to a landing point adjacent to the Parava Track (Figure 1) for processing. Additional eels were gaffed by one of the local men, who would quietly paddle his canoe until sighting an eel head emerged from the algal mat. The eel could then normally be gaffed with a swift upward thrust and pulled into the canoe.

Eels from fyke nets were anesthetized in a solution of benzocaine. The length of all eels caught was recorded (± 1 mm), and the weight of most was measured to the nearest 10 g. Where eel numbers allowed, a minimum of 10 pairs of otoliths were taken from each 50-mm length group represented. The stomach contents of these eels were also recorded using a points system, where 0 points denoted an empty stomach, 40 points a full stomach, and 45 points a distended stomach. Where digestion permitted, food items were identified and their numbers recorded.

Three experiments were carried out as steps to estimate the number of catchable eels in the lake (i.e., eels >350 mm and hence large enough to be fyke-netted). The first was carried out to provide information on the number of eels accessible to a net set at one location. The technique itself was a progressive removal experiment using nets set for three or more successive nights at the same site. The second experiment was designed to give a measure of the effective area of a net; it was presumed that this area would equate to the average home range of an individual eel. That most eels within a population exhibit localized movements within a home range has been established for *A. rostrata* by LaBar and Facey (1983) and Bozeman et al. (1985). For this experiment, eels captured at one shoreline location were fin-clipped for later recognition and then released at the capture site. The following night five nets were set equidistantly at a radius 75 m from the capture site, and any marked eels were recorded and removed. On subsequent nights, the five nets were set at radii of 50 m and 25 m, respectively.

The third experiment was a mark-recapture study using individually numbered metal strap tags that were clamped at the base of the pectoral fin. Eels not killed for otolith removal or fin-clipped for the home range estimate were tagged and released at the capture site. Population size was estimated by both the Schumacher and Schnabel multiple census techniques (Ricker 1975).

Meristics

Proportional body measurements and vertebral counts are widely used to distinguish between the various species of *Anguilla*. As it was thought possible that the Australasian shortfinned eel, *Anguilla australis*, might occur in small numbers, several measurements were taken to identify eels to species level. *Anguilla australis* and *A. obscura* can be differentiated by origin of the dorsal fin relative to the anus and the position of the eye relative to the lower jaw (Ege 1939). Measurements recorded were total length, predorsal length, preanal length, length of lower jaw, and the distance from the gape to a perpendicular line passing through the midpoint of the eye. Indices of the origin of dorsal and anal fins and the position of the eye relative to jaw length were calculated according to the method of Ege (1939) and Beumer et al. (1981). Vertebral counts were made from X rays of a sample of 19 eels collected from Lake Te Rotonui in 1978 by P. R. Todd (Freshwater Fisheries Centre, Christchurch).

Condition and Growth

The condition factor (K) of individual eels was calculated using the formula:

$$K = W \times 10^6 / L^{3.38}$$

where W = weight in grams, L = length in mm, and 3.38 = the exponent derived from the length-weight relationship.

Age was determined by viewing burned otoliths; this technique has been widely used for determining the age of freshwater eels (e.g., Aprahamian 1987). For this, whole otoliths were held directly over a hot Bunsen burner flame. After burning, the otolith was broken transversely using gentle pressure from a scalpel blade and the two halves embedded by the base in a small quantity of silicon-rubber adhesive placed on a microscope slide. A drop of microscope immersion oil placed on the broken surface highlighted the ring formation, and otoliths were viewed using a binocular microscope (30 × power) with strong side illumination.

An overall readability index (scale 1–5) was recorded for each pair of otoliths, and the otolith diameter (across the shortest axis) was measured with a graduated eyepiece. Age in fresh water was calculated by counting the number of dark (hyaline) "winter" zones. Where available, all four halves of each pair of otoliths were read; if age varied, the modal age was recorded, or if one half was noticeably more readable, age from that portion was taken.

Statistics used were simple linear regression.

RESULTS

Eel Species

All eels examined (287) were nonvariegated and shortfinned. Proportional measurement data confirmed that they were *A. obscura*. Measurements of dorsal fin origins and eye position from a sample of 30 eels (422–845 mm) gave mean indices of 5.2 (range 3.1–7.2, S.D. ± 1.1) and 44.5 (range 33.3–53.6, S.D. ± 5.7), respectively. Although the mean fin origin index was within the range recorded by Ege (1939), the mean eye index was outside Ege's range. However, Ege's data were for generally smaller eels than in the present study. When Ege's data (given as mean eye index per 100-mm length group) are combined with similar data from the present study, there is a strong linear relationship between eye position and total fish length ($r = 0.95$, $P < 0.01$). Vertebral counts ranged from 101 to 104, with a mean of 103.79 (S.D. ± 0.69, $n = 19$).

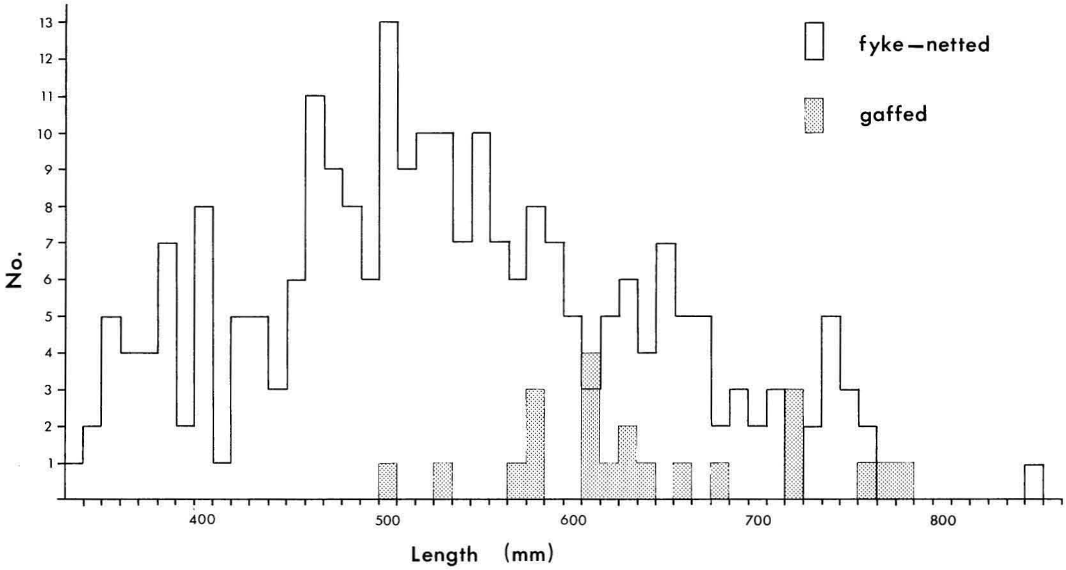

FIGURE 2. Length frequency histograms of all eels captured ($n = 287$).

Catches and Sizes of Eels

A total of 264 eels were caught over seven nights' fishing. Catches per net ranged from 0 to 26, with overall catch per unit effort (CPUE) being 3.14 eels per net per night. An additional 23 eels were gaffed.

The smallest eel caught by fyke net was 337 mm, although sizes <380 mm were not well represented (Figure 2). The mean length of fyke-netted eels (538 mm, S.D. ± 105 mm) was smaller than that for gaffed eels (647 mm, S.D. ± 74 mm).

The length-weight relationship was

$$\log_e W = 3.3832 (\log_e L) - 15.3713$$
$$(n = 145, r = 0.99)$$

where L = length in mm and W = weight in grams.

The mean condition factor of eels ($n = 145$) was 2.12 (range 1.62–2.91, S.D. ± 0.23), and there was no relationship between total length and condition.

Age and Growth

Otolith diameter was strongly correlated with eel length ($r = 0.88$, $P < 0.01$). The equation for linear regression was

$$L = 0.0031 (D) + 0.7949 \ (n = 118)$$

where L = fish length in mm and D = otolith diameter in mm.

Only one pair of otoliths was rejected as unreadable although otoliths were generally considered difficult to read. Hyaline zones tended to be broad and diffuse rather than narrow and distinct, meaning that the differentiation between adjacent hyaline and opaque zones was often difficult to determine. Ages ranged from 6 to 28 yr in fresh water. The age–length relationship for eels is shown in Figure 3. The average growth curve is shown by the line and was derived from the equation:

$$\log_e L = 0.5817 (\log_e A) + 4.7238$$
$$(n = 117, r = 0.71)$$

where L = length in mm and A = age in years.

The first 69 eels netted were all aged and so constitute an unbiased (unstratified) sample. Consequently, otoliths taken from these were used to generate the age frequency distribution (Figure 4). Mean age from this sample was 16.4 yr (S.D. ± 3.6).

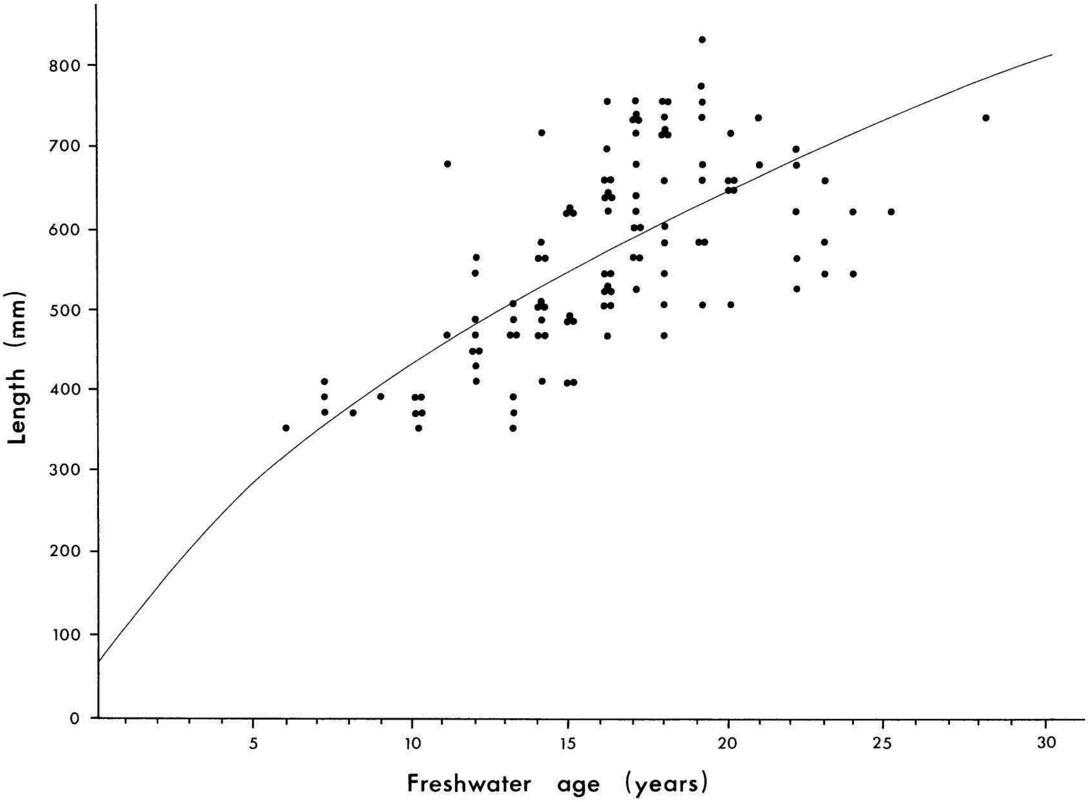

FIGURE 3. Age–length relationship of individual eels. The curved line is the log-transformed least squares regression referred to in the text.

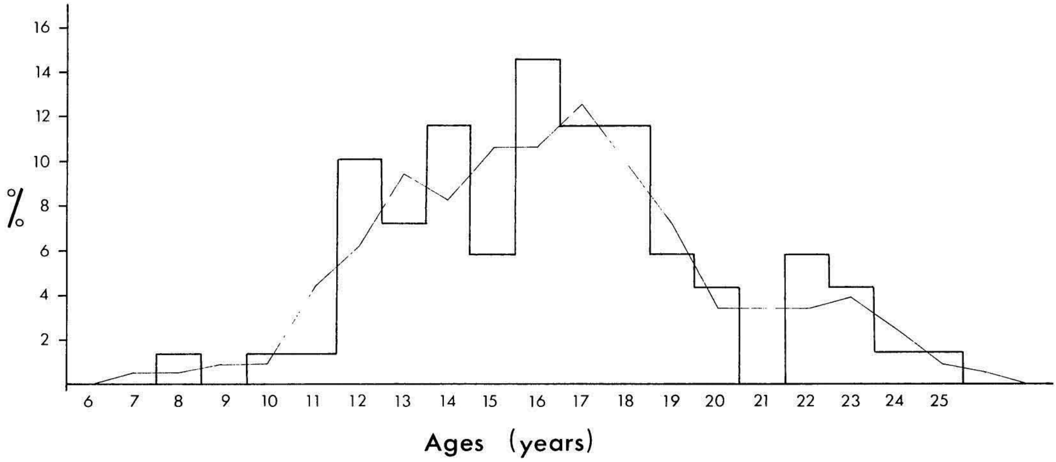

FIGURE 4. Frequency distribution of ages from a random sample of fyke-netted eels ($n = 69$). The continuous line shows the three-point moving average.

TABLE 1

STOMACH FULLNESS OF EELS ($n = 117$)

FULLNESS	STOMACHS NO.	STOMACHS %
Empty	43	37
$<\frac{1}{4}$	20	17
$\frac{1}{4}$–$\frac{1}{2}$	6	5
$\frac{1}{2}$–$\frac{3}{4}$	13	11
$\frac{3}{4}$–full	20	17
Full–distended	15	13

Diet

Because stomachs examined ($n = 117$) came from those eels killed for otolith removal, the sample was stratified by length group but covered the full size range of eels caught. Stomach fullness is given in Table 1. The average score for stomachs that contained food ($n = 74$) was 26.1 points.

Only three food categories were recorded from stomachs. These were *Oreochromis*, unidentifiable fish (due to degree of digestion), and algae. A summary of the information (Table 2) shows the dominance of *Oreochromis* in the diet, and it is very likely that all the "unidentified fish" were also *Oreochromis*. The maximum number of *Oreochromis* per stomach was four and the largest *Oreochromis* found was 140 mm. *Oreochromis* also dominated the diet of gaffed eels ($n = 16$), constituting 76% of all points.

Population Estimates

Eight marked eels were recaptured, only one of which was caught during the home range experiment, at a distance of 25 m from the release point at the lake margin. The seven other recaptures were all tagged eels. Of these, three had moved 30 m from their release point, one moved 100 m, one moved 150 m, and two moved 250 m. The mean distance moved was 108 m. Because of the variability in these few data, it was not possible to establish an area for home range of eels with any confidence.

Population estimates for nets set for three or more nights were also quite variable (Table 3). Because substantial numbers of eels could still be caught after three nights' fishing, the estimates for the six fishing nights were considered to be the more appropriate data. These gave a mean population of 37 eels available to each net.

It had been anticipated that this population estimate would be incorporated with the home range estimate to provide an estimate of eel density. The density estimate could then be extrapolated for the whole lake. In practice, because the home range data proved inconclusive such total population estimates were not carried out.

Population estimates from the modified Schnabel method and the Schumacher method were 1005 eels (95% CL, 460–3652) and 1055 eels (95% CL, 598–3127), respectively. These estimates were relative to a shoreline length of 900 m.

Again, a lack of a sound estimate of home range caused difficulty in converting this shoreline length to the effective area fished by the nets. If the modal recapture distance (30 m) is used as a conservative estimate, then the Schnabel and Schumacher estimates are relative to an area of 2.7 ha. Assuming a

TABLE 2

STOMACH CONTENTS OF EELS ($n = 117$)

FOOD ITEM	NO. OF STOMACHS CONTAINING ITEM	% OF POINTS	AVERAGE POINTS PER STOMACH	NO. OF INDIVIDUAL ORGANISMS	MAXIMUM NO. PER STOMACH
Empty	43	—	—	—	—
Oreochromis	45	85.7	36.8	68	4
Unidentified fish	18	10.3	11.1	5+	3
Algae	16	4.0	4.8	—	—

TABLE 3

CATCHES OF EELS FROM FYKE NETS ON SUCCESSIVE NIGHTS AT THE SAME SITE

NET	NIGHT 1	2	3	4	5	6	TOTAL CATCH	POPULATION ESTIMATE	CL (95%)
A	8	6	6	—*	—	—	20	36	20–86
B	8	1	0	—	—	—	9	9	9– 9
Means	8.0	3.5	3.0				15	16	15–20
C	10	20	0	6	10	0	46	54	46–67
D	14	5	2	3	8	2	34	40	34–51
E	6	0	4	2	3	0	15	16	15–21
Means	10.0	8.3	2.0	3.7	7.0	0.7	32	37	32–47

*— = not fished.

uniform distribution of eels throughout the lake, this equates to total population estimates of 26,050 and 27,350 eels, respectively. Equivalent estimates using the mean recapture distance of 108 m are 7240 and 7600 eels.

DISCUSSION

All eels caught in the present study were nonvariegated and shortfinned, which confirmed their identify as *A. obscura*. Although single specimens of the shortfinned eel *A. australis* have been recorded from both Fiji and Tahiti (Ege 1939), the validity of these identifications is doubtful, and hence it is thought unlikely that *A. australis* occurs in the Cook Islands. *Anguilla megastoma*, a variegated longfinned species, has been recorded from the Cook Islands (Ege 1939), but *A. marmorata*, another variegated longfinned species, has not been recorded even though the Cook Islands are within its geographic range. No longfinned eels were found during the present survey, but local people indicated that a larger species of eel, corresponding in description to *A. megastoma* or *A. marmorata*, was sometimes caught in Lake Te Rotonui but was uncommon. Thus the presence of species other than *A. obscura* in Lake Te Rotonui is suspected but not confirmed.

Measurements for fin origin and the position of the eye relative to jaw length were, respectively, outside or at the upper end of the range of measurements recorded by Ege (1939) for *A. obscura*. It is probable that such relatively high values are due to the larger eels in the present study, as Ege's data indicate that these indices are positively related to increasing size. Vertebral counts (mean 103.8) were similar to those given by Ege (1939) for *A. obscura* from the Cook Islands (mean 103.9) and identical to those of Marquet and Lamarque (1986) for *A. obscura* from French Polynesia.

Although there have been many growth studies of temperate eels, there have been few studies on tropical eels, and none on *A. obscura*. From data in Marquet and Lamarque (1986), it can be calculated that they considered that *A. obscura* reached lengths of 420 mm and 530 mm by the end of the first and second years, respectively, in fresh water. To date, growth rates this rapid for *Anguilla* spp. have only been recorded in culture conditions (e.g., Usui 1974), and it seems unlikely that such rapid growth would occur in the wild.

Use of otoliths for determination of age of tropical fish is successful for some species but not others (Samuel et al. 1987). The technique has already been used for the tropical freshwater eel *A. nebulosa* (Frost 1955, Pantulu and Singh 1962, Balon 1975). Although she used otoliths to determine age in *A. nebulosa*, Frost (1955) expressed some doubt about the annual formation of otolith zones. Pantulu and Singh (1962) studied zone formation on otolith margins over a year and concluded that formation was indeed annual. Reviewing the formation of annual zones on the bony tissue of tropical fish, Balon (1975) suggested that this formation was not due to climatic factors alone but also to an endogenous annual rhythm in fish growth that is regulated but not governed by environmental factors.

In the present study, it was not possible to validate the annual formation of otolith zones in *A. obscura*. Alternating hyaline and opaque zones were present, but, as mentioned previously, the boundaries between zones were less distinct than in the temperate eels that I am familiar with (*A. australis* and *A. dieffenbachii*). The hyaline zone was relatively wide and sometimes split into several supernumerary rings. Despite these differences, it was assumed that, like *A. nebulosa*, the zoning in otoliths of *A. obscura* is annual in formation and can be used to establish age.

Growth rates for *A. nebulosa labiata* (Frost 1955, Balon 1975) and *A. nebulosa nebulosa* (Pantulu and Singh 1962) were considerably faster than those for *A. obscura* in the present study. Although *A. obscura* is a tropical species, growth rates from the present study were comparable to those of temperate species (e.g., *A. mossambica* [McEwan and Hecht 1984], *A. anguilla* [Sinha and Jones 1967], *A. rostrata* [Ogden 1970], *A. australis* [Burnet 1969], and *A. reinhardtii* [Sloane 1984]).

Eels examined from Lake Te Rotonui had fed exclusively on *Oreochromis*, a shallow-water demersal species, which was available over a size range of 8–200 mm. In common with *Oreochromis* elsewhere, it is likely that some breeding occurs throughout the year (e.g., Huet 1972). During breeding, nest guarding by male *Oreochromis* probably increases their vulnerability to nocturnal predation by eels. In addition to small *Oreochromis*, guppies and mosquitofish were also present in the shallows but were not found in eel stomachs. No eels <300 mm were captured, thus diet of juvenile eels is unknown, but small fish would be readily available.

The incidence of fish in the diet of eels invariably increases with increasing size of the eel (e.g., Jellyman 1989). Fish do not become an important part of the diet of *A. australis* until eels are >300 mm, but Sloane (1984) recorded some fish in the diet of small eels (<200 mm). Because of the cryptic behavior of juvenile eels, it is unlikely that they would commence feeding on fish immediately upon their arrival as glass-eels (mean length ca. 50 mm [Ege 1939, Marquet and Lamarque 1986]) in Lake Te Rotonui. Although no benthic invertebrates were observed in the lake, it is probable that juvenile eels are principally benthic scavengers for their first few years in Lake Te Rotonui before changing to an exclusive fish diet.

Given the abundant supply of fish prey, it is surprising that the growth rate of eels in Lake Te Rotonui was not faster, approaching that of *A. nebulosa*. A possible explanation lies in the temperature extremes of the lake itself. During the sampling period, the maximum water temperature recorded was 30.0°C, although higher water temperatures would be expected during summer.

No data are available on temperature tolerances of *A. obscura* or other tropical eels, but temperatures greater than 30°C are stressful for temperate species, with the upper lethal limit for *A. anguilla* being 38°C (Sadler 1979). For temperatures above the optimum of 26.5°C, activity and appetite decline in *A. anguilla*, although metabolic rate continues to increase (Seymour 1989). Perhaps high daily water temperatures in combination with low levels of dissolved oxygen at night from algal respiration produce some physiological stress during summer with resultant slow growth. This is consistent with islanders' observations that the now-abandoned baited trap ("hinaki") fishery was only successful from May to September, as higher water temperatures outside these months caused eels to become torpid and "hibernate in the mud."

Cook Island specimens of *A. obscura* (present study) were heavier than specimens of equivalent length from French Polynesia (Marquet and Lamarque 1986). Similar geographic variation in length–weight relationships is seen in *A. nebulosa*, where two studies (Frost 1955, Wickstrom and Enderlein 1988) indicate that the species is lighter than *A. obscura* for a given length, while a third (Balon 1975) indicates the reverse.

Because of difficulties in establishing the effective fishing area of nets and a reliable estimate of eels present within the area fished, it was not possible to establish a total population estimate with any certainty. For example, using modal and mean recapture distances produced a 3.6-fold difference in such estimates. Assuming the smaller estimate (7240–7600 eels) to be a conservative one, then correspondingly conservative biomass estimates (relative to the mean size of fyke-netted eels of 538 mm) are 38–40 kg/ha of eels accessible to fyke nets.

Both the length and age frequency distributions for *A. obscura* show a nearly normal distribution, whereas positively skewed distributions would be anticipated in populations where recruitment is unrestricted and some harvesting of adult eels takes place. Certainly the present limited gaff fishery appears selective for larger eels (>500 mm) and should accentuate such skewness. A likely explanation for this lack of skewness is that annual recruitment is intermittent, possibly due to the difficulty of glass-eels in locating the submarine outfall(s). Islanders have no knowledge of recruitment of juvenile eels from the sea and hence believe that eels breed within the lake. Castle (1968) recorded a similar situation from Rennell Island (Solomon Islands) where Lake Tegano contains *A. obscura* but has no surface connection with the sea. Here also the islanders believe that eels breed in the lake although a connection through the coral is now known.

Recruitment times for *A. obscura* glass-eels are not well known. Ege (1939) obtained samples of glass-eels from New Caledonia from March to July and October, while Marquet and Lamarque (1986) captured glass-eels in Tahiti from October to April with the main periods being January and April. These limited data indicate some seasonality of recruitment, with time differences probably reflecting distance from spawning grounds. If correct, this is at variance with the suggestion of Jespersen (1942) that tropical eels spawn throughout the year, or at least for a large part of it. It also differs from information contained in Tabeta et al. (1976) where glass-eels of two tropical species, *A. celebensis* and *A. marmorata*, were present almost year-round in an estuary in the Philippine Islands.

Spawning grounds of *A. obscura* are unknown. Leptocephali have been recorded from four areas: near Tahiti and Fiji (Jespersen 1942), near the New Hebrides (Castle 1963), and off northeastern New Guinea (Matsui et al. 1970). The larva occurring farthest east (Tahiti) was also the smallest (27 mm), indicating dispersal from east to west. Jespersen (1942) presumed that this small size indicated proximity of the spawning ground, but as larvae have been recorded at 10° latitude north of Tahiti, it is likely that the spawning ground is northeast of Tahiti, possibly east of the Marquesas Islands.

Larval transport would be similar to that proposed for *A. australis* by Jellyman (1987), with larvae transported to New Guinea and the east coast of Australia by the westerly flow of the South Equatorial Current, while a southwest branch of the same current would convey larvae to New Caledonia, Tonga, Samoa, Fiji, and the Cook Islands.

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