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Nocturnal and diurnal feeding by *Galaxias auratus*, a lentic galaxiid fish

Author

Richard Stuart-Smith, Leon Barmuta, White, RWG

Bibliographic citation

Stuart-Smith, Richard; Barmuta, Leon; White, RWG (2006). Nocturnal and diurnal feeding by *Galaxias auratus*, a lentic galaxiid fish. University Of Tasmania. Journal contribution.

https://figshare.utas.edu.au/articles/journal_contribution/Nocturnal_and_diurnal_feeding_by_Galaxias_auratus_

Is published in: [10.1111/j.1600-0633.2006.00192.x](#)

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ECOLOGY OF
FRESHWATER FISH

Nocturnal and diurnal feeding by *Galaxias auratus*, a lentic galaxiid fish

Stuart-Smith RD, Barmuta LA, White RWG. Nocturnal and diurnal feeding by *Galaxias auratus*, a lentic galaxiid fish
Ecology of Freshwater Fish 2006: 15: 521–531. © 2006 The Authors.
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**R. D. Stuart-Smith, L. A. Barmuta,
R. W. G. White**

School of Zoology and Tasmanian Aquaculture
and Fisheries Institute, University of Tasmania,
Hobart, Tas., Australia

Abstract – We examined the diel feeding pattern, gastric evacuation and daily ration of a lentic, endemic Tasmanian galaxiid fish, *Galaxias auratus*. Analysis of stomach contents and consumption estimates based on collections of fish every 3 h over three 24-h periods in summer 2002/2003 revealed that feeding always occurred during both day and night, with no obvious peaks. We also estimated the gastric evacuation rate of *G. auratus* in a laboratory experiment using the two prey species found to be dominant in stomachs of field-sampled fish. The relationship was best described by an exponential model, with rate parameters (R) of 0.104 and 0.081 for the evacuation of the amphipod, *Austrochiltonia australis*, and the cladoceran, *Daphnia carinata*, at water temperatures of 11.5 and 16.5 °C, respectively. Daily ration of *G. auratus* in summer was estimated to be approximately 3% (dry body weight) using the models of Elliot & Persson and Eggers. *Galaxias auratus* appears to be unusual in that its feeding pattern cannot be classified as nocturnal, diurnal or crepuscular, but its gastric evacuation and daily ration estimates are still similar to other comparable Northern Hemisphere freshwater fishes.

Key words diel feeding; *Galaxias auratus*; daily ration; gastric evacuation

R. D. Stuart-Smith, School of Zoology and
Tasmanian Aquaculture and Fisheries Institute,
University of Tasmania, Private Bag 5, Hobart,
Tas. 7001, Australia;
e-mail: rstuarts@utas.edu.au

Accepted for publication June 23, 2006

Introduction

Whether they are nocturnal, diurnal or crepuscular, most fishes exhibit a distinct diel pattern in feeding (Fraser et al. 1993; Brännäs & Alanärä 1997; Fraser & Metcalfe 1997). The potential causes of such patterns are complicated and may include factors such as prey availability (Glova et al. 1987), predation risk (Metcalfe et al. 1999), potential for intra- or interspecific competition (Keast & Welsh 1968), capabilities of each fish species (e.g., dependence on vision for locating prey: Forrester et al. 1994; Kreivi et al. 1999) or a range of seasonal effects, (e.g., temperature and day length: Riehle & Griffith 1993; Fraser et al. 1995). Many of these are also interdependent. Studying the diel feeding pattern of a fish species can thus suggest a lot about its ecology and provides the foundation for estimating the amount of food it consumes daily.

There are some cases where the feeding of a fish species has both diurnal and nocturnal peaks (e.g.,

rock bass, *Ambloplites rupestris*; Keast & Welsh 1968). For fishes that occur in high densities (or when food is limited) this may be caused by temporal partitioning of feeding: in order to reduce the effects of intraspecific competition, some individuals feed nocturnally and some diurnally (Brännäs & Alanärä 1997). This partitioning may be size-structured and brought about by social interactions, where only the larger, more dominant individuals feed at the most preferred time of day ('preferred' in terms of the trade-off between optimising foraging efficiency and avoiding predators *sensu* Lima & Dill 1990).

Members of the Galaxiidae form an important component of the native freshwater fish fauna in temperate regions of the Southern Hemisphere, yet diel feeding patterns are unknown for most species. The lotic galaxiids of New Zealand have been the best studied in this respect, and many are nocturnal foragers (Glova & Sagar 1989a,b). *Galaxias auratus* (Johnston) is a lentic Tasmanian galaxiid that has co-existed with introduced brown trout (*Salmo trutta*

Linnaeus) in lakes Crescent and Sorell, to which it is endemic, since 1868 and still remains in very high densities. Little is known, however, of its ecology. It is believed that the activity of this species is greater at night, but its diel feeding pattern is unknown (Hardie et al. 2006). We hypothesised that *G. auratus* would also be a nocturnal forager both because of the prevailing evidence from New Zealand congeners and because the potential selective pressures imposed by brown trout (the major predator of *G. auratus*) would foster feeding in low light conditions. Thus, the primary objective of this study was to examine the diel feeding pattern of this lentic galaxiid. The potential for size-based temporal partitioning of feeding was also examined in relation to the observed feeding patterns.

When the diel feeding pattern is known, daily ration (or daily food intake) can be estimated with greatest accuracy (Darnell & Meierotto 1962; Mann 1978; Madon 1998). If samples of stomach contents have been collected in the field and the nature of gastric evacuation is known, daily ration can be estimated using a number of existing models, the most commonly used being those of Elliot & Persson (1978) and Eggers (1977) (Boisclair & Marchand 1993; Specziár 2002). Despite the importance of galaxiids in temperate Southern Hemisphere freshwater systems, there are no published estimates of daily ration for any species. A secondary objective of this study was to use the diel feeding data in conjunction with an estimate of the rate of gastric evacuation to estimate daily ration.

Methods

Study species and site

Galaxias auratus is a relatively large galaxiid [max total length (TL) approx. 240 mm, but more commonly to 140 mm], which is endemic to the interconnected lakes Crescent and Sorell on the Tasmanian Central Plateau (c. 42°5'S; 147°10'E). It is an opportunistic feeder, with adults eating a variety of aquatic and terrestrial invertebrates, but most often consuming epibenthic crustaceans and insect larvae and plankton when available (Hardie et al. 2004). Brown trout are also abundant in these lakes, which also contain smaller numbers of rainbow trout (*Oncorhynchus mykiss* Walbaum), short-finned eel (*Anguilla australis* Richardson) and common carp (*Cyprinus carpio* L.). The brown trout prey heavily on *G. auratus*, although their efficiency appears to have been reduced since the mid-1990s, when both lakes became highly turbid (Uytendaal 2003) and *G. auratus* presumably became harder to locate and capture (Stuart-Smith et al. 2004).

Galaxias auratus is listed as 'rare' under the Tasmanian *Threatened Species Protection Act 1995* and 'vulnerable' under the national *Environment Protection and Biodiversity Conservation Act 1999* due to its restricted distribution, yet within these lakes it occurs in arguably the highest densities of any of Tasmania's lentic galaxiids. Although lakes Crescent and Sorell are relatively large (23.1 and 51.6 km², respectively), they are shallow (2.3 and 3.1 m average depth, respectively) and there are estimated to be in excess of 2 million and 0.5 million *G. auratus* in lakes Crescent and Sorell, respectively (A. Uytendaal, unpublished data).

Diel feeding patterns

Galaxias auratus were captured using a backpack electrofishing unit (Model 12-B; Smith-Root Inc., Vancouver, Washington, USA) at 3-h intervals for 24 h. A replicate sample was taken exactly 24 h from the first. This was done on three occasions over summer 2002–2003, with two of these from Lake Crescent (11–12 December 2002 and 6–7 February 2003) and one from Lake Sorell (13–14 February 2003). The study was conducted in both lakes Crescent and Sorell in case the feeding pattern of *G. auratus* was affected by differences in their own populations, or trout or prey populations between the lakes. On each occasion, a suitable stretch of shoreline consisting of uniform cobble rock habitat was chosen and divided into nine shorter stretches, each to be sampled once in that day. Immediately after capture, the fish were killed by overdosing in benzocaine (300 mg l⁻¹), weighed, measured (TL) and preserved in 4% formalin with their abdominal cavity slit open. The water temperature was measured at the time and place of each sample.

Stomachs were dissected from fish and contents were removed. Each prey taxon was identified at least to genus, and the relative proportion of volume made up by each was estimated. Stomach contents were then dried (60 °C > 48 h) and weighed (to 0.1 mg) using a Mettler AE 100 (Mettler Toledo, Columbus, O.H., USA) analytical balance. A subsample of contents from 40 stomachs was ashed (540 °C > 24 h) and ash-free dry weight (AFDW) was estimated for the remainder of stomach contents using the relationship between AFDW and dry weight (DW) of stomach contents in the subsample (linear regression, $AFDW = 0.8324 \times DW + 0.0007$, $r^2 = 0.99$, $P < 0.001$, $N = 40$). To calculate the DW of whole fish minus their stomach contents, the emptied stomachs were returned to the abdominal cavity of the fish, which were then also dried (60 °C > 96 h) and weighed. For graphical purposes and use in daily ration estimation, the relative stomach contents weight (F_i) was also calculated for fish captured each time using equation (1):

$$F_t = \frac{G_t}{D_t \times 1000}, \quad (1)$$

where G_t is the weight of the stomach contents (mg DW) and D_t is the DW (g) of a fish captured at time t .

Stomach contents AFDW were log transformed to homogenise variances and compared between times of day by one-way analysis of covariance (ANCOVA) with $\log_e(\text{fish DW})$ as the covariate. The positive relationships between transformed fish weights and stomach content weights were similar for all times on all days, satisfying the ANCOVA assumption of homogeneity of slopes. Any differences in fish sizes are thus unlikely to affect interpretation of results. Where significant differences across the nine samples were identified, Tukey's *post hoc* test was used to determine which pairs of times differed. In addition to analysis of the amount of food in the stomach, estimates of consumption during each of the 3-h intervals were also used to determine the diel feeding pattern of *G. auratus*. These were based on the model of Elliot & Persson (1978) (equation 2, below).

Trellis plots, as implemented in the lattice package of R (Sarkar 2005), were used to examine whether there was any evidence of size-based temporal partitioning in feeding. On each sample date, the fish were split into six slightly overlapping size classes (i.e., 'shingles' *sensu* Cleveland 1994) with equal numbers of fish in each size class, and F_t was plotted against time. Any trends were visualised using a loess smoother. If size-based partitioning occurred, we expected that these plots would show different trends over time for small and large fish.

Epibenthic prey

Samples of epibenthic invertebrate prey were also taken with fish samples with the aim of detecting if diel changes in prey positioning resulted in changes in abundance of prey that may be available to the fish at different times of the day, a phenomenon well documented in lotic invertebrates (Cowan & Peckarsky 1994; McIntosh & Townsend 1994). Immediately before electrofishing each stretch of shoreline, prey were sampled using a suction sampler, with three randomly located quadrats of 576 cm² sampled in each stretch. This method samples prey from exposed surfaces of the substrate, so it probably more closely represents prey that were available to the fish than other sampling methods which sample interstitial and other subsurface habitats (e.g., cores or grabs). Prey samples were preserved in 80% ethanol and later identified to a minimum of genus level and enumerated in the laboratory using a dissecting microscope. The densities of the amphipod, *Austro-*

chiltonia australis on 6–7 February 2003 were estimated by subsampling because of the particularly large numbers of this species. Precision of estimates based on subsampling ranged up to $\pm 23\%$, but for most samples was approximately $\pm 15\%$.

The diet of the fish was very low in diversity, with a single prey taxon forming the bulk of stomach contents on each day (Table 1). Only the amphipod *Austrochiltonia australis* and the gastropod *Austropyrgus* sp. were used in analyses as these were the most dominant epibenthic prey found in stomach contents. The densities of each in the environment at each sample time were analysed for correlation with their mean relative proportion in stomach contents of fish at those times. Densities of *Austrochiltonia australis* on 11–12 December 2002 were log transformed as they differed by more than an order of magnitude between times.

Gastric evacuation

The rates at which prey are evacuated from the stomach of *G. auratus* were determined under controlled laboratory conditions. Due to the dominance of *Austrochiltonia australis* and *Daphnia carinata* in the diets of field-sampled fish on different days (Table 1), two experiments were conducted, one with each prey species. Water temperature influences the rate of gastric evacuation (Elliot 1972; Dos Santos & Jobling 1991; Andersen 1999), so as the purpose of the gastric evacuation experiments was to allow estimation of daily ration on different days, experiments were run at the mean temperatures recorded on the days on which these prey were dominant (11.5 °C for *Austrochiltonia australis* and 16.5 °C for *D. carinata*). Otherwise, both experiments followed the same protocol.

Fish were captured in Lake Crescent by electrofisher ($N = 54$, mean TL = 103 mm, range 84–144 mm) and maintained in the laboratory in two large holding tanks (approx. 350 l) for a minimum of 2 weeks to allow them to acclimate. At the beginning of a trial, they were placed in individual, food-free tanks (350 × 210 × 260 mm) for 48 h. A known number of prey was introduced and the fish were allowed to feed for 3 h. Fish were then transferred into new tanks without any prey and the number of remaining prey was counted. The DW of prey consumed by each fish was estimated from linear regression of number and DW of each prey species (*Austrochiltonia australis*: $\log_e(\text{DW}) = -0.9182 + 1.0362 \log_e(\text{number})$, $r^2 = 0.95$, $P < 0.001$, $N = 20$; *D. carinata*: $\log_e(\text{DW}) = -1.8949 + 0.9860 \log_e(\text{number})$, $r^2 = 0.93$, $P < 0.001$, $N = 20$). Fish were killed at each of a series of predetermined intervals after the feeding period and the fish and remaining stomach contents were dried

Date	Time	N	Mean total length (range)	% <i>Austrochiltonia australis</i>	% <i>Daphnia carinata</i>	% <i>Austropyrgus</i>
11 December 2002	15:15	27	103 (83–123)	40.85	0	45.10
	18:15	29	104 (79–143)	93.57	0	5.63
	21:15	28	103 (81–145)	88.73	0	0
12 December 2002	00:15	27	101 (84–124)	83.71	0	5.09
	03:15	23	107 (82–166)	63.48	0	20.89
	06:15	27	106 (89–136)	83.53	0	14.46
	09:15	26	100 (80–131)	98.34	0	0.30
	12:15	26	104 (81–132)	97.44	0	0
	15:15	25	100 (82–128)	82.03	0	16.41
6 February 2003	09:15	21	91 (76–112)	25.32	73.55	0
	12:15	20	95 (85–116)	20.06	77.33	0
	15:15	21	93 (82–114)	48.34	51.01	0
	18:15	21	88 (78–101)	20.63	70.16	0
	21:15	17	89 (79–111)	8.02	91.83	0
7 February 2003	00:15	7	89 (81–100)	30.12	69.28	0
	03:15	10	95 (88–114)	28.89	71.11	0
	06:15	24	93 (84–113)	34.45	65.55	0
	09:15	28	91 (78–123)	27.21	69.36	0
13 February 2003	09:15	21	98 (87–120)	0	99.24	0
	12:15	20	99 (81–147)	2.68	97.32	0
	15:15	18	98 (86–136)	2.42	97.58	0
	18:15	20	95 (80–144)	0.26	99.48	0
	21:15	20	94 (76–117)	0.28	99.44	0.28
14 February 2003	00:15	20	97 (81–134)	10.88	83.08	0
	03:15	22	96 (78–120)	1.75	98.00	0
	06:15	24	99 (81–149)	2.36	97.41	0
	09:15	21	97 (82–130)	6.87	91.66	0

Table 1. Times of fish sampling, sample and fish sizes and %volume of dominant prey found in stomachs of *Galaxias auratus* sampled from Lake Crescent (11–12 December 2002 and 6–7 February 2003) and Lake Sorell (13–14 February 2003).

and weighed separately, following the same procedures and equipment as for the field-sampled fish.

Regression analysis was used to identify the best model to describe the evacuation of *Austrochiltonia australis* and *D. carinata* from the stomach of *G. auratus* and for estimation of the rate parameter R , which was required for the Elliot & Persson and Eggers models. We used nonlinear regression, rather than linear regression on transformed variables, so that the best model could be chosen and comparisons could be made based on r^2 and SE values (Elashoff et al. 1982; Bromley 1994).

Daily ration

It is widely reported that the Elliot & Persson model usually provides accurate estimates of consumption (Hayward 1991; Héroux & Magnan 1996; Specziár 2002), but it is subject to two major sources of error. The first is that as it is based on differences in mean relative stomach content weights between sample times, and does not account for variation about these means, or when data are not normally distributed or do not satisfy parametric assumptions. Some researchers have used geometric means or medians rather than arithmetic means because of this (Amundsen & Klemetsen 1986; Parrish & Margraf 1990). The second is that there is error associated with the measurement of the gastric evacuation rate (R), which is not accounted for. Many studies have completely neglected this.

In our study, estimates of consumption based on the Elliot & Persson model (C_i) for each 3-h interval were made using the bootstrap method, which allowed the error associated with both F_t and R to be estimated (Trudel & Boisclair 1993). Transformed (arcsine $\sqrt{\cdot}$) F_t values from each time period were sampled 5000 times with replacement and means from each were back-transformed. Each of the 5000 back-transformed means (multiplied by 100 to convert to %DW of fish) (F_t^*) was then used in the Elliot & Persson model:

$$C_i^* = \frac{(F_{(t+1)}^* - F_t^* e^{-R^* t}) R^* t}{1 - e^{-R^* t}}, \quad (2)$$

where C_i is the mean of the 5000 C_i^* estimates the consumption during the interval i (always 3 h in this study) expressed as %DW of fish, F_t^* and $F_{(t+1)}^*$ are mean back-transformed relative stomach content weights (%) at two successive sampling times, and R^* is a bootstrap estimate of the evacuation rate. Values of R^* were generated using equation (3):

$$R^* = R + (\text{SE}_R \times \text{RN}), \quad (3)$$

where SE_R is the standard error of R , and RN is a normally distributed random number with a mean of 0 and a standard deviation of 1 (Trudel & Boisclair 1993). Values of R and SE_R were estimated from the nonlinear regressions of gastric evacuation (i.e., of *Austrochiltonia australis* for 11–12 December 2002, and of *D. carinata* in calculations for 6–7 and 13–14

February 2003). Using Hall's basic method, 95% confidence intervals of bootstrap estimates were calculated (Davison & Hinkley 1997). These analyses were conducted in the package 'boot' (Canty & Ripley 2005) in R version 2.2.0 (R Development Core Team 2005).

Daily ration using the Elliot & Persson model is equal to the sum of C_i for each day. The bootstrap method was also employed to estimate daily ration using the Eggers model (C_{24}), with re-sampling of transformed F_t values (5000 permutations) and combining the back-transformed means (%) with appropriate R^* values in equation (4):

$$C_{24} = F^* \times R^* \times 24, \quad (4)$$

where C_{24} is the daily ration expressed as %DW of fish and F^* is the mean of all F_t for that day. The correction method of Eggers (1979) was not used as F_t values did not differ significantly between replicate samples at the same time 24 h apart on any day (ANOVA: 11–12 December: $F_{1,50} = 0.001$, $P = 0.971$; 6–7 February: $F_{1,47} = 1.279$, $P = 0.264$; 13–14 February: $F_{1,40} = 0.098$, $P = 0.756$).

Results

Diel feeding pattern

Only four empty stomachs were found in 593 fish sampled, and AFDW of stomach contents were consistently high and variable. Differences in AFDW between times on any of the days sampled were not significant, with the exception of the sample at 18:15 hours on 6 February 2003, in which stomach contents weights were significantly lower than samples at 12:15, 15:15 and 00:15, 03:15 hours and at 09:15 hours on the following day (ANCOVA: $F_{8,159} = 2.153$, $P = 0.034$). Estimates of consumption in each of the time intervals revealed feeding during both day and night, but did differ significantly between some sample times, as indicated by nonoverlapping confidence intervals (Fig. 1). The greatest feeding occurred between 15:15–18:15 and 00:15–03:15 hours on 11–12 December 2002, and 18:15–00:15 hours on 6–7 February 2003. Feeding was more consistent in Lake Sorell on 13–14 February. There were also periods in which Elliot & Persson estimates were negative. However, confidence intervals of all of these overlapped zero. These were between 15:15–18:15 and 00:15–03:15 hours on 6–7 February 2003, and 03:15–06:15 hours on 13–14 February 2003 (Fig. 1).

Although feeding occurred during both the day and night, this was not the result of different sized fish feeding at different times, i.e., there was no evidence of any size-based differences or temporal partitioning

of feeding. Visual inspection of the Trellis plots of relative stomach contents weights from different size classes of fish (Fig. A1) revealed no differences in trends over the day on any of the sampling dates. There were also no significant differences in the size (TL) of fish captured at each time on any day (ANOVA: 11–12 December: $F_{8,229} = 0.641$, $P = 0.743$; 6–7 February: $F_{8,160} = 1.680$, $P = 0.107$; 13–14 February: $F_{8,177} = 0.312$, $P = 0.961$).

Epibenthic prey

Austrochiltonia australis dominated both stomach contents and epibenthic prey samples on 11–12 December 2002. There was a strong, positive linear relationship between the proportion of *Austrochiltonia australis* in stomachs of *G. auratus* and its densities in environmental samples on this day (Pearson correlation coefficient, $r = 0.76$), with peaks early in the night and early in the day (Fig. 2). There were no correlations between stomach contents and the densities of *Austropyrgus* sp. on this day despite the fact that this species increased in proportion in stomach contents late in the day and late in the night. There were no correlations between stomach contents and the densities of either prey on the 6–7 and 13–14 February 2003 (all $|r| < 0.13$).

Gastric evacuation

The evacuation of both *Austrochiltonia australis* and *D. carinata* from the stomach of *G. auratus* followed a curvilinear decay with time (Fig. 3). A simple exponential model yielded the greatest r^2 and smallest SE for both prey species (equation 5):

$$M_t = M_0 e^{-Rt}, \quad (5)$$

where M_t is the amount of prey remaining in the stomach at time t (mg DW) and M_0 is the initial meal size (mg DW).

Daily ration

Daily ration estimates ranged from 2.2% DW (0.43 g·100 g-wet wt⁻¹·day⁻¹, Eggers model, 6–7 February 2003) to 3.9% DW (0.76 g·100 g-wet wt⁻¹·day⁻¹, Eggers model, 11–12 December 2002) (Fig. 4), with the overall mean close to 3%. This equates to around 118 amphipods (*Austrochiltonia australis*) or 406 *Daphnia carinata* for a fish of the average sampled size (1.87 g DW, 98 mm TL). Eggers and Elliot & Persson estimates differed by almost 1% on 6–7 February 2003, but this was not statistically significant, and estimates on other days were more similar. Elliot & Persson estimates were almost identical for all 3 days. Although not statistically significant, the

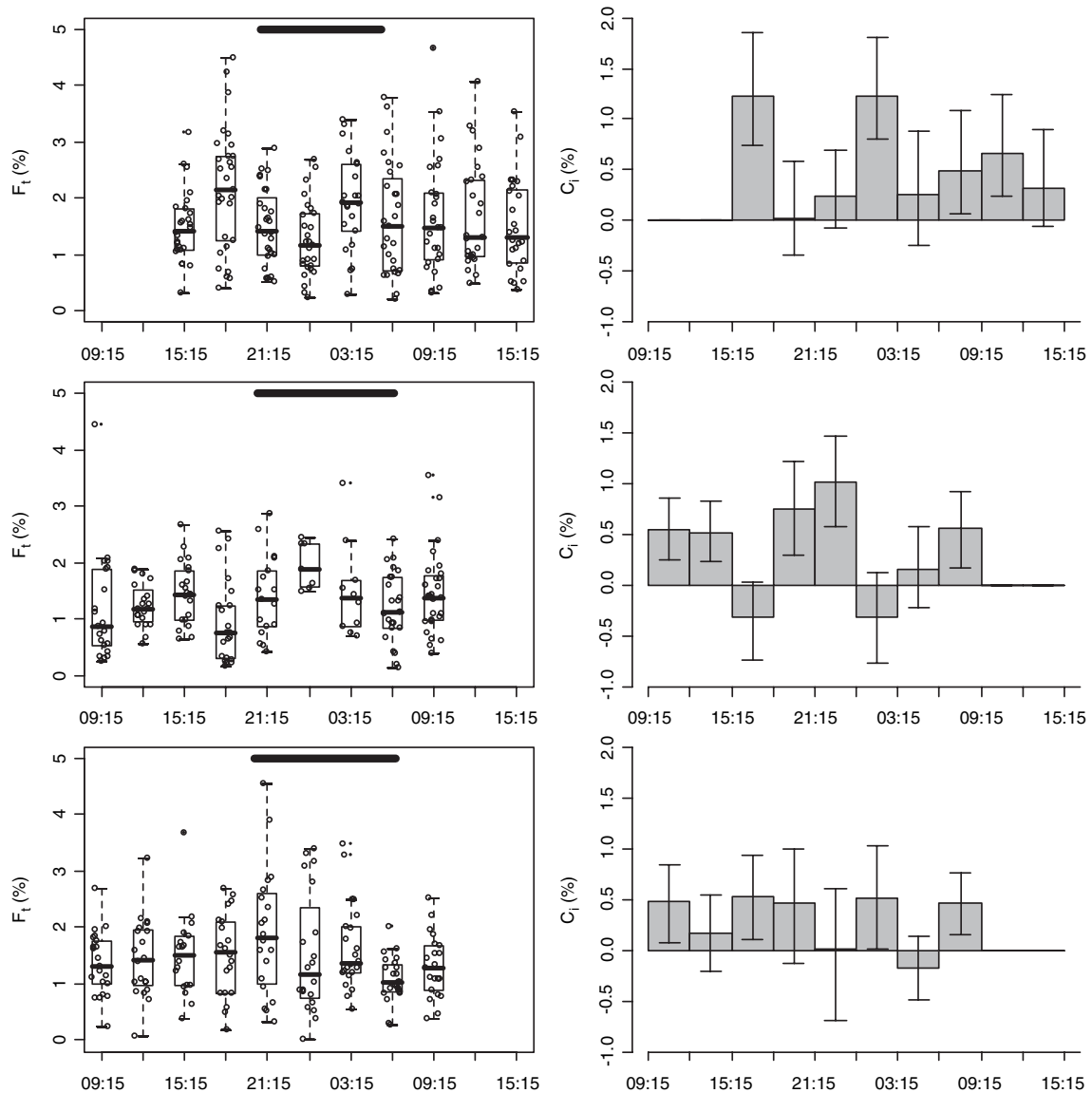


Fig. 1. Diel patterns in relative stomach contents weights (F_t , left column) and corresponding Elliot and Persson three-hourly consumption estimates (C_t , right column) for *Galaxias auratus* sampled from Lake Crescent on 11–12 December 2002 (top), 6–7 February (middle) and from Lake Sorell on 13–14 February (bottom) 2003. Relative stomach contents weights are plotted as box-and-whisker plots with raw data overlaid as open circles. Consumption estimates are bootstrap estimates of mean values + 95% confidence intervals. Horizontal black bars represent hours of darkness.

highest estimates were on 11–12 December 2002, despite the water temperature being considerably cooler on this day (mean 11.5 °C as opposed to mean 16.5 °C on the other 2 days).

Discussion

Both analysis of stomach content weights and the estimation of consumption using the Elliot & Persson model show that there were no significant peaks in feeding by *G. auratus* and that they fed rather consistently during both night and day on all the dates sampled and in both lakes. Thus, the hypothesis

that they feed primarily at night was not supported by our findings. Feeding appeared to be more consistent throughout the 24-h day in fish sampled from Lake Sorell, but this does not alter the conclusions of the study, with *G. auratus* still observed feeding during day, night and twilight periods. Although the variability in stomach content weights was high, this is characteristic of fish feeding (Jenkins & Green 1977; Grant & Kott 1999; Hartman 2000), and, in the context of other similar studies, these data were remarkably free of the problems emphasised by Amundsen & Klemetsen (1986): weights of stomach contents were not skewed, nor were there many empty

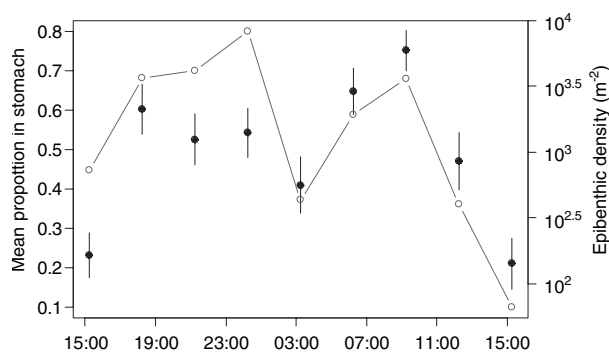


Fig. 2. Density of *Austrochiltonia australis* in samples of epibenthic prey (open circles) and the mean (\pm SE) proportion by volume of stomach contents made up by this prey in *Galaxias auratus* (closed circles) on 11–12 December 2002. No significant correlations were found between prey density and stomach contents on any of the other days sampled.

stomachs. Our sample sizes were also comparable to, or larger than most similar studies (e.g., Brodeur & Pearcy 1987; Johnson & Dropkin 1995; Madon 1998).

One of the assumptions of the Elliot & Persson model is that feeding is continuous during each 3-h interval (Elliot & Persson 1978). Failure to satisfy this assumption can lead to errors in estimates of consumption and possibly negative estimates during intervals in which consumption is low and not continuous. By keeping the sampling interval short (≤ 3 h, Elliot & Persson 1978; Cortés 1997), and because the diet was ‘fine-grained’ (large numbers of small food particles, Cochran & Adelman 1982), the likelihood of violating this assumption was minimised. However, this assumption may still be violated when fish are feeding close to satiation (Elliot & Persson 1978; Cochran & Adelman 1982; Persson 1983). As there were very few empty stomachs found in *G. auratus* and stomach content weights were consistently high, it is possible that they were feeding close to satiation, and therefore, in an inconsistent manner. Elliot & Persson (1978) experimentally tested the effects of violating this assumption and found that

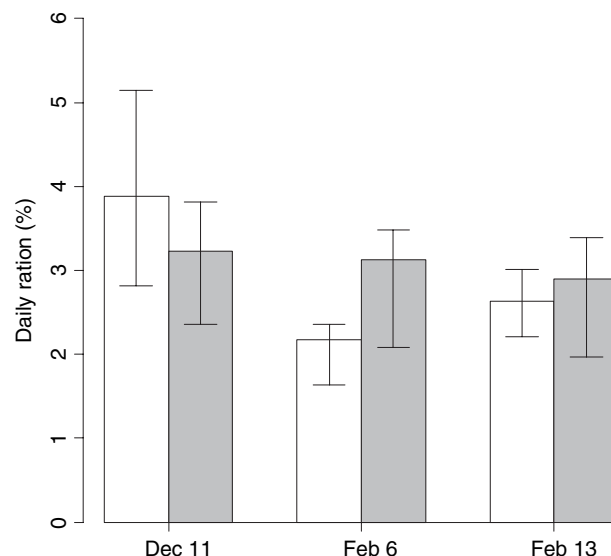
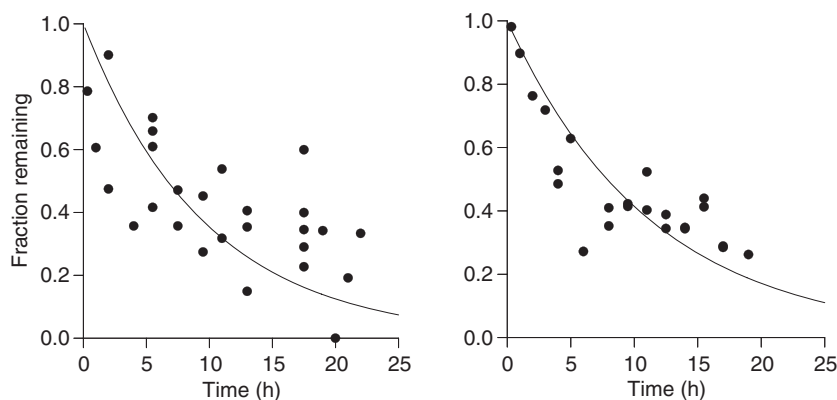


Fig. 4. Daily ration estimates (%DW) (and 95% CI) for *Galaxias auratus* on the 3 days sampled using the Eggers (1977) model (unshaded bars) and the Elliot & Persson (1978) model (shaded bars).

even in extreme cases (a fish feeding for only 20 min every 3 h) their model still provided good estimates of actual consumption when the interval was 3 h, but that when there were differences between estimates and actual consumption, the estimates were normally slightly lower than actual consumption. Thus, even if the assumption of continuous feeding was not satisfied in our study, the resulting estimates are unlikely to differ considerably from the real consumption of *G. auratus*; but if at all, they may be slight underestimates. This may help explain those estimates that were low (some negative but with 95% CI overlapping zero).

Feeding of *G. auratus* was consistent and was not significantly greater during night, day or twilight periods. Although this pattern has occasionally been seen in other species (e.g., coho salmon, *Oncorhynchus kisutch*: Ruggerone 1989, and brook charr,

Fig. 3. Evacuation of *Austrochiltonia australis* (left) and *Daphnia carinata* (right) from the stomach of *Galaxias auratus* at 11.5 and 16.5 °C, respectively. Circles represent the fraction (by dry weight) of the original meal remaining in the stomach at each time. The rate parameter, R (\pm its asymptotic standard error), for the evacuation of *A. australis* = 0.1044 ± 0.0158 and the $r^2 = 0.8096$. For the evacuation of *D. carinata*, R (\pm its asymptotic standard error) = 0.0805 ± 0.0052 and $r^2 = 0.8277$.



Salvelinus fontinalis: Héroux & Magnan 1996) it is unusual amongst fish (Fraser et al. 1993; Fraser & Metcalfe 1997). Although McIntosh & Townsend (1995) found that *Galaxias vulgaris* (the common river galaxias) foraged both nocturnally and diurnally, most galaxiid species have been reported to be nocturnal foragers (Cadwallader 1975; Glova & Sagar 1989a,b; McDowall 1990) and there is evidence that activity and movement of this species is also greater at night. Diel surveys of *G. auratus* in a recently translocated population in a trout-free, clear-water dam (Hardie et al. 2006) have suggested that *G. auratus* spends more time in the cover of complex habitats such as macrophytes during the day, and then moves about in search of food at night. This was supported by preliminary electrofishing for this study, which indicated that numbers of *G. auratus* in areas of uniform silt substrate were low throughout the day but increased at night. Interestingly, McIntosh & Townsend (1995) recorded this type of activity/habitat use pattern for *G. vulgaris* even though this species also feeds during the day. They found that *G. vulgaris* spent most of the daylight hours in cover, emerging only to capture prey, but actively moved about in search of food during the night.

Although further research is needed to establish whether the proposed diel activity/habitat use pattern of *G. auratus* persists in the presence of brown trout, it appears that like *G. vulgaris*, *G. auratus* still captures prey during times in which it uses complex habitats. This may be due either to a change in feeding strategy from ambush or sit-and-wait foraging from the edge of complex habitats during the day, to actively searching for prey at night, or to the ability to search for, and capture prey amongst the complex habitat. The latter may be realistic in habitats such as macrophytes, because the ability to feed at night suggests that this species is capable of locating and capturing prey using nonvisual stimuli, which would also be advantageous in habitats that reduce or break up the visual field. This ability also suggests that the current high turbidity of lakes Crescent and Sorell may not negatively affect their feeding ability.

Another reason that we hypothesised that *G. auratus* would show a nocturnal peak in foraging is because the risk of predation by brown trout is also likely to differ during the diel cycle. Brown trout are primarily visual predators; although they are capable of nocturnal foraging, they present the greatest predation threat from dawn through to dusk (Allan 1978; Ringler 1979). Brown trout were introduced into lakes Crescent and Sorell in 1868 and it is possible that they have provided a selective pressure for *G. auratus* to forage nocturnally. While this study cannot determine whether brown trout influence habitat use by *G. auratus*, however, it does appear that threat of

predation by brown trout has not resulted in a nocturnally biased feeding pattern by *G. auratus*.

Diel patterns in prey availability are also known to influence feeding patterns of fishes, and have been implicated in causing the nocturnal peaks in the feeding of other galaxiids (Glova & Sagar 1989a,b). Prey availability in our study was consistently high throughout the day and night and we suggest that it did not influence the feeding pattern of *G. auratus*. The evidence for this includes the presence of very few empty stomachs, very high densities of sampled epibenthic invertebrates (the mean density of *Austrochilontia australis* was 13,300 m⁻² and *Austropyrgus* sp., 264 m⁻²), and the observation of very large, dense swarms of *Daphnia carinata* during all fish sampling periods on the 6–7 and 13–14 February 2003. Unfortunately *Daphnia carinata* were not quantitatively sampled as a part of this study due to the absence of planktonic prey in the diet of *G. auratus* in preliminary samples and the added logistical considerations of attempting to quantitatively and efficiently sample an invertebrate with such a patchy distribution.

Feeding during both day and night may be caused by intraspecific interactions. Size is the most commonly recorded determinant of social structure in fishes (Danylchuk & Tonn 2001; Whiteman & Cote 2004), and size-based resource partitioning has been reported in other galaxiids (Whitehead et al. 2002; David & Stoffels 2003). Although, we could not test explicitly for differences in feeding patterns of individuals in this study because we did not sample the same individual fish at each time of day, there was no evidence of size-based differences in feeding when we examined the amount of food in the stomach throughout the day in different sized individuals within the range of sizes sampled.

The gastric evacuation rates and daily ration estimates of *G. auratus* are slightly lower than, but still similar to other similar sized lentic fishes from studies undertaken in the Northern Hemisphere (Persson 1982; Boisclair & Leggett 1988). Interestingly, even though consumption by *G. auratus* may be a little less than other planktivorous fish (e.g., dace, *Phoxinus eos* × *P. neogaeus*: Trudel & Boisclair 1993; Gauthier & Boisclair 1997), adult *G. auratus* may still consume around 400 *Daphnia carinata* per day. *Daphnia carinata* are relatively large zooplankters (up to 6 mm), and are probably the dominant algal grazers in lakes Crescent and Sorell (Uytendaal 2003). Thus, the predation pressure exerted by such high densities of *G. auratus* on *D. carinata* may possibly have a strong influence on algal biomass in these lakes. There has been a growing number of studies that have demonstrated such abilities of fishes to exert top-down control on lower trophic levels through trophic cascades (He &

Wright 1992; Karjalainen et al. 1999; Zambrano et al. 2001). This study has not only provided an unusual example of a fish that feeds throughout both night and day, but has also provided empirical data on the predatory capabilities of a galaxiid fish, which offer insight into their role as predators in Southern Hemisphere freshwater systems.

Acknowledgements

The authors wish to thank Jemina Stuart-Smith, Jed MacDonald and Sarah Stuart-Smith for help in the field, and Scott Hardie, Adam Uytendaal and the Carp Team of the Inland Fisheries Service of Tasmania (IFS) for valuable comments on the manuscript and for access to unpublished data. R.D.S-S. was supported by a Tasmanian Aquaculture and Fisheries Institute Postgraduate Scholarship, and further support was provided by the School of Zoology, University of Tasmania. The research was carried under appropriate permits from the Inland Fisheries Service of Tasmania and with the approval of the University of Tasmania Animal Ethics Committee. The authors also wish to thank two anonymous referees for helpful comments on the original manuscript.

References

- Allan, J.D. 1978. Trout predation and the size composition of stream drift. *Limnology and Oceanography* 23: 1231–1237.
- Amundsen, P. & Klemetsen, A. 1986. Within-sample variabilities in stomach contents weight of fish – implications for field studies of consumption rate. In: Simenstad, C.A. & Cailliet, G.M., eds. *Contemporary studies on fish feeding*. Dordrecht: Dr W. Junk Publishers, pp. 307–314.
- Andersen, N.G. 1999. The effects of predator size, temperature, and prey characteristics on gastric evacuation in whiting. *Journal of Fish Biology* 54: 287–301.
- Boisclair, D. & Leggett, W.C. 1988. An in situ experimental evaluation of the Elliot and Persson and Eggers models for estimating fish daily ration. *Canadian Journal of Fisheries and Aquatic Sciences* 45: 138–145.
- Boisclair, D. & Marchand, F. 1993. The guts to estimate fish daily ration. *Canadian Journal of Fisheries and Aquatic Sciences* 50: 1969–1975.
- Brännäs, E. & Alanärä, A. 1997. Is diel dualism in feeding activity influenced by competition between individuals? *Canadian Journal of Zoology* 75: 661–669.
- Brodeur, R.D. & Pearcy, W.G. 1987. Diel feeding chronology, gastric evacuation and estimated daily ration of juvenile coho salmon, *Oncorhynchus kisutch* (Walbaum), in the coastal marine environment. *Journal of Fish Biology* 31: 465–477.
- Bromley, P.J. 1994. The role of gastric evacuation experiments in quantifying the feeding rates of predatory fish. *Reviews in Fish Biology and Fisheries* 4: 36–66.
- Cadwallader, P.L. 1975. Distribution and ecology of the Canterbury mudfish, *Neochanna burrowsius* (Phillips) (Salmioniformes: Galaxiidae). *Journal of the Royal Society of New Zealand* 5: 21–30.
- Canty, A. & Ripley, B. 2005. *boot: Bootstrap R (S-Plus) functions*. R package version 1.2–24. Vienna, Austria: R Foundation for Statistical Computing. Available at: <http://www.R-project.org> (accessed 22 December 2005).
- Cleveland, W.S. 1994. *The elements of graphing data*. Murray Hill, NJ: AT&T Bell Laboratories.
- Cochran, P.A. & Adelman, I.R. 1982. Seasonal aspects of daily ration and diet of largemouth bass, *Micropterus salmoides*, with an evaluation of gastric evacuation rates. *Environmental Biology of Fishes* 7: 265–275.
- Cortés, E. 1997. A critical review of methods of studying fish feeding based on analysis of stomach contents: application to elasmobranch fishes. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 726–738.
- Cowan, C.A. & Peckarsky, B.L. 1994. Diel feeding and positioning periodicity of a grazing mayfly in a trout stream and a fishless stream. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 450–459.
- Danylchuk, A.J. & Tonn, W.M. 2001. Effects of social structure on reproductive activity in male flathead minnows (*Pimephales promelas*). *Behavioural Ecology* 12: 482–489.
- Darnell, R.M. & Meierotto, R.R. 1962. Determination of feeding chronology in fishes. *Transactions of the American Fisheries Society* 91: 313–320.
- David, B.O. & Stoffels, R.J. 2003. Spatial organisation and behavioural interaction of giant kokopu (*Galaxias argenteus*) in two stream pools differing in fish density. *New Zealand Journal of Marine and Freshwater Research* 37: 315–322.
- Davison, A.C. & Hinkley, D.V. 1997. *Bootstrap methods and their application*. Cambridge: Cambridge University Press.
- Dos Santos, J. & Jobling, M. 1991. Factors affecting gastric evacuation in cod, *Gadus morhua* L., fed single-meals of natural prey. *Journal of Fish Biology* 38: 697–713.
- Eggers, D.M. 1977. Factors in interpreting data obtained by diel sampling of fish stomachs. *Journal of the Fisheries Research Board of Canada* 34: 290–294.
- Eggers, D.M. 1979. Comments on some recent methods for estimating food consumption by fish. *Journal of the Fisheries Research Board of Canada* 36: 1018–1020.
- Elashoff, J.D., Reedy, T.J. & Meyer, J.H. 1982. Analysis of gastric emptying data. *Gastroenterology* 83: 1306–1312.
- Elliot, J.M. 1972. Rates of gastric evacuation in brown trout, *Salmo trutta* L. *Freshwater Biology* 2: 1–18.
- Elliot, J.M. & Persson, L. 1978. The estimation of daily rates of food consumption for fish. *Journal of Animal Ecology* 47: 977–991.
- Forrester, G.E., Chace, J.G. & McCarthy, W. 1994. Diel and density-related changes in food consumption and prey selection by brook char in a New Hampshire stream. *Environmental Biology of Fishes* 39: 301–311.
- Fraser, N.H.C. & Metcalfe, N.B. 1997. The costs of becoming nocturnal: feeding efficiency in relation to light intensity in juvenile Atlantic salmon. *Functional Ecology* 11: 385–391.
- Fraser, N.H.C., Metcalfe, N.B. & Thorpe, J.E. 1993. Temperature-dependent switch between diurnal and nocturnal foraging in salmon. *Proceedings of the Royal Society of London B, Biological Sciences* 252: 135–139.
- Fraser, N.H.C., Heggenes, J., Metcalfe, N.B. & Thorpe, J.E. 1995. Low summer temperatures cause juvenile Atlantic salmon to become nocturnal. *Canadian Journal of Zoology* 73: 446–451.

- Gauthier, S. & Boisclair, D. 1997. The energetic implications of diel onshore-offshore migration by dace (*Phoxinus eos* × *P. neogaeus*) in a small oligotrophic lake. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 1996–2006.
- Glova, G.J. & Sagar, P.M. 1989a. Feeding in a nocturnally active fish, *Galaxias brevipinnis*, in a New Zealand stream. *Australian Journal of Marine and Freshwater Research* 40: 231–240.
- Glova, G.J. & Sagar, P.M. 1989b. Prey selection by *Galaxias vulgaris* in the Hawkins River, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 23: 153–161.
- Glova, G.J., Sagar, P.M. & Docherty, C.R. 1987. Diel feeding periodicity of torrentfish (*Cheimarrichthys fosteri*) in two braided rivers of Canterbury, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 21: 555–561.
- Grant, S.M. & Kott, E. 1999. Variation in field estimates of daily ration in young yellow perch. *Journal of Fish Biology* 54: 396–403.
- Hardie, S.A., Barmuta, L.A. & White, R.W.G. 2004. Threatened fishes of the world: *Galaxias auratus* Johnston, 1883 (Galaxiidae). *Environmental Biology of Fishes* 71: 126.
- Hardie, S.A., Barmuta, L.A. & White, R.W.G. 2006. Comparison of day and night fyke netting, electrofishing and snorkelling for monitoring a population of the threatened golden galaxias (*Galaxias auratus*). *Hydrobiologia* 560: 145–158.
- Hartman, K.J. 2000. Variability in daily ration estimates of age-0 striped bass in the Chesapeake Bay. *Transactions of the American Fisheries Society* 129: 1181–1186.
- Hayward, R.S. 1991. Bias associated with using the Eggers model for estimating fish daily ration. *Canadian Journal of Fisheries and Aquatic Sciences* 48: 1100–1103.
- He, X. & Wright, R.A. 1992. An experimental study of piscivore-planktivore interactions: population and community responses to predation. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 1176–1183.
- Héroux, D. & Magnan, P. 1996. In situ determination of food daily ration in fish: review and field evaluation. *Environmental Biology of Fishes* 46: 61–74.
- Jenkins, B.W. & Green, J.M. 1977. A critique of field methodology for determining fish feeding periodicity. *Environmental Biology of Fishes* 1: 209–214.
- Johnson, J.H. & Dropkin, D.S. 1995. Diel feeding chronology of six fish species in the Juniata River, Pennsylvania. *Journal of Freshwater Ecology* 10: 11–18.
- Karjalainen, J., Leppä, M., Rahkola, M. & Tolonen, K. 1999. The role of benthivorous and planktivorous fish in a mesotrophic lake ecosystem. *Hydrobiologia* 408/409: 73–84.
- Keast, A. & Welsh, L. 1968. Daily feeding periodicities, food uptake rates, and dietary changes with hour of day in some lake fishes. *Journal of the Fisheries Research Board of Canada* 25: 1133–1144.
- Kreivi, P., Muotka, T., Huusko, A., Mäki-Petäys, A., Huhta, A. & Meissner, K. 1999. Diel feeding periodicity, daily ration and prey selectivity in juvenile brown trout in a subarctic river. *Journal of Fish Biology* 55: 553–571.
- Lima, S.L. & Dill, L.M. 1990. Behavioral decisions made under the risk of predation: a review and prospectus. *Canadian Journal of Zoology* 68: 619–640.
- Madon, S.P. 1998. Low-effort regression estimation of daily ration in young walleye, *Stizostedion vitreum*. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 2058–2066.
- Mann, K.H. 1978. Estimating the food consumption of fish in nature. In: Gerking, S.D., ed. *Ecology of freshwater fish production*. Oxford: Blackwell Scientific Publications, pp. 250–273.
- McDowall, R.M. 1990. *New Zealand freshwater fishes: a natural history and guide*. Auckland: Heinemann Reed. 553 pp.
- McIntosh, A.R. & Townsend, C.R. 1994. Interpopulation variation in mayfly anti-predator tactics: differential effects of contrasting predatory fish. *Ecology* 75: 2078–2090.
- McIntosh, A.R. & Townsend, C.R. 1995. Contrasting predation risks presented by introduced brown trout and native common river galaxias in New Zealand streams. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 1821–1833.
- Metcalf, N.B., Fraser, N.H.C. & Burns, M.D. 1999. Food availability and the nocturnal vs. diurnal foraging trade-off in juvenile salmon. *Journal of Animal Ecology* 68: 371–381.
- Parrish, D.L. & Margraf, F.J. 1990. Gastric evacuation rates of white perch, *Morone americana*, determined from laboratory and field data. *Environmental Biology of Fishes* 29: 155–158.
- Persson, L. 1982. Rate of food evacuation in roach (*Rutilus rutilus*) in relation to temperature, and the application of evacuation rate estimates for studies on the rate of food consumption. *Freshwater Biology* 12: 203–210.
- Persson, L. 1983. Food consumption and competition between age classes in a perch (*Perca fluviatilis*) population in a shallow eutrophic lake. *Oikos* 40: 197–207.
- R Development Core Team 2005. R: a language and environment for statistical computing. Version 2.2.0. Vienna, Austria: R Foundation for Statistical Computing. Available at: <http://www.R-project.org>. (accessed 14 August 2006).
- Riehle, M.D. & Griffith, J.S. 1993. Changes in habitat use and feeding chronology of juvenile rainbow trout (*Oncorhynchus mykiss*) in fall and the onset of winter in Silver Creek, Idaho. *Canadian Journal of Fisheries and Aquatic Sciences* 50: 2119–2128.
- Ringler, N.H. 1979. Selective predation by drift-feeding brown trout (*Salmo trutta*). *Journal of the Fisheries Research Board of Canada* 36: 392–403.
- Ruggerone, G.T. 1989. Gastric evacuation rates and daily ration of piscivorous coho salmon, *Oncorhynchus kisutch* Walbaum. *Journal of Fish Biology* 34: 451–463.
- Sarkar, D. 2005. Lattice: lattice graphics. R package version 0.12–10. R Foundation for Statistical Computing. Vienna, Austria.
- Specziár, A. 2002. An in situ estimate of food consumption of five cyprinid species in Lake Balaton. *Journal of Fish Biology* 60: 1237–1251.
- Stuart-Smith, R.D., Richardson, A.M.M. & White, R.W.G. 2004. Increasing turbidity significantly alters the diet of brown trout: a multi-year longitudinal study. *Journal of Fish Biology* 65: 376–388.
- Trudel, M. & Boisclair, D. 1993. An in situ evaluation of the day-to day variation in the quantity of food consumed by fish. *Canadian Journal of Fisheries and Aquatic Sciences* 50: 2157–2165.
- Uytendaal, A. 2003. Water quality in lakes Sorell and Crescent: underlying processes and management options. Inland Fisheries Service. Available at: <http://www.ifs.tas.gov.au> (29 October 2003).
- Whitehead, A.L., David, B.O. & Closs, G.P. 2002. Ontogenetic shift in nocturnal microhabitat selection by giant kokopu in a New Zealand stream. *Journal of Fish Biology* 61: 1373–1385.

Whiteman, E.A. & Cote, I.M. 2004. Dominance hierarchies in group-living cleaning gobies: causes and foraging consequences. *Animal Behaviour* 67: 239–247.

Zambrano, L., Scheffer, M. & Martínez-Ramos, M. 2001. Catastrophic response of lakes to benthivorous fish introduction. *Oikos* 94: 344–350.

Appendix

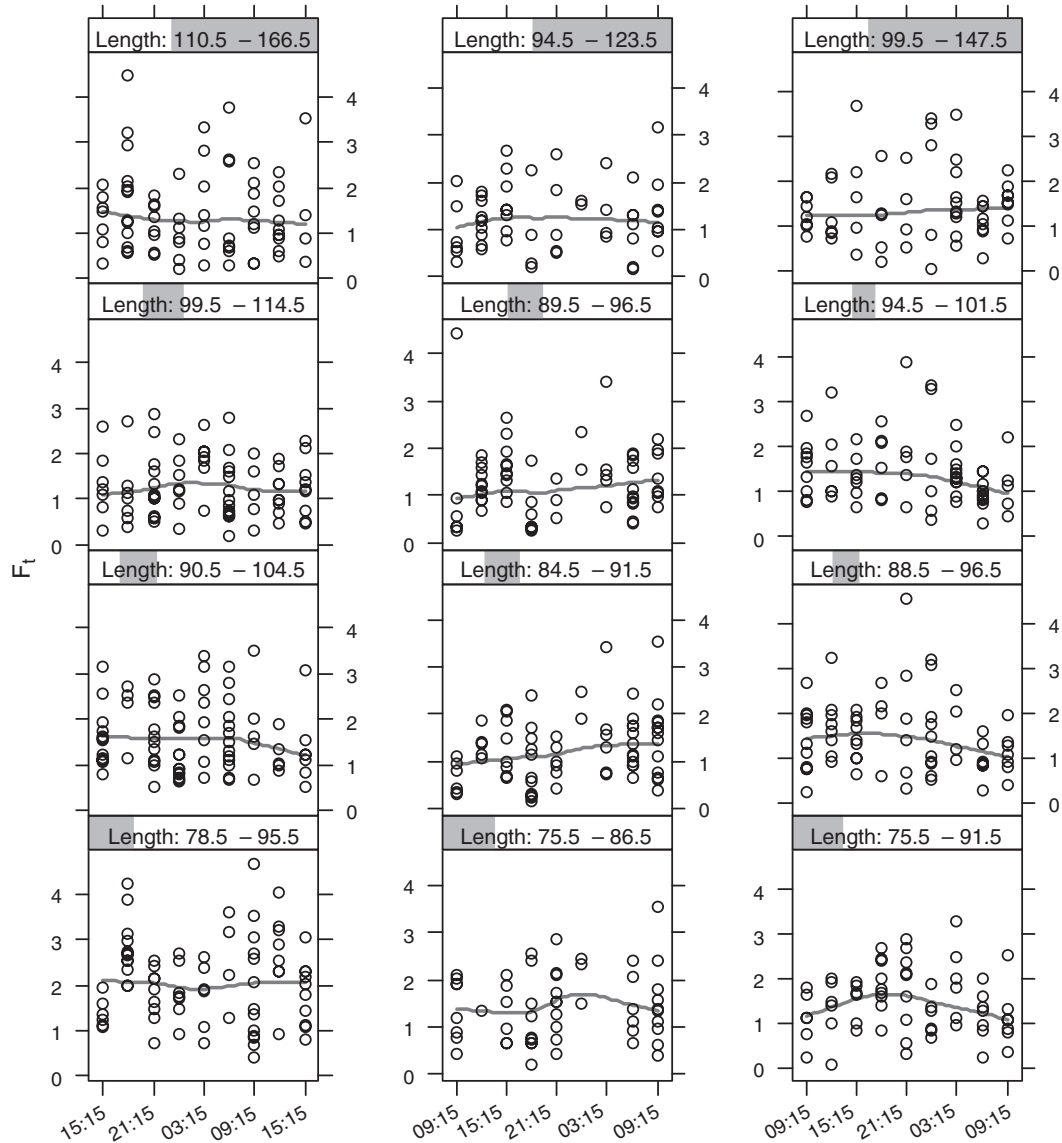


Fig. A1. Trellis plots of relative stomach contents weights (F_t) of different size classes of fish (total length in mm) on 11–12 December 2002 (left column), 6–7 February 2003 (middle column) and 13–14 February 2003 (right column) with a loess smoother superposed (gray line) to assist in visualising any trends. Each panel has an equal number of fish, and the lengths of the fish included in each panel increase from bottom to top with a slight overlap in the fish included in each panel as indicated by the sizes specified in each title strip. The shading in the title strip of each panel provides a graphical key to the size range of fish included in each panel.