4. Standardisation of catch and effort data

4.1 Commercial sector data

Catch and effort data were analysed to provide a measure of abundance of red throat emperor in each year and region by means of a standardised catch rate or catch-per-unit-effort (CPUE).

A unit of effort was defined to be one day’s fishing by a boat, including all of its dories. Data were not available to resolve effort down to the dory level.

The CFISH data contained a field for the number of days’ duration of the trip. Most of the records (98.9%) were a single day’s duration, but some trips were longer than one day. The longer trips were dealt with by allowing second and subsequent days to constitute less than, or more than, a single unit of effort. A second or subsequent day could constitute less than a full unit of effort if the boat was still at sea but not actively fishing for all of that day, and could constitute more than one unit of effort if, for example, a boat travelled a long way from land where red throat emperor were more plentiful. A parameter was included in the model to allow for the effective fishing effort expended on a second or subsequent day.

Location was resolved down to 30-minute grid squares.

Catch and effort data were analysed by a log-linear model. The analysis was performed in the statistical package *R* (R Development Core Team 2005). A separate analysis was performed for each region. The *R* code generating the log-linear model object for each grid square was:

```r
lme(log(Catch.kg) ~ offset(log(TripDays)) +
I(1/(TripDays+1)) + fYear + fMonth + Lunar1 + Lunar2 +
fCatchGrid, random = ~ 1 | fBoatMark)
```

The terms can be explained as follows:

- `log(Catch.kg)`: log of catch by a boat over a trip (98.9% of which were single-day trips)
- `offset(log(TripDays))`: term to convert log-catch into log-CPUE, having the effect of dividing the catch by the number of days; `TripDays` denotes the duration of the fishing trip
- `I(1/(TripDays+1))`: term to allow CPUE to depend on duration of trip, allowing (approximately) the first day of a trip to constitute a full unit of effort, but subsequent days to constitute less (or potentially more) than a full unit of effort
- `fYear`: effect of year, as a 14-level factor covering the years 1991–2004 (data for 2004 were later excluded from subsequent analysis)
- `fMonth`: effect of month, as a 12-level factor
- `Lunar1`: measure of brightness of the moon
- `Lunar2`: relative brightness of the moon, displaced seven days (approximately a quarter of a lunar cycle): the combination of `LunarPhase1` and `LunarPhase2` in the model closely approximates a sinusoidal curve with amplitude and phase as parameters
- `fCatchGrid`: effect of location, as a factor with one level for each 30-minute grid square
- `random = ~ 1 | fBoatMark`: random effects term for fishing vessel, which accounts as best we can for the different capabilities of different boats (e.g. numbers of dories, degree to which different boats target red throat emperor, etc.).

The coefficients of the `fYear` factor, when exponentiated, provided the standardised CPUE for each year in each grid square. Standardised CPUE was defined to equal 1 in 1991.

Standardised effort can then be defined as catch divided by standardised CPUE; this was used in Section 3.4.2 and in the ‘Overall’ results shown below. Catch and standardised effort can
be summed over all regions, and a CPUE for all regions combined can be defined by dividing the summed catch by the summed standardised effort.

Standardised commercial CPUE by region is plotted in Figure 21 and listed in Table 21.

The Cairns North, Townsville, Storm Cay and Swains regions all show a substantial downward trend since 1991. Standardised CPUE in 2003 was 31% of the 1991 level for the Cairns North region, 78% for Townsville and Storm Cay, and 62% for the Swains. CPUE in 2003 was very close the 1991 levels for the Mackay and Capricorn-Bunker regions. The 2003 Mackay level, however, was 75% of the 1992 level. Capricorn-Bunker CPUE declined to 84% of the 1991 level in 1999, and had fully recovered by 2003; this recovery may be related to reduced catch sizes in that region in 1997–2001 after the peak in 1996 (Figure 20).

Cyclone Justin in 1997 obviously constituted an exceptional event, dramatically raising catch rates in the Townsville region. It appears to have reduced catch rates in the Storm Cay, Swains and Capricorn-Bunker regions, although the age-structured model explains this fall by a period of several years of below-average recruitment (see Section 6.2 below). We checked daily CPUE around March 1997, and a sharp increase in CPUE in the Townsville region corresponded exactly to the dates when Cyclone Justin was present. CPUE stayed high in the Townsville region for several years afterwards.

The low values of CPUE in 2004 occurred at a time of major upheaval in the fishery, and are almost certainly related to fishers’ targeting behaviour rather than low abundance of red throat emperor. Reef fish quota holders stated to us that, with the introduction of quotas from July 2004, they were ‘banking’ their red throat emperor quotas to use later in the quota year when they had either filled their quotas on other reef fish species or had difficulty finding those species (CRC Reef Stakeholder Workshop participants, pers. comm. 2004).

CPUE values for 2004 were therefore excluded from the assessment.
Figure 21: Standardised commercial catch per unit effort by region. Scaled to a level of 1 in 1991, together with an overall curve formed by weighting the regions by catch size. Low catch rates in 2004 probably relate to targeting rather than abundance of red throat emperor, and were excluded from further analysis (source: CFISH database).

Table 21: Values of standardised commercial catch per unit effort used in the assessment. Standardised to a level of 1 in 1991. The ‘Overall’ CPUE was formed by weighting the regions by catch size. Low catch rates in 2004 probably relate to targeting rather than abundance of red throat emperor.

<table>
<thead>
<tr>
<th>Year</th>
<th>CairnsNth</th>
<th>Townsville</th>
<th>Mackay</th>
<th>StormCay</th>
<th>Swains</th>
<th>CapBunker</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1992</td>
<td>0.581</td>
<td>1.027</td>
<td>1.323</td>
<td>1.049</td>
<td>0.996</td>
<td>1.073</td>
<td>1.098</td>
</tr>
<tr>
<td>1993</td>
<td>0.405</td>
<td>0.887</td>
<td>1.365</td>
<td>1.018</td>
<td>0.883</td>
<td>1.059</td>
<td>1.036</td>
</tr>
<tr>
<td>1994</td>
<td>0.570</td>
<td>0.896</td>
<td>1.258</td>
<td>0.974</td>
<td>0.938</td>
<td>1.039</td>
<td>1.024</td>
</tr>
<tr>
<td>1995</td>
<td>0.643</td>
<td>0.729</td>
<td>1.105</td>
<td>0.930</td>
<td>0.997</td>
<td>1.071</td>
<td>0.946</td>
</tr>
<tr>
<td>1996</td>
<td>0.531</td>
<td>0.669</td>
<td>1.044</td>
<td>0.981</td>
<td>1.050</td>
<td>1.012</td>
<td>0.936</td>
</tr>
<tr>
<td>1997</td>
<td>0.444</td>
<td>1.450</td>
<td>1.057</td>
<td>0.772</td>
<td>0.740</td>
<td>0.868</td>
<td>1.024</td>
</tr>
<tr>
<td>1998</td>
<td>0.394</td>
<td>1.215</td>
<td>1.162</td>
<td>0.764</td>
<td>0.754</td>
<td>0.868</td>
<td>0.956</td>
</tr>
<tr>
<td>1999</td>
<td>0.363</td>
<td>1.118</td>
<td>1.175</td>
<td>0.887</td>
<td>0.769</td>
<td>0.840</td>
<td>0.951</td>
</tr>
<tr>
<td>2000</td>
<td>0.335</td>
<td>0.868</td>
<td>1.115</td>
<td>0.902</td>
<td>0.818</td>
<td>0.861</td>
<td>0.893</td>
</tr>
<tr>
<td>2001</td>
<td>0.392</td>
<td>0.742</td>
<td>1.028</td>
<td>0.907</td>
<td>0.842</td>
<td>0.908</td>
<td>0.864</td>
</tr>
<tr>
<td>2002</td>
<td>0.391</td>
<td>0.628</td>
<td>0.912</td>
<td>0.836</td>
<td>0.667</td>
<td>0.975</td>
<td>0.763</td>
</tr>
<tr>
<td>2003</td>
<td>0.305</td>
<td>0.781</td>
<td>0.995</td>
<td>0.779</td>
<td>0.624</td>
<td>1.015</td>
<td>0.819</td>
</tr>
<tr>
<td>2004</td>
<td>0.170</td>
<td>0.483</td>
<td>0.786</td>
<td>0.567</td>
<td>0.412</td>
<td>0.689</td>
<td>0.572</td>
</tr>
</tbody>
</table>
4.2 Recreational sector data

Catch and effort data for the non-charter recreational sector were available for only the three RFISH survey years, 1997, 1999 and 2002. Therefore they contained little information on long-term catch-rate trends in the fishery, but because 1997, the year of Cyclone Justin, was one of those years, it was thought worthwhile to attempt an analysis of RFISH raw data to estimate recreational CPUE.

A unit of effort was defined to be a fishing trip by one person.

Location was resolved only to the level of Region (six of which embrace the whole GBR). Location was specified in the RFISH raw data as a place name rather than a grid square; usually the reef name was given, but sometimes only the nearest town.

Catch and effort data were analysed by a log-linear model similar to that used for the commercial data. A single analysis was performed for the entire set of RFISH diary data. Fishing trips were included where any emperor, nannygai, red emperor or coral trout were caught. Catches analysed included released fish. The R code generating the log-linear model object was:

\[
\text{lme}(\log(Rte+1) \sim \text{Region} \times \text{fYear}, \text{random} = \sim 1 \mid \text{fLogNo})
\]

The terms can be explained as:

- \(\log(Rte+1)\): log of number of red throat emperor caught, including those released, plus one fish
- \(\text{Region} \times \text{fYear}\): compound term including the effects of region, year and the interaction between region and year
- \(\text{random} = \sim 1 \mid \text{fLogNo}\): random effects term for fisher’s diary number (fisher ID).

The coefficients of the \(\text{Region} \times \text{fYear}\) term, when exponentiated, provided the standardised CPUE for each year in each region. Standardised CPUE was defined to equal 1 in 2002; this year was chosen because it was distant from 1997 which was atypical, being the year of Cyclone Justin.

Terms involving month and lunar phase were initially included in the model but were not significant.

The resulting standardised recreational CPUE by region is plotted in Figure 22. The results confirm those from the commercial CPUE; in particular, 1997 catch rates are higher than the other years in the Townsville and Cairns North regions and lower in the Capricorn-Bunker region. Values for the Storm Cay and Swains regions are based on relatively few records and are subject to high uncertainty.
Figure 22: Standardised recreational catch per unit effort by region. Scaled to a catch rate of 1 in 2002. Values for the Storm Cay and Swains regions are based on relatively few records and are subject to high uncertainty (source: RFISH database).

4.3 Charter sector

Sufficient charter data were available for a catch per unit effort analysis from 1994 to 2004 (see analysis of catch records in Section 3.2.5). The model was identical to that used for the commercial data (see Section 4.1).

The standardised charter vessel CPUE by region is plotted in Figure 23. The curves are remarkable for being flat, showing almost no trend except for very high catch rates in Townsville in 1997, most likely as a result of Cyclone Justin.

The commercial CPUE estimates were used as an index of relative abundance of red throat emperor for the assessment because we believe that targeting behaviour of charter boats may be correlated with availability of different species. Charter operators may target certain species when they are available, and avoid them when they are scarce. In times of low abundance of red throat emperor, charter operators may well pursue other species instead. Commercial operators, on the other hand, have skills, equipment and marketing connections applicable to certain target species, and will not always find it worthwhile to target other species when their preferred species are scarce.
Figure 23: Standardised charter vessel catch per unit effort by region. Scaled to a catch rate of 1 in 1996 (source: RFISH database).
5. **Surplus production population dynamic model**

5.1 **Methods**

5.1.1 *Description of the basic surplus production model*

Surplus production models are widely used in fisheries stock assessments. It was considered advantageous to apply this model in addition to the more detailed age-structured model (Section 6 below) in order to compare the results of the two models and possibly gain insight from where the results of the two models disagree.

Surplus production models use catch and abundance (CPUE) data only, without considering age structure of the catch (Haddon, 2001, Ch. 10). Given the surplus production model’s simplicity, it was considered worthwhile to fit it to the red throat emperor catch and CPUE data, and contrast the results to those of the age-structured model presented in Section 6 below.

The Schaefer form of the surplus production model is used here (Haddon, 2001, pp. 288–9):

\[ B_{t+1} = B_t + rB_t (1 - B_t / K) - C_t, \]

where \( B_t \) is the biomass at the beginning of year \( t \), \( C_t \) is the total catch from all sectors in year \( t \), and \( r \) (the population replenishment rate) and \( K \) (the maximum population biomass or ‘carrying capacity’) are parameters that are estimated. The catch rate or CPUE, \( I_t \), is assumed indicative of the exploitable biomass, and the trend in \( I_t \) is matched to the trend in \( B_t \) for the years in which both \( I_t \) and \( B_t \) are available. The parameter \( r \) is a combined effect of growth, natural mortality and recruitment, while \( K \) depends on both the size distribution and number of animals in the population prior to exploitation.

The basic surplus production model used for this assessment estimates only two parameters, \( r \) and \( K \). Variants of the surplus production model can include catchability (\( q \); see below) and initial biomass (\( B_1 \), also discussed below).

To fit the model, \( B_t \) was taken to be deterministic (i.e., subject to no random error), and \( I_t \) was assumed to be subject to lognormal errors. The model was fitted by minimising the following sum of squares:

\[
\sum_i \left[ \log I_i - \log \left\{ q (B_i + B_{i+1}) / 2 \right\} \right]^2,
\]

where \( q \) is the catchability, estimated by

\[
q = \prod_i I_i / \prod_i B_i + B_{i+1} / 2.
\]

The quantity \((B_i + B_{i+1}) / 2\) is an approximation to the midyear biomass which is recommended by Haddon (2001, p. 293).

5.1.2 *Application to the red throat emperor fishery*

The red throat emperor population and fishery is regional in nature; hence we considered it prudent to model each of the regions separately. The equations described above were applied to each region to produce a biomass time series by year and region. The population replenishment rate \( r \) was assumed to be the same for all regions, while a separate carrying capacity \( K \) was included for each region. We note that the case of region-specific \( r \) parameters would be biologically interesting, but available data do not permit their accurate estimation.

The initial biomass \( B_1 \) was generated for each region assuming that the population was in equilibrium with an annual catch given by the average of the total catches from 1946 to 1969, a period when catches were relatively stable prior to increasing levels.
As noted in Section 4.1, the 2004 CPUE was excluded from analysis because of concern that it represented changed targeting behaviour of fishers rather than abundance of fish.

It was also necessary to include a special parameter to fit the increase in exploitable biomass in the Townsville region in 1997, associated with Cyclone Justin. The cyclone was assumed to have switched unexploitable biomass to exploitable biomass, which then remained exploitable and also constituted additional breeding stock.

The model was coded in the statistical package R (R Development Core Team 2005).

5.1.3 Model assumptions

The major assumptions of the surplus production model applied to red throat emperor were:

1. Commercial CPUE is an accurate index of abundance.
2. The biomass dynamics of the populations follow the Schaefer functional form described in Section 5.1.1.
3. The effect of Cyclone Justin was to switch unexploitable biomass to exploitable biomass in the Townsville region in 1997; this biomass remained exploitable in subsequent years and also constituted additional breeding stock. The assumption is supported by the age structure of the samples collected from Townsville in 1997, which contained many more young fish (2, 3 and 4 years old) than samples collected from Townsville in other years. These cohorts could also be seen in the samples from subsequent years.

Further assumptions arising from the regional model are:

4. The population growth rate \( r \) is the same over all regions of the GBR.
5. There is no more than a moderate amount of mixing of red throat emperor between regions. This assumption is supported by the different age distributions observed on reefs open to fishing and reefs closed to fishing in the same region (see Section 6.2.2 below).

5.2 Results

The model produced an estimate of the population replenishment rate \( r \) which appears a little too low to be realistic (\( r = 0.12 \text{ yr}^{-1} \)). This rate is the rate at which the population biomass would increase if fishing were terminated after first reducing the population to a small fraction of its virgin size; a figure of 12% per year increase in population biomass under these circumstances implies a low rate of population recovery.

To provide an apparently more reasonable value of \( r \), the model was also run with \( r \) set to its upper 95% confidence limit of 0.30 \( \text{yr}^{-1} \). This confidence limit was generated by profile likelihood; the difference between the log-likelihoods of this value of \( r \) and the maximum likelihood value was set to 1.92 which is half the 95\textsuperscript{th} percentile of the \( \chi^2_1 \) distribution, in accord with maximum likelihood theory. The model was allowed to freely estimate all other parameters when \( r \) was fixed.

The results are quite pessimistic. Parameter estimates for both models are listed in Table 22. The estimated maximum sustainable yield (MSY) is only 760 \text{ t yr}^{-1} for the maximum likelihood solution, and 964 \text{ t yr}^{-1} for the solution with \( r = 0.30 \text{ yr}^{-1} \). These figures include both the commercial and recreational harvests. It is generally considered wise to set the total allowable catch somewhat lower than the estimated MSY, in order to provide a margin of safety over statistical error in the estimates and lack of exact fit of the model.

Trajectories of catch rate, exploitable biomass and harvest rate are plotted in Figure 24, Figure 25 and Figure 26 respectively for the model in which \( r \) is estimated, and Figure 28, Figure 29 and Figure 30 for the model in which \( r \) is fixed to 0.30 \text{ yr}^{-1}. They show large declines in both catch rate and biomass since the 1970s, with biomass down to about 40% of virgin in the northernmost regions of Townsville and Cairns North. Estimated recent harvest rates are well
below their peaks, but this apparently has still not resulted in a substantial recovery in the biomass (right-hand sides of Figure 25 and Figure 29).

Figure 27 and Figure 31 show steady-state yield curves for the fishery; the curves show the annual yields that would result if effort were held constant for many consecutive years. The observed year-by-year catch and standardised effort points are superimposed. Many of the observed catch–effort points have catches above the estimated MSY (top of the parabolic curve), and effort levels above the levels associated with MSY (where the curve is a maximum). These figures show the red throat emperor fishery as over-exploited up to 2003 in all areas except possibly Capricorn-Bunker.

Standard errors for the maximum likelihood estimates are high; this is mainly because the $r$ and $K$ parameters are correlated (higher $r$ and lower $K$ give very similar log-likelihood).

Table 22: Parameter estimates from the surplus production model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$r$ estimated by maximum likelihood</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$, replenishment rate (yr$^{-1}$)</td>
<td>0.12</td>
<td>0.0970</td>
</tr>
<tr>
<td>$B_{37} / B_{96}$ for Townsville</td>
<td>2.1486</td>
<td>0.2131</td>
</tr>
<tr>
<td>$K$ Cairns North (t)</td>
<td>1003.6</td>
<td>523.2</td>
</tr>
<tr>
<td>$K$ Townsville (t)</td>
<td>3427.4</td>
<td>1079.8</td>
</tr>
<tr>
<td>$K$ Mackay (t)</td>
<td>6912.9</td>
<td>4071.8</td>
</tr>
<tr>
<td>$K$ Storm Cay (t)</td>
<td>3602.4</td>
<td>1996.9</td>
</tr>
<tr>
<td>$K$ Swains (t)</td>
<td>3186.3</td>
<td>1480.2</td>
</tr>
<tr>
<td>$K$ Capricorn-Bunker (t)</td>
<td>7213.4</td>
<td>4753.2</td>
</tr>
<tr>
<td>$K$ Cairns North (t)</td>
<td>523.0</td>
<td>3.9</td>
</tr>
<tr>
<td>$K$ Townsville (t)</td>
<td>2299.1</td>
<td>126.0</td>
</tr>
<tr>
<td>$K$ Mackay (t)</td>
<td>3281.5</td>
<td>391.9</td>
</tr>
<tr>
<td>$K$ Storm Cay (t)</td>
<td>1757.2</td>
<td>135.6</td>
</tr>
<tr>
<td>$K$ Swains (t)</td>
<td>1720.8</td>
<td>83.2</td>
</tr>
<tr>
<td>$K$ Capricorn-Bunker (t)</td>
<td>3274.1</td>
<td>584.0</td>
</tr>
<tr>
<td>$MSY = \Sigma r K / 4 (t \text{ yr}^{-1})$</td>
<td>760.4</td>
<td>224.2</td>
</tr>
</tbody>
</table>

$r$ fixed to its upper 95% confidence limit

| $r$, replenishment rate (yr$^{-1}$)           | 0.30                                | –              |
| $B_{37} / B_{96}$ for Townsville              | 2.3978                              | 0.2458         |
| $K$ Cairns North (t)                          | 523.0                               | 3.9            |
| $K$ Townsville (t)                            | 2299.1                              | 126.0          |
| $K$ Mackay (t)                                | 3281.5                              | 391.9          |
| $K$ Storm Cay (t)                             | 1757.2                              | 135.6          |
| $K$ Swains (t)                                | 1720.8                              | 83.2           |
| $K$ Capricorn-Bunker (t)                      | 3274.1                              | 584.0          |
| $MSY = \Sigma r K / 4 (t \text{ yr}^{-1})$   | 964.2                               | 55.0           |
Figure 24: Catch rates from the surplus production model with $r = 0.12 \text{ yr}^{-1}$, the maximum-likelihood estimate. The points plotted are the observed values.

Figure 25: Biomass trend from the surplus production model with $r = 0.12 \text{ yr}^{-1}$, the maximum-likelihood estimate.
Harvest rate, $r = 0.12$

Figure 26: Harvest rate (proportion of population that is caught in each year) from the surplus production model with $r = 0.12 \text{ yr}^{-1}$, the maximum-likelihood estimate.
Figure 27: Catch, effort and steady-state yield from the surplus production model with $r = 0.12 \text{ yr}^{-1}$, the maximum-likelihood estimate.
Figure 28: Catch rates from the surplus production model with \( r = 0.30 \text{ yr}^{-1} \), the upper 95% confidence limit.

Figure 29: Biomass trend from the surplus production model with \( r = 0.30 \text{ yr}^{-1} \), the upper 95% confidence limit.

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Figure 30: Harvest rate (proportion of population that is caught in each year) from the surplus production model with $r = 0.30$ yr$^{-1}$, the upper 95% confidence limit.
Figure 31: Catch, effort and steady-state yield from the surplus production model with \( r = 0.30 \, \text{yr}^{-1} \), the upper 95% confidence limit.