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The seine-net fishery of Rodrigues Island, western Indian Ocean: is it sustainable or in terminal decline?

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Abstract

Despite their importance, catches of small-scale fisheries are often unreported or underestimated. This study, the first to analyse the seine-net fishery in Rodrigues, aimed to examine whether the fishery is sustainable, as suggested by government data, or in long-term decline as reported by fishers. Using government data, a Fox surplus production model suggests that a seine-net buy-back scheme may have sufficiently reduced fishing pressure to allow the fishery to be sustainable. However, the mean trophic level of the catch declined significantly from 1994 – 2006, with many locally preferred fish becoming rare. Furthermore, a detailed study of the catches of four seine-net teams over five years indicated that catch per unit effort (CPUE) and fisher earnings declined significantly. Mean trophic level was 2.7 with over half of the catch comprised of herbivores and detritivores. When the government data are reanalysed to account for a change in fishing subsidies, they too indicate a significant decline in CPUE. Overall the data show that the seine-net fishery is over-exploited and unless management measures are taken urgently it will shortly cease to be viable. The study highlights the importance of measuring fishing effort appropriately and the need for multiple information sources for effective fisheries management.

Keywords: western Indian Ocean, Rodrigues, artisanal fisheries, seine-net fishery, fishing down

1. Introduction

Around the world, fish catches have declined since the late 1980s (Pauly et al., 2002) and although coral reef fisheries only account for a small percentage of global fisheries catches (Sadovy, 2005), a high dependency on fish protein and rapid population growth has meant that there is now widespread unsustainability of both island coral reef fisheries (Newton et al., 2007) and those of mainland countries (e.g., Mangi and Roberts 2006; McClanahan *et al.* 2008). While small-scale fisheries, especially near-shore subsistence fisheries, have been recognised as important for social, cultural, and food security reasons (Zeller et al., 2007a), they are often marginalised (Pauly, 1997) and their catches often unreported or underestimated. This may be due to either the perceived difficulties of estimating a widely dispersed fishery or to limited financial and human resources (Bunce et al., 2009; Dalzell et al., 1996). Re-estimation of catches in Guam for example, revealed a 2.5-fold discrepancy between the re-estimated catches and the reported statistics (Zeller et al., 2007a). Similarly, in Madagascar, catches according to the national fisheries agencies were underreported by at least 40% (Le Manach et al., 2012) and in Mozambique and Tanzania

respectively, total marine catches were estimated to be 6.2 and 1.7 times greater than data reported to the Food and Agriculture Organisation of the United Nations (FAO) (Jacquet et al., 2010). The unreliability of such official data presents a significant challenge for small-scale fisheries management and can potentially contribute to their overexploitation, highlighting the need for better monitoring (Zeller et al., 2007b).

On the island of Rodrigues (Republic of Mauritius) fishing is one of the largest employment sectors, employing about 13% of the total workforce in 2006 (Central Statistical Office 2007) and the artisanal fisheries provide food for a large proportion of the population. There have been concerns about the status of the lagoon fishery in Rodrigues going back to 1901 (Bunce *et al.*, 2009). Tarbit (1980) reported that the fishery appeared to have been in decline since 1955 when it included 34 seine nets and exported 750 tonnes of salt fish (1500 tonnes fresh weight equivalent), noting that exports in 1974 had declined to just 98 tonnes. The seine-net fishery is one of the most important of the lagoon fisheries, accounting for 42 % of the total reported lagoon fish catch in 2006, according to unpublished data of the government's Fisheries Research and Training Unit (FRTU).

Seine-net fishing has been practised in Rodrigues since 1822 (North-Coombes, 2002). It is carried out within the shallow lagoon by teams of fishers in small 'pirogues' who use a semi-circular net and herd fish into the net by walking or sailing towards it, beating the water with poles. Some coral may be snagged during retrieval of the net or damaged by fishers' feet, however, because the seine is not dragged through the lagoon, damage to the habitat is much less than for beach seines. The seine-net fishery is the most regulated of the artisanal fisheries in Rodrigues. Following concerns about overfishing, the Fisheries Act (1980) limited the number of seine-net licences for the island to 17 and introduced a number of management measures, including a 5-month closed season (start of October to end of February), five inshore areas (totalling 15.9 km²) where seine-net fishing is permanently prohibited (Fig. 1), a minimum mesh size of 9 cm and minimum catch sizes for several fish species. In addition, a buy-back scheme was initiated in 1997 to pay compensation for fishing teams who relinquish their licences; as a result, there were only 8 seine-net licences in place in 2006. The closed season appears to coincide with one of the two main spawning periods for several important fishery species in nearby Mauritius including at least three *Lethrinus* species and *Siganus sutor* (Wheeler 1945; Ommannney 1949) and is at a time of year when the weather is relatively good for fishing. Thus it constrains fishing at a critical time of year.

In 1965 a Bad Weather Allowance was introduced to compensate registered fishers through the payment of an allowance on days on which they are unable to go fishing because of sea conditions. This allowance was characterised by Bunce et al. (2008) as a "perverse fishing incentive" because it provided a strong incentive for people to register as full-time fishers in order to collect the subsidy. Numbers on the register rose from under 500 in the 1970s to 2,069 in 1992 (Bunce *et al.*, 2008) and stood at 1,975 in 2006 (Fisheries Protection Service, unpublished data). Unlike the professional seine-net fishers, many of those entering the register were more interested in the subsidy than fishing, although they have to show up at fishing sites in order to qualify for the allowance. Thus the subsidy may not have only increased fishing pressure but also exacerbated the environmental impacts of fishers trampling through the lagoon, seeking fish and octopus among the corals (Mangi and Roberts, 2006; Pearson, 1988). In 2006, the method by which the allowance was assessed was changed (see Supplementary material) with the result that the number of bad weather days when most fishers were entitled to the allowance was almost halved.

Fig. 1. The sites of seine net hauls taken by the four fishing teams studied in 2002–2006. The bases of each fishing team, boundaries of the five inshore closed areas (...) and the boundaries of the new northern marine reserves and the southern marine park (—) are also shown.

Monitoring of the lagoon fisheries in Rodrigues (fin fish and octopus) is undertaken by the FRTU, with catch data collected from 23 landing stations around the island. The published data seem to suggest that although the octopus fishery and total lagoon fish catches have declined in recent years, catches from the seine-net fishery remained relatively stable between 1994 and 2006. In contrast, seine-net fishers complain of declines in fish catches, and fishers around the island report depletion of many species, especially large predators, in the last 25 years (Bunce et al., 2008), such that many fishers are now dependent on government subsidies. This study, the first detailed analysis of the seine-net fishery in Rodrigues, aimed to investigate this apparent discrepancy by comparing the officially reported catch data with detailed catch assessments conducted with local seine-net fishing teams over five years and use these two sources of data to determine whether the fishery is indeed sustainable (in the sense that catches similar to those during the study may persist for many years to come (cf Costanza and Patten 1995), albeit that these catches may be sub-optimal) or, as suggested by the fishers, in decline. To see how baselines might have shifted in the longer term (cf. Jackson et al., 2001), the results are discussed in the context of unpublished fisheries data from 1978 - 1979 for Rodrigues, accounts of the similar lagoon fishery in nearby Mauritius from the 1940s, and local fishers perceptions reported by Bunce et al. (2008).

2. Methods

2.1 Catch and effort data from FRTU

Catch data are collected at 23 fish landing stations around the island on a regular basis by the FRTU and collated annually. For the seine-net fishery, data are collected for 13 species, or groups of species plus a miscellaneous category (<10 % of total weight) and summed for each month of the fishing season (March - September). The primary indicator of

effort is the number of registered seine-net fishers in each year. The combined catch and effort data for the seine-net fishery from 1994 – 2006 (Appendix A, Table A.1) were subjected to surplus production analysis using the Fox model (which fitted better than the Schaefer: $R^2 = 0.856$ for Fox vs. 0.719 for Schaefer) to obtain an estimate of maximum sustainable yield (MSY) for the multispecies stock and the fishing effort at MSY. Despite the multi-species nature of the fishery, the same half dozen species tend to dominate the catch each year, and we considered that a surplus production model approach would give a broad indication of the fishery's status and sustainability.

Since the number of registered seine-net fishers declined slightly over the five years (Table A.1) of our detailed study, we did not expect any detectable change in species. However, over the 1994 - 2006 period for which FRTU statistics were available we expected that some evidence of “fishing down the food web” (Pauly *et al.*, 1998) might be apparent. Thus, the contribution of each taxon to the catch in each year was examined to see if there were any significant trends over the 13-year period using regression analysis on Box-Cox transformed data.

2.2 Detailed catch composition and catch and effort data

Surveys were undertaken working in collaboration with four seine-net fishing teams (half of those licensed) based respectively at Pointe l'Aigle (north), Baie du Nord (north-west), Pointe Corail (south-west) and Port Sud Est (south) during the seine-net fishing season (1st March – 30th September) in 2002 – 2006. Catch assessments were undertaken by following a seine-net team during the course of a fishing day. A total of 124 fishing days consisting of 1,119 hauls were sampled over the 5 year period (Fig. 1). For each fishing day, details of the fishing team, date, weather, departure and return times to base, time spent on breaks between hauls, number of hauls made, and number sampled were recorded. For each haul, the GPS position, start and finish time, and number of fishers and boats involved were recorded. For each sampled haul, all the fish caught were transferred to the survey boat, where the species of each fish was determined and its total length measured on a measuring board to the nearest 0.5 cm total length (TL). Data were entered into a specially designed hierarchical relational database set up in Microsoft Access to facilitate analysis. This allowed each fish sampled to be related to a specific haul and fishing team. A key aim was to generate catch per unit effort estimates that would better reflect fish availability and be less impacted by fisher behaviour. *A priori* we decided that the measures of CPUE that were least likely to be affected by fishers' work ethics or team strategies would be kg net-h^{-1} or $\text{kg fisher}^{-1} \text{net-h}^{-1}$ (Table 1) with the former metric expected to be the best because it seemed unlikely that adding a few fishers to fishing teams of minimum size 15 – 19 (Table 1) would increase the catch *pro rata*. However, for comparisons with other studies in the region and with FRTU data, it was necessary to also calculate CPUE as $\text{kg fisher}^{-1} \text{d}^{-1}$.

Samples of the main species caught (from across the size range of each species) were also taken back to the laboratory and subjected to more detailed measurements including weight, standard length (SL), fork length (FL), greatest body depth, and girth. The weight of each fish was estimated using local length-weight relationships established for the commoner species by regressing the weights of samples against total length (cm) using the equation $W = a \times L^b$ where W is weight in grams and L is total length in cm (Appendix A, Table A.2). For less common species, published length-weight relationships (Froese and Pauly, 2011) were used.

Table 1

Comparison of the performances of the four fishing teams between 2002 and 2006, based on 124 fishing days. Median and interquartile ranges are shown for each metric.

Fishing team	Pointe Corail	Baie du Nord	Pointe l'Aigle	Port Sud Est
Fishing days sampled (n)	34	23	44	23
Number of fishers	21 (18–24)	20 (15–25)	21 (19–22)	16 (15–20)
Number of boats	8 (6–9)	7 (6–7)	7 (6–7)	5 (5–6)
Number of hauls d ⁻¹	14 (12–17)	8 (5–9)	6 (4–9)	8 (5–12)
Length of fishing day (h)	7.00 (5.90–8.17)	8.33 (7.25–9.50)	5.75 (4.44–7.48)	5.67 (4.58–7.08)
% time net submerged	41 (33–47)	31 (22–38)	25 (18–30)	31 (18–35)
Weight of fish per day (kg)	237 (182–326)	217 (106–339)	96 (43–194)	60 (44–188)
Number of fish per day	822 (596–1376)	579 (257–818)	219 (146–480)	196 (74–510)
CPUE (kg fisher ⁻¹ d ⁻¹)	11.3 (8.6–15.5)	9.8 (4.0–16.4)	5.3 (2.1–9.5)	5.8 (3.2–10.1)
Hauls sampled	481	162	284	192
Length of hauls (min)	10 (9–14)	19 (14–25)	10 (8–15)	10 (7–13)
Weight of fish per haul (kg)	11 (4–25)	22 (1–48)	10 (1–23)	6 (0–18)
Number of fish per haul	37 (12–87)	61 (4–137)	29 (6–65)	18 (0–43)
CPUE (kg net-h ⁻¹)	86.2 (66.5–132.0)	92.2 (47.5–131.5)	73.9 (36.1–134.5)	65.6 (40.6–120.6)
CPUE (kg fisher ⁻¹ net-h ⁻¹)	4.1 (3.2–6.2)	4.1 (3.0–6.2)	4.1 (2.0–7.1)	3.9 (2.3–7.6)

The Catch Per Unit Effort (CPUE) data were found not to be normally distributed and so initial comparisons were conducted using non-parametric statistics (e.g. Kruskal-Wallis test). Where significant differences among medians were found, data were transformed to achieve normality so that differences between individual means could be tested for significance using Tukey's test. Because of the non-normality, variables in Table 1 are listed as medians and interquartile ranges. The trophic level for each species within the catch was obtained from FishBase (Froese and Pauly, 2011). When fish were not identified to species level, the average trophic level for species of that genus (or family for some FRTU categories) known to occur in Rodrigues was used. The mean trophic level ($\overline{\text{TrL}}$) of the catch each year (k) was calculated as:

$$\overline{\text{TrL}}_k = \frac{\sum_{i=1}^n \text{TrL}_i Y_{ik}}{\sum_{i=1}^n Y_{ik}}$$

where Y_{ik} is the catch of species i in year k (Pauly et al., 2001).

2.3 Fisher earnings

One fishing team leader (Pointe l'Aigle) made available his records of weekly earnings (Mauritian rupees) of fishers from 2002 – 2006. Mean monthly earnings for each 7-month fishing season (not adjusted for inflation) were compared to see if there was any trend among years using least-squares regression analysis. Since mean CPUEs ($\text{kg fisher}^{-1} \text{ net-h}^{-1}$) among fishing teams were very similar (Table 1), earnings were assumed to be representative.

3. Results

3.1 Catch and effort data reported by the FRTU

Although there appeared to be a short-lived rise in the total lagoon fish catch (which also includes catches from the basket trap and hand-line fisheries) from 1997 - 1999, the overall catch has declined significantly ($F = 17.7$; $df = 1, 7$; $P < 0.005$) since 1998, despite the seine-net licence buy-back (Fig. 2), with on average 75 tonnes less caught each year and the catch in 2006 (641 t) being approximately half that in 1999 (1,240 t). Throughout the period, octopus catches showed a steady and significant ($F = 46.8$; $df = 1, 11$; $P < 0.001$) decline (averaging about 40 tonnes less each year), with the catch in 2006 (266 t) being about one third that in 1994 (775 t). By contrast, there was no significant trend in the seine-net catches according to these figures, with catches fluctuating about a mean of 224 tonnes per year between 1994 and 2006.

The Fox surplus production model fitted to the multi-species data (Fig. 3) suggests a maximum sustainable yield (MSY) of around 260 tonnes per year (close to the 2006 catch) from the lagoon seine-net fishery at a fishing effort of about 140 fishers (compared to the 64 registered in 2006). In 1994 – 1997, prior to the licence buy-back, an average of 274 fishers caught a mean of 202 tonnes per year; after the buy-back (1998 - 2006) an average of 89 fishers caught a mean of 233 tonnes per year. Mean annual CPUE increased from 735 kg fisher^{-1} before to 2,801 kg fisher^{-1} after the buy-back (Table A.1). Although this measure of CPUE showed a significant increase over the post-buy-back period 1998 - 2006 (least squares regression, $P = 0.001$), there was no significant trend in CPUE in the FRTU data for 2002 - 2006 ($P = 0.53$) during the period of our detailed study. In summary, the analysis indicates that

prior to the licence buy-back in 1997, the fishing effort was excessive and the fishery severely overexploited. Following the reduction in effort between 1997 and 1998, seine-net catches improved until 2002 and have remained above pre-buy-back levels in most years (Fig. 3). Since the buy-back, the Fox model suggests that the fishery has been slightly under-exploited.

Fig. 2. Annual catch (tonnes) for a) all lagoon fish (◆—◆), b) octopus (□), and c) the large seine net fishery (●- -●) between 1994 and 2006 (FRTU annual statistics). The dashed lines show the least squares regression relationships for all lagoon fish against year for 1998 - 2006 ($P < 0.004$) and for octopus against year from 1994–2006 ($P < 0.001$). About half of the large seine net licences were bought back by the government after the 1997 fishing season.

3.2 Behaviour of fishing teams and choosing a robust measure of catch per unit effort (CPUE)

Fishing teams typically consisted of 16 - 21 fishers operating from 5 - 8 boats (Table 1). The seine net is set in a semi-circle from the surface to the lagoon floor from two boats and then the fishers drive fish towards it by walking or sailing towards it (depending on the state of the tide) beating the water with poles and/or drumming on the bottom of their boats. Teams travelled an average distance of between 10 km and 18 km per fishing day. Among fishing teams, the median length of a fishing day varied from 5 h 40 min to 8 h 20 min and the median length of hauls ranged from 10 - 19 minutes (Table 1). No significant changes in distance travelled per fishing day, the length of fishing day, nor the mean length of hauls made each day over the study period were evident (regression analysis of variables against year by fishing team), thus there did not appear to be any hidden creep in effective fishing effort (cf Daw et al. 2011). Overall ~22 % of hauls contained no fish and both the Pointe l'Aigle and Port Sud Est teams had a few days (<10 % of those sampled) when no fish were caught at all, with fishing being abandoned after 3 – 6 h.

The performances of the four fishing teams are compared in Table 1. There was no significant difference among teams (Kruskal-Wallis test, $p > 0.50$ and $p > 0.90$ respectively) in median CPUE in terms of either $\text{kg net}^{-1}\text{h}^{-1}$ (range = 65.6 – 92.2) or $\text{kg fisher}^{-1}\text{net}^{-1}\text{h}^{-1}$ (range = 3.9 – 4.1). However, we found that median catches per fisher per day differed significantly among seine-net teams as a result of differing fishing strategies and work ethics (Kruskal-

Wallis, $P < 0.001$) with the Baie du Nord ($9.8 \text{ kg fisher}^{-1} \text{ d}^{-1}$) and Pointe Corail ($11.3 \text{ kg fisher}^{-1} \text{ d}^{-1}$) teams having significantly higher daily catch rates than the other two teams which caught only $5.3 - 5.8 \text{ kg fisher}^{-1} \text{ d}^{-1}$ (Tukey's test on data normalised by a square-root transform, $p < 0.01$). The former team had significantly higher median haul times, i.e. submerged their nets for longer during each haul, (and had higher catches per haul) than the other teams (Kruskal-Wallis test among teams, $p < 0.001$, Tukey's test on log-transformed data, $p < 0.01$), whereas the latter team averaged significantly more hauls per fishing-day (median of 14 hauls d^{-1}) (Tukey's test on square-root transformed data, $p < 0.01$) than the other three teams (medians of 6 – 8 hauls d^{-1}) (Table 1). In summary, the fishing teams that worked the longest hours and had their seine nets deployed for longer, took home the most catch in a day. Thus CPUE expressed in the widely used units of $\text{kg fisher}^{-1} \text{ d}^{-1}$ or $\text{kg per seine-net day}$ was strongly influenced by fisher behaviour but this significant between-team source of variation could be removed by using kg net-h^{-1} or $\text{kg fisher}^{-1} \text{ net-h}^{-1}$. Using these CPUE measures made data from each fishing team comparable, better reflected fish availability, and allowed each team's data to be treated as a replicate independent sample for each year such that inter-annual trends could be studied.

Fig. 3. Fox surplus production model to see what effect the sudden change in effort between 1997 and 1998 had on the seine net fishery. Open diamonds show levels of annual catch per unit effort (CPUE in kg fisher^{-1}) against effort (number of registered seine net fishers). Filled circles show the catch (tonnes) for each year's effort. The solid curve shows the predicted catch for each level of effort whilst the dashed line shows the best-fit relationship between CPUE and effort using a Fox model. Estimated maximum sustainable yield (MSY) and fishing effort needed to achieve this are also indicated. (Based on FRTU data for 1994 - 2006.)

3.3 Annual trends in CPUE and fisher earnings

The CPUE of the four fishing teams on each fishing day sampled were compared among years to see if there was any trend. For both the kg net-h^{-1} (Fig. 4a) and $\text{kg fisher}^{-1} \text{ net-h}^{-1}$ measures of CPUE there was a significant decline ($P < 0.02$ and $P < 0.025$ respectively; least-squares regression after normalisation of the data) from 2002 to 2006. Median CPUE declined from 132 to 66 kg net-h^{-1} and 5.9 to 3.1 $\text{kg fisher}^{-1} \text{ net-h}^{-1}$ over the five-year period, an approximate halving. This was reflected in the recorded earnings of fishers in one of the teams (Fig. 4b). For 2002 - 2006, average monthly earnings per fisher during the 7-month

fishing season were regressed against year and showed a significant decline ($P < 0.03$), with 2006 mean monthly earnings being about 60% of those in 2002. Both indicators thus suggest a significant decline in the fishery during the 5-year study period. Even more disturbingly, if the lines of best fit in Figures 4a and 4b were extended forward in time, they suggest that positive catches and earnings would cease in 2010 - 2012. This appears contrary to the FRTU statistics which show no trend from 2002 - 2006 and indeed suggest that CPUE ($\text{kg fisher}^{-1} \text{y}^{-1}$) was 1.35 times higher in 2006 than 2002.

Fig. 4. a) Square-root transformed CPUE $\pm$ SE (kg net-h^{-1}) for the four fishing teams (black squares) from 2002-2006 with official FRTU CPUE ($\text{kg fisher}^{-1} \text{yr}^{-1}$) overlaid (open diamonds); b) Mean monthly earnings in Mauritian Rupees (Rs) $\pm$ SE for fishers in one of the teams during the 7-month fishing season over the same period (Rs 100 = US\$ 3.45, March 2012). The dashed lines show the least-squares regression relationships for CPUE (kg net-h^{-1}) against year ($P=0.015$) and earnings against year ($P=0.018$).

3.4 Comparison of the two data sets

Given the apparent conflict between our data and the FRTU statistics and the importance we have shown of the precise measure of CPUE used, we revisited the FRTU data to see if the crude measure used of $\text{kg fisher}^{-1} \text{yr}^{-1}$ could be refined. For 2003 - 2006 we were able to obtain data on the number of days when the Bad Weather Allowance (BWA) was paid. The introduction of a new system in mid-2006 effectively meant that fishers were paid for not going fishing on far fewer days, and thus seine-net teams were likely to have had to go out fishing on more days. Assuming that the number of potential fishing days minus the number of days when the BWA was paid during the fishing season equates to the number of fishing days in each fishing season, CPUE can be recalculated as $\text{kg fisher}^{-1} \text{fishing-day}^{-1}$ (Fig. 5). The adjusted FRTU data now show a decline in CPUE from 73 kg to 30 $\text{kg fisher}^{-1} \text{fishing-day}^{-1}$ between 2003 and 2006. This approximates to the level of decline seen from our detailed catch and effort data (approximate halving). However, comparison of Fig. 5 and Table 1 shows that, although the trend is similar, the daily CPUE based on the FRTU data is up to 8 times higher than that calculated in this study. The reason for this large difference is not clear and requires further investigation.

3.5 Detailed catch composition

A total of 114 species were recorded in the catch over five years, however, just eight species made up 75 % of the catch (Table 2), and 17 species comprised over 90 % of the catch by weight. Combining all five years of data from each of the four fishing teams, the Shoemaker spinefoot *Siganus sutor*, was the most important species by weight, followed by

the Spangled emperor *Lethrinus nebulosus* and the Bluespot mullet *Moolgarda seheli*. Overall about 44 % of the catch by weight (51 % by numbers) was comprised of herbivorous fishes, 35 % by weight were invertebrate feeders, 11 % were detritivores and only 9 % were piscivores. The mean trophic level of the catch was 2.7 (SE $\pm$ 0.08), varying between 2.4 and 2.8 over the five years but with no significant trend.

Fig. 5. Catch per unit effort (CPUE) derived from FRTU statistics for 2003 - 2006 adjusted for the number of fishing days not subject to the bad weather allowance in each year (filled black diamonds). The unadjusted CPUE is overlaid (open squares) to show effect of bad weather days on effort and in particular the impact of the reduction in the number of days Bad Weather Allowance was paid in mid-2006.

Between 1994 and 2006 the relative importance of several locally preferred food fish (*Rhabdosargus sarba*, *Lethrinus harak*, *Chanos chanos*, *Kyphosus* spp. and *Polydactylus plebeius*) declined dramatically and carangid catches also declined significantly (see Table 3). The majority of these taxa are at higher trophic levels. By contrast, the annual catches and relative importance of *S. sutor* and *Naso unicornis* (lower trophic levels) increased significantly according to these data (Table 3). The mean trophic level for the “non-miscellaneous” part of the catch declined significantly ($F = 24.9$; $P = 0.0005$) from 2.9 in 1994 to 2.5 in 2006 (Fig. 6), with the mean value of 2.6 for 2002 - 2006 being similar to the 2.7 mean trophic level found in our detailed study. Species composition of the catch was also similar in both datasets with the same 7 taxa making up the majority of the catch. *S. sutor* however made up a greater proportion of the catch in our dataset: 27.2 % compared with 19.7 % in FRTU’s data from 2004 – 2006, whereas *N. unicornis* was more important in the FRTU dataset: 17.3 % compared with 4.8 % in our study.

Table 2

Species composition of the catch for the 8 taxa comprising 75% of the total catch sampled for the 4 fishing teams between 2002 and 2006. The first number is the % by weight for each year with the % by numbers in parentheses. Taxa are ranked by total contribution by weight for all years.

Species	Feeding type	Trophic level	Catch composition (%)					
			2002	2003	2004	2005	2006	All years
<i>Siganus sutor</i>	Herbivore	2.00	46.6 (66.0)	26.8 (33.2)	23.7 (33.1)	23.5 (29.4)	31.4 (35.1)	27.2 (34.7)
<i>Lethrinus nebulosus</i>	Invertivore	3.32	5.1 (4.6)	9.9 (8.4)	23.0 (21.5)	9.1 (8.8)	3.8 (4.2)	11.9 (10.3)
<i>Moolgarda seveli</i>	Detritivore	2.32	0.6 (0.2)	8.1 (1.7)	13.6 (5.2)	12.6 (5.5)	3.7 (1.5)	9.4 (3.2)
<i>Mulloidichthys flavolineatus</i>	Invertivore	3.27	3.7 (5.2)	11.0 (15.9)	2.3 (3.7)	8.3 (15.3)	7.1 (8.2)	6.7 (10.3)
<i>Gerres longirostris</i>	Invertivore	3.50	3.5 (4.1)	8.6 (8.7)	5.1 (7.1)	4.8 (7.2)	10.1 (9.2)	6.7 (7.9)
<i>Caranx melampygus</i>	Piscivore	4.49	3.7 (3.4)	6.6 (4.8)	7.1 (7.6)	4.5 (5.6)	4.3 (6.1)	5.6 (5.9)
<i>Naso unicornis</i>	Herbivore	2.17	15.3 (3.2)	1.1 (0.3)	2.2 (1.2)	10.8 (5.1)	2.0 (0.5)	4.8 (1.7)
<i>Acanthurus triostegus</i>	Invertivore	2.78	1.1 (3.0)	1.1 (2.3)	2.0 (5.3)	2.9 (7.9))	4.9 (11.1)	2.5 (6.5)

Table 3

Comparison of the mean annual catch and % contribution by weight of 13 fish taxa to the total catch of large seine net teams in 1994-1996 and 2004-2006 (based on unpublished FRTU data). The remainder of the catch was placed in a “miscellaneous” category, comprising 4.8% and 8.0% of the catch in 1994-96 and 2004-06 respectively. Categories are ranked on basis of abundance in 1994-1996. Due to considerable inter-annual variation catches are averaged for three year periods at start and end of the 12 years. Percentage changes in catch of each taxon over the period are included in parentheses where regression analysis showed significant trends in catch by year over the 1994-2006 period.

Taxon (% change)	Trophic level	1994-1996		2004-2006		Significance of regression
		kg y ⁻¹	%	kg y ⁻¹	%	
Mugilidae	2.27	34981	16.0	27530	11.3	P=0.460
Carangidae (-44%)*	4.42	24581	11.3	13647	5.6	P=0.030
<i>Lethrinus nebulosus</i>	3.32	23068	10.6	41052	16.8	P=0.149
<i>Siganus sutor</i> (+123%)**	2.00	21628	9.9	48146	19.7	P=0.007
<i>Naso unicornis</i> (+103%)*	2.17	20774	9.5	42256	17.3	P=0.031
<i>Gerres longirostris</i>	3.50	18385	8.4	18964	7.8	P=0.826
Mullidae	3.35	18204	8.3	24278	10.0	P=0.171
<i>Kyphosus</i> spp. (-99%***	2.30	10046	4.6	110	<0.1	P<0.001
<i>Chanos chanos</i> (-96%***	2.03	9542	4.4	383	0.2	P<0.001
Scaridae	2.00	8028	3.7	7482	3.1	P=0.542
<i>Rhabdosargus sarba</i> (-99%)*	3.37	7992	3.7	45	<0.1	P=0.017
<i>Lethrinus harak</i> (-92%)*	3.56	7424	3.4	570	0.2	P=0.043
<i>Polydactylus plebeius</i>	3.59	2922 [†]	1.3	0	0.0	No data
Mean trophic level***		2.9		2.6		P<0.001

[†] Last recorded in 1994 when an estimated 8767 kg were landed. Level of significance: * P<0.05. ** P<0.01. *** P<0.001.

Fig. 6. Mean trophic level of the seine-net fishery as calculated from unpublished FRTU data from 1994 to 2006. Regression analysis shows a significant decline over the period ($P < 0.001$).

4. Discussion

Official data from the FRTU indicate that although there was a large decline (c. 600 t) in total lagoon catches from 1999 - 2006, seine-net catches showed no such trend, remaining stable at around 224 t per year. A Fox surplus production model based on aggregated data indicated that the buy-back scheme in 1997 appeared to have resulted in a sufficient decline in fishing effort to allow the seine-net fishery to be sustainable (effort was reduced below that predicted to give MSY and catches rose). However, a detailed analysis of the catches of four seine-net fishing teams (half of those then operating) suggests that the fishery is in rapid decline. CPUE for the four seine-net teams (expressed as either weight per time net submerged, or weight per fisher per time net submerged) approximately halved between 2002 and 2006. This was accompanied by a significant decline in monthly earnings (39 %) for the Pointe l'Aigle team despite an increase in fish prices of 20 – 28 % between 2003 and 2006 (Ministry of Agro Industry, Food Production and Security, 2007) and inflation averaging 5.8% per year over the period, making the decline in real terms even worse.

Daw et al. (2011) found a discrepancy between trends over a 10-year time period from landing data and fisher perceptions and suggested that this may have been due to increases in effective fishing effort, which was not evident in the reported data. In contrast, our data do not show any significant change in distance travelled, haul times or fishing-day length over the 5 year period. The apparent contradiction between the declining trend in CPUE we found and the lack of such a trend in the unadjusted FRTU CPUE data can however be explained by the change in the method of calculating the Bad Weather Allowance (BWA) in 2006. Based on the earnings of the Pointe l'Aigle team and the number of bad weather days in 2003 - 2005, the BWA would have represented 25 % of combined fishing and BWA earnings for fishers (Appendix A, Fig. A.1). We estimate that the change in method of calculation would have almost doubled the number of days when no BWA was paid and thus approximately halved this source of income. Thus an unintended consequence of reducing the BWA subsidy in 2006 appears to have been an increase in fishing effort by those primarily dependent on fishing for their livelihoods.

Recalculation of the CPUE from the FRTU data from 2003 to 2006 as kg fisher⁻¹ fishing-day⁻¹ showed it to be consistent with our findings of a decline in CPUE. This highlights the importance of reporting sufficiently detailed scientific information to support the effective management of artisanal fisheries. The importance of measuring fishing effort appropriately is supported by Daw et al (2011) who found that in the Seychelles artisanal basket trap fishery, reporting fisheries data as catch per day gave a different result to catch per trap. Unfortunately, collection rather than analysis of the fishery statistics appears to be the main aim of FRTU and resources to allow detailed analysis to inform fisheries management in Rodrigues are lacking. This lack of resources for small and marginal “sister” islands within island states is flagged up as a widespread issue by Bunce et al. (2009).

Assessment of the catch composition indicates that the seine-net fishery shares many characteristics with other heavily exploited coral reef fisheries. Most of the species caught tend to have a small maximum size (<50 cm TL) and a short lifespan (<10 years) (Jennings et al., 1999). Both datasets show that the catch is dominated by herbivores and small invertebrate feeders with a paucity of piscivores (<9 % by weight), similar to the situation in heavily fished coral reef areas in for example, Fiji, Seychelles and Kenya reported by Jennings and Polunin (1996), Jennings et al. (1995) and McClanahan et al. (2008) respectively. The low mean trophic level of the Rodrigues seine-net catch (2.7) was somewhat lower than that recorded for heavily exploited beach seine and net fisheries in Madagascar (3.17 - 3.67) by Davies et al. (2009) but very close to values obtained for artisanal gill-net and beach seine fisheries in southern Kenya (2.6 - 2.9) by McClanahan and Mangi (2004). However, daily catches for seine-net fishermen averaged 9.9 kg fisher⁻¹ d⁻¹ in Rodrigues over the study period, about four times the catch rates (~2.3 kg fisher⁻¹ d⁻¹) recorded by McClanahan et al. (2008) at Kenyan sites where beach seines dominated. The overall picture is of a fish community under excessive fishing pressure (e.g. de Boer et al., 2001; McClanahan and Mangi, 2004).

The FRTU data indicate that the relative importance of several locally favoured food fish (Goldlined seabream, *Rhabdosargus sarba*; Thumbprint emperor, *Lethrinus harak*; Jacks, Carangidae; Milkfish, *Chanos chanos*; Sea chub, *Kyphosus* spp.; Striped threadfin, *Polydactylus plebeius*) declined dramatically between 1994 and 2006. These six taxa accounted for ~29 % of the catch in 1994 - 96 but comprised only 6 % in 2004 - 06 with the five non-carangids making up <0.5 % of the total catch in 2006. Pet-Soede et al. (1999) noted that aggregation of fisheries data can obscure trends at lower aggregation levels, which seems to have been the case here, where increases in catches of lower trophic level species (*Siganus sutor* and *Naso unicornis*) masked declines in catches of several higher trophic level preferred food-fish species. A study of fisher perceptions in Rodrigues by Bunce et al. (2008) shows that fishers are aware of these declines. They found that 91 % of fishers believed that the lagoon fishery had declined, with large serranids and *R. sarba*, being the species most frequently cited as depleted, and *P. plebeius* and *L. harak* also commonly cited. Our data show that serranids comprise only 0.001 % of the total seine-net catch by weight. The agreement between fishers' perceptions and our data support the view that the knowledge possessed by fishers can be very useful for fisheries management in situations where there is a lack of resources to collect and process data (Johannes, 1998). Daw et al. (2011) found that in Seychelles, fishers' perceptions of CPUE were concordant with official landings data and these studies highlight the importance of multiple information sources for effective fisheries management.

A few earlier reports shed light on the nature of the fishery in the latter part of the last century. Tarbit (1980) reported that the emperors, *Lethrinus mahsena* and *L. nebulosus* (trophic levels 3.43 and 3.32 respectively) accounted for 40 % of the seine-net catch in 1978

– 1979 (*L. mahsena* listed under the synonym *L. sanguineus* Smith), yet these species comprised just 12 % of the catch of the four seine-net teams in 2002 – 2006, with the former species now rare (<0.5 % total catch by weight). Ommanney (1949) working on the seine-net fishery in the Mauritius lagoon in 1947 found these two species (with *L. mahsena* being more common than *L. nebulosus*) making a similar contribution (46.8 % of the catch) and reported *L. harak* and *R. sarba* among the 7 commonest species in the seine catch. Thus the depletion of favoured species seen in the FRTU data seems to be part of a much longer term decline in the two islands which, apart from these isolated snapshots, is largely undocumented. It is notable that *R. sarba*, *L. harak*, *L. mahsena*, *Kyphosus* spp. and *P. plebeius*, which are now insignificant constituents of the fishery, were all considered important enough to be included among only 11 taxa for which minimum legal landing size limits were listed in the Fisheries Act 1980.

Despite the management measures instigated in the 1980s and 1990s and reported in the introduction (closed season, closed areas, reduction in the number of seine-net licences), the lagoon fisheries appear to continue to decline. Our study suggests that unless there is effective management action, the seine-net fishery of Rodrigues would cease to be economically viable around 2010 – 2012 based on the rates of decline we observed. For this outcome to occur, there is an assumption of “business-as-usual”, i.e. further seine-net licences are not surrendered, there is not a switch to offshore fishing and gazetted marine reserves do not become operational. In fact, two seine-net licences have been surrendered since 2006 (driven by decline in earnings from fishing), the Rodrigues Regional Assembly are promoting offshore fishing, a Voluntary Redeployment Scheme has been instituted (which has resulted in the number of registered fishers falling from 1,975 in 2006 to 1,407 in 2010), four marine reserves are currently being implemented and a large Marine Protected Area has been established in the SE lagoon (Fig. 1). Despite all these measures, in 2012 on the opening day of the seine-net fishing season (when catches are normally particularly high after the 5-month closed season) only one out of the six remaining seine-net teams landed any fish (mostly *S. sutor* and *L. nebulosus*) despite fishing all day (Shoals Rodrigues, pers. comm.). Thus our prediction of terminal decline seems unfortunately to have been close to the truth, and unless management actions currently underway eventually allow stock recovery the future of the fishery remains in doubt. On a positive note, studies on similarly heavily fished areas in Kenya suggest that stocks could recover quite fast with appropriate management (McClanahan and Hicks, 2011; McClanahan et al., 2008).

The seine-net fishery is the most regulated of the lagoon fisheries and employed just 64 people in 2006 (3 % of the registered fishers). If it really caught 42 % of the total lagoon fish catch then, as FRTU figures indicate, it is also clearly the most efficient fishery. How much of the decline in fish catches is due to seine-net operations and how much is due to illegal fishing, which is a serious problem in Rodrigues, is unknown. In 2003, the Fisheries Protection Service (FPS) seized 24 illegal seine nets totalling 1434 m in length (FPS, unpublished data). Despite such seizures, the current regulations are not rigorously enforced and unregistered fishers often fish illegally during the seine-net closed season using small mesh (<9 cm) nets. Illegal fishing can have significant effects on fish stocks and it has been shown that there is a relationship between high levels of illegal fishing and poor governance (Agnew et al. 2009). There are however many difficulties associated with implementing traditional fisheries control mechanisms based on effort and gear restrictions in tropical countries with limited resources. Zeller et al. (2007b) suggest that in such cases, serious consideration should be given to spatial and temporal closure management options as these management approaches are more readily enforced and monitored for infringements. ‘No Take Zones’ have been shown to be an effective method of increasing fish catches for

example in the Philippines where catches of jacks and surgeonfish tripled after 18 years of protection (Russ et al., 2004) and in Kenya where protected areas had higher abundances and species richness of commercially important triggerfish, surgeonfish, and parrotfish (McClanahan and Arthur, 2001). It can only be hoped that the new Marine Protected Area (MPA) network in Rodrigues, which will potentially protect 27 % of the lagoon area, combined with more effective enforcement of existing fishing regulations outside of the MPAs may allow the fish stocks in the lagoon to recover.

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Appendix A. Supplementary data

Supplementary data associated with this article (<http://dx.doi.org/10.1016/j.fishres.2012.10.013>) area appended at the end of the article).

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Appendix A

Table A.1. Catch and effort data for the large seine net lagoon fishery from 1994 to 2006 (*Source:* Fisheries Research & Training Unit, Rodrigues).

Year	Registered seine-net fishers	Seine-net catch (tonnes)	CPUE kg fisher ⁻¹
1994	294	263.5	896.3
1995	285	197.5	693.0
1996	292	192.9	660.6
1997	225	155.6	691.5
1998	116	159.9	1378.5
1999	97	180.6	1862.1
2000	110	226.3	2057.1
2001	103	237.0	2301.0
2002	97	297.9	3071.1
2003	72	262.8	3649.8
2004	71	278.1	3916.7
2005	67	188.7	2816.8
2006	64	266.2	4159.4

Table A.2. Calculated local a and b coefficients to convert total lengths (cm) to weight (g) using the equation $W = a \times L^b$. Numbers of fish measured (n), coefficients of determination (R^2) and range of total lengths (TL_{min} , TL_{max}) used to establish each relationship for the Rodrigues populations are listed. Median a and b parameters obtained from FishBase are also shown for comparison (Froese and Pauly 2011).

Family	Fish species	a	b	n	R^2	TL_{min}	TL_{max}	a (FishBase)	b (FishBase)
Acanthuridae	<i>Acanthurus triostegus</i>	0.0223	3.1054	33	0.9386	12.5	23.0	0.0213	3.0810
	<i>Naso unicornis</i>	0.0186	2.9773	37	0.9300	22.5	56.0	0.0228	2.9220
Balistidae	<i>Rhinecanthus aculeatus</i>	0.1559	2.4059	17	0.9559	14.0	27.0	0.0179	3.1000
Carangidae	<i>Caranx melampygus</i>	0.0096	3.0576	162	0.9866	18.0	57.7	0.0211	2.9410
	<i>Gnathanodon speciosus</i>	0.0072	3.1805	21	0.9824	17.5	34.1	0.0199	2.9950
Gerreidae	<i>Gerres longirostris</i>	0.0106	3.0287	216	0.9570	20.5	41.0	0.0140	2.9640
Lethrinidae	<i>Lethrinus harak</i>	0.0163	2.9673	22	0.9555	25.1	42.0	0.0170	3.0423
	<i>Lethrinus nebulosus</i>	0.0193	2.8897	189	0.9802	14.5	59.0	0.0161	2.9700
Mullidae	<i>Mulloidichthys flavolineatus</i>	0.0056	3.1758	70	0.9492	24.5	36.7	0.0089	3.0602
	<i>Mulloidichthys vanicolensis</i>	0.0062	3.1590	66	0.9388	15.5	35.0	0.0099	3.0150
Scaridae	<i>Chlorurus sordidus</i>	0.0138	3.1245	19	0.9252	18.0	28.3	0.0127	3.1410
Serranidae	<i>Epinephelus merra</i>	0.0334	2.7333	50	0.9636	11.5	24.0	0.0096	3.1960
Siganidae	<i>Siganus argenteus</i>	0.0120	3.0208	40	0.9863	17.7	35.5	0.0131	3.0880
	<i>Siganus sutor</i>	0.0130	3.0238	478	0.9759	14.5	48.0	0.0596	2.7560

Fig. A.1. Estimates of seine-net fisher monthly income during the 7 month fishing season (converted to US\$) from both fishing and the Bad Weather Allowance* (BWA). Estimates are based on the earnings of the Point l'Aigle team and the number of bad weather days in 2003–2006. *Until 2006, a bad weather day was defined as a day when the sea was rough (2.5–4 m wave height) or wind exceeded 19.2 km h^{-1} or both and payments were made each month. In 2006, the Rodrigues lagoon was split into four zones for assessment of the state of the sea, and the state of the open sea was assessed separately. A bad weather day became defined as a day when the sea-state was rough, rough to moderate (1.25–2.5 m wave height) or moderate to rough in a particular zone. The change in method of BWA calculation approximately halved this source of income.