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The Isle of Man *Aequipecten opercularis* fishery stock assessment 2012

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Summary

A fishery for queen scallops, *Aequipecten opercularis*, has been prosecuted in and around the Isle of Man's territorial sea since the 1950s, becoming of increasing importance during the late 1960s. Until recently queen scallops were targeted almost entirely with either toothed dredges or skid dredges. However, most Manx vessels now fish for queen scallops with otter trawls, while UK vessels usually use toothless dredges. The trawl fishery commences in June each year, thus the queen scallop fishing year is taken to run from June to May the following year.

A precautionary management strategy for the Isle of Man's queen scallop fishery was set out in 2010 and reviewed by a Marine Stewardship Council (MSC) assessment team. The trawl fishery was MSC certified in May 2011, while the dredge fishery failed to meet the necessary standard due to the negative impact of dredging on benthic habitats. A key aspect of ensuring the sustainability of the fishery is that management responds to stock status and that the impact of the fishery on the seabed remains limited.

Queen scallop abundance increased sharply in the Isle of Man's territorial sea between 2007 and 2010. This increase, combined with strong market demand, has led to increased fishing effort and landings of queen scallop in 2010 and 2011. Over 65% of landings were taken by UK dredgers in 2010 and 2011. Otter trawling is currently a relatively small component of the fishery taking 20-24% of landings annually.

The first formal stock assessment of the Isle of Man queen scallop stock was undertaken in 2012 using the Catch-Survey Analysis (CSA) method. The CSA method estimates stock size using abundance indices and is well-suited to the data available for the Isle of Man's queen scallop fishery. The stock assessment shows that the biomass of recruits and post-recruits has declined from 2010 to 2012. Total biomass is estimated to have declined by 11000t in 2010 and 14000t in 2011. Over 50% of total biomass was removed between June 2011 and May 2012, while fishing mortality increased from only 0.2 in 2009 to 0.7 in 2011. It is recommended that ≤30% of the total biomass is removed from ICES statistical rectangles 36E5 and 37E5 annually to minimise the risk of queen scallop biomass depletion. Biomass is likely to be depleted leading to the fishery becoming recruitment-dependent where >40% of biomass is removed annually. To meet these recommendations landings would need to be reduced substantially in 2012/2013 compared to the previous two years.

1. Background

1.1 The fishery

A fishery for queen scallops, *Aequipecten opercularis*, has been prosecuted in and around the Isle of Man's territorial sea since the 1950s, becoming of increasing importance during the late 1960s. Until recently queen scallops were targeted almost entirely with either toothed dredges or skid dredges. However, most Manx vessels now fish for queen scallops with otter trawls, while UK vessels use toothless dredges. The fishery within the territorial sea is governed by several management measures that include areas where dredging is prohibited, a closed season and a minimum landing size (Sea-Fisheries Act 1971. Isle of Man Sea-Fisheries (queen scallop fishing) bye-laws 2010. Statutory document No. 668/10). Outside of the territorial sea the fishery is subject to very few management measures.

1.2 Marine Stewardship Council certification

A precautionary management strategy for the Isle of Man's queen scallop fishery was set out in 2010 and reviewed by a Marine Stewardship Council (MSC) assessment team (Andrews *et al*., 2010). The trawl fishery was MSC certified in May 2011, while the dredge fishery failed to meet the necessary standard due to the negative impact of dredging on benthic habitats (Hinz *et al*., 2011). A key aspect of ensuring the sustainability of the fishery is that management responds to stock status and that the impact of the fishery on the seabed remains limited. Certification of the fishery was made on the basis of nine conditions being met over various timescales and the actions required to meet these conditions were set out in an action plan (Bangor University/DEFA, 2011). These conditions include developing a habitat management strategy and undertaking a formal stock assessment.

1.3 Recent increases in fishing effort

An increase in the demand for queen scallops in 2010 has prompted discussions about the management of the fishery. A meeting between relevant attendees of the UK National Scallop Group was held on 29th June 2011 in Manchester to discuss concerns over high fishing pressure on queen scallops in the Irish Sea. The possibility of a need for voluntary measures to manage the fishery was raised. A second meeting, held between the Seafish Industry Authority (Seafish) and several scallop processors in Preston on 21st July 2011, identified an increase in demand for queen scallops combined with increased catching capacity.

1.4 Stock assessment

A stock assessment of the Isle of Man queen scallop stock was undertaken using the Catch-Survey Analysis (CSA) method, first developed by Collie and Sissenwine (1983), the results of which are presented in this report. The CSA method estimates stock size using abundance indices and is well-suited to the data available for the Isle of Man's queen scallop fishery. The method is currently used in the Gulf of Maine shrimp fishery (Cadrin *et al*., 1999; Idoine, 2006). Comparisons of CSA with a surplus production model (ASPIC) were favourable although particular care is needed in correctly identifying recruits and post-recruits (Cadrin, 2000). CSA has been advocated as a valuable method to support management advice where age data is not available (Mesnil, 2003). Absolute estimates of stock size and fishing mortality derived from CSA are sensitive to input parameters, although trends over time are more robust to changes in these input parameters (Mesnil, 2003).

2. Methods

Stock assessment

The stock assessment was implemented using CSA v3.1 (NOAA, 2008). Data from the May/June surveys was used since this is when temperature is lower and dredges are a more effective means of sampling queen scallops (Jenkins *et al*., 2003), and before the main queen scallop fishing season. The stock assessment unit is the area covered by ICES statistical rectangles 36E5 and 37E5, which includes the majority of the fishing grounds. Furthermore, historical landings data cannot be resolved to the Isle of Man's territorial sea and landings data from the United Kingdom up to the end of 2010 was available to us for these two ICES statistical rectangles only.

Abundance indices were derived from survey data from 1992 to 2012. The geometric mean across survey stations was used to obtain an abundance index for the stock. A geometric mean was used in order to down-weight stations with very high abundance and is a more precautionary index than the arithmetic mean.

In the CSA model, the population dynamics of the fishery are described by a process equation using the population size of two size classes of queen scallops: fully recruited, *N*, and recruits, *R*:

$$N_{t+1} = (N_t + R_t)e^{-M} - C_t e^{-M(1-\tau)} \quad (1)$$

where t is an annual fishing year and C is the catch in numbers; τ is the proportion of the year over which landings are taken and M is natural mortality. To approximate catches being taken evenly throughout the year, catches were assumed to be taken midway through the year. Therefore, 6 months of natural mortality, ($e^{-0.5M}$), occurs, catches are removed, and then another 6 months of natural mortality occurs. Population estimates of post-recruits and recruits are derived from survey relative abundance indices:

$$n_t = q_n N_t e^{\eta t} \quad (2)$$

and

$$r_t = q_r R_t e^{\delta t} \quad (3)$$

where n_t and r_t are abundance indices of fully recruited queen scallops and recruits; q_n and q_r are the catchability coefficients of the queen scallop dredges used in the annual surveys. The terms $e^{\eta t}$ and $e^{\delta t}$ are log-normal random measurement errors. Catchability of recruits was defined as a proportion, s, of fully recruited queen scallops:

$$s = \frac{q_r}{q_n} \quad (4)$$

Fully recruited queen scallops were considered to be those of ≥55 mm length; thus, catches were assumed to consist of scallops ≥55 mm with sizes in proportion to survey average size frequency distributions. Average individual weights of recruits were derived from the relationship between length and weight measurements of 600 queen scallops from stations across the territorial sea. Historically, 50 to 55 mm has been considered the minimum commercially viable size (Brand, 2006). At present, dredgers typically use belly-rings of 60 mm internal diameter while trawlers use a cod-end with mesh of 80 to 90 mm. Therefore, catches of queen scallops <55 mm are likely to be low, and these smaller scallops remain commercially less desirable. Recent research found almost no landings <55 mm in either dredgers or trawlers (Nall, 2011). Allison (1993) fitted Von Bertalanffy Growth Functions (VBGF) to length at age data of queen scallops from around the Isle of Man. Mean growth rate expressed as VBGF parameters were $L_\infty = 75.91$, k = 0.59 and $t_0 = -0.88$. This equates to approximately 30 mm growth for a scallop of 27.5 mm during 1 year. Therefore, recruits were considered to be queen scallops 25 to 54 mm length. However, the smallest size of scallops caught were 25 mm and these were rare; therefore, the recruitment index was in effect scallops between 30mm and 55mm. Allison (1993) used six different methods to estimate natural mortality, *M*, all yielding different results ranging from 0.037 to 1.88 but identified values of 0.2 to 0.5 as most appropriate. The effects of using values of *M* between 0.2 and 0.4 were examined in an earlier report (Murray and Kaiser, 2012). Based on this earlier work this present stock assessment uses M = 0.2 and s = 0.35. It is important to note that mortality estimates relate only to recruits and fully-recruited scallops not to scallops <25 mm.

The harvest rate (*h*) was calculated using the equation:

$$h = \frac{C_t e^{\tau M}}{R_t + N_t} \qquad (5)$$

Fishing mortality was then estimated as *F* = -ln(1-h) following Collie and Kruse (1998). However, there is no advantage in using this estimate of *F* instead of the harvest rate to set management thresholds and both show the same patterns with time (Mesnil, 2005). The harvest rate is calculated based on population estimates in numbers and differs from calculations made based on weight (i.e. the proportion of the biomass removed). Confidence intervals of harvest rate, fishing mortality, biomass and abundance were derived using a non-parametric bootstrapping procedure. Randomly drawn residuals were applied to survey indices. Since 5% and 95% confidence intervals may not be reliably estimated with this method (Patterson *et al*., 2001, Mesnil, 2003), 10% and 90% confidence limits were used (see Cadrin *et al*., 1999; Mesnil, 2003).

Surplus production was calculated as follows:

$SP_t = B_{t+1} - B_t + CB_t$

where,

SP_t = surplus production in year t
B_{t+1} = biomass in year t+1

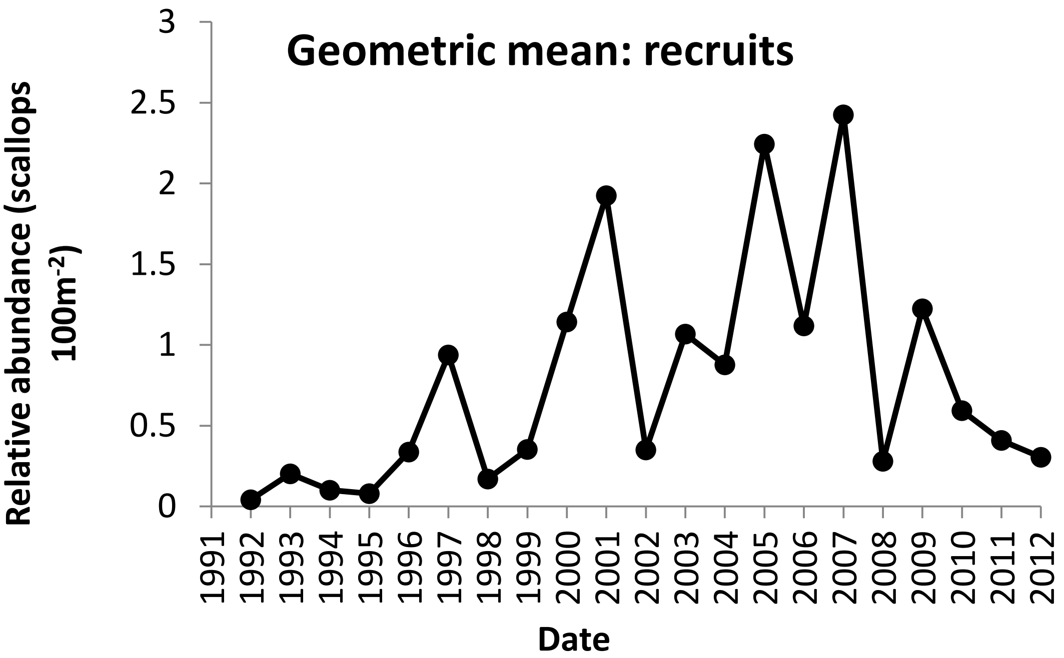
B_t = biomass in year in t
CB_t = catch biomass in year t.

3. Results

3.1 Abundance

Mean abundance of recruits has declined each year since 2009 (Figure 2a) while the abundance of post-recruits declined sharply between 2010 and 2011. Post-recruit abundance showed a slight increase between 2011 and 2012 (Figure 2b). From 2006 to 2010 there were year on year increases in post-recruit abundance, with abundance reaching the highest levels on record in 2009.

a)



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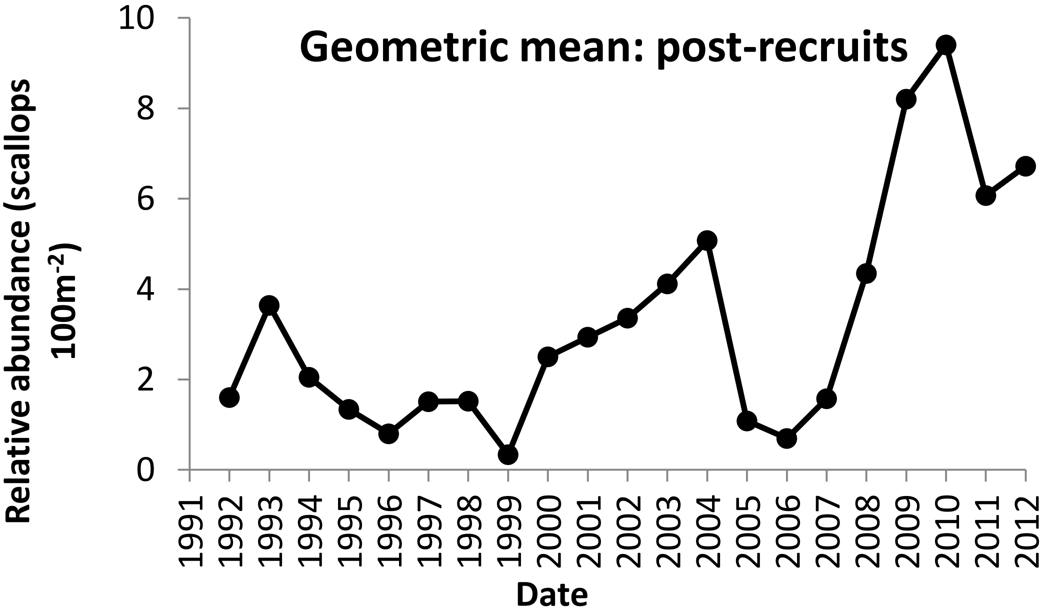


Fig. 2. Abundance index for recruits (a) and post-recruits (b) used in the catch survey analysis model

3.2 Landings and fishing effort

Landings of queen scallops are referenced to ICES statistical rectangles only. Landings from rectangles 36E5 and 37E5 are used as the nearest approximation to landings from the Isle of Man's territorial sea. It is important to note, however, that 36E5 extends south to near Anglesey and that total landings from these two rectangles will be substantially higher than from the territorial sea alone. Landings from Manx vessels in previous years have been spatially referenced to the territorial sea using VMS and logbook data. Logbook data from UK vessels has only recently become available to the Isle of Man for those vessels fishing in ICES rectangles 36E5 and 37E5.

In ICES statistical rectangles 36E5 and 37E5 landings increased between 2010 (Jan. to Dec.) and 2011 (Jan. to Dec.) (Fig. 3 and Fig. 4). By far the greatest increase has occurred due to UK dredgers, with landings increasing from 7028t to 10939t live weight. Manx trawlers also increased landings, from 1998t to 2838t. Manx dredgers increased landings from 1457t to 1526t. Landings by UK trawlers increased from 106t to 1026t. Landings taken from 36E5 and 37E5 by Manx trawlers represented 18% of total landings in 2010 and 17% in 2011 (Fig. 5). UK dredgers took 65% of landings in 2010 and 66% in 2011. Manx dredgers took 16% in 2010 and 9% in 2011. Landings of queen scallops from within the territorial sea increased from 4934t in 2010 to around 8034t in 2011 (Fig. 6). This represents 46% of total landings from 36E5 and 37E5 in 2010 and 49% in 2011. Landings by both dredgers and trawlers increased in the territorial sea between 2010 and 2011, from 3375t to 4673t for dredgers, and from 1559t to 3361t for otter trawlers.

For the stock assessment, landings were estimated from June to May up to 2008, and calculated thereafter, to allow a TAC to be advised from June each year (as is required by the Isle of Man Government). Only annual landings data were available up to 2008. Due to the consistent level of landings over the period from 2000 to 2008 (Murray and Kaiser, 2012) there was little effect of defining the fishing year as running from June to May, rather than January to December. However, in recent years this definition has a greater relevance, particularly between 2009 and 2010. Fortunately, monthly landings are available from 2009 onwards. Where monthly landings were not available landings were allocated to each fishing year in proportion to time i.e. 7 months in $year_i$ (58%) and 5 months in $year_{i+1}$ (42%).

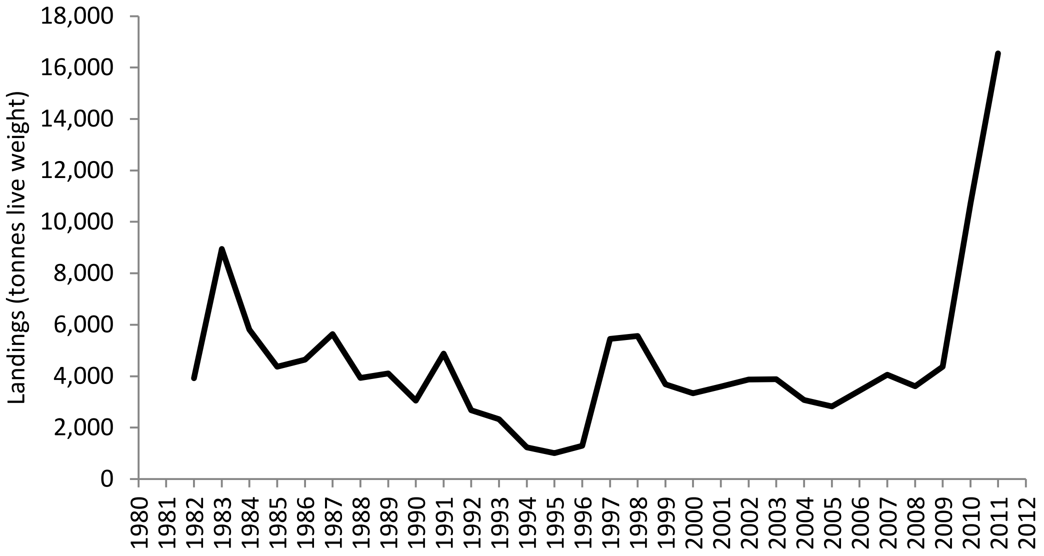


Fig. 3. Landings (live weight) of queen scallops to the UK and Isle of Man. Landings are referenced to ICES statistical rectangles 36E5 and 37E5 (as a proxy for territorial sea landings) where possible. However, Isle of Man landings before 1994 are total landings to the Isle of Man, which are likely to be predominantly from these two statistical rectangles. Data source: Isle of Man Government, DEFA.

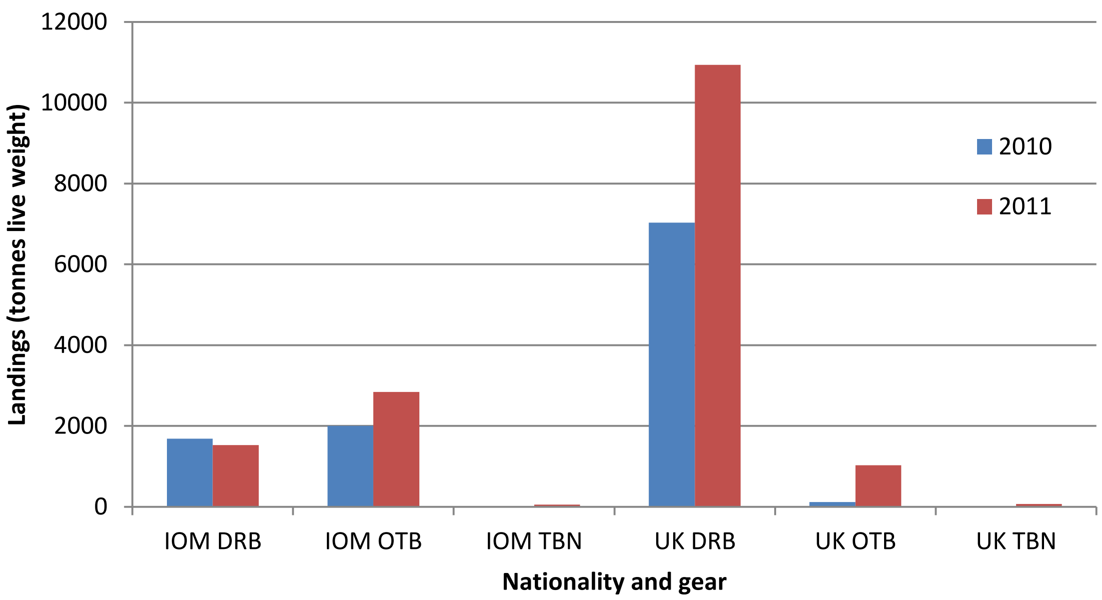
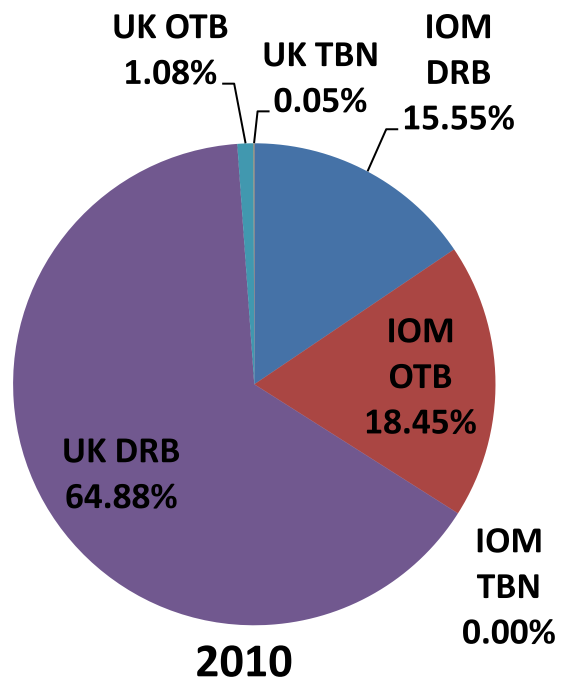


Fig. 4. Landings from 36E5 and 37E5 by UK and Isle of Man (IOM) dredgers (DRB), queen scallop trawlers (OTB) and *Nephrops* trawlers (TBN). Data are derived from the IFISH database and DEFA and are for calendar years (Jan. to Dec.) rather than fishing years.

a)



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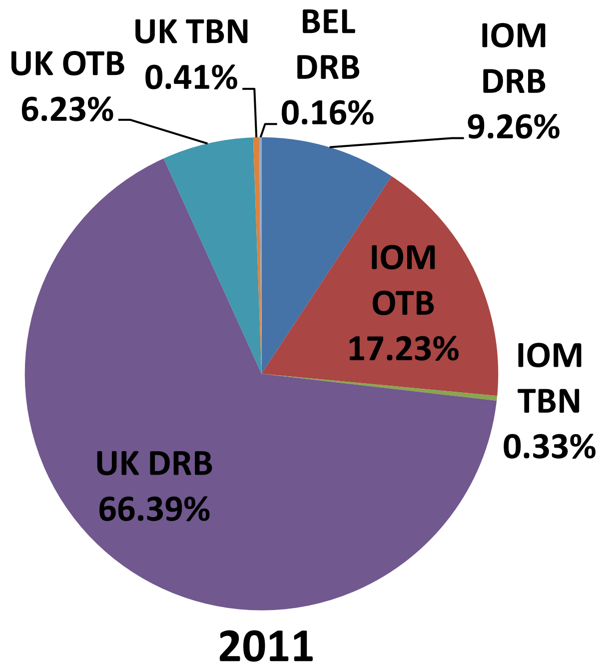

Fig. 5. Percentage of landings from 36E5 and 37E5 taken by UK and Isle of Man (IOM) dredgers (DRB), queen scallop otter trawlers (OTB), *Nephrops* trawlers (TBN), and Belgian (BEL) dredgers. Data are for calendar years (Jan. to Dec.) rather than fishing years.

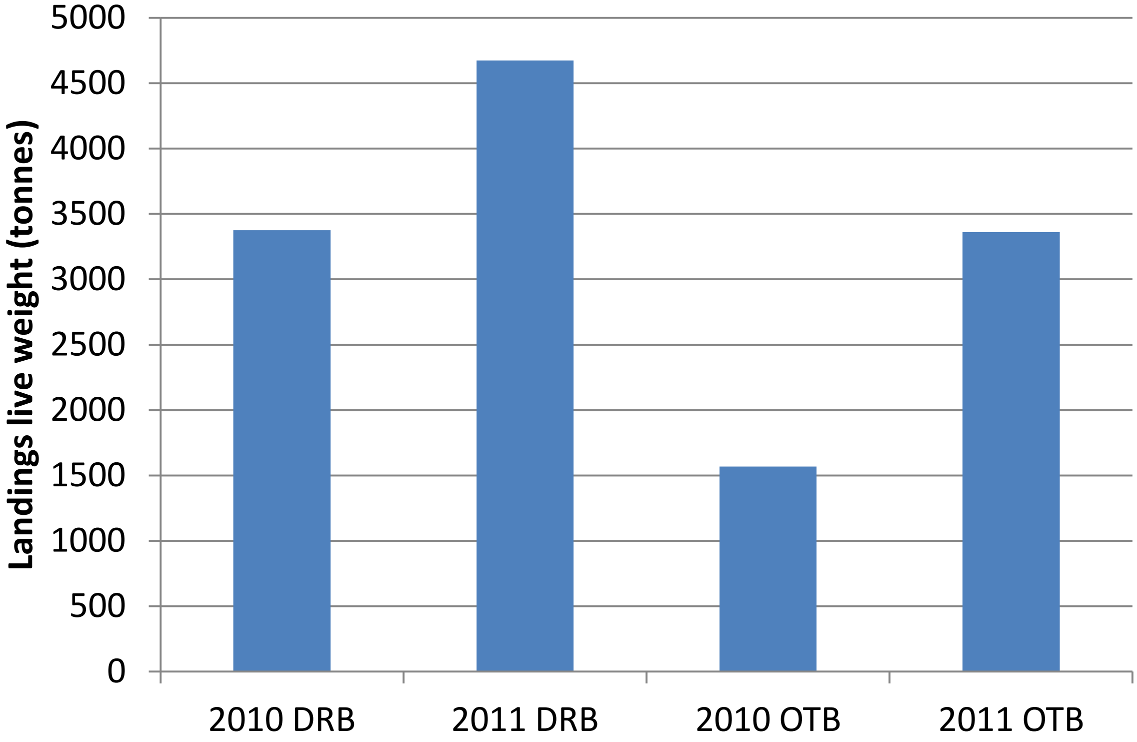

Fig. 6. Estimated landings from the Isle of Man's territorial sea. VMS data was available only until the end of November 2011. An additional 272 tonnes were landed in December from 36E5 and 1369t from 37E5, all from dredgers; it has been assumed that 37E5 landings are from within the territorial sea and 36E5 landings from outside the territorial sea. These estimates are derived from VMS data combined with logbook data and include only data where matches were found between logbooks and VMS records. Data are for calendar years (Jan. to Dec.) rather than fishing years.

3.3 Stock assessment

The results of the Catch Survey Analysis showed consistent trends over time in fishing mortality and biomass estimates over a range of input data (Murray and Kaiser, 2012). However, the magnitude of the parameters did vary with changes in the allocation of recruits and post-recruits, natural mortality estimates and recruit selectivity. The greatest effect on the recruit and post-recruit indices resulted from changing the threshold size from 50 to 55mm (Murray and Kaiser, 2012). The stock assessment revealed sharp increases in fishing mortality in 2010 and 2011 (Fig. 7) together with declining biomass of both recruits and post-recruits in 2010 and 2011 (Fig. 8). Surplus production was substantially lower in 2010 and 2011 than from 2006 to 2009 (Fig. 9). Total biomass increased annually from 2006 to 2009 but declined in 2010 and 2011 (Fig. 10).

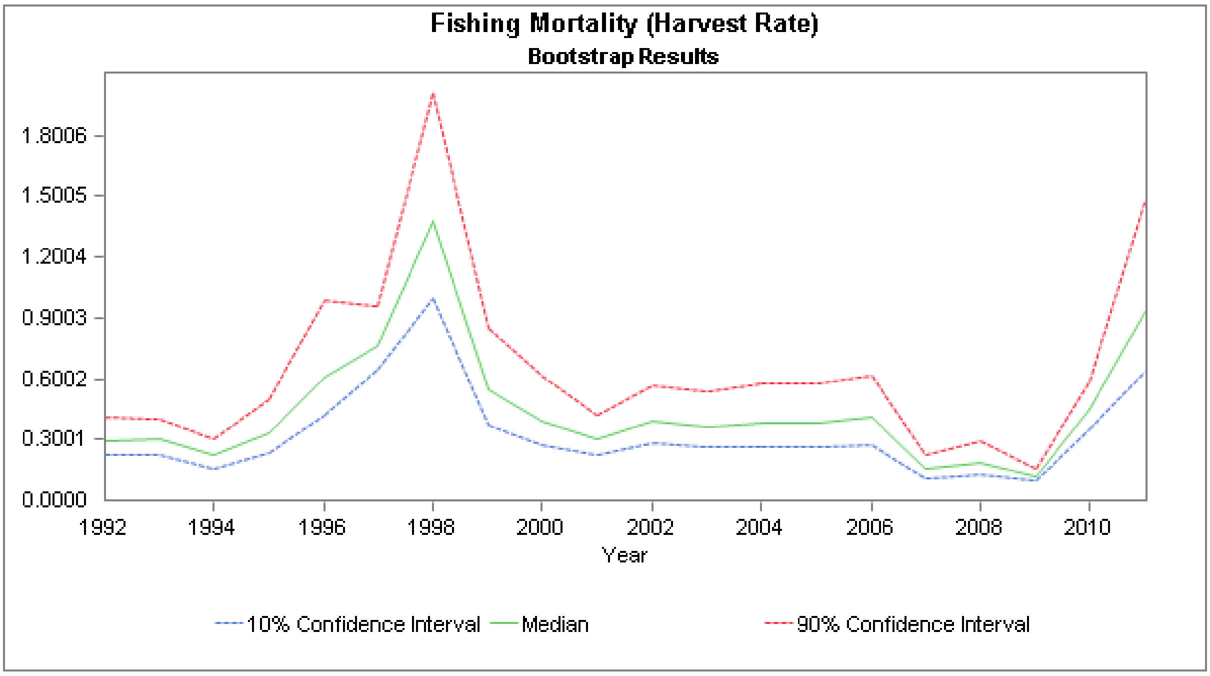

Fig. 7. Fishing mortality estimated from harvest rate.

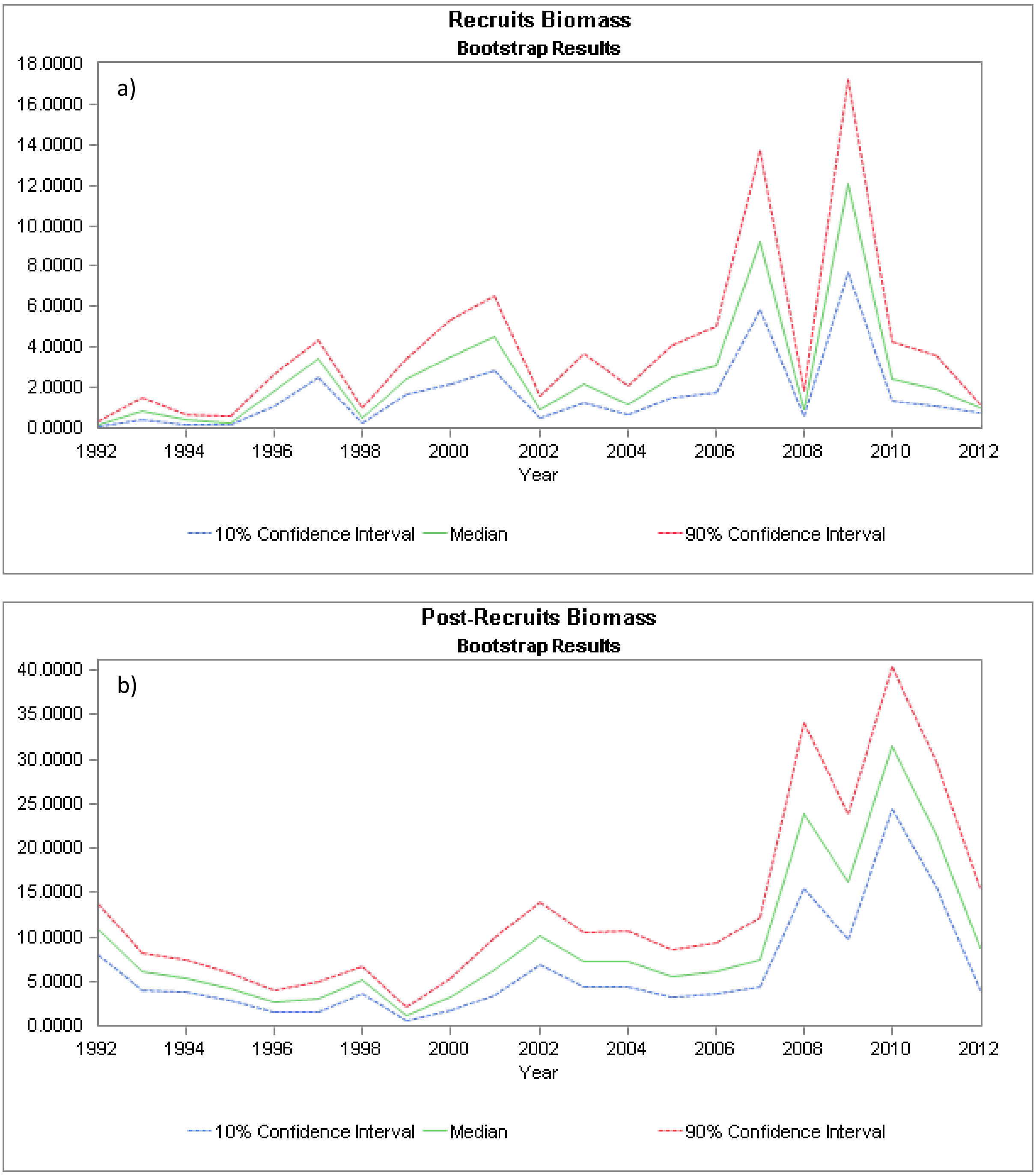

Fig. 8. Recruit biomass (a) and post-recruit biomass (b).

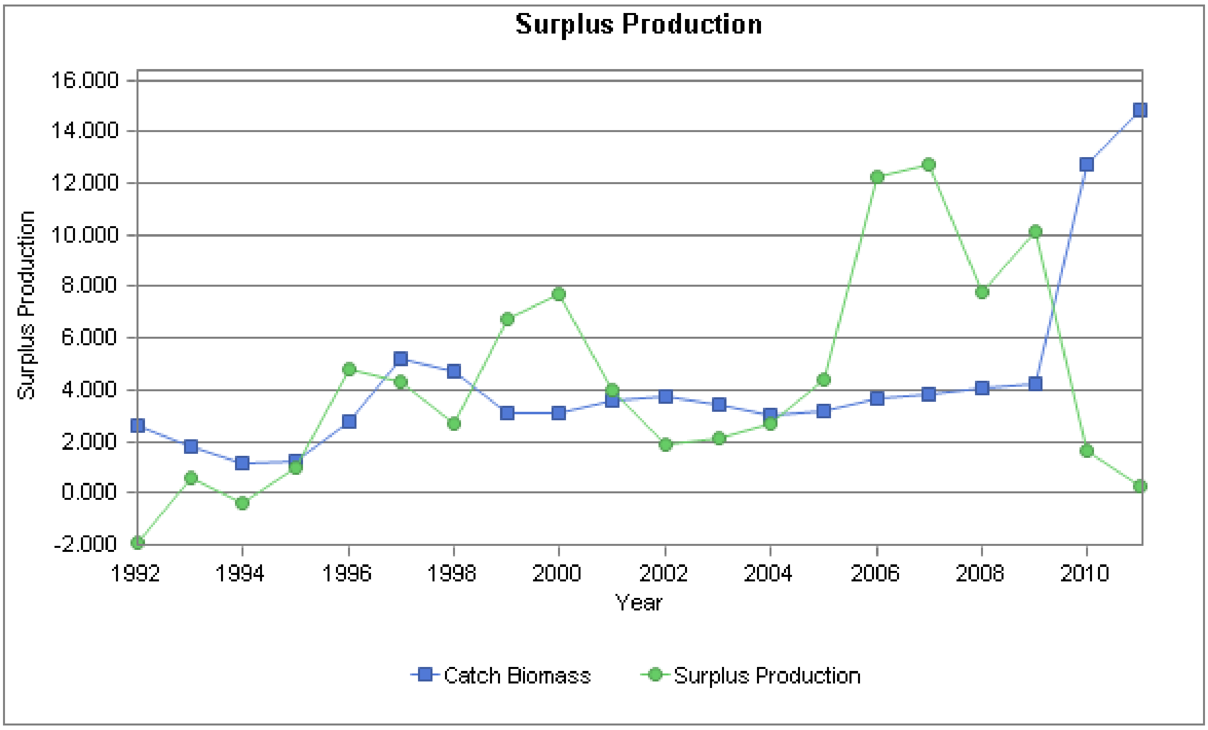

Fig. 9. Catch biomass and surplus production (1000s tonnes).

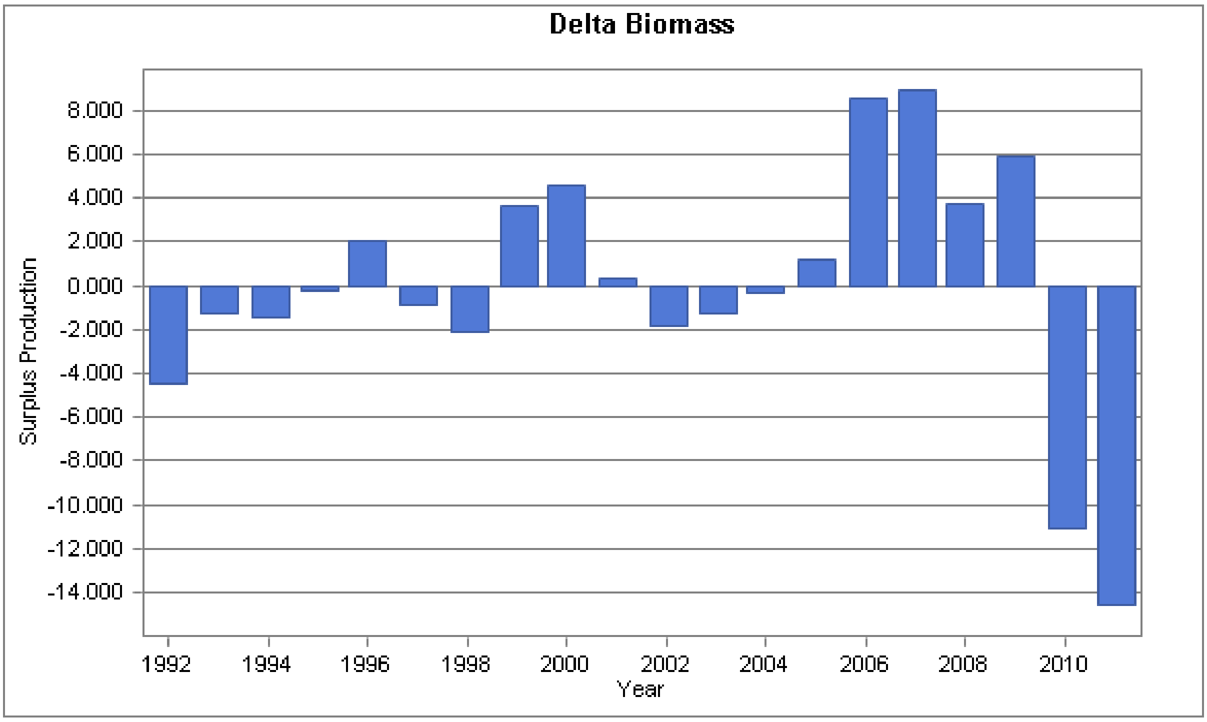

Fig. 10. Annual change in total biomass.

4. Discussion

4.1 Abundance indices

When scallop surveys commenced around the Isle of Man in 1992 queen scallop abundance was around seven times lower than in May 2011 and remained at this low level until 1999. Landings declined steadily between 1983 and 1992. However, relatively low exploitation levels during the past decade have allowed abundance to increase from the low levels observed in the past. The reason for the long period of low abundance is unclear but one possibility is that successful reproduction is dependent on the presence of queen scallops at a particular density as a result of Allee effects (Gascoigne *et al*., 2009). Scallop egg fertilisation success is likely to be higher when adults are present at higher densities (Stokesbury and Himmelman, 1993; Claereboudt, 1999). Therefore, maintaining sufficient densities in at least some areas may be important to the fertilization, recruitment and long-term viability of the fishery.

The apparent increase in abundance of post-recruits between 2011 and 2012 needs to be interpreted with caution as this increase is driven largely by increases at Laxey and Ramsey, which are not major fishing grounds. Furthermore, landings from outside of the territorial sea will not be reflected in the survey indices over the short-term. Consequently, CSA model estimates show declines in biomass and abundance in contrast to the survey indices.

4.2 Impact on benthic habitats

In addition to the direct impact on the target species there are secondary effects that could lead to reduced larval settlement in the future. Trawling is generally considered to be less damaging to benthic habitats than dredging (Kaiser *et al*., 2006). Consequently, the queen scallop dredge fishery failed to achieve MSC certification due to its impact on benthic habitats (Andrews *et al*., 2010). Of particular relevance to the fishery is the fact that the habitats that support queen scallops may be damaged by excessive fishing activity. For example, there is a positive relationship between the presence of macroalgae and maerl and the abundance of juvenile scallops (Howarth *et al*., 2011) and *Aequipecten opercularis* have been found to settle on bryozoans and hydrozoans (Lambert *et al*., 2011). Within the territorial sea the greatest increase in effort is in the trawl fishery, while over the wider area dredging constitutes a much greater proportion of the area of seabed swept and landings. At fishing intensities prior to 2010 benthic conditions were clearly suitable to allow large settlement of queen scallop larvae, as evidenced by the increase in abundance. Therefore, this level of fishing activity may provide an indicator of an appropriate, sustainable, level of fishing in relation to benthic habitats.

4.3 Stock assessment

The CSA model was robust to changes in parameters *s* and *M* in terms of the trends in biomass and fishing mortality. However, the absolute values of the model outputs were susceptible to different values of the input parameters. Increasing *M* resulted in much higher total biomass estimates (Murray and Kaiser, 2012). This would suggest that there has been a large standing stock since 2000. The dependence of the fishery upon scallops recruiting to the fishery in their second year of growth (Vause *et al*., 2007) indicates that this is not the case unless *M* is unusually high for queen scallops over 2 years old. *Pecten maximus* have been found to become increasingly resistant to *Cancer pagurus* predation with increasing shell size, particularly once they reach 60 mm shell length (Lake *et al*., 1987); a similar relationship is likely to occur for *A. opercularis* and its predators. Discarded *A. opercularis* were also found to have high survival rates following fishing (Montgomery, 2008; Nall, 2011). Increasing *s* to 0.48 had a similar effect to increasing *M*, with higher biomass estimates, while decreasing *s* resulted in lower biomass estimates; these lower estimates lead to very high estimates of *F* (Murray and Kaiser, 2012).

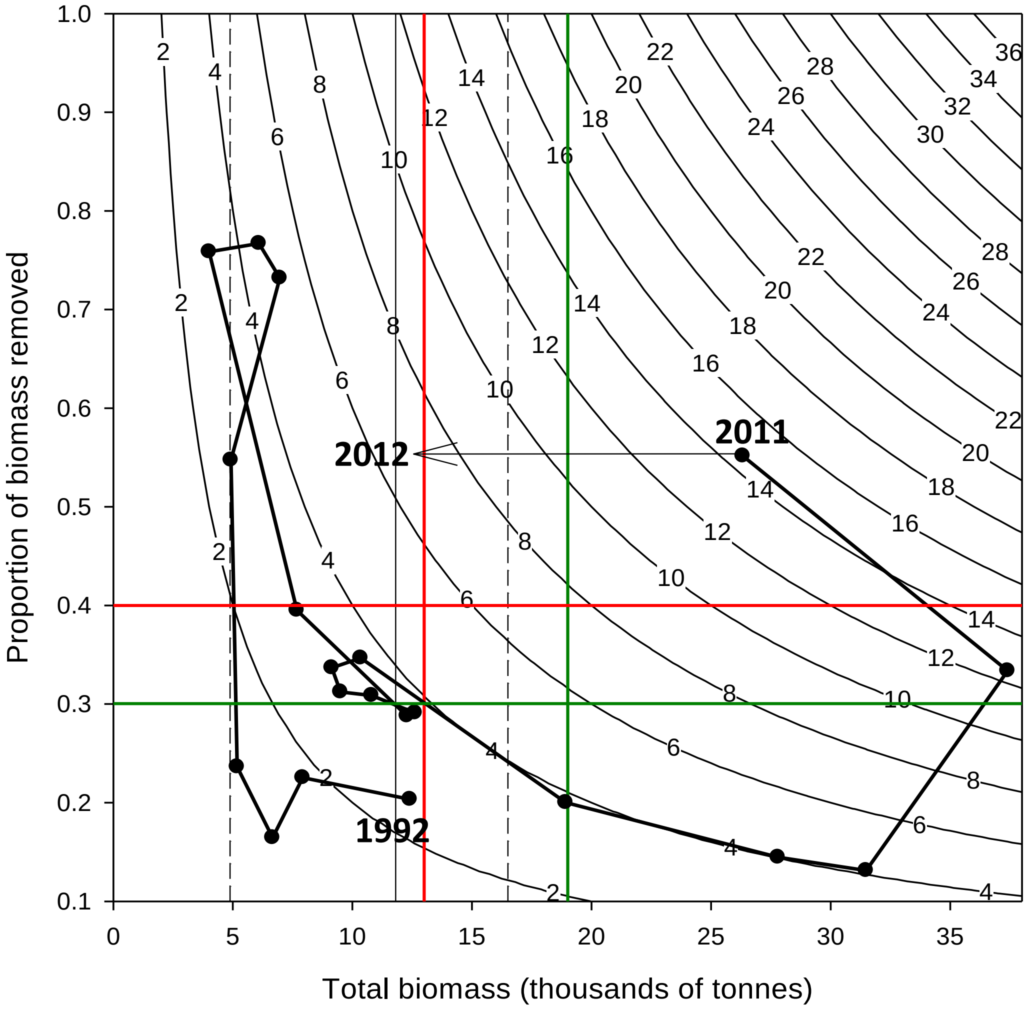

Fig. 11. Landings in thousands of tonnes (contours) at different levels of total biomass and proportion of biomass removed. Solid points and connecting line indicate actual landings at modelled total biomass, and the proportion of biomass those landings are equal to, for each year from 1992 to 2012. Green lines indicate recommended minimum biomass and maximum proportion of biomass removed; red lines indicate recommended critical levels of biomass and proportion of biomass removed;. Solid vertical line shows estimated mean biomass in May 2012 with dashed lines indicating 10% and 90% confidence limits.

With total biomass of 13000t and around 30% or more of biomass removed annually the fishery has experienced both increases and decreases in total biomass, reflecting the fishery's dependence on annual recruitment. Therefore, 13000t is recommended as a critical minimum biomass. Furthermore, at higher total biomass, of 19000t, there is no evidence that the population reached carrying capacity so there is a strong case for maintaining biomass at this higher level. In terms of setting an appropriate threshold for the biomass removed it is clear that removing much more than 30% of biomass increases the risk that biomass will be depleted. By comparison, in the Patagonian scallop fishery the TAC is set at 40% of biomass (Morsan *et al*., 2012) broadly in line with the critical threshold identified for the Isle of Man fishery. However, in the Isle of Man queen scallop fishery, where 40% or more of biomass has been removed there has been no major annual increase in biomass. Given the discrepancy between the abundance index and biomass estimates for 2012 it may be appropriate to take the upper confidence interval limit as the biomass estimate; removing 30% of biomass would then allow landings of 5000t from the two ICES statistical rectangles. This would be substantially lower than in the past two years. To facilitate management of the fishery allocating a proportion of these landings to the territorial sea may be beneficial. In recent years around 50% of landings have been taken within the territorial sea.

These thresholds are subjective but can be used by fisheries managers as a guide in implementing management measures for the fishery. Furthermore, the combination of low total biomass and the removal of a high proportion of biomass must be interpreted as a high risk strategy for the fishery and will sustain only low annual landings. Biomass was still relatively high in May 2011 but high landings in the year since have depleted biomass. The possibility of under-fishing must also be considered. This could lead to the population reaching carrying capacity, reduced growth rates, a high proportion of senescent scallops in the population, and higher natural mortality rates. However, given the recent depletion of biomass and high level of landings this is not of immediate concern. Furthermore, the current fleet has the capacity to increase fishing effort very quickly as evidenced by the increase in fishing effort between 2009 and 2010.

It is important to note the increase in biomass in the fishery occurred following a period of three years when landings exceeded surplus production and was followed by several years of strong recruitment. Therefore, there are clearly variables other than fishing effort that will influence the success of the fishery including environmental variables and fishing activity outside of the stock assessment unit. We have not attempted to identify reasons for this period of strong recruitment in this report, although this will form the basis of future work. Thus at present fishing effort thresholds are recommended to prevent the depletion of biomass. Despite its dependence on scallops recruiting in their second year of growth, the fishery has been resilient to collapse. There are several areas where further work can help to verify or improve data quality. Aspects which can be easily refined with additional work include gear selectivity and recruit abundance, through beam trawling. The abundance index could also be improved by including additional sampling stations to ensure the index is truly representative of the stock size. And further work to establish the appropriate stock assessment unit is also a priority. Queen scallops within the Irish Sea are generally thought to consist of a single stock (Beaumont, 1982; Macleod *et al*., 1985). Therefore, ideally, the Irish Sea fishery would be managed as a single stock with management advice provided based on data collected across the Irish Sea.

4.4 Wider-scale issues

Recruitment of queen scallops can be highly variable. As well as numerous environmental variables that may affect the reproductive success and mortality of queen scallops there have been many changes in the fishery itself. The fishing gear used to target queen scallops has changed over time and dredgers and trawlers are potentially targeting different sizes of scallops. The impact of the various fishing gears on benthic habitats is different and catchability of queen scallops varies between gears (Hinz *et al*., 2009). Catchability of queen scallops is also temperature dependent (Jenkins *et al*., 2003). Management of the fishery has changed substantially during the past year. The introduction of closed areas, increasing minimum landing size (to 50 mm) and a closed season will all impact on the queen scallop populations. The accuracy of historical landings data is unknown but is almost certainly subject to large errors. Therefore, a great deal more research over many years is needed. Nevertheless, there is sufficient information to allow the fishery to be managed to sustain or increase yields; preventing depletion of queen scallop biomass will be essential to achieving this.

5. Conclusions

- Fishing mortality was higher in 2011/2012 than at any other time since 1998 and depleted total biomass between 2010 and 2011 by 14000t.
- Present levels of exploitation appear to be unsustainable and are likely to lead to low levels of total biomass within the next year.
- Depletion of total biomass will render the fishery heavily dependent on annual recruitment.
- It is recommended that the maximum proportion of biomass removed from the fishery is no more than 0.3, and that biomass of the stock is maintained at >19000t.
- For the 2012/2013 fishing year a precautionary limit on landings from ICES statistical rectangles would be approximately 5000t.
- Alternative management measures, such as closed areas, will help to limit the environmental impact of the current high levels of fishing effort.
- Further work is required to understand the relationships between environmental variables and the reproductive success of queen scallops.
- CSA is well-suited to the data available from the queen scallop fishery. Improving, or verifying, the quality of input data will be the focus of ongoing research.
- Further work is needed to define the most appropriate stock assessment unit.

6. References

Allison, E.H. (1993). The dynamics of exploited populations of scallops (*Pecten maximus* L.) and queens (*Chlamys opercularis* L.) in the North Irish Sea. Ph.D thesis, University of Liverpool, pp254.

Andrews, J.W., Brand, A.R. and Holt, T.J. (2010). MSC Assessment Report for Isle of Man Queen Scallop Trawl and Dredge Fishery. Client: Isle of Man Government. Version: 1 Client Draft. Moody Marine Ltd, Derby. pp147.

Bangor University/DEFA (2011). Queen scallop, *Aequipecten opercularis*, fishery action plan. Bangor University/DEFA. pp8.

Beaumont, A.R. (1982). Geographic variation in allele frequencies at three loci in *Chlamys opercularis* from Norway to the Brittany coast. *Journal of the Marine Biological Association of the United Kingdom*, 62:243-261.

Beukers-Stewart, B.D., Mosley, M.W.J. and Brand, A.R. (2003). Population dynamics and predictions in the Isle of Man fishery for the great scallop, *Pecten maximus* (L.). ICES Journal of Marine Science, 60:223-241.

Brand, A.R. (2006). The European scallop fisheries for *Pecten maximus*, *Aequipecten opercularis* and *Mimachlamys varia*. pp991-1058. In: Scallops: Biology, Ecology and Aquaculture. Shumway, S.E. and Parsons, G.J. (Eds). Elsevier.

Cadrin, S.X. (2000). Evaluating two assessment methods for Gulf of Maine Northern shrimp based on simulations. *Journal of Northwest Atlantic Fisheries Science,* 27, 119-132.

Cadrin, S.X., Clark, S.H., Schick, D.F., Armstrong, M.P., McCarron, D. and Smith, B. (1999). Application of catch-survey models to the Northern shrimp fishery in the Gulf of Maine. *North American Journal of Fisheries Management*, 19, 551-568.

Claereboudt, M. (1999). Fertilization success in spatially distributed populations of benthic free-spawners. A simulation model. *Ecological Modelling*, 121, 221-233.

Clarke, K.R. and Gorley, R.N. (2001). PRIMER v5: User Manual/Tutorial. PRIMER-E, Plymouth, pp91.

Collie, J.S. and Kruse, G.H. (1998). Estimating king crab (*Paralithoides camtschaticus*) abundance from commercial catch and research survey data. In: Jamieson, G.S., Campbell, A. (eds). Proceedings of the North Pacific symposium on invertebrate stock assessment and management. *Can. Spec. Pub. Fish. Aquat. Sci*., 27, 193-226.

Collie, J.S. and Sissenwine, M.P. (1983). Estimating population size from relative abundance data measured with error. Canadian Journal of Fisheries and Aquatic Sciences, 40, 1871-1879.

Gascoigne, J., Berec, L., Gregory, S. and Courchamp, F. (2009). Dangerously few liaisons: a review of mate-finding Allee effects. *Population Ecology*, 51:355-372.

Hinz, H., Murray, L.G. & Kaiser, M.J. (2009). Comparison of catch efficiency between the RV' Prince Madog' and the scallop trawler 'Genesis'. Fisheries & Conservation report No.6, Bangor University. pp 14. URL: http://pages.bangor.ac.uk/~oss801/welcome_files/webreports/6.pdf

Hinz, H., Murray, L.G., Gell, F., Hanley, H., Horton, N., Whiteley, H. and Kaiser, M.J. (2010). Seabed habitats around the Isle of Man. Fisheries & Conservation report No. 12, Bangor University. pp.29.

Hinz, H., Murray, L.G., Malcolm, F.R. and Kaiser, M.J. (2011). The environmental impacts of three different queen scallop (*Aequipecten opercularis*) fishing gears. *Marine Environmental Research*, 73:85-95.

Howarth, L.M., Wood, H.L, Turner, A.P., Beukers-Stewart, B.D. (2011). Complex habitat boosts scallop recruitment in a fully protected marine reserve. *Marine Biology*, 158:1767-1780.

Hutchings, J.A. (1996). Spatial and temporal variation in the density of northern cod and a review of hypotheses for the stock's collapse. Canadian Journal of Fisheries and Aquatic Sciences, 53, 943-962.

Idoine, J. (2006). Status of fishery resources off the Northeastern US. Northern Shrimp. URL: http://www.nefsc.noaa.gov/sos/spsyn/iv/shrimp/. Accessed: 15th March 2012.

Jenkins, S.R., Lart, W., Vause, B.J. and Brand, A.R. (2003). Seasonal swimming behaviour in the queen scallop (*Aequipecten opercularis*) and its effect on dredge fisheries. *Journal of Experimental Marine Biology and Ecology*, 289:163-179.

Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M.C.V., Somerfield, P.J. and Karakassis, I. (2006). Global analysis and prediction of the response of benthic biota to fishing. *Marine Ecology Progress Series,* 311:1-14.

Lake, N.C.H., Jones, M.B. and Paul, J.D. (1987). Crab predation on scallop *Pecten maximus* (L.) and its implication for scallop cultivation. *Journal of the Marine Biological Association of the United Kingdom*, 67:55-64.

Lambert G.I., Jennings S., Kaiser M.J., Hinz H., Hiddink J.G. (2011). Quantification and prediction of the impact of fishing on epifaunal communities. *Marine Ecology Progress Series*, 430: 71-86.

Macleod, J.A.A., Thorpe, J.P. and Duggan, N.A. (1985). A biochemical genetic study of population structure in queen scallop (*Chlamys opercularis*) stocks in the Northern Irish Sea. *Marine Biology*, 87: 77-82.

Mesnil, B. (2003). The Catch-Survey Analysis (CSA) method of fish stock assessment: an evaluation using simulated data. *Fisheries Research*, 63, 193-212.

Mesnil, B. (2005). Catch-Survey Analysis: Assessment Program Documentation. IFREMER, Nantes.

Montgomery, J. (2008). Discarding in the Isle of Man queen scallop, *Aequipecten opercularis*, fishery. M.Sc. thesis, Bangor University, pp. 61. URL: http://www.bangor.ac.uk/~oss801/welcome_files/webreports/d2.pdf

Morsan, E., Cranfield, H.J., Bridi, J., Prenski, L.B., Sánchez De Bock, M.F. (2012). Patagonian scallop (*Zygochlamys patagonica*). Assessment against MSC principles and criteria. Final report. Organización Internacional Agropecuaria.

Murray, L.G., Hinz, H. & Kaiser, M.J. (2009) Marine fisheries research report to DAFF 2007/2008. Fisheries & Conservation report No. 7, Bangor University. pp. 67. URL: http://pages.bangor.ac.uk/~oss801/welcome_files/webreports/7.pdf

Murray, L.G., Hinz, H. and Kaiser, M.J. (2010). Update on *Aequipecten opercularis* stock status and recommended total allowable catch. Report to DEFA. pp12.

Murray, L.G., Hinz, H. and Kaiser, M.J. (2011). Functional response of fishers in the Isle of Man scallop fishery. *Marine Ecology Progress Series*, 430: 157-169. URL: http://www.int-res.com/articles/theme/m430p157.pdf

Murray, L.G. and Kaiser, M.J. (2011) *The Isle of Man Aequipecten opercularis fishery*. Research update 2011. Fisheries & Conservation Report No. 15, Bangor University, pp21. URL: http://www.bangor.ac.uk/~oss801/welcome_files/webreports/15.pdf

Murray, L.G. and Kaiser, M.J. (2012) The Isle of Man *Aequipecten opercularis* fishery stock assessment, April 2012. Fisheries and Conservation Report No. 16. First draft. Bangor University. pp38.

Nall, C.R. (2011). Survivability of target species discards in the Isle of Man queen scallop (*Aequipecten opercularis*) fishery. M.Sc. thesis, Bangor University. pp62.

NOAA (2008). Collie-Sissenwine Analysis (CSA) v3.1.1. NOAA Fisheries Toolbox. NOAA's National Marine and Fisheries Service. URL: http://nft.nefsc.noaa.gov/CSA.html. Last accessed 20th March 2012.

Patterson, K., Cook, R., Darby, C., Gavaris, S., Kell, L., Lewy, P., Mesnil, B., Punt, A., Restrepo, V., Skagen, D.W. and Stefánsson, G. (2001). Estimating uncertainty in fish stock assessment and forecasting. Fish and Fisheries, 2: 125-157.

Stokesbury and Himmelman (1993). Spatial distribution of the giant scallop *Placopecten magellanicus* in unharvested beds in the Baie des Chaleurs, Québec. *Marine Ecology Progress Series*, 96: 159-168.

Vause, B.J., Beukers-Stewart, B.D. and Brand, A.R. (2007). Fluctuations and forecasts in the fishery for queen scallops (*Aequipecten opercularis*) around the Isle of Man. *ICES Journal of Marine Science*, 64: 1124-1135.