Boom not bust: Cooperative management as a mechanism for improving the commercial efficiency and environmental outcomes of regional scallop fisheries

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Abstract

The environmental impacts of food production are increasingly influencing consumer's food choices. To maintain market access in this context, the fishing industry must adopt strategies and technologies that reduce their carbon emissions, environmental footprint, bycatch and seabed impact. In this study, closure of a depleted scallop fishing ground, to enable stock recovery, coupled with a transition to a cooperative management system, based on territorial user rights, promoted fishers to make management decisions that have improved the environmental outcomes and economic efficiency of this fishery. Innovative cooperative management systems like territorial user rights that decentralise decision making and provide users rights to a defined fishing area, could help mitigate against the negative impacts and issues traditionally associated with scallop dredge fisheries, and help maintain both stock biomass and consumer demand in a market increasingly dominated by sustainably certified food products.

Key words: Scallops, TURFs, GHG Emissions, LPUE

1. Introduction

Bottom-towed fisheries account for 25% of global seafood landings. Of these, scallop (Pectinid) fisheries make an important contribution with 632,000 t landed, worth $US 1,579 million in 2017 (FAO 2018, 2019). Despite their economic and food security relevance, many scallop fisheries lack the robust management regimes required to regulate effort and landings (Stewart & Beukers-Stewart, 2009), and this is especially true of most European scallop fisheries as they are not an EU-regulated quota species. In the absence of biologically referenced fishing effort and harvest limits the habitat specificity and sessile nature of scallops makes them vulnerable to over fishing (Stewart & Howarth 2016) and can result in significant decreases in catching efficiency and profitability (e.g. reported reduction in landings per unit effort in the United Kingdom, Curtis et al. 2017).

The environmental impacts of scallop dredge fisheries on the seabed are well documented and result in reduced habitat complexity, habitat fragmentation, loss of biodiversity and reduced ecosystem functioning of marine seabed habitats (e.g. Thrush & Dayton 2002; Kaiser et al. 2006; Hiddink et al., 2017). The nature and extent of these impacts are dependent on the physical characteristics of the seabed, the specific gear type, and the composition of the benthic communities (e.g. Collie et al. 2000; Bradshaw et al. 2001; Thrush & Dayton 2002; Kaiser et al. 2006; Hughes et al. 2014; Hiddink et al. 2017). Hiddink et al. (2017) estimated that bottom-towed fishing gears remove 6 – 41 % of faunal biomass per pass with average post-trawl recovery times of 1.9 – 6.4 years, depending on the fishery and environmental context. As scallop fisheries increase fishing intensity, this will correspondingly increase their ecological 'footprint' on the seabed and the recovery period for seabed biota in relation to the frequency of past trawling impacts and the recovery rates of the biota present (Lambert et al. 2011, 2017; Hiddink et al. 2017; Kaiser et al. 2018). Furthermore, future scallop spat settlement and recruitment success may be linked to the presence of benthic biota that act as settlement substrata, thus the fishery has the potential to significantly limit its own long-term sustainability if the impact of benthic biomass removal is not managed appropriately (Lambert et al. 2011).

Direct impacts on the seabed are not the only concern associated with declining productivity of scallop fisheries. Commercial fisheries, which rely heavily on the use of fossil fuels, are known to be a significant contributor to global CO_2 emissions (e.g. Greer et al. 2019; Parker & Tyedmers, 2015; Parker et al. 2018; Tyedmers, 2004) equating to 2-3% of the total emissions from global food production in 2016; Mbow et al. 2019). Inefficient fishing practices (for example scallop vessels targeting low density scallop beds) leads to greater average CO_2 emissions per tonne of target-species landed. This is an emerging pattern which has developed in recent years in commercial fishing across the globe (e.g. Parker et al. 2018). As with other food production industries, commercial fisheries are required to take action to reduce Greenhouse Gas (GHG) emissions following the ratification of the Paris Agreement in 2015, which aims to keep global warming optimally under 1.5 °C (UNFCCC, 2015; Rogelj et al. 2016). This is particularly relevant to scallop dredge fisheries that already have a poor public perception for environmental impacts. Since fuel is a major expense in fishing industry business models (e.g. Parker & Tyedmers, 2015), as well as CO_2 emissions from fuel use representing a major externalised cost to the environment, lower carbon fisheries represent a motivating win-win opportunity for commercial fisheries (Greer et al. 2019).

Globally, the centralised top-down governance of fisheries and conventional input controls have proven inadequate in resolving many issues associated with modern exploitation of fisheries resources (e.g. Pauly et al. 2003; Grafton et al. 2006), particularly on a local scale. Without robust limits on access, effort or the allocation of individual rights to the fishery resource or area, fishers are incentivised to compete in a short-term 'race to fish' (e.g. Tragedy of the commons; Hardin 1968) rather than investing in protecting species and habitats for longer-term sustainability (e.g. Berkes et al. 2001) and reducing wider environmental impacts, such as GHG emissions. By contrast, bottom-up decentralised or co-management governance systems, where management decisions are delegated to local communities or fishers' organisations (e.g. Berkes et al. 2001, Lubchenko et al. 2016), seem to be proving their effectiveness as fishery management tools, especially for sessile or sedentary species (Gelcich et al. 2012; Nguyen et al. 2017). This includes the use of rights-based management systems that can promote incentives for fishers to protect and invest in the resource. Examples of such systems include Individual Quotas (IQs) or Individual Transferable Quotas (ITQs), which provide licenced individuals with a share of the total allowable catch (TAC), and Territorial User Rights Fisheries (TURFs), which provides user rights within a defined fishing area.

Territorial user rights fisheries (TURFs) are a form of rights-based management (RBM) system that is decentralised and allows for a more complete conveyance of property/resource rights to members by defining harvesting access within a defined fishing area. Self-governing associations or organisations are usually established for TURFs with the role of managing and protecting the resources within the fishing area, deciding on allocation of resources to its members and ensuring compliance with regulations (Liu and Qin, 2018). A TURF can therefore provide a suitable context for fishers to adopt management measures that promote economic and harvesting efficiency, encompass ecosystem based management (EBM) and enhance economic viability through stock security, whilst simultaneously eliminating the 'race to fish' found in many open-access fisheries (e.g. Berkes et al. 2001). For scallop dredge fisheries, a move towards TURFs may incentivise fishing behaviours that consider the wider ecosystem and fleet economic efficiency, which is timely given the current increasing economic and environmental concerns related to scallop fisheries. This type of rights-based cooperative approach has been previously conceptualised for the Atlantic Sea Scallop fishery as a means of incentivising rational and sustainable management (Baskaran and Anderson, 2005).

Territorial user rights fisheries (TURFs) are the focus of this paper, which quantitatively evaluated the performance of a fishery management experiment within the *Pecten maximus sc*allop fishery of the Isle of Man (Irish Sea). This opportunity arose when one of the fishing grounds within the wider scallop fishery had been fished to commercially unviable levels under the *status quo* management system. This ground was closed for three seasons to enable stock recovery, and then re-opened as a TURF located within a multi-zoned marine protected area (MPA). Both the TURF and the remaining fishing grounds within the RCA fishery were monitored for a range of performance indicators including commercial (i.e. landings per unit effort; LPUE) and environmental (i.e. greenhouse gas (GHG) emissions and area of seabed impacted per tonne of live shell weight (LSW) of scallops landed). In this way we assessed to what extent the TURF had improved the environmental and economic efficiency of scallop dredge fishing.

2. Methods

2.1 Fishery

The Isle of Man (IoM) is situated in the northern Irish Sea (ICES Statistical Areas VIIa). A dredge fishery for king scallops operates within the IoM's territorial sea (TS) (0-12 M; ≈3998 km^2) with six distinct king scallop fishing grounds ranging in depth from 10 – 95m (Figure 1). Individual grounds represent permanent scallop beds that are known to recruit annually and are delineated as discrete fishing areas determined from historical spatial fishing activity and habitat discrimination. All grounds within the TS have typically been considered as a single management unit.

The main king scallop fishery is permitted under licence within the 12 M territorial limit with gear and quota restrictions, a minimum landing size (MLS) and temporal restrictions used for finer-scale management (Table 1); this *status quo* management system will be referred to hereafter as Regulated Continuous Access (RCA). The Isle of Man Government has sole jurisdiction for fisheries management within the 0 – 3 nm territorial limit (Figure 1), which provided the necessary legal flexibility to trial co-management of a rights-based inshore fisheries within Ramsey Bay (RAM), which falls entirely within the 0-3 nm limit. This novel management system will be referred to hereafter as the territorial user rights fishery (TURF).

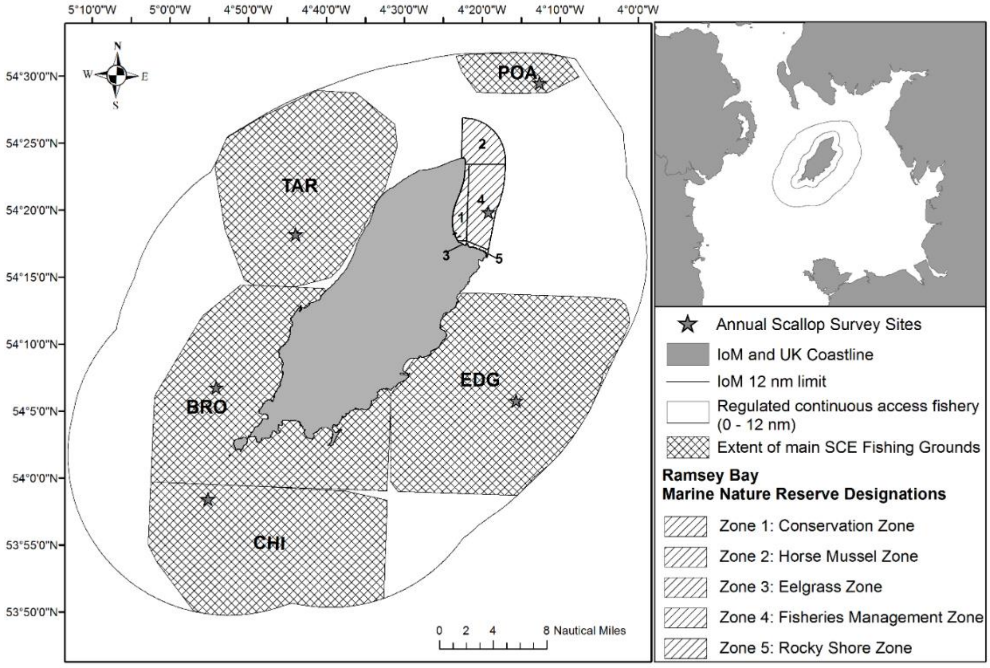

Figure 1: The Isle of Man is situated in the Irish Sea between Ireland and the United Kingdom. Ramsey Bay Marine Nature Reserve (MNR) is situated off the north-east coast of the island. The MNR consists of five zones with different levels of protection. The Fisheries Management Zone (Zone 4; FMZ) has relatively low protection and is managed under a fisheries agreement. The Ramsey Bay fishery occurs exclusively within the FMZ and is delineated from the RCA fishery by the MNR boundary. The outer extents of the five main fished grounds from within the RCA fishery (0 – 12 nm) that are used for comparison are indicated on the map by the hatched areas. CHI: Chickens in the south; BRO (BRA): Bradda in the south/south-west; TAR: Targets in the west; POA: Point of Ayre in the north and EDG: East Douglas in the east. Eleven historic annual scallop survey stations were established in 1992 with one located in each of the six main king scallop fishing grounds, grey stars indicate the location of these survey stations.

Table 1: Management measures and restrictions associated with the RCA king scallop fishery in the Isle of Man territorial sea.

Management Measure	Specification
Open season	1st November to 31st May
Engine power	≤ 221 kW (or grandfather rights)
Dredge width	25 feet (7.62 m) in 0-3 M 35 feet (1.067 m) in 3-12 M
Minimum landing size	110 mm
Daily curfew	18:00 – 06:00
Closed areas	Permanent and Temporary
Total allowable catch	2017/2018 season onwards (variable annually)
Number of 0-12 nm licences	94 as of 2016/2017

Ramsey Bay (RAM), which was historically a productive fishing ground and is likely to be self-recruiting, was closed to fishing in December 2009 for three fishing seasons to enable stock recovery following a period of intense overfishing. In October 2011 RAM was designated as a marine nature reserve (MNR), with five zones covering an area of 94.5 km^2 (Figure 1) protecting priority habitats including horse mussel reef and maerl beds. The MNR also forms one of the core zones of the UNESCO Biosphere Isle of Man. Whilst four of the zones were closed to mobile fishing gear, a fifth zone was designated a fisheries management zone (FMZ) (47.5 km^2) under a TURF management system. The TURF provided user rights to a limited group of local fishers to harvest king scallops from the area. Eligible participants had to be members of the Manx Fish Producers Organisation (MFPO) and hold an active scallop entitlement for the RCA fishery. The number of TURF fishers gradually increased from 27 to 33 over the study period. During the closure period RAM was monitored with annual scientific surveys to monitor stock recovery and by 2013 it was considered to have increased to commercially viable levels. Ramsey Bay was then opened as a TURF under an initial five-year agreement (2013 – 2018), which has since been extended. Users were given responsibility for strategic decisions on where, when and how much to fish, whilst ensuring that the 'ecological integrity' of the area was maintained. Although not formally defined, ecological integrity has been assessed via regular habitat monitoring and by the size and age structure of the scallop stock within the FMZ. Enforcement within the TURF was primarily overseen and administered by its members but with Government support should legal proceedings be required. All fishers involved in the TURF also had access to the wider RCA fishery as well.

The establishment of a TURF for fishermen belonging to the MFPO provided the basis and security of tenure required to introduce positive management measures for sustainable fishing, including: limited harvest (TAC) and effort; a limited fishing season to promote habitat recovery (i.e. 1 – 3 week fishery in Ramsey Bay); timing the fishery to achieve maximum profitability (opening around the more valuable Christmas period); cooperative fishing (i.e. reducing the number of individual vessels fishing and the distance steamed) and pre-fishery surveys to enable fishing to be targeted on high-density areas while allowing lower-density areas to remain unfished for recovery. The latter strategy increases harvesting efficiency and lowers fuel use and gear impacts on the seabed. The TURF has also provided the context for members to limit harvesting so that the scallop population (size and age) structure is maintained, providing a buffer against recruitment failure in a single year and creating the basis for a longer-term sustainability of the fishery. The spatial extent and location of the fishable area and total allowable catch (TAC) within the FMZ is calculated on the basis of stock biomass, which in turn is based on a detailed annual survey carried out by the MFPO, funded by a single TURF-share retained and administered by the MFPO itself. This is in direct contrast to the recruit-driven 'boom and bust' fishery that existed in Ramsey Bay prior to the closure in 2009, and essentially still exists in the wider RCA fishery. From an economic perspective, restricted access to Ramsey Bay negates the general 'race to fish' attitude and empowers fishers to make more rational, longer-term decisions that focus on increasing harvesting efficiency and economic benefits, and maintaining relatively high stock levels, rather than harvesting all available resources as quickly as possible in a 'tragedy of the commons' approach. This enables the fishery to be maintained at high density and catch rates (boom) but with sustainable levels of effort (i.e. reduced relative to current RCA levels) so as not to cause significant intra or inter-seasonal depletion (bust).

2.1 Data collection

Since 1st November 2006 all scallop vessels fishing in the Isle of Man must have a working vessel monitoring system (VMS) collecting positional and instantaneous vessel speed at specified time intervals. Vessels are also required to submit a European Union (EU) logbook record for each fishing activity detailing the landed weight (kg) and value (£) per species. Since 2017 scallop vessels fishing within the Isle of Man must also submit a Daily Catch Return (DCR) with information on the trip landings (kg), fishing location (fished ground), time fished (mins) and gear (number of dredges).

The reporting of Landings per Unit Effort (LPUE) for the Isle of Man RCA and Ramsey Bay TURF has evolved over time and were calculated from Port Erin Marine Laboratory (PEML) logbooks (1983 – 2009); Department of Environment, Food and Agriculture (DEFA) paper logbook records (2007 – 2010); European Union (EU) electronic logbooks (2011 – 2017); DEFA Ramsey Bay Catch Returns (2013 – 2017) and DEFA Daily Catch Returns (2017/2018). Whilst all DEFA and PEML logbooks and returns contain information on hours fished, EU electronic logbooks only report hours at sea and so hours fished were estimated from hours at sea, taking into account typical steaming times and fishing practices based on the observations from vessel monitoring system data (= hrs at sea *0.85).

For consistency, as Ramsey Bay can only be targeted by Isle of Man vessels under 15.7 m length overall, the data used for analysis in this study was first filtered to include only those trips where Isle of Man vessels under 15.7 m were targeting king scallops to ensure comparability between data sets.

2.2 Analytical methods

2.1.1 Fisheries-dependent indicators

Landings per Unit Effort (LPUE) were calculated, as per standard methods, and are expressed in three standardised units dependent on the resolution and variables available for datasets from each time series. LPUE was standardised to scallops per metre of dredge per hour fished (SCE/mDr/hrF) for the long-term time series (1983 – 2019) for comparability with historical values; to tonnes per hour fished (t HrF) for recent seasonal trends (2013-2019); and kg per dredge per hour fished (kg/Dr/hrF) for the most recent fishing season (2017/2018).

Fuel efficiency of Manx dredgers was calculated using logbooks and statistics on fuel consumption. Estimated fuel use (litres) was calculated as 22 litres per hour during fishing and 20 litres per hour during steaming activities using values collated from studies by Walsh (2010) and Dignan et al., (2014).

Fuel intensity ($l\ t^{-1}$) reports the litres of fuel used by a vessel to land a tonne of live shell weight (LSW) scallops and was estimated from the Manx fuel-use data noted above, combined with information from logbooks on the quantity of scallops landed (t) per trip. A density of 0.86 kg/L was used to convert fuel data from litres to kilograms (Xu et al. 2013) for calculation of fuel coefficients for comparability to other fisheries (i.e. kg fuel / kg fish).

2.1.1 Environmental indicators

GHG emissions were estimated for the fishery using information on average speed (derived from satellite-based VMS data) and fuel consumption during different activities (split into steaming and fishing components). Emissions of CO_2, CH_4, and N_2O were estimated using the standard approach of the IPCC Tier 1 method (IPCC 2006) by multiplying the amount of fuel consumed by an appropriate emissions factor (i.e. CO_2 equivalent [CO_2e] emissions factor of 2.67620 kg per litre of combusted diesel). GHG emissions (kg of CO_2e per kg of LSW) were calculated as:

$$GHG\ emissions(\text{kg of CO}_2\text{e per kg of LSW}) = FI\ (l\ per\ kg\ LSW) * 2.67620$$

The amount of seabed impacted by fishing gear for both the RCA and TURF fisheries (i.e. km^2 impacted per tonne of LSW of scallops landed) was calculated for the 2017/2018 fishing season for each fished ground.

$$km^2\ impacted\ per\ tonne\ of\ live\ shell\ weight = \frac{km^2\ impacted\ per\ trip}{tonne\ of\ live\ shell\ weight\ per\ trip}$$

3. Results

3.1: Long-term annual LPUE trends (1982 to 2019)

Historical data (1982 – 2019) on LPUE standardised to scallops (SCE) per metre dredged per hour fished (SCE/Dr m^{-1}/HrF) indicated that prior to December 2009, when RAM was closed, the average annual LPUE for king scallops over the 5 main fished grounds (POA not included here due to limited data) ranged from 12 to 49 SCE/Dr m^{-1}/HrF (1982/1983 – 2009/2010; Figure 2). Following the closure of RAM for three seasons the average annual LPUE for RAM had increased by an order of magnitude in 2013 compared to pre-closure values (12 and 192 SCE/Dr m^{-1}/HrF in 2009 and 2013 respectively; Figure 2). Between 2013 and 2019 the annual average LPUE for RAM ranged from 144 to 192 SCE/Dr m^{-1}/HrF whilst the four RCA grounds ranged from 18 to 91 SCE/Dr m^{-1}/HrF over the same period (Figure 2).

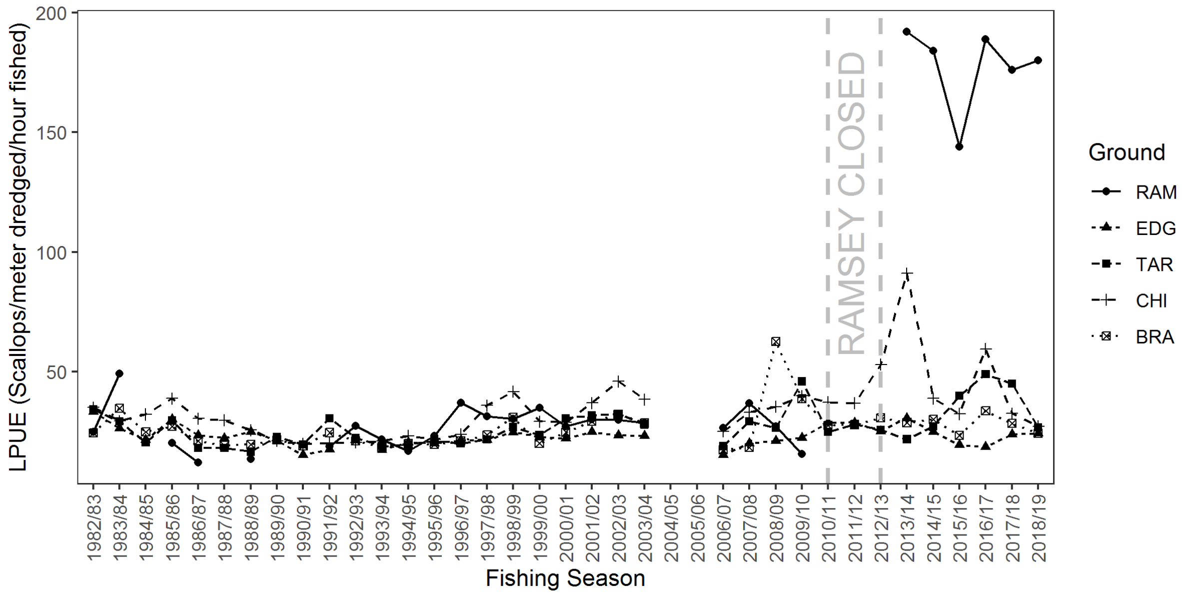

Figure 2: LPUE (Landings per Unit Effort) standardised to scallops per dredge metre per hour fished for each of the main fished grounds (Ramsey Bay = RAM; East of Douglas = EDG, Targets = TAR, Chickens = CHI, Bradda = BRA). It should be noted that prior to 2009 all grounds were part of the RCA fishery. A fishing closure was in place In Ramsey Bay for three full fishing seasons (2010/2011, 2011/2012 and 2012/2013: indicated by vertical dashed grey lines) to allow scallop stocks to recover following depletion. On recovery Ramsey Bay was then managed as a TURF whilst the remaining four grounds continued as part of the RCA fishery. Point of Ayre (POA) was not included in this analysis due to lack of data.

3.2 Recent seasonal LPUE and population trends (2013 – 2019):

Figure 3 illustrates the typical intra-seasonal LPUE pattern (t HrF) within the four main RCA fishing grounds with LPUE starting high at the beginning of the season (November/December) but declining through the remaining months (January – May). The RAM TURF does not exhibit intra-season depletion of LPUE as it is open for less than one month each season (Figure 3). Inter-seasonal variability in the starting LPUE at each ground is also illustrated in Figure 3 for the four main RCA fishing grounds. For the RAM TURF, although LPUE initially declined from the very high levels experienced following the three year closure, in contrast to the RCA grounds the starting LPUE has remained relatively high and stable since 2015 (Season 3) (Figure 3).

The population structure for the five fishing grounds is displayed in Figure 4 with scallop survey sample data from 2013 – 2019, from the historic survey station for each ground (Figure 1), included. In the four main RCA fishing grounds the population structure typically skews towards younger age classes (i.e. scallops below or at the age at which they are considered large enough to recruit to the fishery) with an absence of significant numbers of scallops within the older age classes (Figure 4). The population structure at RAM prior to the closure was also skewed with 80% of scallops sampled in 2008 within the year 2 or 3 age classes. However, following the three-year closure the population structure of sampled scallops in RAM TURF changed with a high proportion of sampled scallops above three years old (age of recruitment for RAM), and in recent years a distribution of individuals of up to 12 years old (Figure 4). Recruitment of scallops is highly variable spatially and temporally and can be inferred from regular surveys of scallop densities at each main ground (Figure 5). High levels of recruitment are evidenced at some sites by peaks in scallop densities in certain years (i.e. CHI and TAR; Figure 5) whilst other sites have relatively stable levels of annual recruitment (i.e. BRA, EDG and POA; Figure 5). In the case of RAM, which prior to 2009 was part of the island-wide RCA fishery, the years when this site was surveyed indicated fairly low densities (~1 scallop per 100 m^2) whilst post-closure densities have been maintained at around ~4-6 scallops per 100 m^2 (except for 2014 when the observed survey density was reduced; Figure 5).

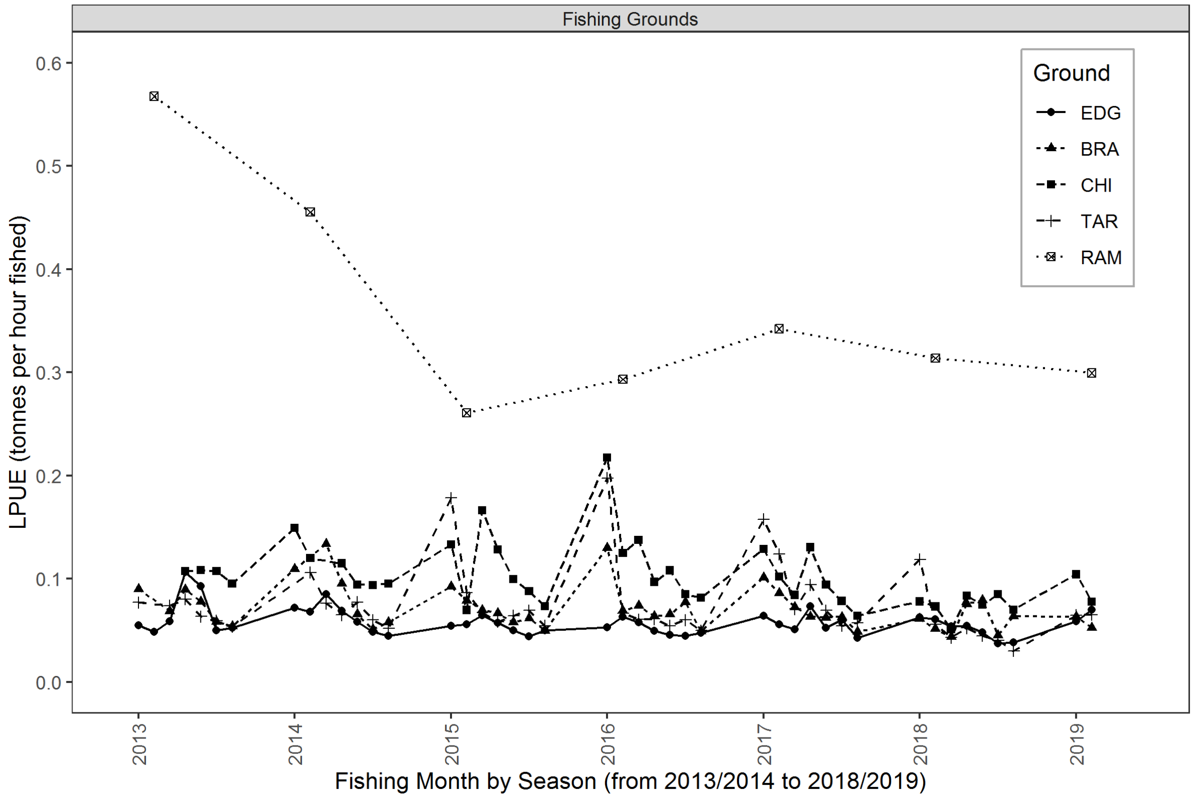

Figure 3: Average monthly LPUE standardised to tonnes per hour fished for each of the five main fished grounds and displayed by month across six fishing seasons (2013/2014 to 2018/2019). The seasons are displayed along the x-axis with data points representing sequential months of the season (each season starts in November Year and finished in May Year^{+1}; RAM (Ramsey Bay) is only fished in one month (December) of each fishing season).

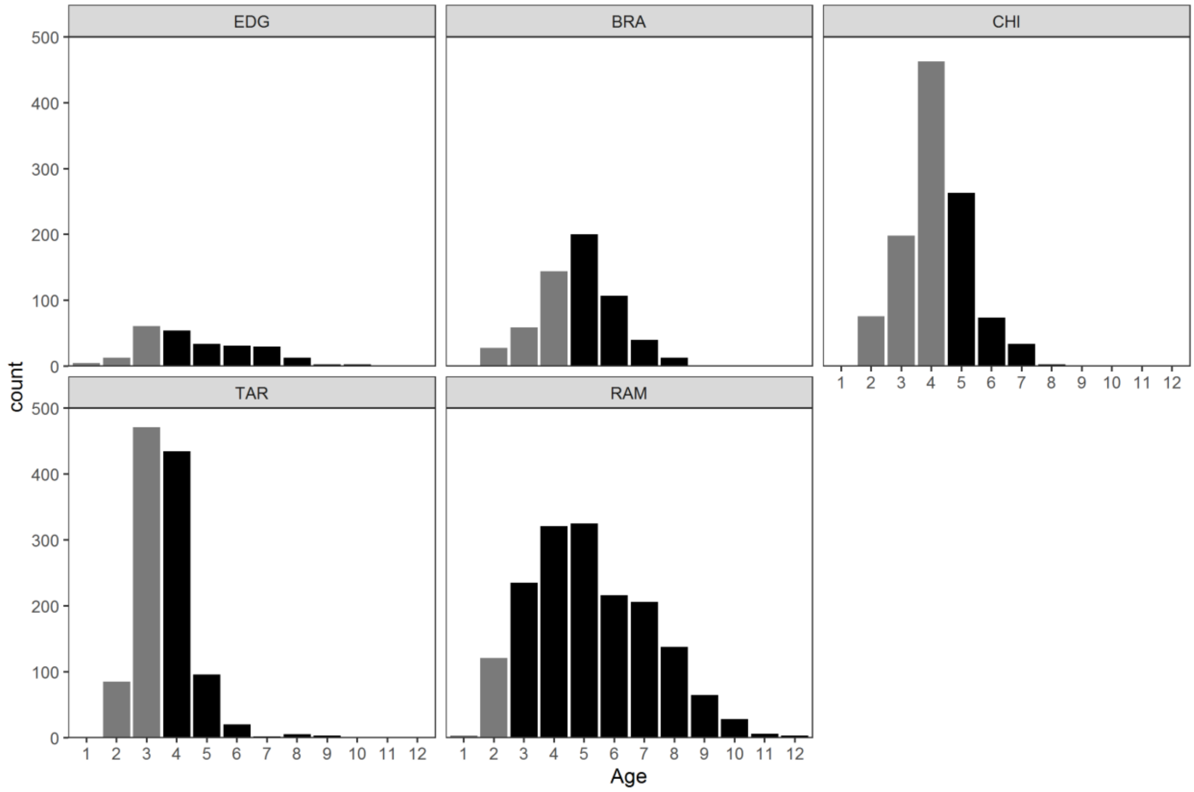

Figure 4: Age frequency distribution for each of the five main fished grounds, using data from the historic survey station within each ground, for the six fishing seasons (2013/2014 to 2018/2019) combined. The grey bars indicate the ages at which scallops within that ground are typically under MLS and the black bars indicate the ages at which scallops within that ground are typically over MLS.

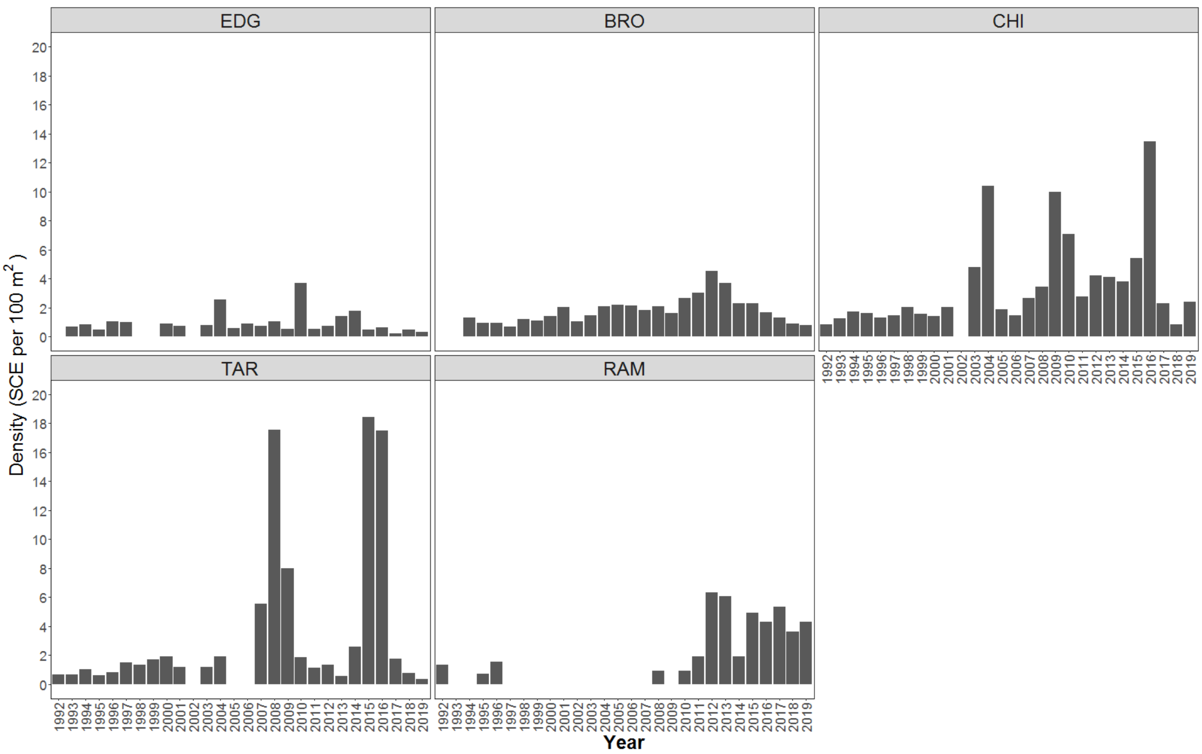

Figure 5: Scallop density per 100 m² from fixed historical stations sampled during the annual scallop survey in the Isle of Man (EDG, BRO/BRA, CHI, TAR, and RAM). Survey data missing at some sites for some years.

3.3: Commercial and environmental indicators (2017/2018 fishing season)

RAM TURF had a mean monthly LPUE of 40 kg/Dr/HrF for the 2017/2018 fishing season with total landings of around 52t. By comparison, three of the RCA fishery grounds had low mean monthly starting LPUE at under 10 kg/Dr/HrF (EDG, CHI, BRA), whilst TAR had the highest mean monthly starting LPUE for the RCA fishery at ~ 17 kg/Dr/HrF. Following total seasonal landings (i.e. all vessels) of 774t the mean monthly LPUE for TAR at the end of the season had dropped to ~ 4 kg/Dr/HrF and by the end of the fishing season all RCA grounds had monthly mean LPUE of less than 5 kg/Dr/HrF (Figure 6).

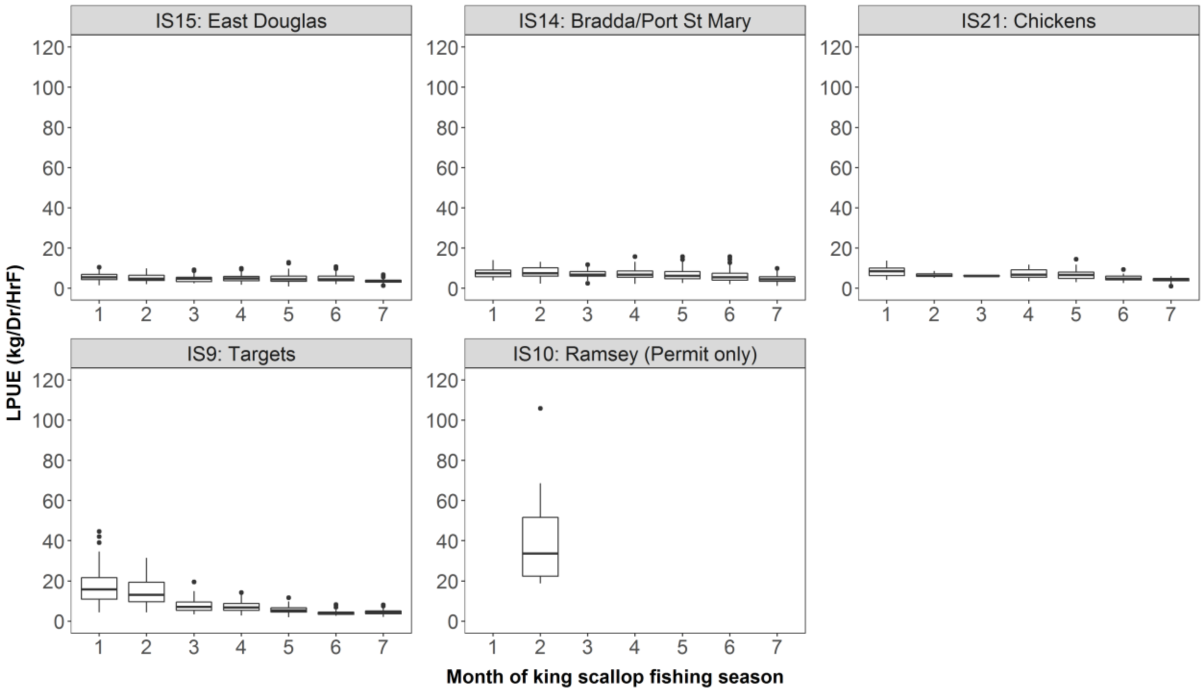

Figure 6: Mean Landings per unit effort (LPUE) standardised to kg per dredge per hour fished (kg/Dr/HrF) displayed by fishing month for the 2017/2018 king scallop fishing season in the Isle of Man territorial sea. The fishing season begins in November each year. Total seasonal landings (i.e. all vessels) were TAR (774 t), CHI (665t), EDG (624t), BRA (561t) and RAM (52t).

Scallop dredge gear impacted around 0.11 km^2 per t LSW landed in the RAM TURF. By comparison, three of the RCA fisheries had relatively high mean monthly starting area impacts of 0.47- 0.73 km^2 per t LSW landed (EDG, CHI, BRA). Whilst TAR had the lowest mean monthly starting area impacts for the RCA fishery at approximately 0.26 km^2 per t LSW landed. By the end of the fishing season all RCA grounds had increased the mean area impacted per tonne of LSW scallops landed to at least 0.86 km^2 per t LSW landed (Figure 7).

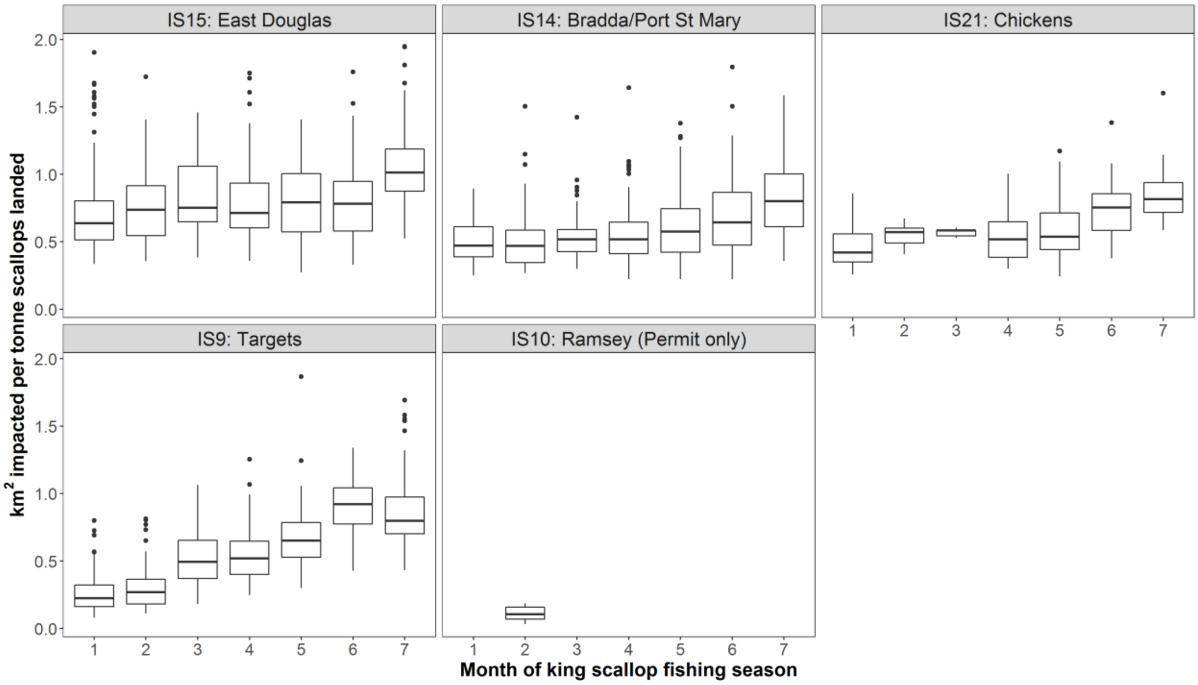

Figure 7: The mean area impacted by scallop dredges per tonne of live shell weight scallop landed (km^2 impacted per t LSW landed) displayed by fishing month for the 2017/2018 king scallop fishing season in the Isle of Man territorial sea.

Mean monthly greenhouse gas emissions within the RAM TURF were 1.73 kg of CO_{2e} kg^{-1} scallop meat. In comparison, three of the RCA fisheries had relatively high mean monthly starting emissions with 5.5 to 8.6 kg of CO_{2e} kg^{-1} scallop meat (EDG, CHI, BRA). TAR had the lowest mean monthly starting emissions for the RCA fishery at approximately 4.07 kg of CO_{2e} kg^{-1} scallop meat. However, by the end of the fishing season all RCA grounds had increased GHG emissions to between 8.60 and 13.61 kg of CO_{2e} kg^{-1} scallop meat (Figure 8).

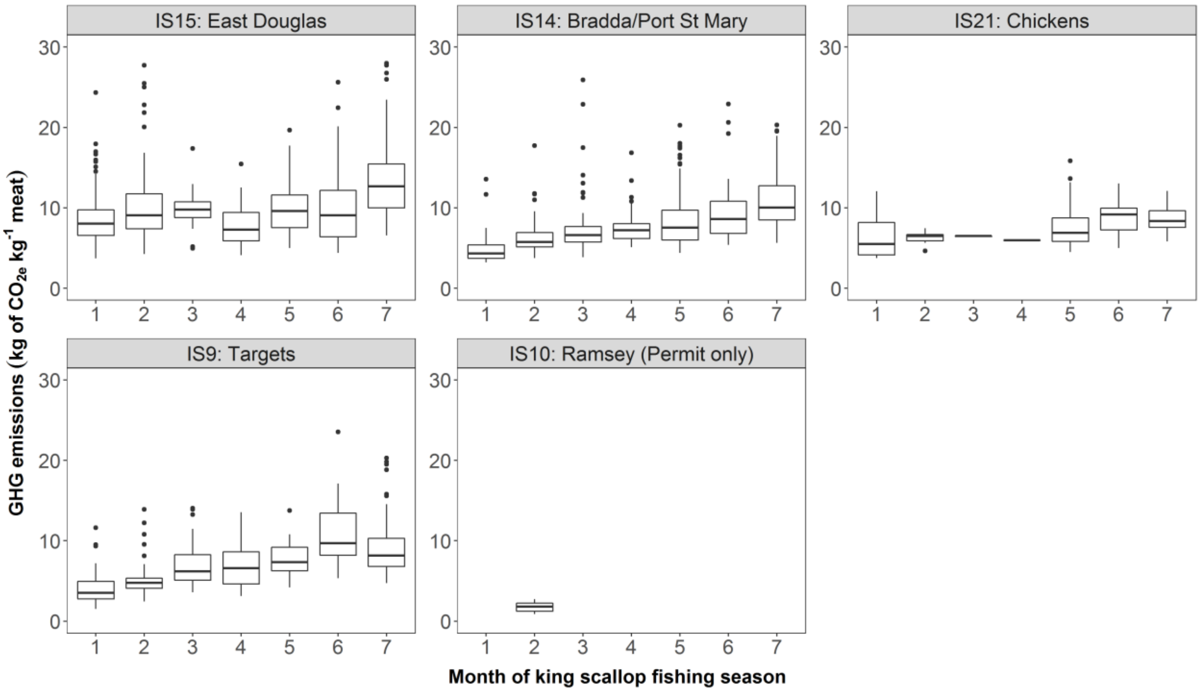

Figure 8: Mean Greenhouse gas emissions (kg of CO_2e kg^{-1}scallop meat) displayed by fishing month for the 2017/2018 king scallop fishing season in the Isle of Man territorial sea.

4. Discussion

Boom not bust

There is increasing concern from the seafood industry, scientists, NGOs and consumers about the environmental, ecological and economic sustainability of scallop dredge fisheries (Duncan et al. 2016). Globally, the use of conventional fisheries input controls, typically operating from centralised top-down governance, have had limited success in preventing issues such as overexploitation, habitat damage and bycatch (Grafton et al. 2006), as evidenced for many scallop fisheries. With some exceptions, the majority of European, towed-gear scallop fisheries have no quotas, daily catch limits or restrictions on overall vessel numbers targeting the fishery. In the absence of harvest controls, scallop densities are reduced quickly to relatively low levels, which introduces undesirable effects of economic inefficiencies and environmental impacts. As a result, many open-access scallop fisheries exhibit 'boom and bust' characteristics (Beukers-Stewart et al., 2003). Subsequent recovery of the ground and the stock can be slow, and takes many years (typically 3-4 years from experience on Manx grounds in 2009 and 2016), and in the interim, fishing is then focused on lower-density areas resulting in additional steaming time, fishing time, fuel use and seabed contact time for less reward.

Fuel use, costs and GHG Emissions

Bottom trawling (including dredging) is energy-intensive (e.g. Schau et al., 2009). In this study fuel use coefficients for scallops dredging averaged 0.09 kg fuel/kg LSW scallop for the RAM TURF fishery during the 2017/2018 king scallop season. This was considerably lower than the values calculated for the RCA which ranged between 0.34 and 0.54 kg fuel/kg LSW scallop during the same period. The fuel use coefficient for the TURF is similar to values reported for less fuel-intensive metiers like purse seining fisheries (e.g. 0.02 -0.09 kg fuel/kg fish) (Schau et al., 2009) and substantially lower than values for more fuel-intensive metiers like international ground fish bottom trawl fisheries (0.28 – 1.50 kg fuel/kg fish; Schau et al. 2009) and shrimp trawl fisheries in Norway (up to 1.04 kg fuel/kg fish; Schau et al. 2009).

Fuel costs represent a significant portion of the associated costs in bottom trawl fishing. Increased fuel use therefore reduces profits. Mean fuel costs per tonne of LSW scallops (2017/2018) were at least 3 x higher for the RCA fishery compared to the TURF (range £182 to £290 for RCA and £47 for TURF; average fuel price was £0.45/litre; MFPO pers. Comm.). Fuel price is not a fixed variable and can fluctuate significantly from year to year with the cost differential having a greater impact on profitability when oil prices are high. For example, in 2005 (a high fuel price year) the fuel costs for shrimp trawling in Norway accounted for more than 30% of the catch value (Schau et al., 2009). By reducing fuel consumption fishers can improve their economic efficiency and reduce their environmental impacts. Energy performance should be considered a fundamental criteria in assessing the sustainability of towed-gear fisheries (Utne, 2008).

There is an increasing urgency for fisheries policy and management to better align with policies that address climate change in order to address consumer concerns regarding GHG emissions and the impact on fishers of increasing fuel prices (Driscoll & Tyedmers, 2010). For this reason carbon-efficiency metrics, which are already used in ecolabelling schemes like KRAV in Sweden, may be increasingly included as sustainability indicators for fisheries in the near future (e.g. Thrane et al. 2009; Madin & Macreadie, 2015). As the trend towards green consumerism increases, the fishing industry must adopt technologies and strategies that lower CO_2e emissions in order to retain market access or competitiveness. In order to quantify future improvements scallop fisheries should provide current benchmarks for this performance indicator. CO_2e emissions for the RCA fishery (2017/2018) were at least 2-fold higher for the RCA fishery than that TURF (range 4.07 and 13.61 kg CO_2e kg^{-1} scallop meat for RCA and 1.73 kg CO_2e kg^{-1} scallop meat for TURF). Globally emissions intensity values for seafood have been estimated to range from 1 to 86 kg CO_2e kg^{-1} meat (Parker et al. 2018). The considerable differences in emissions among species and metiers were highlighted in a review by Nijdam et al. (2012) e.g. Spanish mussels ~ 1 kg CO_2e kg^{-1} meat (Iribarren et al. 2010), 86 kg CO_2e kg^{-1} meat for trawled Norway lobster (*Nephrops norvegicus*) (Ziegler & Valentinsson, 2008) and cod 1.7-4.4 kg CO_2e kg^{-1} fillet (Svanes et al. 2011). The TURF outperforms not only many wild-capture fishing industry systems in terms of GHG emissions, but also many land-based livestock systems (e.g. Poultry 2-6 kg CO_2e kg^{-1} meat, Pork ~ 4-11 kg CO_2e kg^{-1} meat and beef 9-129 kg CO_2e kg^{-1} meat; Nijdam et al. 2012).

Commercial impacts, market performance and reliability

Pre-fishery surveys enabled overall biomass estimates and fine-scale spatial density estimations across the TURF. The ground specific, biomass-linked TAC ensures biomass remains high and fishing ends before significant intra-seasonal reductions in LPUE. Fishing is also permitted only within the highest density areas, which promotes catch efficiency (i.e. high LPUE). Following a build-up of biomass during the three season closure, LPUE was very high in 2013 (season 1) at 0.57 t per hour fished. LPUE declined subsequently to 0.45 and 0.28 t per hour fished in Season 2 and 3 respectively, and has since remained stable at these relatively high levels of ~ 0.30 t per hour fished (Figure 3).

By contrast, the RCA fisheries typically target high-density patches at the start of the season (November/December) with monthly averages up to ~ 0.2 t per hour fished in November in good seasons (e.g. CHI and TAR season 4). However, the lack of biomass-linked, ground-specific TACs, means that these high-density beds are quickly depleted and vessels then sequentially target lower-density patches within the ground for the remainder of the fishing season (Figure 3). LPUE values at the end of the season are often significantly lower than the starting values (i.e. ~ 0.08 and 0.05 t per hour fished respectively at the end of season 4 in CHI and TAR respectively). High fishing mortality in the RCA on scallops over MLS skews the population towards smaller, younger scallops, leaving these grounds almost completely dependent on recruitment and growth of a single year class, during the closed season (i.e. June – October), to replenish the stock for the start of the next season (Figure 3). Thus the initial period of the fishing season can be associated with high LPUE in specific areas of the RCA when annual recruitment is high. Without sustainable limits on the TAC for each ground, or the presence of older age classes, rapid intra-seasonal declines in LPUE occurs (e.g. TAR and CHI; Figure 5). This strategy reduces the average seasonal LPUE index closer to minimum economic viability. A period of recovery (seabed and stock) is then typically required before another recruitment peak can occur (i.e. “boom and bust” fishery).

Reliability of supply to the market is of vital importance for the fishing industry. The RCA grounds are predominantly dependent on the annual recruitment success of a single year class. The significant inter-annual variability in biomass and LPUE associated with recruit-driven scallop fisheries makes the sustainability of product for market supply difficult to guarantee. Conversely, in the TURF population the progressive increase in the presence of older age classes has effectively buffered against recruitment failure in any one year by increasing the variability in age-class components within the fishable stock (Figure 4). By harvesting the catch in December for the higher-value Christmas market fishers achieved a minimum £0.50 per kg more compared to the average price for the rest of the season (a 22% increase in harvest value). In addition, the higher quality of the Ramsey Bay scallops compared to the rest of the RCA fishery (typically larger scallops with higher meat weight: e.g. 2019 RAM was 7-9 scallops per lb; EDG was 13-14 scallops per lb and CHI was 14-15 scallops per lb; pers. comm. MFPO) has resulted in a premium price paid for the product. The TURF has thus enabled processors to develop a reputation for high quality, high-yielding scallops, particularly pre-Christmas, which has helped them retain market share, using the assured quality, larger size, and guaranteed availability from Ramsey Bay as a marketing tool for Isle of Man seafood products (pers. comm. MFPO).

Environmental benefits:

The environmental impacts of food production have become an increasing concern for consumers and for the major retail chains in Europe it is perceived as a competitive advantage to promote the cause of the consumer (Schau et al., 2009). Consumer demand for dredged scallops may be threatened if the environmental impacts resulting from their production are considered outside acceptable consumer limits. Pre-fishery surveys in Ramsey Bay directed fishing to high-density areas (with areas that were of low-density, or that support vulnerable marine ecosystems voluntarily closed), thereby minimising the total footprint of the fishery and providing direct ecosystem benefits to surrounding areas. On average ≈ 95% of the TURF has remained unfished by mobile fishing gear each year. By focusing fishing activity on high-density areas, using data from pre-fishery surveys, and limiting the TAC in the TURF to approximately 15% of the estimated fishable biomass, the LPUE is maintained at relatively high levels and the area impacted is only 0.11 km^2 per t LSW landed, compared to between 0.26 and 0.86 km^2 per t LSW landed for the RCA fishery. In the case of Ramsey Bay the security of restricted access tenure to the fishery, ensured by effective Government enforcement, created a context where fishers were able to consider marketing strategies which highlighted the reduced environmental impact of the fishery and which in turn helped secure its future market opportunities.

A limited fishing season (two to three weeks) within the TURF minimises scallop dredge disturbance during critical spawning, settlement and recruitment periods. By contrast the fishing grounds in the island's RCA fishery are fished by scallop dredges for up to 31 weeks each year (the fishery is closed annually from June to October). A shorter season allows greater recovery time for the seabed and associated communities impacted by dredges. It can also reduce the impacts on benthic structures upon which scallop spat settlement depends (e.g. hydroids, maerl etc.; Howarth et al. 2015; Oreska et al. 2017). The higher quality (size and yield) of Ramsey Bay scallops, and resulting premium price, compared to the rest of the RCA territorial sea, may simply be linked to better local physical and biological conditions (i.e. water current, food availability, temperature etc.), which are known to impact growth and gamete production (e.g. Harris & Stokesbury 2006, Shephard et al. 2010). However, the reduction in frequency of physical interactions between scallop gear and scallops in Ramsey Bay, as a result of the limited fishing season and TAC, may also be linked to the enhanced quantity and yield of scallops in the TURF compared to the RCA, as reported by Kaiser et al. (2007) where the gonads of scallops in a closed area were on average 25% larger compared to gonads from commercially fished grounds.

Success and challenges for sustainable scallop fishery management

Changes in management of most European scallop fisheries are required if stock biomass, commercial profitability, environmental efficiency and consumer demand are to be maintained. It is acknowledged that a suite of management options exist ranging from open-access to full rights-based cooperative management with a number of intermediate management options in between. Where the legislative context restricts rights-based management, traditional management methods such as limited entry, restrictions on effort and limits on total catch through government licencing can still provide successful improvements to scallop management, as long as fishing capacity is well matched to scallop resource productivity (Orensanz et al., 2016). A successful approach based on traditional management systems is demonstrated in the Saint Brieuc fishery in France where intensive management is framed through government legislation. A restricted licence system was introduced in 1963 to avoid overfishing and effort was then further restricted through limits on time at sea per day and a days-at-sea scheme which resulted in dramatic increases in scallop catch rates (Beukers-Stewart & Beukers-Stewart 2009). The majority of the US sea scallop fishery has also successfully implemented a range of traditional management measures after it was officially declared overfished in 1997 (Beukers-Stewart & Beukers-Stewart 2009). Measures included limited access permits, caps on days-at-sea, rotational closures, individual trip catch limits and fleet-wide annual catch limits (Orensanz et al., 2016). These measures also proved successful in improving biomass and size class structure of the scallop stock (Beukers-Stewart & Beukers-Stewart 2009). The marked change in management of the US sea scallop fishery was triggered by a crisis that arose from over-fishing and has similarities to the Ramsey Bay fishery that was closed due to its overfished status, providing the necessary 'pause' in fishing to permit stock recovery and the introduction of a novel approach to management.

Where the legislative context does permit, the additional environmental and ecosystem based management incentives provided by rights-based management schemes may be significant for fisheries like scallops. Rights-based management can provide a means to improve not only the commercial efficiency of scallop fisheries but also their environmental status and consumer image, as demonstrated in Ramsey Bay. A range of rights-based management systems have been successfully adopted by scallop fisheries. For example, Enterprise Allocations (EAs) were introduced in the Canadian sea scallop fishery at Georges Bank in 1986 and changed the behaviour of the fleet, with voluntary closures of juvenile areas and fleet modernization and rationalisation, compared to management using traditional input controls (Stevens et al., 2008). Since the implementation of EAs in 1986 fishing effort has reduced and catch rates have tripled (Beukers-Stewart & Beukers-Stewart 2009). The territorial user-rights management approach used in Ramsey Bay conferred a level of ownership for the resource on the fishers, within a defined fishing area. At the start of the Ramsey Bay TURF, there were individual differences in fisher's attitudes to this resource management approach, with some fishers perceiving that the tighter controls imposed denied them the freedom to fish in a manner that suited them. A two-way exchange of information between scientists and the fishers, which included an annual discussion regarding survey results and harvesting options, underpinned the annual decision making process on how, when, and how much to fish. This cooperative and participatory approach, whereby the fishers ultimately became responsible for undertaking the surveys, and subsequent harvesting of the resource, increased fisher confidence and acceptance of the management strategy and supporting data. Allowing fishers the opportunity to see for themselves the potential of the fishery to achieve a sustained and improved status has reassured those that might have doubted the veracity of the approach. Importantly, the security of tenure has enabled the fishers to move away from a 'race to fish' management style and instead incentivised the implementation of management measures to reduce fishing pressure, implement conservation measures, enhance stocks and the habitat on which the target species depend; and to consider the long-term wellbeing of industry members. These management measures have not only proved successful in improving the biomass and size class structure of the scallop stock and the efficiency of commercial harvesting within the fishing area but, just as importantly, they have also provided benefits for the wider ecosystem and for the market potential of the product.

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