Title: Spatial and Temporal Changes in Fishing Effort and Habitat Use

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Abstract

Habitat and fisheries usage data are key components for ecosystem based fisheries management (EBFM). Significant gaps in knowledge remain for fisheries–habitat interactions, particularly in inshore fisheries where vessels are <12m. Here we show changes in inshore fishing effort distribution (<12m) and habitat use over the decade 2004-2013.

Sightings data of fishing vessel activity recorded by the Northumberland Inshore Fishery and Conservation Authority (NIFCA) were combined with landings data to estimate and map pot-fishing activity between 2004 and 2013. Spatial temporal changes were investigated using Monte Carlo simulation of randomly sampled fishing effort maps. High resolution (1m) broadscale (EUNIS level 3) predictive habitat maps of the Coquet to St Marys' Marine Conservation Zone (CQSM MCZ) were used to investigate spatial temporal changes in fishers' habitat selection using compositional analysis.

Fishing effort in Northumberland increased between 2004 and 2013 (233,642-354,193 pots.year $^{-1}$). Fishing effort distribution differed between individual years, decreasing over large areas between 2004-2007, followed by increases, especially inshore, between 2008-2013. Fishers in the CQSM MCZ showed a preference for rocky habitats over sediment habitats. Habitat preference did not vary between years although all habitats experienced increasing fishing pressure. Spatial temporal changes in fishing effort and habitat use were discussed in relation to EBFM.

Key words: Baited traps, ecosystem based fisheries management, fishing effort distribution, fisheries-habitat interactions, potting, spatio-temporal analysis.

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1. Introduction

Fishing provides an important socio-economic function in many parts of the world as a source of food and income (Pauly *et al.*, 2002; Kaiser, 2014). The traditional model of fisheries management focusses on single species bio-economic modelling, although this method is increasingly perceived as incomplete (Caddy and Cochrane, 2001; Hilborn and Ovando, 2014). Habitat quality and health have now been recognised as being integral to an ecosystem based approach to fisheries management (EBFM) (Pikitch et al., 2004; Armstrong and Falk-Petersen, 2008; Howarth et al., 2011; Salomidi et al., 2012). Knowledge of fisheries effort distribution and marine habitat usage is needed (Stelzenmüller *et al.*, 2008; Eno *et al.*, 2013; Kaiser, 2014) in order to minimize the risk of irreversible changes to species assemblages and ecosystem processes as part of EBFM (Pikitch *et al.*, 2004; Parnell *et al.*, 2010).

Seabed habitats and their associated communities are determined by their ambient biotic and abiotic conditions (Dayton, 1985; McGowan *et al.*, 1998; Shears and Babcock, 2002; Connor *et al.*, 2004; Smale *et al.*, 2011). In addition to natural environmental conditions, the physical interaction of fishing gears on the seafloor may exert further pressure on benthic communities (Lambert *et al.*, 2011; Nielsen *et al.*, 2013). Vulnerability of habitats to fishing impacts will be determined by the intensity, frequency and extent of natural disturbance to which the habitat and its associated species are subject to (Kaiser *et al.*, 2006; Kaiser, 2014). For example, in high-energy environments, fishing disturbances may have negligible effects when compared to natural disturbance (Kulbicki *et al.*, 2007; Sciberras *et al.*, 2013). In many cases, mobile fishing gears adversely affect the marine environment (Kaiser et al., 1996; MacDonald et al., 1996; Collie et al., 1997; Collie et al., 2000a; Collie et al., 2000b; Kaiser et al., 2006; Lambert et al., 2011). Static fishing gears have been widely assumed to be relatively benign (Eno et al., 2001; Lewis et al., 2009; Shester and Micheli, 2011; Coleman et al., 2013) yet there is limited evidence to support this (Shester and Micheli, 2011) even though these fisheries are substantial; UK landings were 86,600 tonnes and worth £173 million in 2014 (MMO, 2015). High-value species such as lobster and crab constitute 41% of the landings and are primarily caught inshore using pots or traps (MMO, 2015). The need for information on impacts of these fisheries in UK designated conservation areas (European Marine Sites [EMSs] and Marine Conservation Zones [MCZs]) has become increasingly urgent for inshore static-gear fishing (MMO, 2016). Understanding effects of static fishing gears on the marine environment requires an understanding of the distribution, frequency, intensity and fisheries-habitat interactions (Pedersen *et al.*, 2009; Parnell *et al.*, 2010; Eno *et al.*, 2013; Caveen *et al.*, 2014; Kaiser, 2014).

To date, research has predominately focussed on mapping mobile gear fishing activity using VMS and overlaying this information on existing broadscale habitat datasets (Nilsson and Ziegler, 2007; Stelzenmüller *et al.*, 2008). However, a primary limitation of VMS data is that it is only recorded for large vessels (>12m). Static-gear fishing fleets, largely operate inshore and are composed of small vessels (<12m) which do not have VMS equipment (Breen *et al.*, 2014). Alternative approaches to mapping small vessels fishing activity (<12m), such as surveillance methods, have successfully described distribution and intensity of various static fishing gears, however, only over a single time period (Breen *et al.*, 2014; Turner *et al.*, 2015). This does not account for changing use of habitats by fishers. Spatial fishing patterns have been shown to vary over time (Kaiser *et al.*, 2002; Nilsson and Ziegler, 2007), the availability of target species, gear and fishers’ territorial behaviour being important drivers (Acheson, 1975; Rijnsdorp *et al.*, 2001; Turner *et al.*, 2012). These inter-annual variations in fishing activity may make short-term studies inadequate

(Lynch, 2014); spatio-temporal variability must be better understood to inform appropriate management (Parnell *et al.*, 2010). Some temporal trends for large vessels (>18m) over broadscale marine landscapes (Connor *et al.*, 2006) at 2x2 nautical mile (NM) resolution (Stelzenmüller *et al.*, 2008) have been described, but finer resolution fishing activity has been repeatedly highlighted as a priority for future research (Breen *et al.*, 2014; Campbell *et al.*, 2014), particularly for smaller vessels (Caveen *et al.*, 2014; Brehme *et al.*, 2015).

Here, spatio-temporal changes in inshore static-gear fishing effort and habitat use were investigated for the first time. The Northumberland fishery was used as a case study for the assessment of other inshore fisheries due to the rich data available. Northumberland's fishery (Fig 2) is mixed (Garside *et al.*, 2003), vessels largely operate close to shore; approximately 90% of fishing effort is estimated to occur within the 6NM limit (Turner, 2010) and is primarily composed of <10m fishing vessels (70 ± 9% between 2003 and 2014, Table 3). The majority of Northumberland fishers target crustaceans, European lobster (*Homarus gammarus*), velvet crab (*Necora puber*) and edible crab (*Cancer pagurus*), using baited pots (or traps). These shellfish species use habitats differently from each other; their distributions, movements and abundances are influenced by habitat type, quality and location (Galparsoro *et al.*, 2009; Geraldi *et al.*, 2009; Skerritt *et al.*, 2015). Lobster (*Homarus gammarus*) and velvet crab (*Necora puber*) are found predominantly on shallow rocky ground (Wilson, 2008; Galparsoro *et al.*, 2009). The edible crab (*Cancer pagurus*) is found in all habitat types but evidence suggests preferences for coarse sediment and offshore muddy sand (Neal and Wilson, 2008). Thus fishers are likely to select by habitat when targeting different shellfish species. Fishing with mobile gear may vary inter-annually in both extent and habitats selected (Jennings *et al.*, 2012; Diesing *et al.*, 2013), but there have evidently been no comparable studies of fishing with static potting gear. These may differ, for example, due to fishers' territorial behaviours (Turner *et al.*, 2012).

The aim of this research was to investigate spatio-temporal changes in pot fishing effort and habitat use in Northumberland coastal waters between 2004 and 2014. This was achieved using routine patrol vessel sightings in combination with high resolution habitat maps, providing a case study for the assessment of other inshore fisheries. The scale needed for management of fisheries–habitat interactions were also explored.

2. Methods

2.1. Fishing activity

Sightings data of fishing vessel activity recorded by the Northumberland Inshore Fisheries Conservation Authority (NIFCA) on routine patrols were combined with landings data to estimate and map fishing activity in the NIFCA district. This method was based on Turner *et al.* (2015) and adapted for this research (Fig 1).

Fishing vessel sightings were recorded during routine NIFCA patrols between 2004 and 2013. Vessel name, registration, home port, geographic position and observed activity were recorded. Sightings of potting vessels targeting crab and lobster in 2004–2013 were mapped as point data using ArcView GIS version 10.2 (ESRI, 2014) (Table 1). Sightings data provide strong confidence of association with actual fishing activity because of the direct recording by the NIFCA officers of activity such as shooting, hauling or attendance of gear by a fishing vessel. In order to standardise sightings across years, all years' sightings data were randomly reduced to the minimum number of patrol days (n=71 in 2009) (Table 1).

Frequency and location of fishing vessel sightings were influenced by the timing and route of NIFCA patrols (Breen *et al.*, 2014; Turner *et al.*, 2015). Thus, sightings were adjusted for patrol effort (Turner *et al.,* 2015), using patrol routes to weight the probability of vessel sightings; heavily patrolled areas were negatively weighted and lightly patrolled areas were positively weighted.

Due to low numbers of vessel sightings in some years, caused by the small number of fishing vessels operating from some ports and the limited number of routine patrols, sightings data were pooled in 2-year groupings (2004-2005; 2006-2007; 2008-2009; 2010-2011 and 2012-2013).

The pooled adjusted vessel sightings point data were transformed to a continuous surface using a non-parametric quadratic kernel density estimation (KDE) method (cell size 100x100m) in ESRI ArcGIS 10.2 (Silverman, 1986). A normal distribution approximation bandwidth estimation method (Silverman, 1986) was chosen as the density data was unimodal, fairly symmetric and did not have large tails (Wand and Jones, 1995; Kie *et al.*, 2010). Highly clustered data can result in an exaggerated bandwidth, over-smoothing the data and creating inaccurate utilization areas (Kie *et al.*, 2010). By reducing this bandwidth to a fixed proportion of 0.8 over-smoothing was reduced (Bertrand *et al.*, 1996; Kie and Boroski, 1996; Kie *et al.*, 2002; Kie *et al.*, 2010).

2.2. Distribution of potting density

Percentage volume contours (PVCs) delineate the smallest area accounting for a specific proportion of the probability density distribution. These were created from the potting activity KDEs using the ‘Isopleth’ tool in Geospatial Modelling Environment (GME) software (St. Martin and Hall-Arber, 2008; Beyer, 2012). PVC polygons of 50, 60, 70, 80, 90 and 95% were created, uploaded into ArcGIS 10.2, and area calculated (Turner *et al.*, 2015).

The numbers of pots worked per month over the period 2001-2014 in the Northumberland district were provided by the NIFCA. Annual fishing effort (*f,* pots.year $^{-1}$) was calculated:

Eqn 1: $$Mean\ Annual\ f = \frac{\Sigma\ \text{pots.month}^{-1}}{n}$$

Where n is the number of years. For years 2006-2009 fishing effort data were missing for vessels 10-12m. Total numbers of pots deployed between 2006 and 2009 were estimated by averaging the proportion of pots fished per year by 10-12m vessels for years 2004-2005 and 2010-2014. The mean proportion of fished pots by 10-12m vessels was added to the available data for years 2006-2009. Average proportion of pots fished by 10-12m vessels was 14.3 ± 5.8%.

To estimate annual potting density, 50, 60, 70, 80, 90 and 95% of the mean annual fishing effort was calculated and apportioned to the corresponding PVC polygon (Turner *et al.*, 2015); for example, 50% of annual fishing effort was allocated to the 50% PVC with pot density calculated as number of pots.km $^{-2}$.year $^{-1}$.

2.3. Confidence assessment

Some areas were infrequently or never patrolled and therefore have uncertain or unknown fishing activity intensity and distribution (Breen *et al.*, 2014). A confidence assessment was made based on the frequency of patrol tracks contained within each 3NM^2 grid cell between 2004 and 2013 (Table 2).

Of the patrols within each 3NM^2 grid cell, 63.3% of the NIFCA district was mapped with moderate or high confidence (Fig 2). Potting effort distribution in areas with low confidence (26.7%) were excluded from the analysis.

2.4. Habitat distribution

A broadscale habitat map (European Nature Information System (EUNIS) level 3, 1m resolution, overall accuracy 80%) was available for the Coquet to St Mary's Marine Conservation Zone (CQSM MCZ) (Fig 3, C). Three broadscale habitat types were identified (Fig 3, C): 'Atlantic and Mediterranean moderate energy circalittoral' (A4.2) hereafter referred to as rock habitat, 'Sublittoral sand' (A5.2) hereafter referred to as sand habitat, and 'Sublittoral mud' (A5.3) hereafter referred to as mud habitat. Full descriptions of habitats and species assemblages are available from the EUNIS website (http://eunis.eea.europa.eu).

2.5. Data analysis

All analyses were conducted in R (R Core Team, 2013). Temporal changes in number of pots fished per month were analysed using a negative binomial model with number of active vessels as a covariate. In order to account for seasonality, a harmonic function was included but these covariates were non-significant and it was deemed that monthly active vessel number encapsulated seasonality. Since total numbers of pots deployed between 2006 and 2009 were estimated, three linear models were run using low, mean and high estimates of pots fished by 10-12m vessels (8.5, 14.3 and 20.1% respectively).

Spatio-temporal changes in Northumberland shellfishing effort were investigated by comparing fishing effort values of randomly sampled locations (from fishing effort distribution maps) between years (i.e. 2004–2005 vs 2006–2007, 2006–2007 vs 2008–2009, etc) using a permuted Monte Carlo simulation. Fishing effort distribution maps were converted to raster format (pixel size 100x100m) each containing 88,604 unique pixels, of which 5000 were randomly sampled from each map. The fishing effort values of sampled pixels were compared between years using a two-tailed paired t-test permuted 50,000 times (Jackson and Somers, 1989). If greater than 95% of all permutations yielded significantly different results, it was deemed that the compared maps differed. The number of statistically significant t-tests, mean t-values and p-values from the permuted t-tests were calculated. All fishing effort maps were tested against each other using this method. In order to visualise change across all years, absolute change thematic maps were created using all fishing effort distribution maps (Remmel, 2009). These highlight pixels where values change over time.

Compositional analysis (Aebischer *et al.*, 1993) of fishers' habitat use was undertaken by investigating the relationship between observed and expected potting use of each habitat category in the CQSM MCZ, assuming that habitat use is proportional to availability. This used 500 randomisation tests for annual groupings of potting vessel sightings conducted in the adehabitatHS R package (Calenge, 2006). The significance of habitat selection was tested using Wilk's lambda and a ranking matrix constructed. The ranking matrix indicated whether the habitat type was used significantly more or less than expected for each yearly fishing vessel sightings value, and ranking of habitat selection by fishing vessels and year in order of preference was displayed (Calenge, 2006). Although fishers target habitats outside the CQSM MCZ, habitat data for these areas were not available. Therefore for this analysis the CQSM MCZ polygon outline was selected as fishing vessel home range (second order habitat selection, Johnson (1980)).

In order to further explore differences in habitat use between years an eigenanalysis of selection ratios was undertaken (Calenge and Dufour, 2006). This method uses an additive linear partitioning of the White and Garrott statistic (White and Garrott, 1990) to maximise the difference between habitat use and availability on the first factorial axis (Calenge and Dufour, 2006).

3. Results

3.1. Temporal changes in fishing effort

NIFCA district pot-fishing permit (i.e. the number of fishing vessels which have a licence to fish in the NIFCA district), decreased in number steadily from 2001 (155 permits) to 2011 (107 permits), there was then a small increase to 114-119 permits between 2012 and 2014, and since 2014 the number of permits has remained constant (Table 3). A similar trend was observed for the number of active vessels per year, although not all vessels with permits were active; ~70-80% of permit holders operating in any one year (except 2010 when only 43% of vessels with permits were active) (Table 3). The proportion of the active <10m fishing vessels increased to 2011 (86%) before decreasing slightly from 2012-2014 (Table 3). The median number of pots deployed per vessel per month doubled from 2001 to 2014 (Table 3). The total number of pots fished in the district per year also showed a general increase over time from 2001 to 2014 (Table 3).

Fishing effort per month declined between 2001 and 2007, increased between 2008 and 2010, and increased substantially from 2010 to 2014 (Fig 4). This trend was best explained by a model with covariates: time (z-value = 17.4, $p < 0.0001$, where each additional month predicted an increase of 1.01 pots fished), and number of active vessels per month (z-value = 18.3, $p < 0.0001$, where each additional fishing vessel accounted for a monthly increase of 1.1 pots fished) (Fig 4). The linear model run using both low and high estimates of pots for vessels 10-12m (8.5 and 20.1% of pots fished, respectively) did not change the overall trend with time (months) and the number of active vessels significant (see supplementary materials).

3.2. Spatial-temporal changes in fishing effort

Fishing effort distribution differed between all years (all years, $p < 0.001$). Fishing effort decreased over large areas between 2004-2005 and 2006-2007 (Fig 5, t-value = 36.1, $p < 0.001$), but increased in many areas between 2006 and 2013 (Fig 5, all t-value < -19.2, all $p < 0.001$). These changes were particularly close to the shore (<2NM), with large increases in fishing effort between 2006 and 2013, although the magnitude of differences between years was variable. Many areas further from shore

(>3NM) had decreasing fishing effort and increasing area with no fishing effort, particularly between 2010 and (Fig 5).

Cumulative spatial changes across all years highlights these trends with either stable or decreasing fishing effort further from shore, with most inshore areas increasing in fishing effort (Fig 6). The maximum increase in fishing effort is much larger than the maximum decrease in fishing effort: increases of up to 1150 pots.km $^{-2}$.year $^{-1}$ compared to decreases of 450 pots.km $^{-2}$.year $^{-1}$ (Fig 6).

3.3. Fishers' habitat use over time

At a broadscale habitat level, potting vessel sightings differed among substrate types in all years (Lambda = 0.0152; p-value = 0.004). Vessels showed a significant preference for rock habitat (A4.2) over both sand (A5.2) and mud habitats (A5.3) (p-value <0.05). Fishing vessels in most years tended to target sand (A5.2) over mud (A5.3) habitats, although these differences were not significant. The eigenanalysis showed all year groups following a similar pattern with a strong selection for rock over other substrates (Fig 7).

3.4. Changes in habitat potting pressure

Potting pressure (pots.km $^{-2}$.year $^{-1}$) in the NIFCA district increased over the period 2004-2013 (Fig 5), especially in areas close to shore such as the CQSM MCZ. Unfished areas in the CQSM decreased in extent over time (Fig 5). Across all years the highest fishing pressures were on rock habitats (A4.2), sand habitats (A5.2) were moderately fished and mud habitats (A5.3) were the least fished (Table 4, supplementary materials). Potting pressure more than doubled on each habitat between 2004 and 2013 (Table 4, supplementary materials) but the proportion of total pots deployed on each habitat has remained constant, with only slight increases or decreases between years (Table 4, supplementary materials). Between 2004 and

2013 fishers consistently targeted the same habitats each year, but increasing potting effort.

4. Discussion

This study demonstrates the potential of existing datasets, collected through routine fisheries patrols (Breen *et al.*, 2014; Turner *et al.*, 2015), to investigate temporal and spatial changes in fishing effort. This may offer a viable alternative to VMS for monitoring smaller vessel inshore fisheries (Breen *et al.*, 2014), particularly for static gear fisheries because fishing vessel sightings provide strong confidence of association with actual fishing activity. In addition, fishing effort distribution combined with habitat data provide an insight into habitat selection, albeit at a broad scale in this study. These fisheries–habitat interactions are the first step towards spatially relevant habitat vulnerability assessments; data which are required for EBFM but which is often lacking, particularly for the understudied inshore static gear fisheries. The Northumberland shellfishery has been reported to have the highest vessel sightings per unit effort in the UK (Vanstaen and Breen, 2014). This may make the fishery particularly vulnerable to changes in legislation or area closures. The rich data available make it well suited as a case study on the effects of area closures and other types of management. However, in order to fully understand the implications of fisheries spatial management, fisheries–habitat interactions must be understood.

4.1. Temporal change in fishing effort

Fishing effort (pots.month^{-1}) increased substantially in the study area between 2001 and 2014. Changes in fleet composition or fishers' behaviour may explain increases in effort, although available information is largely anecdotal and further work is recommended. The proportion of vessels <10m in the study area steadily increased over time. These smaller vessels are not subject to as much legislation as vessels >10m and have cheaper fishing licenses. Concurrently, increased uptake by local fishers of improved fishing technology, including GPS and sonar, better vessel layouts and hydraulic trap haulers, was reported (NIFCA, personal communication), changes that would allow a greater number of pots per month to be fished and more specific areas or habitats to be targeted, in-line with reports from other static-gear fisheries (Acheson and Brewer, 2003; Brewer, 2010).

Non technological factors may also have contributed to the observed increase in potting effort. Traditionally the Northumberland fishery has been a mixed and seasonal fishery, with an array of species caught using different gears throughout the year. For example, salmon (*Salmo salar*) was targeted using drift nets from June-August; nephrops (*Nephrops norvegicus*) and white fish (e.g. cod, *Gadus morhua*) using trawls in winter; and lobster and crab using pots in summer (NIFCA, personal communication). However, declines in stocks of finfish and nephrops and the increasing operational costs of maintaining and participating in these fisheries may have resulted in many fishers solely fishing in the less regulated pot fishery targeting high value lobster on a full time basis (Acheson and Brewer, 2003; Turner *et al.*, 2012; Molfese *et al.*, 2014). Although the number of active vessels in the district per year has not increased (Table 3), fishers may be devoting more time to fishing lobster full time and therefore increasing their effort.

Fishers may have increased effort in order to maintain levels of catch in the face of decreasing abundance of target species (Pauly *et al.*, 2002). However direct measure of the abundance of lobster and crab are impossible with current data. Landings for both lobster and crab increased between 2001 and 2014 (NIFCA, personal communication). However, calculating CPUE for trap fisheries is problematic (Hilborn and Walters, 1992; Skerritt *et al.*, 2015) because the volume of pots and frequency of hauling are often highly variable between fishermen and can significantly alter CPUE estimates. Thus it remains unknown whether the increases in pots in the fishery is due to declining landings, although this information may be particularly useful for future studies.

4.2. Spatio-temporal changes in fishing effort distribution

Commercial fishing activities are often reported at very large scales (e.g. ICES rectangles, approximately 30x60NM) (Brehme *et al*., 2015). These data rarely accurately reflect the heterogeneity of ocean activities (Parnell *et al.*, 2010; Brehme *et al.*, 2015) and only allow the broadest of fishery-habitat interactions to be examined. Knowledge of fine-scale fishing effort is important, particularly as a prerequisite for the assessment and management of fisheries impacts on the seabed; interactions with other industries or proposed MPAs (Crowder and Norse, 2008; Stewart *et al.*, 2010); and conflict reduction between competing marine sectors (Katsanevakis *et al.*, 2011). Here, predictions of potting activities at a resolution of 1km^2 are made for the first time, these are of much finer resolution than previous research, which has mapped fishing activities from 6 to 50km^2 (Breen *et al.*, 2014; Brehme *et al.*, 2015). The more accurately activities can be mapped in these areas, the greater the ability of policy makers to develop successful marine spatial plans that minimise conflict (Dalton et al., 2010).

This study demonstrates fishing effort increases, but these were not uniform across the district over time. Activity became highly concentrated inshore; particularly in 2010-2011 and 2012-2013 (Fig 5). From a socio-economic perspective, potting may therefore be more vulnerable to changes in legislation (e.g. limitations of pot numbers, zonal management, fisheries exclusions) in the busy inshore marine environment where competing demands exist between larger numbers of users and where conflicts between different stakeholder groups occur (Dalton *et al.*, 2010). Increased inshore fishing effort may be related to the increase in small boats within the fleet which has been seen in a Greek fishery, where small <9m vessels’ average travel time to fishing locations was much lower than that of fishing vessels >15m (Tzanatos *et al.*, 2006); smaller vessels being more likely to fish closer to shore than larger vessels (FAO, 2005). Increasing fuel prices may also change behaviour, for example there is evidence volatile fuel prices have led to fishing occurring closer to port and reduced exploratory fishing in the UK (Abernethy *et al.*, 2010) although further evidence is required to state this with confidence for Northumberland.

Although fishing distribution maps are increasingly proposed for marine spatial management, temporal distribution of fishing effort has often been neglected (Brehme *et al.*, 2015). This study highlights the high inter-annual variability of fishing effort distribution over time at a regional scale and usefulness of monitoring fisheries over long-time periods (Lynch, 2014). The lobster fishery in Maine has been shown to change and evolve over time depending on fishers' responses to market forces (Steneck *et al.*, 2011), informal rules amongst fishers (Acheson and Brewer, 2003; Brewer, 2010), lobster population responses to changes in oceanographic conditions (Steneck and Wilson, 2001; Incze *et al.*, 2006; Holland, 2011; Zhang *et al.*, 2011) and to harvesting practices within the fishery (Acheson, 1988; Acheson and Brewer, 2003; Brewer, 2010). Fishers in the UK are likely to respond to similar drivers and changes in fishing behaviour (Turner *et al.,* 2015) and therefore for accurate management decisions, spatio-temporal patterns must also be understood. For example, spatial-temporal dynamics of fishing have been shown to be important when investigating effects of MPAs on fishing behaviour, where if patchy distributions of concentrated effort densities through time are ignored, general overestimations of fishing effort around no-take zones can occur (Stenzmuller et al., 2008). In turn, this could lead to an erroneous assessment of the fisheries benefits of the respective MPAs (Stenzmuller *et al*., 2008).

4.3. Change in fishers' habitat use over time

Results of temporal fisher-habitat interactions presented here had finer spatial resolution than previous studies (Nilsson and Ziegler, 2007; Stelzenmüller *et al.*, 2008; Lambert *et al.*, 2011). A quantified estimate of fishers' historical use of an MCZ was also provided; evidence which is often lacking during stakeholder engagement process of designations (Caveen *et al.*, 2014). Fishers in the CQSM MCZ showed a clear preference for rock habitats over sediment habitats in all years studied (2004–2013). This assumes that the distribution and extent of habitats predicted from data collected in 2014 are representative of the seabed throughout 2004-2013; but in this moderate energy environment at circalittoral depths, major changes in the distribution of substrata types are unlikely. Whether fishing grounds are chosen by fishers' knowledge of habitat, target catch, or a combination of both, is unknown. Based on historical knowledge and the widespread use of echo-sounder, fishers may target broadscale habitat types. Habitat preference varied very little between 2004 and 2013 (Fig 7), albeit fishing pressure increased (Table 4). Infralittoral rock, which is known to be fished in the CQSM MCZ, has not yet been included in the predictive habitat maps used (Fitzsimmons *et al.* (2015) but is present within the CQSM MCZ. As fishing pressure is high and increasing in the shallow inshore areas (Fig 5), analysis of fisher-habitat interactions of these biodiverse areas is recommended for any future management plans.

Analyses using broad habitat classification had high mapping accuracy (80%). However, higher classification levels which include biological components (EUNIS level 4-6), are particularly useful for locating and potential conservation of species of interest and is often recommended in the literature in order to inform EBFM (Cogan *et al.*, 2009; Caveen *et al.*, 2014). However, topographic, hydrographic and biological homogeneity within the study site make creating maps with greater biological resolution particularly problematic, resulting in relatively low accuracy (EUNIS level 5-6, 51% accuracy, Lightfoot *et al.*, unpublished). Investigation of fisheries-habitat interactions using maps with high biological resolution holds great potential for wider application, for example during designation or monitoring of fishers' use of MPAs, particularly in areas of greater spatial heterogeneity where the prediction of biological communities from acoustic data can be achieved with higher accuracy (Hill *et al.*, 2014; Sotheran *et al.*, 2014).

Incomplete knowledge of benthic assemblages and fishing gear–habitat interactions, and uncertainties around resulting displacement of fishers from closed areas have been obstacles to the successful implementation of MPAs (Caveen *et al.*, 2014). This work has helped fill some of these knowledge gaps for the newly designated CQSM MCZ. However, the information here is limited and maps predicting the distribution of biological communities coupled with usage information are recommended, to allow adaptive management for EBFM (Eno *et al.*, 2013). Fine-scale spatial assessments will be particularly useful for prioritising protection of the most vulnerable or biologically important habitats (Eno *et al.*, 2013). However, the impact of any closures that this may require on fishers' distribution and fishing effort is not well understood.

5. Conclusion

This study has demonstrated the potential for using fisheries enforcement data for the monitoring of temporal and spatial fishing effort of static fishing gears in inshore fisheries. Results of this research provide a crucial step towards a better understanding of long term fishing effort and spatial distribution for Northumberland. The analyses used here could be applied to other static fisheries and geographical areas where fishers' sightings data have been collected (Breen *et al.*, 2014; Turner *et al.*, 2015). The increase in effort and concentration of fishing activities over the study period illustrates the importance of monitoring fishing distribution over appropriate time scales; data which are required for EBFM but which is often lacking (Campbell *et al.*, 2014), particularly for the understudied inshore fisheries. At a broadscale, fisheries-habitat interactions were investigated, however, further work using higher biological resolution maps are required for spatially relevant habitat vulnerability assessments. The decline in finfish stocks in parts of the UK and the US may have led to an increase in those participating in the pot fishery (Acheson and Brewer, 2003; Turner, 2010; Molfese *et al.*, 2014). In light of the observed increase in effort, understanding the distribution, intensity and fisheries-habitat interactions of pot fishing is crucial in order to ensure sustainable shellfish stocks.

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Supplementary materials

Results of temporal changes in number of pots fished per month using a negative binomial regression model with the lower estimate (8.5%) of pots fished for vessels 10 -12 m between 2006 and 2009.

Regression coefficients, standard errors, t - value, and p-values significance for each variable using a negative binomial regression model with lower estimates for 2006 – 2009 pots fished.

	Estimate	Std Error	z - value	p- value

Intercept	8.5	0.07	124.4	< 0.0001
Months	0.005	0.0002	17.91	< 0.0001
Active vessels	0.012	0.0006	19.62	< 0.0001

Results of temporal changes in number of pots fished per month using a negative binomial regression model with the upper estimate (20.1%) of pots fished for vessels 10 -12 m between 2006 and 2009.

Regression coefficients, standard errors, t - value, and p-values significance for each variable using a negative binomial regression model with higher estimates for 2006 – 2009 pots fished.

	Estimate	**Std Error**	**z - value**	**p- value**
Intercept	8.6	0.07	124.6	< 0.0001
Months	0.005	0.0003	16.15	< 0.0001
Active vessels	0.010	0.0007	16.1	< 0.0001

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Tables

Table 1. Shellfish vessel sightings and NIFCA patrol route data.

Year	Shellfish vessel Sightings	Standardised vessel sightings	NIFCA patrols	Patrol routes available (%)*
2004	1159	905	104	90 (87)
2005	771	578	99	47 (47)
2006	749	672	86	4 (4.7)
2007	515	478	86	49 (58)
2008	433	378	75	56 (75)
2009	529	509	71	45 (63)
2010	546	532	72	59 (81)
2011	539	451	101	79 (78.2)
2012	496	452	85	84 (98.8)
2013	479	431	83	71 (85.5)
2014	490	443	86	76 (88.4)

* The number of patrol routes (GIS shapefile) provided by NIFCA.

Table 2. Confidence classification used for the confidence assessment (modified from Breen et *al.*, 2014).

Mean patrol effort for years 2004–2013	**Confidence class**
More than once in 2 weeks	High
Less than once in 2 weeks but more than once in 2 months	Moderate
Less than once in 2 months	Low

Table 3. Annual Northumberland potting fleet statistics (2001–2014) collated from NIFCA shellfisheries landings data. Not available (NA).

Year	Permits issued	Active Vessels (% active)	Active Vessels <10m (%)	Median pots month $^{-1}$	Max pots worked month $^{-1}$ *	Total pots worked year $^{-1}$
2001	155	108 (70%)	52	250	32,624	257,450
2002	151	111 (74%)	54	250	33,087	250,030
2003	153	117 (76%)	57	250	31,121	242,391
2004	136	97 (71%)	60	270	28,620	233,642
2005	130	97 (75%)	60	300	31,433	246,085
2006	120	61 (51%)	NA	300	17,770	179,365
2007	NA	55	NA	300	24,140	179,538
2008	NA	61	NA	335	26,806	194,651
2009	NA	60	NA	360	29,326	221,687
2010	121	52 (43%)	82	400	24,341	186,740
2011	107	87 (81%)	86	430	43,252	345,086
2012	114	81 (71%)	85	450	42,666	332,471
2013	118	89 (84%)	84	400	39,934	354,193
2014	119	92 (77%)	80	500	41,044	388,575

* Total pots worked per month: sum of the maximum number of pots deployed per month by each vessel

Table 4. Mean potting pressure (pots.km^{-2}.year^{-1}) per habitat (EUNIS level 3) and proportion of pots deployed in the CQSM MCZ.

	2004 – 2005		2006 – 2007		2008 – 2009		2010 – 2011		2012 – 2013	
	Potting pressure	Proportion of pots	Potting pressure	Proportion of pots	Potting pressure	Proportion of pots	Potting pressure	Proportion of pots	Potting pressure	Proportion of pots
Rock	448.0	0.45	363.2	0.46	565.9	0.50	800.3	0.47	1117.4	0.48
Sand	377.4	0.31	286.8	0.29	414.2	0.29	642.4	0.30	898.5	0.31
Mud	319.5	0.24	275.7	0.25	327.9	0.21	521.8	0.22	649.8	0.21

Figures legends

Fig 1. Diagram of GIS processes undertaken to map distribution of potting effort densities across the Northumberland IFCA district (modified from Spencer, 2013). Raw data (black cylinders), GIS mapping procedures (grey boxes) and final potting effort density distribution map (black dashed box) are shown.

Fig 2. Confidence data layer for the NIFCA district annual potting density map (2004-2013).

Fig 3. Location of Northumberland in Great Britain (A). Location of the Coquet to St Mary’s MCZ within the NIFCA district (B). Broadscale habitat map (EUNIS Level 3, for details on methodology see Fitzsimmons *et al.* (2015)) (C).

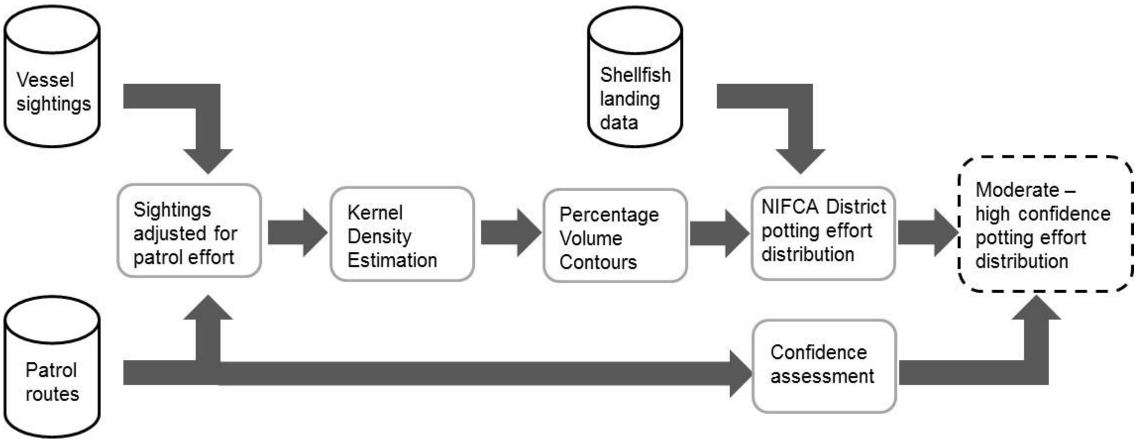
Fig 4. Monthly number of pots fished in the NIFCA district (2001–2014) with a line of best fit (black line) and 95% confidence interval (grey polygon) modelled from the regression coefficients obtained in the negative binomial regression analysis. The number of pots deployed between 2006 and 2009 were estimated for vessels with length 10-12m using mean estimates.

Fig 5. Distribution of fishing effort (pots.km^{-2}.year^{-1}) in areas with moderate – high confidence for years: 2004-2005; 2006-2007; 2008-2009; 2010-2011; 2012-2013.

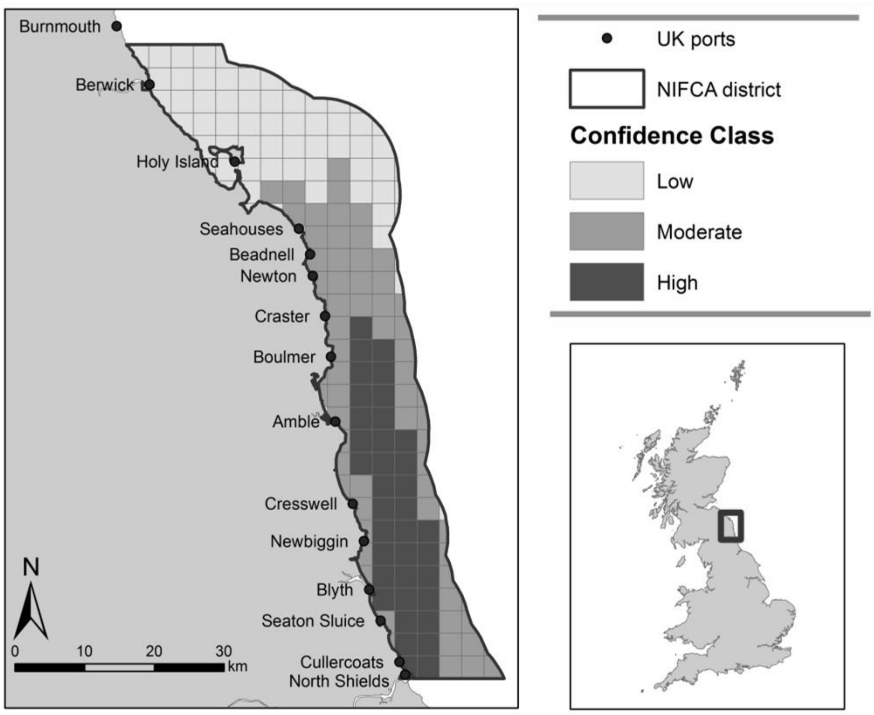
Fig 6. Changes in distribution of fishing effort (pots.km^{-2}.year^{-1}) in areas with moderate - high confidence between 2004-2013.

Fig 7. Results of the eigenanalysis of selection ratios for habitat selection by potting vessels during 2004-2013 (labelled 1-10) on broadscale habitat variables.

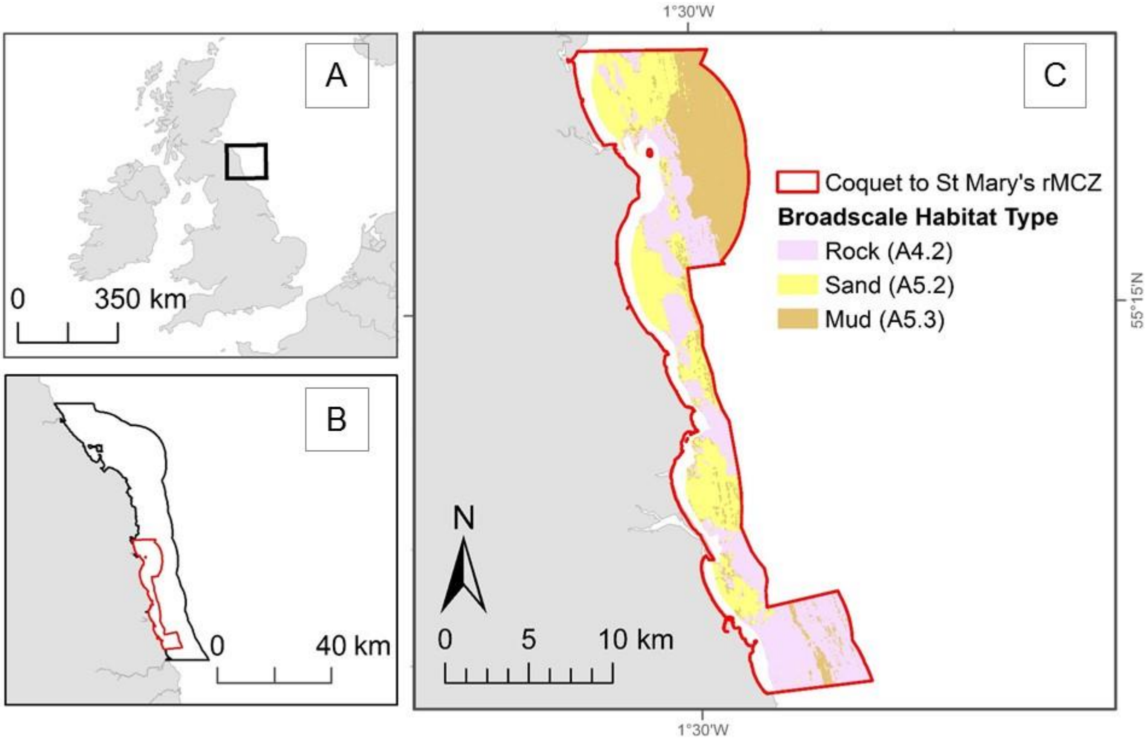
Figures

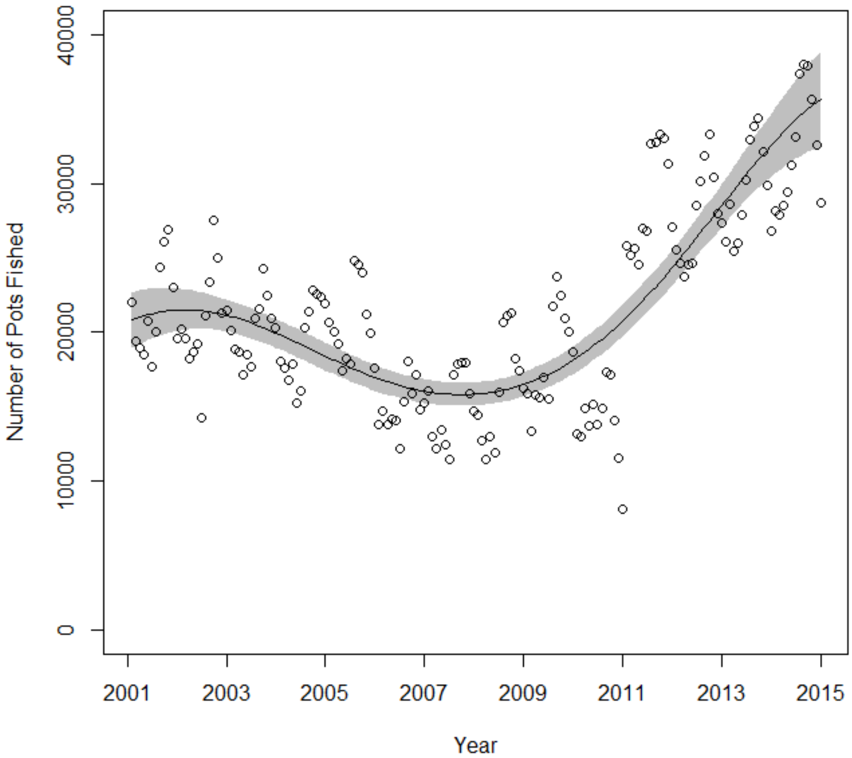


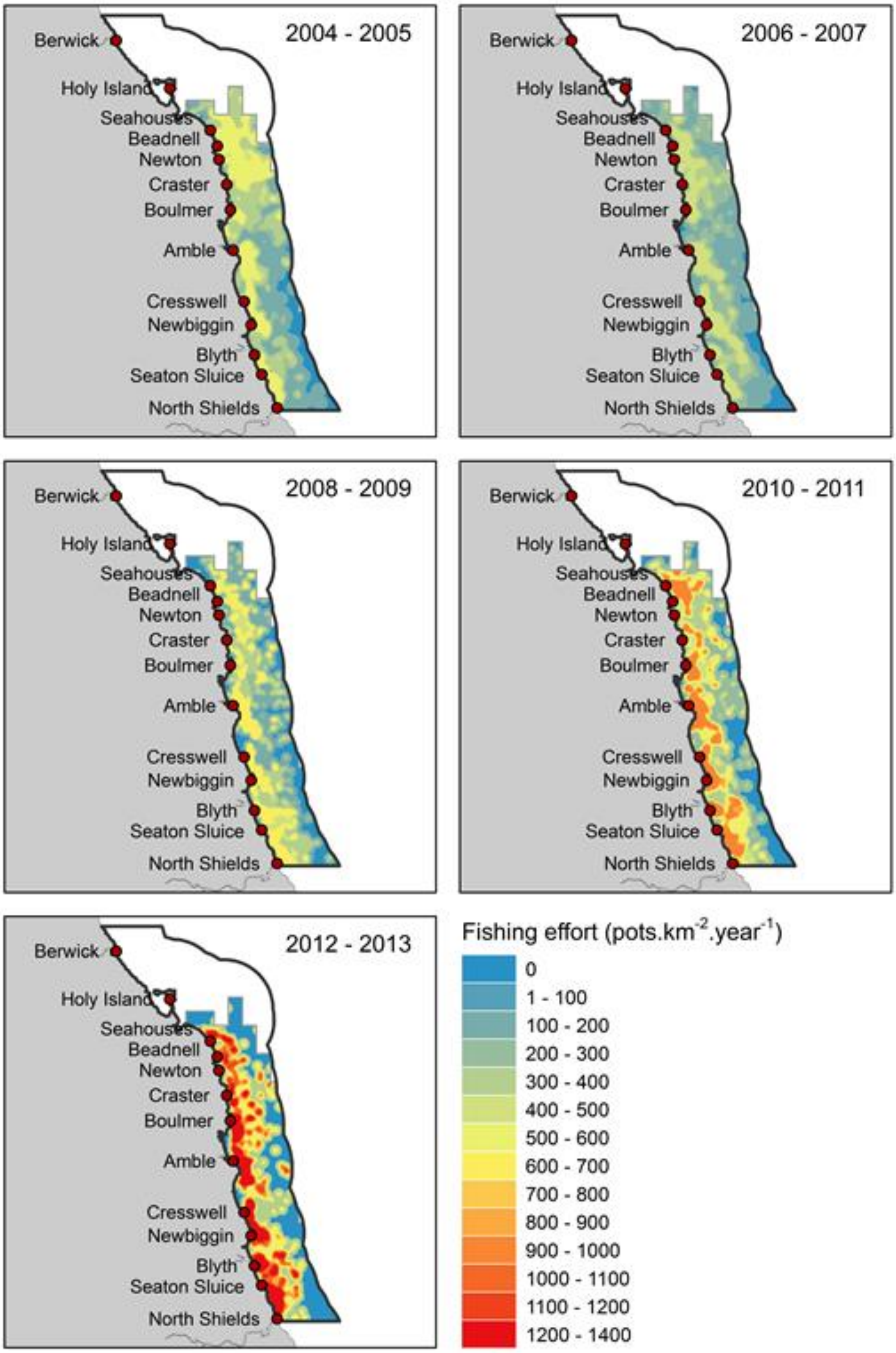
Vessel sightings
Shellfish landing data
Sightings adjusted for patrol effort
Kernel Density Estimation
Percentage Volume Contours
NIFCA District potting effort distribution
Moderate – high confidence potting effort distribution
Patrol routes
Confidence assessment

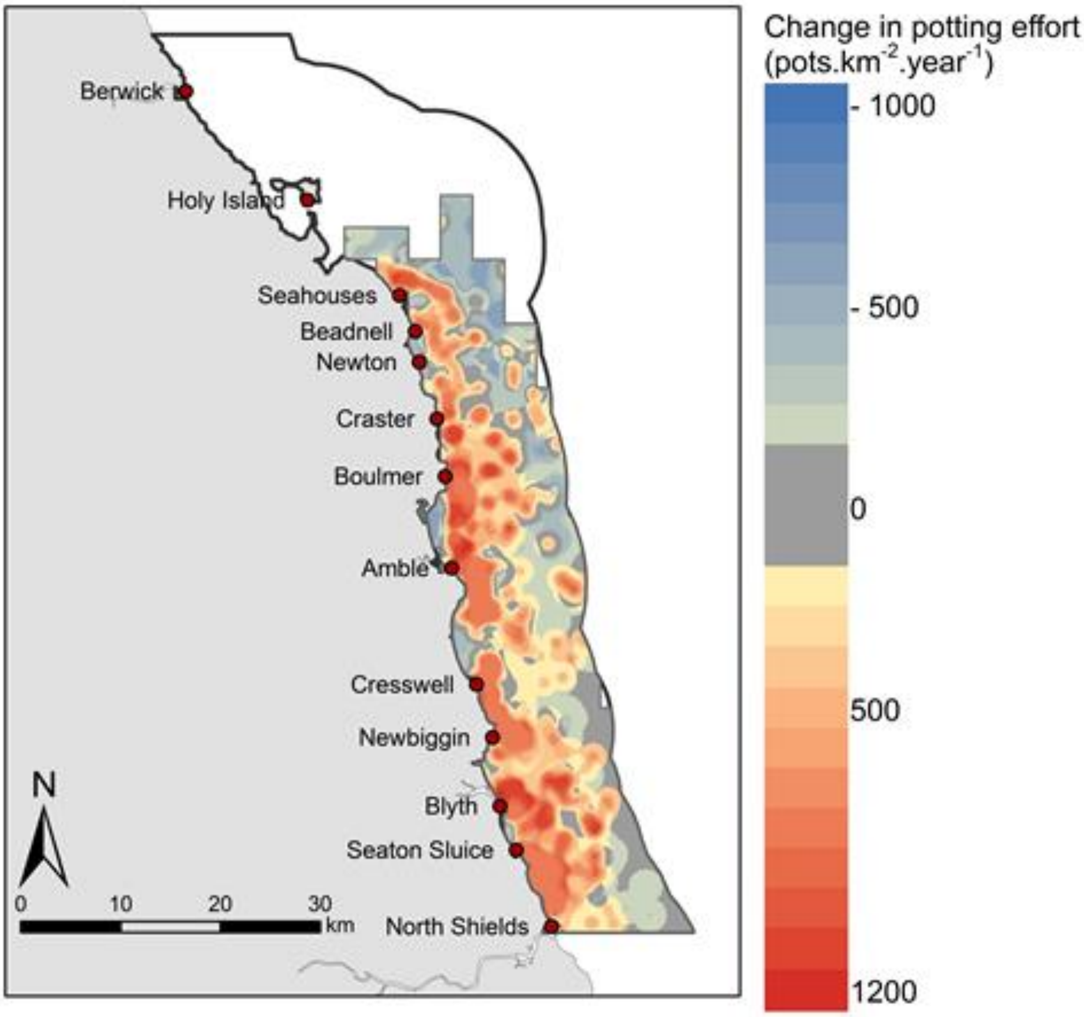


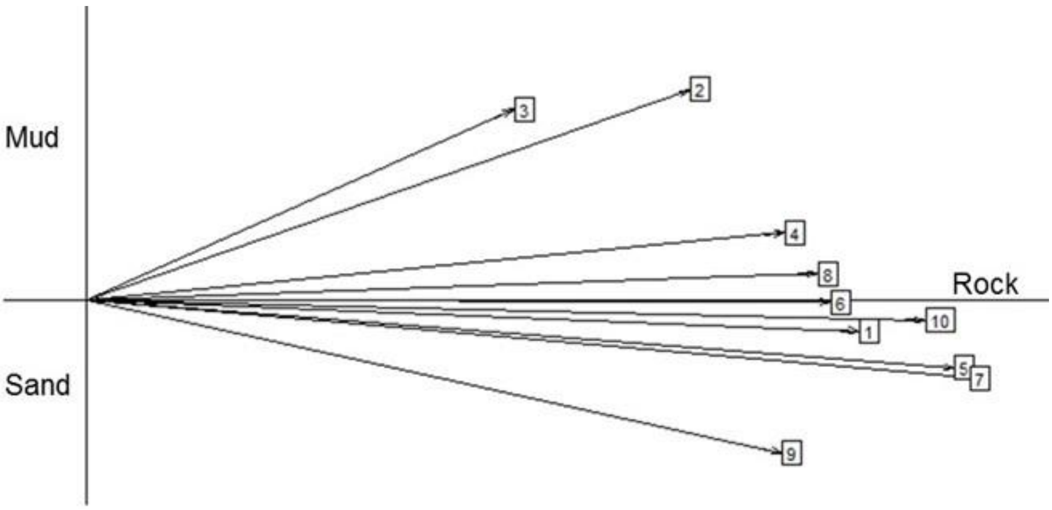
Burnmouth
Berwick
Holy Island
Seahouses
Beadnell
Newton
Craster
Boulmer
Amble
Cresswell
Newbiggin
Blyth
Seaton Sluice
Cullercoats
North Shields
N
0
10
20
30
km
UK ports
NIFCA district
Confidence Class
Low
Moderate
High


A
0
350 km
B
0
40 km
C
1°30'W
55°15'N
Coquet to St Mary's rMCZ
Broadscale Habitat Type
Rock (A4.2)
Sand (A5.2)
Mud (A5.3)
N
0
5
10 km


Number of Pots Fished
0
10000
20000
30000
40000
2001
2003
2005
2007
2009
2011
2013
2015
Year


2004 - 2005
2006 - 2007
2008 - 2009
2010 - 2011
2012 - 2013
Berwick
Holy Island
Seahouses
Beadnell
Newton
Craster
Boulmer
Amble
Cresswell
Newbiggin
Blyth
Seaton Sluice
North Shields
Fishing effort (pots.km^{-2}.year^{-1})
0
1 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
800 - 900
900 - 1000
1000 - 1100
1100 - 1200
1200 - 1400


Change in potting effort
(pots.km^{-2}.year^{-1})
- 1000
- 500
0
500
1200
Berwick
Holy Island
Seahouses
Beadnell
Newton
Craster
Boulmer
Amble
Cresswell
Newbiggin
Blyth
Seaton Sluice
North Shields
N
0
10
20
30
km


Mud
Sand
Rock
1
2
3
4
5
6
7
8
9
10