Managed realignment for habitat compensation: use of a new intertidal habitat by fishes

A. D. NUNN[1,*], D. CLIFTON-DEY[2] and I. G. COWX[1]

[1]*Hull International Fisheries Institute, School of Biological, Biomedical & Environmental Sciences, University of Hull, Hull, HU6 7RX, UK.*

[2]*Environment Agency, Kings Meadow House, Kings Meadow Road, Reading, RG1 8DQ, UK.*

Running headline: Use of a new intertidal habitat by fishes

Key words: climate change; coastal squeeze; flood defence; habitat creation; habitat loss; mudflat development.

ABSTRACT

Managed realignment has become an increasingly common mechanism to increase the efficiency and sustainability of flood defences, reduce defence costs or compensate for habitat losses. This study investigated the use by fishes of a new intertidal habitat, created by managed realignment, intended to compensate for the loss of mudflat associated with a major port development. Although broadly similar, statistically significant differences in fish species composition, abundance, biomass, size structure, diversity and diet composition indicate that the managed realignment is not yet

[*]Author to whom correspondence should be addressed. Tel.: +44 (0)1482 466429; fax: +44 (0)1482 465458; email: a.d.nunn@hull.ac.uk

functioning in an identical manner to the mudflat in the adjacent estuary, most likely due to differences in habitat between sites. Notwithstanding, similarity in the species composition of fyke catches in the managed realignment and estuary increased annually during the 5-year study period, suggesting that the mudflat in the realignment is still developing. Indeed, the site will inevitably change over time with accretion, establishment of vegetation and possibly development of creeks. This will not necessarily prevent the aim of the realignment scheme being achieved, as long as sufficient suitable mudflat remains.

INTRODUCTION

Intertidal habitats support high biological productivity (McLusky *et al*., 1992; Ysebaert *et al*., 2003), contribute to flood defence (Dixon *et al*., 1998) and provide important habitats for fishes (Elliott *et al*., 2007; Ramos *et al*., 2012) and birds (Atkinson *et al*., 2004; Mander *et al*., 2007). Many intertidal areas, however, are subjected to a range of anthropogenic pressures. Of particular importance is land claim for industrial development (McLusky *et al*., 1992; Esteves, 2014). Land claim can have direct negative impacts on intertidal biota, and profound implications for ecosystem functioning through the role of the biological communities in sediment dynamics, biogeochemical cycling, benthic metabolism and trophic interactions (Herringshaw & Solan, 2008). Loss of intertidal areas can also increase the risk of flooding, which is likely to be exacerbated by the effects of climate change, especially in areas already experiencing coastal squeeze (Mazik *et al*., 2007; Pontee, 2013; Esteves, 2014). It is therefore desirable, sometimes necessary, to compensate for habitat losses due to land claim, especially those predicted to compromise the integrity of designated conservation areas (Morris, 2013; Esteves, 2014).

Managed realignment – the deliberate process of realigning river, estuary or coastal flood defences – has become an increasingly common mechanism to increase the efficiency and sustainability of flood defences, reduce defence costs or compensate for habitat losses (e.g. Ledoux *et al*., 2005; Garbutt *et al*., 2006; Mazik *et al*., 2007; Rupp-Armstrong & Nicholls, 2007; Shih & Nicholls, 2007; Esteves, 2013; Morris, 2013; Pétillon *et al*., 2014). Managed realignment also has the potential to enhance fish diversity, recruitment and production by increasing the availability and diversity of intertidal habitats, such as mudflats and salt marshes (Dixon *et al*., 1998; Colclough *et al*., 2005; French, 2006). It is essential, however, that the physical characteristics and biological communities of managed realignments replicate those being lost if habitat compensation is to be truly successful (Mazik *et al*., 2010).

A port and logistics centre is being developed on the north bank of the Thames Estuary, England. The development includes a container terminal to accommodate the largest deep-sea container ships, and was considered likely to have an adverse impact on the integrity of the Thames Estuary and Marshes Special Protection Area (SPA) and Ramsar Site. Predicted direct impacts of the development on physical habitats included: (1) conversion of 5 ha of designated intertidal habitat to shallow subtidal habitat; (2) destruction of 25 ha of undesignated intertidal habitat; (3) changes in accretion over 60 ha of intertidal habitat, potentially converting 10 ha of mudflat to saltmarsh; (4) long-term impacts on 90 ha of subtidal habitat affected by capital dredging; and (5) temporary damage to >1700 ha of subtidal habitat outside the SPA and Ramsar Site (Morris & Gibson, 2007). To compensate for part of the impacts on the Thames Estuary and Marshes SPA and Ramsar Site and ensure the overall coherence of the Natura 2000 network is maintained, a minimum of 74 ha of new intertidal mudflat is being created through managed realignment (Morris & Gibson, 2007). Habitat creation and improvement of flood defences are common objectives of managed realignment schemes (French, 2006; Esteves, 2013), but few studies have assessed their use by fishes (e.g. Colclough *et al*., 2005). The aim of this study was to advance the understanding of the use by fishes of intertidal habitats created through managed realignment by investigating changes over a 5-year period. The hypothesis was that the species composition, size structure, abundance, biomass and diet composition of fishes in the realignment and adjacent estuary would increase in similarity as the mudflat in the realignment developed. High similarities in these parameters in the two sites should suggest that the realignment is functioning in a similar manner to the mudflat in the adjacent estuary, and that the aim of the realignment scheme, namely to compensate for losses of mudflat associated with port development, is being achieved (*cf.* Mazik *et al*., 2007, 2010; Mossman *et al*., 2012).

METHODOLOGY

Sampling strategy, methods and techniques

London Gateway Site A managed realignment (51.50232 °N, 0.44799 °E; also known as Stanford Wharf Nature Reserve) is located to the east of Mucking Creek, near Stanford-le-Hope, on the north bank of the Thames Estuary, England. The site was created in 2010 by reducing the level of 27 ha of former agricultural land and creating a 300-m-wide breach in the sea defences to the south. Fish surveys were conducted during spring tides in October and November 2010 and April, June and August 2011-2014. These timeframes coincide with the larval and juvenile periods of many fishes, thus enabling assessment of the function of the habitat (e.g. nursery) for specific species (*cf.* Nunn *et al*., 2007). The sampling frequency therefore accounts for temporal variations in fish community structure associated with the phenology of fish hatching and ontogenetic and seasonal shifts in habitat use. A combination of active (seine, epibenthic trawl) and passive (fyke) gear types with replicated sampling stations was included in the design, to provide as accurate an assessment as possible of the species composition, size structure, density and biomass of fishes in the realignment and adjacent estuary (immediately to the east of the realignment); using a range of methods at fixed stations in a seasonal format is recommended to obtain a robust assessment of intertidal fish communities (Colclough *et al*., 2005). Gear types were selected based on the potential operational constraints imposed by realignment sites (e.g. deep mud, benthic obstructions, semi-permanent flooding regimes, deep creeks) and the usual development of newly created intertidal areas (e.g. accretion, establishment of vegetation). Fine-meshed gears were employed due to the expected dominance of small-sized species or individuals in the fish assemblages using newly created intertidal areas. Multi-method approaches, recognised as European best practice (Hemingway & Elliott, 2002), have been successfully employed elsewhere to examine the use of intertidal areas by fishes, including in managed realignments, and as a tool for assessing the ecological status of estuaries (e.g. Laffaille *et al*., 2000; Colclough *et al*., 2002, 2005; Coates *et al*., 2007). Up to 50 individuals of each fish species were measured (total length, L_T, mm) and weighed (0.01 g) for each sample, with the remainder identified and counted. There were no significant differences in water temperature (paired *t*-test, d.f. = 13, $t = 0.929$, $P = 0.370$) or salinity (paired *t*-test, d.f. = 11, $t = 0.150$, $P = 0.884$), recorded at 15-minute intervals using an Aqua TROLL 200 data logger, in the realignment and adjacent estuary.

Fyke netting

Fykes were deployed at four stations in the realignment and two in the estuary, and left for one tidal cycle. The nets were emptied as they became exposed by the receding tide and then left for another tidal cycle, thereby allowing separate analysis of diurnal and nocturnal catches (total $n = 180$). Each gear consisted of two fykes (53-cm entrance, 10-m central panel, 14-mm mesh) joined entrance-to-entrance by their leader panels; data from each gear were expressed as the abundance and biomass of fishes per ‘fyke-hour’ (i.e. the number of hours that the gear was inundated). Fykes were set at the same shore height in the realignment and estuary to ensure they sampled comparable water depths, allowing an assessment of the larger fishes using the area (Colclough *et al*., 2005).

Seine netting

A micromesh beach seine (25-m long, 3-m deep, 3-mm hexagonal mesh) was set at eight stations in the realignment and two in the estuary; data from each sample (total n = 150) were expressed as the abundance and biomass of fishes per m^2. The area sampled by the seine was calculated from direct *in situ* measurements (i.e. length × width of the area enclosed by the net). This method allowed an assessment of the smaller fishes using the area (Cowx *et al*., 2001; Colclough *et al*., 2002, 2005; Coates *et al*., 2007).

Trawling

Trawling was conducted using an epibenthic sledge fitted with a tickle chain and a 0.5-mm-meshed cod-end (Nitex cloth), to target benthic species and individuals for which the fyke mesh was too large (Colclough *et al*., 2002, 2005; Coates *et al*., 2007). The trawl was pulled by hand at ~1 m s^{-1}; data from each sample (total n = 135) were expressed as the abundance and biomass of fishes per m^2. The area sampled by the trawl was calculated by multiplying the width of the trawl entrance (1 m) by the length of each transect (20 m). Three replicates were collected at each of three stations in the realignment (nine trawls in total); trawling was not conducted in the estuary due to safety issues.

Data analysis

The relative abundance of each fish species in the managed realignment and the estuary was calculated for the entire study period and each gear type. Bray-Curtis similarity matrices (Bray & Curtis, 1957) were calculated using the relative abundance of each fish species and ordinated using non-metric multidimensional scaling (MDS) to investigate similarities in the species composition of fyke and seine catches in the realignment and estuary. The matrices were then submitted to permutational multivariate analysis of variance (PERMANOVA) (9999 random permutations) to assess the statistical significance of any differences in the species composition of fyke and seine catches in the realignment and estuary (Anderson, 2001; Anderson *et al*., 2008). In addition, similarity percentages (SIMPER) analysis was used to calculate the percentage contributions of key fish species to dissimilarities in fyke and seine catches in the realignment and estuary (Clarke & Warwick, 2001). Mean Shannon-Wiener diversity (*H'*) and Pielou's evenness (*J*) were compared for fyke and seine catches in the realignment and estuary using independent samples *t*-tests (Washington, 1984).

Mean lengths of the most abundant fish species were compared for fyke and seine catches in the realignment and estuary, and diurnal and nocturnal fyke catches, using independent samples *t*-tests (Dytham, 2003). Length distributions of the most abundant species were compared for fyke and seine catches in the realignment and estuary, and diurnal and nocturnal fyke catches, using two-sample Kolmogorov-Smirnov tests (Dytham, 2003). For seine and trawl catches, the density (fish m^{-2}) and biomass (g m^{-2}) of fishes in each sample were calculated by dividing their abundance and biomass, respectively, by the area sampled. For fyke catches, abundance and biomass were expressed, respectively, as catch-per-unit-effort (CPUE; fish h^{-1}) and biomass-per-unit-effort (BPUE; g h^{-1}). Mean densities, biomasses, CPUE and BPUE were compared between the realignment and estuary, and diurnal and nocturnal fyke catches, using independent samples *t*-tests (Dytham, 2003).

For each sampling occasion, the stomach contents were removed from a sample of juvenile bass (*Dicentrarchus labrax* (L.)) (n = 139, realignment L_T range 14-103 mm, estuary L_T range 17-110 mm) and common goby (*Pomatoschistus microps* (Krøyer)) (n = 167, realignment L_T range 11-51 mm, estuary L_T range 11-46 mm) captured in the realignment and estuary. Catches of other species were insufficient for a comparison of diet composition in the realignment and estuary in all 5 years. Prey items were identified to the lowest practicable taxonomic level and recorded as percent volume. The diet composition of the most abundant fish species in the realignment and estuary was then compared using PERMANOVA and SIMPER analysis, as described for fish composition.

RESULTS

A total of 39 376 specimens of 16 fish species was captured during the study. Common goby was the most abundant species, accounting for 62% of the total catch, followed by herring (*Clupea harengus* L.) (24%). Other species captured were bass, eel (*Anguilla anguilla* (L.)), flounder (*Platichthys flesus* (L.)), plaice (*Pleuronectes platessa* L.), sand goby (*Pomatoschistus minutus* (Pallas)), sand smelt (*Atherina presbyter* Cuvier), smelt (*Osmerus eperlanus* (L.)), sole (*Solea solea* (L.)), sprat (*Sprattus sprattus* (L.)), ten-spined stickleback (*Pungitius pungitius* (L.)), thick-lipped grey mullet (*Chelon labrosus* (Risso)), thin-lipped grey mullet (*Liza ramada* (Risso)), three-spined stickleback (*Gasterosteus aculeatus* L.) and whiting (*Merlangius merlangus* (L.)).

Species composition

There was a significant difference in the species composition of fyke catches in the realignment and estuary (Fig. 1; PERMANOVA, d.f. = 1, F = 5.277, P < 0.001). Catches in both sites were dominated by bass and flounder (76% in the realignment, 66% in the estuary), but the relative abundances of bass and eel were higher in the realignment, whereas those of flounder, smelt and sole were higher in the estuary (Table 1). Notwithstanding, similarity between the realignment and estuary increased annually during the study period, from 29% in 2010 to 43% in 2014 (2011 = 33%, 2012 = 34%, 2013 = 41%). There was no significant difference in species composition between years (PERMANOVA, d.f. = 4, F = 1.801, P = 0.120), and there was no significant interaction between site and year (PERMANOVA, d.f. = 4, F = 0.854, P = 0.604). Although the relative abundances of bass and flounder were highest during daylight and those of eel and sole were highest at night (Table 2), there were no statistically significant differences in the species composition of diurnal and nocturnal fyke catches in the realignment (PERMANOVA, d.f. = 1, F = 0.623, P = 0.718) or estuary (PERMANOVA, d.f. = 1, F = 1.646, P = 0.188). Over the 5-year study period, the mean diversity of fyke catches was significantly higher in the estuary than the realignment (independent samples t-test, d.f. = 86, t = 3.252, P = 0.002), but there was no significant difference in evenness (independent samples t-test, d.f. = 86, t = 1.756, P = 0.083).

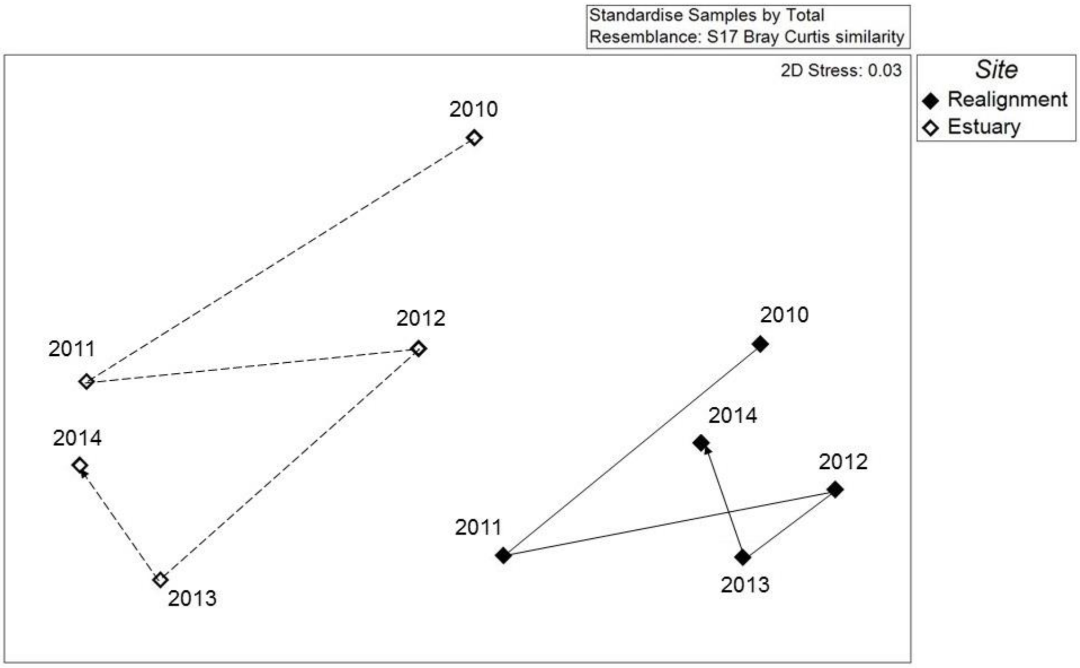

Fig. 1. Non-metric multidimensional scaling (MDS) ordination plot comparing the fish species composition of fyke catches (2010-2014 centroids with trajectories) in the managed realignment and estuary.

Table 1. Similarity percentages (SIMPER) analysis of the mean relative abundances of key fish species and their percentage contributions to dissimilarities in fyke and seine catches in the managed realignment (R) and estuary (E).

	Fyke				**Seine**		
Species	**R**	**E**	**%**	**Species**	**R**	**E**	**%**
Bass	47.9	18.2	32.6	Bass	24.3	37.9	27.0
Flounder	27.7	47.6	27.7	Common goby	32.0	30.3	26.7
Eel	16.4	9.5	14.8	Herring	17.2	8.4	15.3
Smelt	4.2	15.2	13.2	Three-spined stickleback	8.0	8.1	9.8
Sole	0.5	6.6	6.0	Thin-lipped grey mullet	7.2	7.8	8.8
				Flounder	2.4	4.9	4.7

Mean dissimilarity	**56.3**	**Mean dissimilarity**	**73.3**

Table 2. Similarity percentages (SIMPER) analysis of the mean relative abundances of key fish species and their percentage contributions to dissimilarities in diurnal (D) and nocturnal (N) fyke catches in the managed realignment and estuary.

Realignment				**Estuary**			
Species	**D**	**N**	**%**	**Species**	**D**	**N**	**%**
Bass	52.4	35.2	34.9	Flounder	52.2	49.5	32.2
Flounder	28.5	32.2	28.2	Bass	20.0	14.1	21.8
Eel	11.9	25.6	24.7	Smelt	12.2	13.1	16.6
Smelt	4.1	3.6	6.3	Eel	8.8	10.1	13.1
				Sole	4.8	11.5	13.0
Mean dissimilarity			**53.9**	**Mean dissimilarity**			**53.4**

In seine catches, the relative abundance of herring was highest in the realignment whereas those of bass and flounder were highest in the estuary (Table 1), but there were no statistically significant differences in species composition between sites (PERMANOVA, d.f. = 1, F = 1.341, P = 0.240) or years (PERMANOVA, d.f. = 4, F = 0.820, P = 0.660) (Fig. 2); there was also no significant difference in the composition of trawl catches between years (PERMANOVA, d.f. = 4, F = 1.237, P = 0.353). Over the 5-year study period, there were no significant differences in the mean diversity (independent samples t-test, d.f. = 130, t = 1.318, P = 0.190) or evenness (independent samples *t*-test, d.f. = 130, *t* = 1.271, *P* = 0.206) of seine catches in the realignment and estuary.

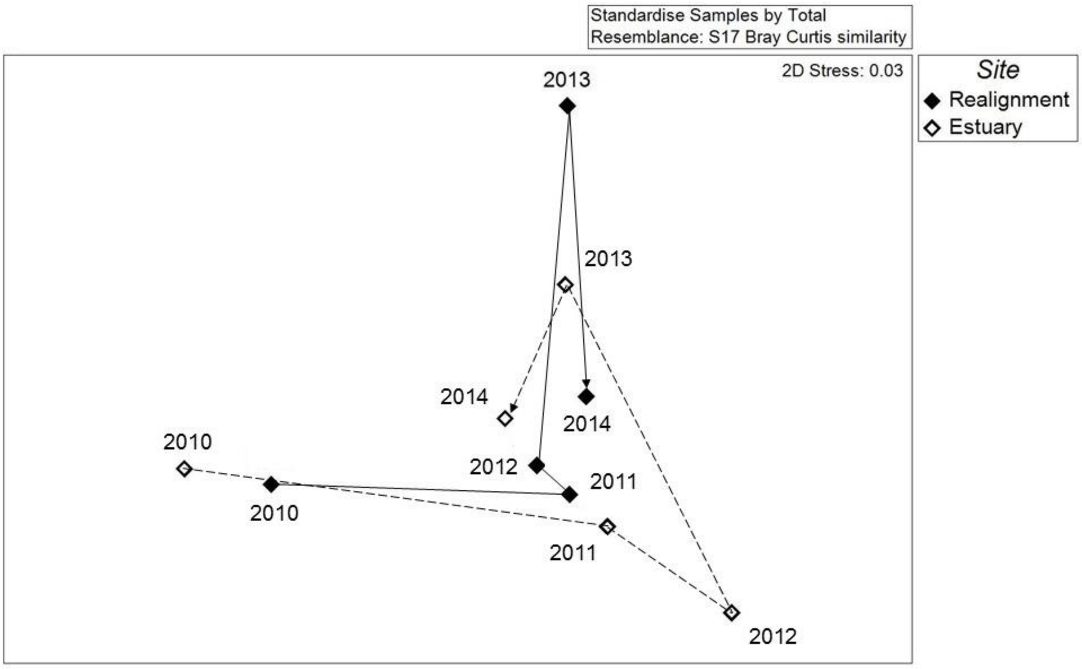

Fig. 2. Non-metric multidimensional scaling (MDS) ordination plot comparing the fish species composition of seine catches (2010-2014 centroids with trajectories) in the managed realignment and estuary.

Size structure

Overall, the mean lengths of bass (independent samples *t*-test, d.f. = 860, *t* = 4.875, *P*<0.001) and flounder (independent samples *t*-test, d.f. = 281, *t* = 7.202, *P*<0.001) in fyke catches and common goby (independent samples *t*-test, d.f. = 1102, *t* = 14.016, *P*<0.001) in seine catches were significantly larger in the realignment than the estuary, whereas bass in seine catches were larger in the estuary (independent samples *t*-test, d.f. = 1183, *t* = 9.015, *P*<0.001). In addition, bass (independent samples *t*-test, d.f. = 706, *t* = 2.056, *P* = 0.040) and eel (independent samples *t*-test, d.f. = 118, *t* = 2.030, *P* = 0.045) in fyke catches in the realignment were significantly larger during daylight than at night, but there were no other diel differences in the mean lengths of bass, eel and flounder in the realignment or estuary (independent samples *t*-tests, all $P>0.05$).

Modes representing the 0+ age class were present in the length distributions of bass, common goby, flounder and herring in all years, with juveniles of most other species also caught in some years. Overall, there were significant differences in the length distributions of bass (two-sample Kolmogorov-Smirnov test, $Z = 3.388$, $P<0.001$) and flounder (two-sample Kolmogorov-Smirnov test, $Z = 4.350$, $P<0.001$) in fyke catches and bass (two-sample Kolmogorov-Smirnov test, $Z = 6.509$, $P<0.001$) and common goby (two-sample Kolmogorov-Smirnov test, $Z = 5.653$, $P<0.001$) in seine catches in the realignment and the estuary (Fig. 3), and also of bass (two-sample Kolmogorov-Smirnov test, $Z = 1.849$, $P = 0.002$) and flounder (two-sample Kolmogorov-Smirnov test, $Z = 1.390$, $P = 0.042$) in fyke catches in the realignment during the day and at night. Data were insufficient for between-site and diel comparisons of length distributions for other species.

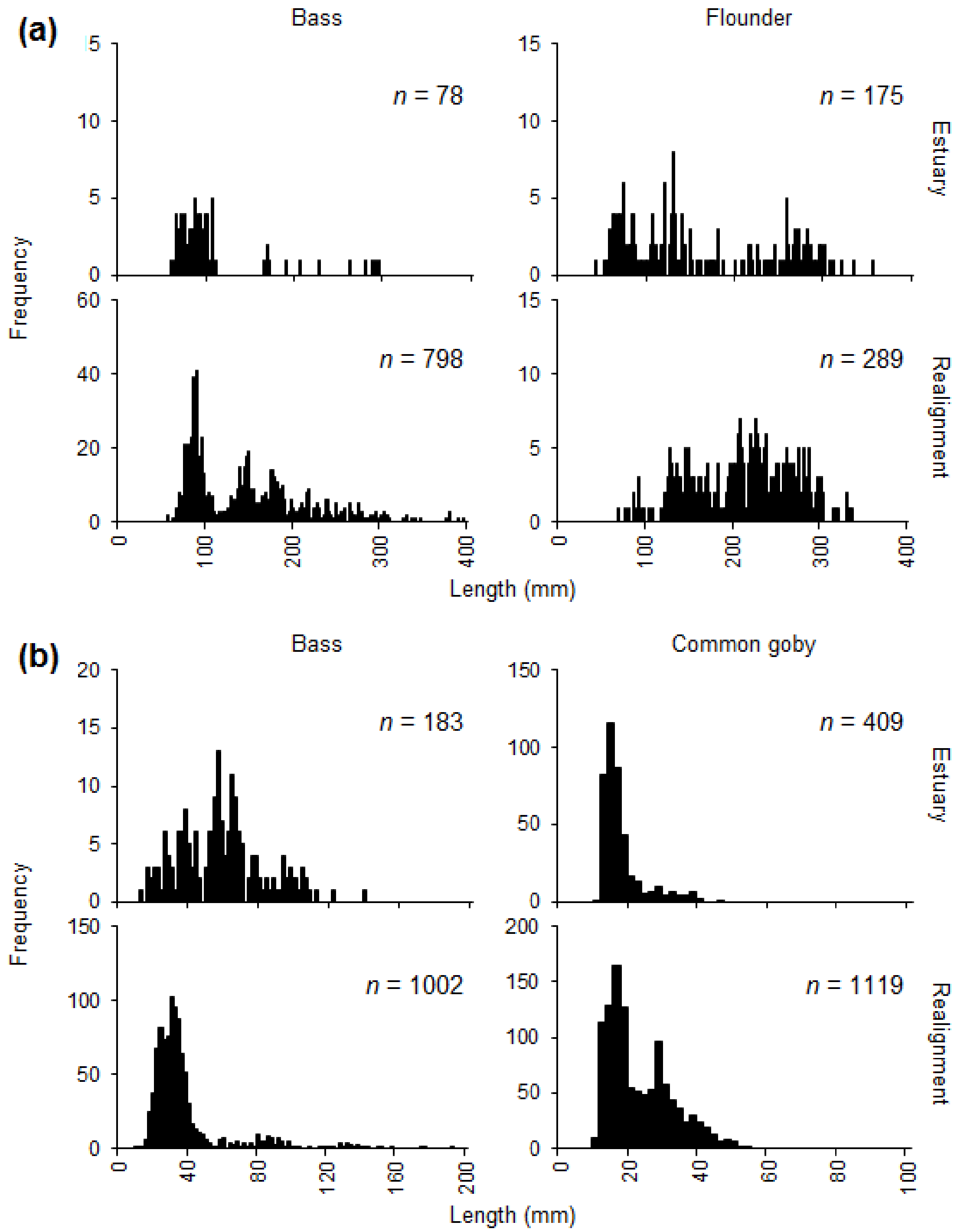

Fig. 3. Length distributions of (a) bass and flounder in fyke catches and (b) bass and common goby in seine catches in the managed realignment and estuary.

Abundance and biomass

With the exceptions of BPUE in 2010 and density and CPUE in 2014, mean annual catches were always highest in the realignment (Fig. 4), and overall mean densities (independent samples *t*-test, d.f. = 126, *t* = 2.327, *P* = 0.022), biomasses (independent samples *t*-test, d.f. = 117, *t* = 2.437, *P* = 0.016), CPUE (independent samples *t*-test, d.f. = 77, *t* = 3.171, *P* = 0.002) and BPUE (independent samples *t*-test, d.f. = 84, *t* = 4.142, *P*<0.001) were significantly higher in the realignment than the estuary. In addition, mean CPUE (independent samples *t*-test, d.f. = 85, *t* = 2.947, *P* = 0.004) and BPUE (independent samples *t*-test, d.f. = 63, *t* = 5.299, *P*<0.001) in the realignment and CPUE in the estuary (independent samples *t*-test, d.f. = 40, *t* = 2.126, *P* = 0.040) were significantly higher during daylight than at night, but there was no significant diel difference in BPUE in the estuary (independent samples *t*-test, d.f. = 50, *t* = 1.719, *P* = 0.092).

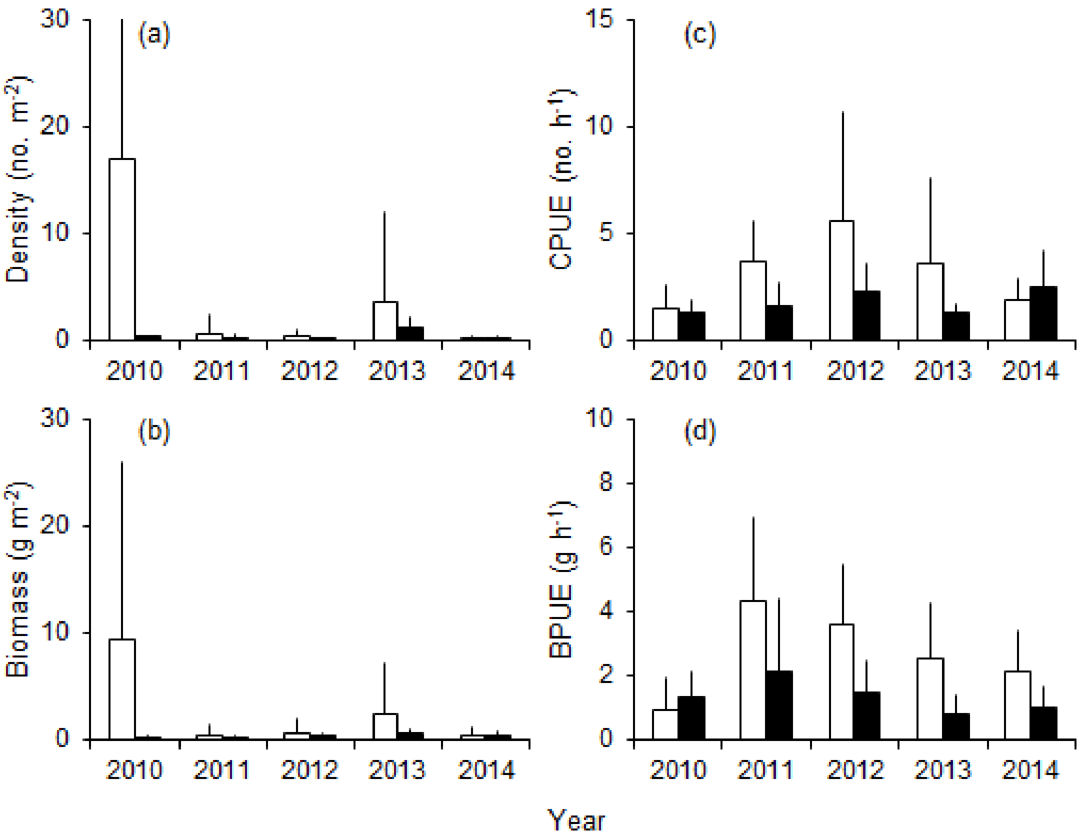

Fig. 4. Mean (± S.D.) fish (a) density and (b) biomass in seine catches and (c) catch-per-unit-effort (CPUE) and (d) biomass-per-unit-effort (BPUE) in fyke catches in the managed realignment (white bars) and estuary (black bars), 2010-2014.

Diet composition

In 2010, the diets of bass in the realignment were dominated by harpacticoid copepods, with palaemonids and gammarids also consumed; insufficient fish were captured from the estuary for analysis of diet composition (Fig. 5a). In 2011, bass in the realignment preyed mainly upon oligochaetes, mysids and corophiids, while mysids and corophiids dominated diets in the estuary (Fig. 5a). Corophiids dominated the diets of bass in both the realignment and estuary in 2012, with small amounts of mysids also consumed in both habitats (Fig. 5a). In 2013, bass in the realignment preyed mainly upon corophiids and polychaetes, although mysids, oligochaetes and harpacticoid copepods were also consumed; insufficient fish were captured from the estuary for analysis (Fig. 5a). Corophiids were the main prey of bass in the estuary in 2014, whereas corophiids, polychaetes and mysids were consumed in the realignment (Fig. 5a). There were no consistent differences in the diets of bass in the realignment and estuary (PERMANOVA, d.f. = 1, F = 1.741, P = 0.184), although the mean relative abundances of polychaetes, harpacticoid copepods and oligochaetes were higher in the realignment than the estuary, whereas corophiids were more abundant in the estuary (Table 3).

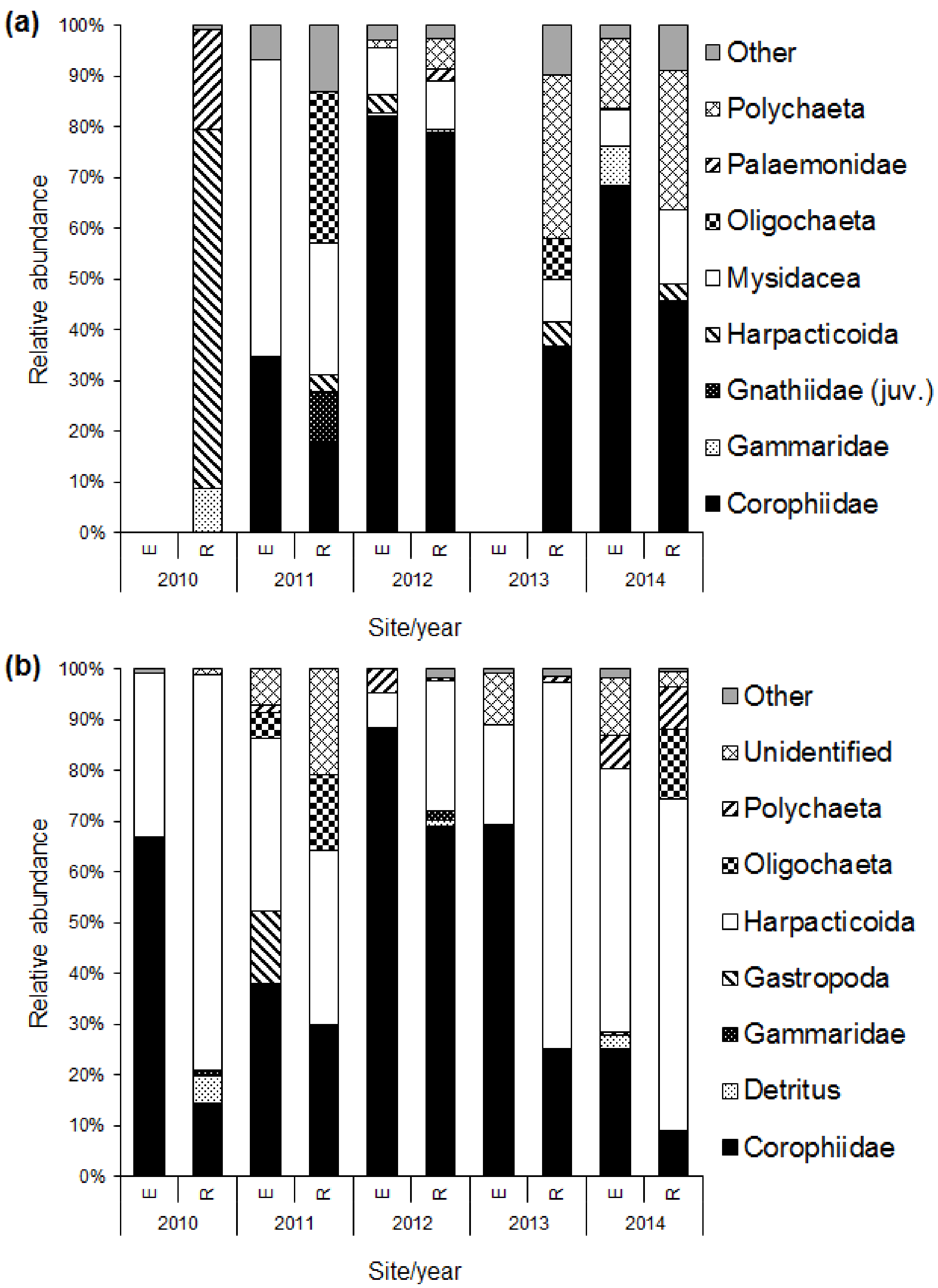

Fig. 5. Diet composition of juvenile (a) bass and (b) common goby in the managed realignment (R) and estuary (E), 2010-2014.

Table 3. Similarity percentages (SIMPER) analysis of the mean relative abundances of key prey taxa and their percentage contributions to dissimilarities in the diets of juvenile bass and common goby in the managed realignment (R) and estuary (E).

	Bass				C. goby		
Taxa	**R**	**E**	**%**	**Taxa**	**R**	**E**	**%**
Corophiidae	45.5	70.4	38.3	Corophiidae	30.3	55.9	38.9
Mysidacea	11.1	17.7	18.8	Harpacticoida	50.8	30.2	36.6
Polychaeta	15.5	4.2	14.6	Oligochaeta	7.3	0.8	6.2
Harpacticoida	10.4	2.0	9.9				
Oligochaeta	5.3	0.0	4.4				
Mean dissimilarity			**60.6**	**Mean dissimilarity**			**63.2**

In 2010 and 2013, the diets of common goby in the realignment were dominated by harpacticoid copepods, whereas corophiids were dominant in the estuary (Fig. 5b). In 2011, corophiids, harpacticoid copepods and oligochaetes characterised the diets in both the realignment and estuary, with gastropods also important at the latter site (Fig. 5b). Corophiids dominated the diets of common goby in both the realignment and estuary in 2012, although harpacticoid copepods were also consumed, especially in the realignment (Fig. 5b). The diets in 2014 were similar to those in 2011, with harpacticoid copepods the most abundant prey in both the realignment and estuary (Fig. 5b). There was a significant difference in the diets of common goby in the realignment and estuary (PERMANOVA, d.f. = 1, F = 7.730, P = 0.004), with the mean relative abundances of harpacticoids and oligochaetes higher in the realignment than the estuary, whereas corophiids were more abundant in the estuary (Table 3).

DISCUSSION

French (2006) concluded, from a review of the literature, that fish use of suitable managed realignments and reference sites is virtually identical. In this study, however, there was a significant difference in the species composition of fyke catches in the realignment and estuary. In addition, mean densities, CPUE, biomasses and BPUE were higher in the realignment than the estuary, whereas the mean diversity of fyke catches was higher in the estuary. Catches in the realignment are necessarily dependent upon the fishes present in the adjacent estuary, as the site drains at low water, so the causes of the differences are not immediately obvious. It is possible that the manner in which the site floods, or where the gears were deployed in relation to the routes that certain fish species use to enter and leave the site, may have had an influence on the catches. For example, it is possible that fishes enter the drainage ditches with the flooding tide and then disperse across the realignment when the ditches over-top, as observed elsewhere (Colclough *et al*., 2005; Fonseca *et al*., 2011). Indeed, densities in seine catches in November 2010 were substantially higher than at any other time during the study because large numbers of fishes were aggregated, and efficiently captured, in a drainage ditch that did not over-top. It is also possible that the deployment of the fykes close to ditches and the breach effectively increased their efficiency relative to those in the estuary, because fishes using the realignment must pass the gears when entering and leaving the site, whereas fishes in the estuary may only pass the gears once. However, the species composition of fyke catches in the realignment and estuary increased in similarity annually during the study period, suggesting that there are differences in habitat between sites but, moreover, that the mudflat in the realignment is still developing. By contrast, there was no significant difference in the species composition of seine catches in the realignment and estuary, possibly because small fishes (targeted by the seine) moved passively into the sampling areas, whereas larger individuals (targeted by the fykes) exhibited active habitat selection (Colclough *et al*., 2002; Gibson, 2003).

The majority of catches were dominated by juvenile individuals, demonstrating the importance of the realignment as a nursery area; a similar observation was made by Colclough *et al*. (2005). Larger fishes, especially bass and flounder, also used the realignment, presumably to forage on the abundant juvenile fishes and crustaceans in the site. Overall, the mean lengths of bass and flounder in fyke catches and common goby in seine catches were significantly larger in the realignment than the estuary, whereas bass in seine catches were larger in the estuary. These were unlikely to have been caused by spatial differences in growth rate linked to temperature regime or food availability because the site drains at low tide, so any fishes using the site will necessarily mix with others in the estuary. More likely is that it was caused by size-related differences in habitat use (Gibson, 2003; Colclough *et al*., 2005; Elliott *et al*., 2007) linked to differences in habitat characteristics in the realignment and estuary.

Although the mean relative abundance of bass was highest during daylight and that of eel was highest at night, there was no statistically significant difference in the species composition of diurnal and nocturnal fyke catches in the realignment (or the estuary). Contrary to expectations, however, mean CPUE and BPUE in the realignment and CPUE in the estuary were significantly higher during daylight than at night, and the mean lengths of bass and eel in the realignment were significantly larger during daylight than at night (due to an absence of the largest individuals at night). These results suggest that fewer fishes entered the sampling area at night than during daylight, and that there were size-specific, but not species-specific, differences in diel use of the realignment. By contrast, Colclough *et al*. (2005) observed that large bass entered Abbotts Hall managed realignment (Blackwater Estuary, England) at night, possibly because the water was too shallow for larger fish to risk entering during daylight. Nocturnal surveys should therefore be considered when assessing the use of managed realignment sites by fishes, as resource use may be substantially greater over the diel cycle than during daylight or darkness alone (Copp, 2008).

Bass and common goby had relatively narrow diet spectra, with small numbers of taxa, mainly corophiids, copepods, gastropods, mysids or polychaetes, accounting for the majority of the diet; similar results have been obtained elsewhere (Hampel & Cattrijsse, 2004; Laffaille *et al*., 2001; Fonseca *et al*., 2011; Nunn *et al*., 2012; Leclerc *et al*., 2014). There were no consistent differences in the diets of bass in the realignment and estuary, but there was a significant difference in the diets of common goby, with the mean relative abundances of harpacticoid copepods and oligochaetes higher in the realignment than the estuary, whereas corophiids were more abundant in the estuary. Such differences could be caused by spatial variations in prey abundance, prey size, fish size, foraging behaviour and/or microhabitat characteristics. Regarding the latter possibility, the sediment in parts of the realignment appears to have changed little since the site was breached (A. D. Nunn, *pers. obs.*), and may not yet support high densities (or large sizes) of certain benthic species; macroinvertebrate abundance in Paull Holme Strays managed realignment (Humber Estuary, England) was still an order-of-magnitude lower than in the adjacent mudflat 5 years after the site was first flooded (Mazik *et al*., 2010). Similarly, Fonseca *et al*. (2011) observed that 30-59 mm bass consumed benthic prey in natural saltmarshes, but mainly copepods in artificial saltmarshes (managed realignments), which was assumed to have been due to differences in microhabitat characteristics and prey availability.

Although broadly similar, statistically significant differences in fish species composition, abundance, biomass, size structure, diversity and diet composition indicate that the managed realignment is not yet functioning in an identical manner to the mudflat in the adjacent estuary, most likely due to differences in habitat between sites. Notwithstanding, similarity in the species composition of fyke catches in the managed realignment and estuary increased annually during the 5-year study period, suggesting that the mudflat in the realignment is still developing. Indeed, the site will inevitably change over time with accretion, establishment of vegetation and possibly development of creeks (Dixon *et al*., 1998; French, 2006; Garbutt *et al*., 2006; Mazik *et al*., 2010; Kadiri *et al*., 2011; Mossman *et al*., 2012; Spencer *et al*., 2012; Morris, 2013; Pétillon *et al*., 2014). The eastern and northern edges of the site have already accumulated relatively deep mud, similar in depth but of a different consistency to in the estuary, whereas other areas appear largely unchanged since the site was breached (A. D. Nunn, *pers. obs.*). Large numbers of fishes were captured in isolated pools and a drainage channel in 2010, demonstrating the importance of such habitats to fishes in intertidal areas, and similar results have been reported elsewhere (e.g. Colclough *et al*., 2005). However, the depth of water in the pools and drainage channels at low water is now very shallow (due to accretion), and is likely to provide shelter only for small numbers of gobies and juvenile flatfishes; creeks could therefore provide refuge for small fishes at low water and areas of deeper water for larger fishes at high water (Kelley, 1988; Desmond *et al*., 2000; Laffaille *et al*., 2001; Colclough *et al*., 2005;

Fonseca *et al*., 2011). Little vegetation has established to date, although it is likely that coverage will increase in the future, especially along the eastern edge of the site, which is more sheltered from wave action than the western edge and area around the breach; the rate and extent of colonisation will be partly determined by propagule pressure, the elevation of the site, the rate of accretion and the redox potential of the sediment (Mossman *et al*., 2012). Establishment of (some) vegetation will increase habitat complexity, and not necessarily prevent the aim of the realignment scheme being achieved, as long as sufficient suitable mudflat remains.

Acknowledgements

The authors would like to thank the Environment Agency and DP World for their support in the project. Many thanks also to Natalie Angelopoulos, Mike Bailey, Chris Baulcomb, Jon Bolland, Jon Butterfield, Liam Byrne, Terry Coddington, Jamie Dodd, Dave Mitchell, Taya Parker-Mian, Rafa Pérez-Domínguez, Tim Smith, Marie Taylor, Ryan Taylor, Karen Twine, Dan Upsher, Sam Walton and Connor Whiteley for assistance in the field. The work was funded by DP World and administered by the Environment Agency. The views expressed in the paper are those of the authors and not necessarily those of DP World or the Environment Agency.

REFERENCES

Anderson, M. J. (2001). Permutation tests for univariate or multivariate analysis of variance and regression. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 626-639.

Anderson, M. J., Gorley, R. N. & Clarke, K. R. (2008). PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth.

Atkinson, P. W., Crooks, S., Drewitt, A., Grant, A., Rehfisch, M. M., Sharpe, J. & Tyas, C. J. (2004). Managed realignment in the UK – the first 5 years of colonization by birds. *Ibis* **146**, 101-110.

Bray, J. R. & Curtis, J. T. (1957). An ordination of the upland forest communities of Southern Wisconsin. *Ecological Monographs* **27**, 325-349.

Clarke, K. R. & Warwick, R. M. (2001). *Change in Marine Communities: an Approach to Statistical Analysis and Interpretation.* Second Edition. PRIMER-E, Plymouth.

Coates, S., Waugh, A., Anwar, A. & Robson, M. (2007). Efficacy of a multi-metric fish index as an analysis tool for the transitional fish component of the Water Framework Directive. *Marine Pollution Bulletin* **55**, 225-240.

Colclough, S. R., Gray, G., Bark, A. & Knights, B. (2002). Fish and fisheries of the tidal Thames: management of the modern resource, research aims and future pressures. *Journal of Fish Biology* **61** (Suppl. A), 64-73.

Colclough, S., Fonseca, L., Astley, T., Thomas, K. & Watts, W. (2005). Fish utilisation of managed realignments. *Fisheries Management and Ecology* **12**, 351-360.

Copp, G. H. (2008). Putting multi-dimensionality back into niche: diel vs. day-only niche breadth separation in stream fishes. *Fundamental and Applied Limnology* **170**, 273-280.

Cowx, I. G., Nunn, A. D. & Harvey, J. P. (2001). Quantitative sampling of 0-group fish populations in large lowland rivers: point abundance sampling by electric fishing versus micromesh seine netting. *Archiv für Hydrobiologie* **151**, 369-382.

Desmond, J. S., Zedler, J. B. & Williams, G. D. (2000). Fish use of tidal creek habitats in two southern California saltmarshes. *Ecological Engineering* **14**, 233-252.

Dixon, A. M., Leggett, D. J & Weight, R. C. (1998). Habitat creation opportunities for landward coastal re-alignment: Essex case studies. *Journal of the Chartered Institution of Water and Environmental Management* **12**, 107-112.

Dytham, C. (2003). *Choosing and Using Statistics: a Biologist's Guide*. Second Edition. Blackwell Science, Oxford, 248 pp.

Elliott, M., Whitfield, A. K., Potter, I. C., Blaber, S. J. M., Cyrus, D. P., Nordlie, F. G. & Harrison, T. D. (2007). The guild approach to categorizing estuarine fish assemblages: a global review. *Fish and Fisheries* **8**, 241-268.

Esteves, L. S. (2013). Is managed realignment a sustainable long-term coastal management approach? *Journal of Coastal Research*, Special Issue No. 65, 933-938.

Esteves, L. S. (2014). *Managed Realignment: a Viable Long-term Coastal Management Strategy?* Springer, New York.

Fonseca, L., Colclough, S. & Hughes, R. G. (2011). Variations in the feeding of 0-group bass *Dicentrarchus labrax* (L.) in managed realignment areas and saltmarshes in SE England. *Hydrobiologia* **672**,15-31.

French, P. W. (2006). Managed realignment – the developing story of a comparatively new approach to soft engineering. *Estuarine, Coastal and Shelf Science* **67**, 409-423.

Garbutt, R. A., Reading, C. J., Wolters, M., Gray, A. J. & Rothery, P. (2006). Monitoring the development of intertidal habitats on former agricultural land after the managed realignment of coastal defences at Tollesbury, Essex, UK. *Marine Pollution Bulletin* **53**, 155-164.

Gibson, R. N. (2003). Go with the flow: tidal migration in marine animals. *Hydrobiologia* **503**, 153-161.

Hampel, H. & Cattrijsse, A. (2004). Temporal variation in feeding rhythms in a tidal marsh population of the common goby *Pomatoschistus microps* (Krøyer, 1838). *Aquatic Sciences* **66**, 315-326.

Hemingway, K. L. & Elliott, M. (2002). Field methods. In: *Fishes in Estuaries* (eds M. Elliott & K. L. Hemingway). Blackwell Science, Oxford, pp. 410-509.

Herringshaw, L. G. & Solan, M. (2008). Benthic bioturbation in the past, present and future. *Aquatic Biology* **2**, 201-205.

Kadiri, M., Spencer, K. L., Heppell, C. M. & Fletcher, P. (2011). Sediment characteristics of a restored saltmarsh and mudflat in a managed realignment scheme in Southeast England. *Hydrobiologia* **672**, 79-89.

Kelley, D. F. (1988). The importance of estuaries for sea-bass *Dicentrarchus labrax* (L.). *Journal of Fish Biology* **33** (Supplement A), 25-33.

Laffaille, P., Feunteun, E. & Lefeuvre, J. C. (2000). Composition of fish communities in a European macrotidal saltmarsh (the Mont Saint-Michel Bay, France). *Estuarine, Coastal and Shelf Science* **51**, 429-438.

Laffaille, P., Lefeuvre, J. C., Schricke, M. T. & Feunteun, E. (2001). Feeding ecology of 0-group sea bass, *Dicentrarchus labrax*, in saltmarshes of Mont Saint Michel Bay (France). *Estuaries* **24**, 116-125.

Leclerc, J., Riera, P., Noël, L. M. J., Leroux, C. & Andersen, A. C. (2014). Trophic ecology of *Pomatoschistus microps* within an intertidal bay (Roscoff, France), investigated through gut content and stable isotope analyses. *Marine Ecology* **35**, 261-270.

Ledoux, L., Cornell, S., O'Riordan, T., Harvey, R. & Banyard, L. (2005). Towards sustainable flood and coastal management: identifying drivers of, and obstacles to, managed realignment. *Land Use Policy* **22**, 129-144.

Mander, L., Cutts, N. D., Allen, J. & Mazik, K. (2007). Assessing the development of newly created habitat for wintering estuarine birds. *Estuarine, Coastal and Shelf Science* **75**, 163-174.

Mazik, K., Smith, J. E., Leighton, A. & Elliott, M. (2007). Physical and biological development of a newly breached managed realignment site, Humber estuary, UK. *Marine Pollution Bulletin* **55**, 564-578.

Mazik, K., Musk, W., Dawes, O., Solyanko, K., Brown, S., Mander, L. & Elliott, M. (2010). Managed realignment as compensation for the loss of intertidal mudflat: a short term solution to a long term problem? *Estuarine, Coastal and Shelf Science* **90**, 11-20.

McLusky, D. S., Bryant, D. M. & Elliott, M. (1992). The impact of land-claim on macrobenthos, fish and shorebirds on the Forth Estuary, eastern Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems* **2**, 211-222.

Morris, R. K. A. (2013). Managed realignment as a tool for compensatory habitat creation: a re-appraisal. *Ocean and Coastal Management* **73**, 82-91.

Morris, R. K. A. & Gibson, C. (2007). Port development and nature conservation: experiences in England between 1994 and 2005. *Ocean and Coastal Management* **50**, 443-462.

Mossman, H. L., Davy, A. J. & Grant, A. (2012). Does managed coastal realignment create saltmarshes with 'equivalent biological characteristics' to natural reference sites? *Journal of Applied Ecology* **49**, 1446-1456.

Nunn, A. D., Harvey, J. P. & Cowx, I. G. (2007). Benefits to 0+ fishes of connecting man-made waterbodies to the lower River Trent, England. *River Research and Applications* **23**, 361-376.

Nunn, A. D., Tewson, L. H. & Cowx, I. G. (2012). The foraging ecology of larval and juvenile fishes. *Reviews in Fish Biology and Fisheries* **22**, 377-408.

Pétillon, J., Potier, S., Carpentier, A. & Garbutt, A. (2014). Evaluating the success of managed realignment for the restoration of salt marshes: lessons from invertebrate communities. *Ecological Engineering* **69**, 70-75.

Pontee, N. (2013). Defining coastal squeeze: a discussion. *Ocean and Coastal Management* **84**, 204-207.

Ramos, S., Amorim, E., Elliott, M., Cabral, H. & Bordalo, A. A. (2012). Early life stages of fishes as indicators of estuarine ecosystem health. *Ecological Indicators* **19**, 172-183.

Rupp-Armstrong, S. & Nicholls, R. J. (2007). Coastal and estuarine retreat: a comparison of the application of managed realignment in England and Germany. *Journal of Coastal Research* **23**, 1418-1430.

Shih, S. C. W. & Nicholls, R. J. (2007). Urban managed realignment: application to the Thames Estuary, London. *Journal of Coastal Research* **23**, 1525-1534.

Spencer, T., Friess, D. A., Möller, I., Brown, S. L., Garbutt, R. A. & French, J. R. (2012). Surface elevation change in natural and re-created intertidal habitats, eastern England, UK, with particular reference to Freiston Shore. *Wetlands Ecology and Management* **20**, 9-33.

Washington, H. G. (1984). Diversity, biotic and similarity indices: a review with special relevance to aquatic ecosystems. *Water Research* **18**, 653-694.

Ysebaert, T., Herman, P. M. J., Meire, P., Craeymeersch, J., Verbeek, H. & Heip, C. H. R. (2003). Large-scale spatial patterns in estuaries: estuarine macrobenthic communities in the Schelde estuary, NW Europe. *Estuarine, Coastal and Shelf Science* **57**, 335-355.