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Review Article

Large-scale historic habitat loss in estuaries and its implications for commercial and recreational fin fisheries

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Estuaries provide important nursery and feeding habitat for numerous commercially and ecologically important fish, however, have been historically subject to substantial habitat alteration/degradation via environmental fluctuations, sea level rise, human activity on intertidal habitats, and adjacent land management. This review has summarized estuarine habitat use for 12 economically important finfish in the United Kingdom, of which seven were found to utilize estuarine habitats e.g. saltmarsh during their life cycle. This review reveals that ∼2500 km^2 of intertidal habitat has been lost from estuaries in England and Wales since 1843. The implications of this large-scale habitat loss and continued anthropogenic disturbance within estuaries for a variety of fish species is discussed, in particular the requirement of finfish for particular habitats to be accessible and in a suitable condition. As a result of the high economic and social value of commercial and recreational fisheries, it is suggested that further research attention should investigate the spatial ecology of fish. Holistic fisheries management policies should also be considered, which would both sustainably manage fisheries landings but also account for the habitat requirements of the fisheries species.

Keywords: ecosystem approach, habitats, holistic management, marine fisheries.

Introduction

Estuaries are defined under the European Commission's Habitats Directive (Council Directive 92/43/EEC) as the downstream part of a river valley, subject to the tide and extending from the limit of brackish water (Davidson *et al.*, 1991). These ecosystems host a complex mosaic of subtidal and intertidal habitats which are closely associated with surrounding terrestrial environment. In northern Europe, these habitats include but are not limited to mudflats, sandflats, saltmarshes, seagrass beds, rocky, and biogenic reefs. These are important ecosystems for numerous finfish species at a variety of life stages, such as adult feeding, refuge, nursery grounds, and as migration routes (Table 1). In particular, a number of species targeted by commercial and recreational fisheries use estuaries as key nursery areas, or estuaries are thought to provide a nursery role along with other shallow coastal environments (Pickett and Pawson, 1994 Wennhage *et al.*, 2007; Seitz *et al.*, 2014; Swadling *et al.*, 2022).

The ability of fish to access essential habitats within estuaries is thought to directly support increased fish production (Sundblad *et al.*, 2014; Swadling *et al.*, 2022), via provision of high food availability and shelter from predation (Figure 1) (Mendes *et al.*, 2020). Notably, vegetated habitats such as saltmarsh as well as other intertidal habitats such as mudflat, are thought to be highly utilized by a range of species (Pickett and Pawson, 1994; Laffaille *et al.*, 2001; Green *et al.*, 2012), which in combination may cumulatively contribute to the overall local fish production (Nagelkerken *et al.*, 2015; Swadling *et al.*, 2022). This is well illustrated in a number of dietary and growth studies, which highlight that a number of fish species at varying life stages (Pickett and Pawson, 1994; Laffaille *et al.*, 2001; Green *et al.*, 2012; Cambie *et al.*, 2016) exploit and are highly dependent on estuaries in general, or the specific habitats that they host.

Despite the important role estuaries provide in regard to nursery and feeding habitats for finfish, in northern Europe they are typically highly impacted by anthropogenic activities (Airoldi *et al.*, 2008). These activities include: direct removal or adaptation of intertidal habitat (Elliott *et al.*, 1990; Sheehan *et al.*, 2010a, b water abstraction (Greenwood, 2008), and the introduction of harmful substances (including sewage effluent, agricultural waste, industrial chemicals, heavy metals, and increased levels of suspended solids). It has therefore been argued that anthropogenic activities such as those listed above have reduced the capacity of estuarine ecosystems to support fish populations relative to historic levels (Mclusky *et al.*, 1992; Rochette *et al.*, 2010).

Within the European Union (EU) and United Kingdom (UK), estuaries and some relevant habitats e.g. Saltmarsh, are legally protected via legislative polices (e.g. Habitat's directive: Council Directive 92/43/EEC; or as Sites of Special Scientific interest), which aim to reduce anthropogenic disturbance and, maintain or increase the ecological condition of designated habitats or species within site boundaries. However, these site designations do not often incorporate dependent fish species or assemblages within management or monitoring plans (Vasconcelos *et al.*, 2007). The requirement to specifically protect Essential Fish Habitat (EFH)—habitats which fish require to complete their lifecycle (NOAA, 2019), is however recognized within several EU and UK policies aimed at implementing

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Table 1. Economically important species/taxa identified through UK landings within the inshore and offshore commercial fishing fleet (MMO, 2020), and recreational fisheries captures (Armstrong *et al.*, 2013) listed in descending order of economic importance.

Taxa	Summary of estuary use	Reference list
Mackerel (*Scomber scombrus*)	No significant use of estuaries found in peer reviewed literature	Ware and Lambert, 1985; Jansen and Burns, 2015
European bass (*Dicentrarchus labrax*) ∗	**Shallow coastal bays and estuaries used as nursery habitat until year 2–4 (Pickett & Pawson, 1994). Estuaries may also provide significant adult feeding habitat (Costa and Bruxelas, 1989; MAFF, 1990; Pickett and Pawson, 1994; Laffaille *et al.*, 2001; Leitão *et al.*, 2006; Martinho *et al.*, 2008; Leakey *et al.*,2009; Fonseca *et al.*,2011; Green *et al.*, 2012; Cambiè *et al.*, 2016; Cambiè *et al.*,2016; Doyle *et al.*, 2017)**	**Costa and Bruxelas, 1989; MAFF, 1990; Pickett and Pawson, 1994; Laffaille et al., 2001; Pickett *et al.*,2004; Leitão et al., 2006; Martinho et al., 2008; Leakey et al., 2009; Fonseca et al., 2011; Green et al., 2012; Cambiè et al., 2016; Cambiè et al., 2016; Doyle et al., 2017**
Sole (*Solea solea*) ∗	**Shallow coastal bays and estuaries used as nursery habitat until year 2 Please note reference list is not exhaustive due to the high volume of research conducted on this species. However, there is consensus across studies**	**Coggan and Dando, 1988; Marchand, 1991; Marshal and Elliot, 1998; Cabral and Costa, 1999; Amara *et al.*,2000; Cabral, 2000; Pape *et al.*, 2003; Vinagre *et al.*, 2005; Fonseca *et al.*,2006; Vinagre *et al.*, 2006; Nicolas *et al.*, 2007; Martinho *et al.*, 2008; Vinagre *et al.*, 2008; Leakey *et al.*, 2009; Kostecki *et al.*, 2010; Rochette *et al.*, 2010; Tanner *et al.*,2012**
Whiting (*Merlangius merlangus*) ∗	**Larvae found in shallow coastal bays; however, 0 group and adults known to form dominant component of the fish assemblages in Thames and Severn estuaries**	**Nagabhushanam, 1964; Arntz and Weber, 1972; Gordon, 1977; Van den Broek, 1979, 1980; Potter *et al.*, 1988; Potter *et al.*, 1988; Henderson and Holmes, 1989; Elliott *et al.*, 1990; Hamerlynck and Hostens, 1993; Armstrong and Dickey-Collas, 1997; Power *et al.*,2002; Gerritsen *et al.*,2003; Leakey *et al.*, 2009; Henderson and Bird, 2010; Bastrikin *et al.*, 2014**
Cod (*Gadus morhua*) ∗	**Larvae/juveniles found in shallow coastal bays (Tupper et al., 1995); however, may also use estuaries as nursery area. Some adult presence/use recorded within estuaries**	**Elliott *et al.*, 1990; Cohen *et al.*, 1991; Gotceitas *et al.*,1998; Lazzari, 2013; Bastrikin *et al.*,2014**
Monkfish (*Lophius sp.*)—UK species include: *Lophius piscatorius* *Lophius budegassa*	Information on stock structure, behaviour, or spawning biology of monkfish is scarce (Solmundsson *et al.*, 2010) No significant use of estuaries found in peer reviewed literature	Solmundsson *et al.*, 2010; Colmenero *et al.*, 2013; Hernández *et al.*, 2015; Ofstad *et al.*, 2017
Pollack (*Pollachius pollachius*) ∗	**Juveniles spend 2–3 years in coastal areas, typically found in the following habitats rocky areas, kelp beds, sandy shores and estuaries (Cohen *et al.*, 1991)**	Costa & Bruxelas, 1989; Cohen *et al.*, 1991
Haddock (*Melanogrammus aeglefinus*)	Literature regarding Haddock life history is scarce. No significant use of estuaries found in peer reviewed literature	Olsen *et al.*, 2010; Wright *et al.*, 2010; Castaño-Primo *et al.*, 2014
Herring (*Clupea harengus*) ∗	**Several herring stocks spawn in inshore waters and estuaries (Fox *et al.*,1999). Juvenile herring (Year 1) are amongst one of the most abundant fish within UK estuaries (Henderson, 1989), where they are known to feed within habitats such as saltmarsh (Green *et al.*, 2012)**	**Chenoweth, 1971; Chenoweth, 1971; Dempsey and Bamber, 1983; Henderson *et al.*, 1984; Henri *et al.*, 1985; Claridge *et al.*, 1986; Henderson, 1989; Elliot *et al.*, 1990; Lazzari *et al.*, 1993; Fox *et al.*, 1999; Maes and Ollevier, 2000; Power *et al.*, 2000; Lacoste *et al.*, 2001; Thiel and Potter, 2001; Maes *et al.*, 2005; Henderson and Bird, 2010; Green *et al.*, 2012**
Catshark (*Scyliorhinus sp.*)	No significant use of estuaries found in peer reviewed literature	Ellis and Shackley, 1997
Hake (*Merluccius bilinearis*)	No significant use of estuaries found in peer reviewed literature	Fahay, 1974; Steves and Cowen, 2000; Lock and Packer, 2004
Dab (*Limanda limanda*) ∗	**Larvae/juveniles found in open coastal bays (Bolle *et al.*,1994); however, estuaries may also be used as nursery habitat for short periods: 1–3 months (Forth estuary: Elliott *et al.*, 1990)**	Elliot *et al.*, 1990; Bolle *et al.*, 1994

Estuary use has been summarized for each species/taxon via peer-reviewed publications. Google scholar search terms include: "Species/taxa name" + "estuary"/"Nursery". Search completed on 25/01/2019. All species/taxa highlighted with ∗ and emboldened text indicate evidence found for significant use of estuarine habitats.

Ecosystem Based Fisheries Management (EBFM) e.g. Marine Spatial Planning, Common Fisheries Policy (CFP).

Despite the legislative drivers providing a legal framework at both an EU and UK level since 2008, little political attention or progress has been made to implement protection for fishery-dependent habitats across Europe (Oceana, 2019). This review was written to highlight the scale of estuarine ecosystem change within the UK and its relevance to dependent fish populations and fisheries they support. This has wider ramifications for marine fisheries more broadly across northern Europe, and other similar eco-regions where estuaries represent important EFH.

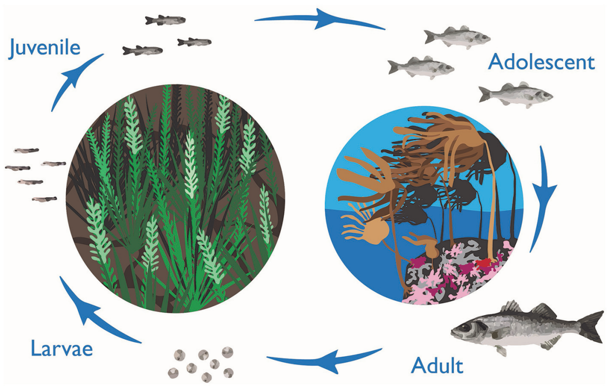

Figure 1. Example schematic of European bass (*Dicentrarchus labrax*) habitat use throughout life history. Adult/sexually mature fish associated with coastal habitats e.g. rocky reefs. Juvenile fish associated with estuarine and coastal vegetated habitats e.g. Saltmarsh or Seagrass. Adapted from Pickett and Pawson (1994).

Summary of commercial and recreational fisheries in the UK

Commercial fisheries in the UK directly employ an average of 12262 fishermen per year, plus an additional estimated 13455 Full Time Equivalent (FTE) jobs within processing plants and employment within the associated supply chain (Curtis *et al.*, 2018). The UK fishing fleet lands 297k tonnes of finfish per year (average from 2014 to 2018). These landings have an estimated value of £322 million per year and account for ~60% of the total landed value of UK fisheries. The remaining 40% of which is comprised of shellfish such as Nephrops (*Nephrops norvegicus*), Scallops (*Pecten maximus* and/or *Aequipecten opercularis*), Brown crab (*Cancer pagurus*), or European lobster (*Homarus gammarus*) (MMO, 2020).

In 2018, the UK commercial fishing fleet comprised 6036 fishing vessels (MMO, 2020), which can broadly be split into those above and below 10 m in length (Davies *et al.*, 2018). Those above 10 m are typically termed the "offshore fleet" and characteristically fish further than 6 nm of the coastline, whereas smaller vessels (<10 m) typically fish within inshore waters (<6 nm). The offshore fleet accounts for an average of 94.1% of the landed catch per year (MMO, 2020), however, the inshore fleet accounts for ~80% of the number of vessels and 65% of the direct employment (Davies *et al.*, 2018; MMO, 2020). It is therefore important to consider the species and habitats which are important to support both the offshore and inshore fishing fleets.

Marine Recreational Fisheries (MRF) are also an economically and socially important sector in the UK (Armstrong *et al.*, 2013; Hyder *et al.*, 2017), with an estimated 2% of the adult population (1.08 million people) actively participating (Armstrong *et al.*, 2013). While annually variable, recreational sea angling (in isolation) is estimated to contribute £831 million to the UK economy and support 10400 FTE jobs (estimate for 2012) (Armstrong *et al.*, 2013). Furthermore, the presence of specialist forums and fishing clubs, in particular for iconic species like Bass (*Dicentrarchus labrax*), demonstrate the social importance of MRF to the general public.

Defining economically important finfish species

Commercial fisheries in the UK are highly diverse, and landings data provided by the Marine Management Organisation (MMO) report that 182 different fish species are landed. At the time of writing, UK landings data were available from 2014 to 2018. For the purposes of this review any species which individually accounted for >5% of the total landed value from 2014 to 2018 was considered economically important for the inshore or offshore fishery. Mackerel (*Scomber scombrus*), Cod (*Gadus morhua*), Monkfish (*Lophius* sp.), Haddock (*Melanogrammus aeglefinus*), Herring (*Clupea harengus*), and Hake (*Merluccius merluccius*) individually accounted for >5% of the landed value for the offshore fleet (vessels >10 m) (Figure 2). Bass (*Dicentrarchus labrax*), Sole (*Solea solea*), Mackerel (*Scomber scombrus*), and Pollack (*Pollachius pollachius*) individually accounted for >5% of the landed value for the inshore fleet (vessels <10 m) (Figure 2).

In 2012, the Department for Environment, Food and Rural Affairs (DEFRA) and MMO commissioned the sea angling review (Armstrong *et al.*, 2013). The survey collected catch data from marine recreational sea anglers, to help improve scientific understanding of the diversity of species captured and the economic and social value of recreational sea angling (Ares, 2016). This was achieved using a variety of techniques, including an "Opinions and Lifestyle survey" conducted by the Office of National Statistics to estimate the number of recreational sea anglers in England and how actively they participated in recreational sea angling. This was combined with an online survey, as well as random shore and boat-based surveys conducted by the Inshore Fisheries and Conservation Authorities (IFCAs). The collected data was used to estimate the diversity of fish species captured by recreational sea anglers and the proportion of fish caught and released (Armstrong *et al.*, 2013).

Armstrong *et al.* (2013) represents the most recent publicly available assessment of fish species caught by recreational sea anglers; however, a further assessment is being produced via the Sea Angling Diary (CEFAS and Substance, 2019). MRF covers capture methods such as netting or sea angling, however, information regarding fish species captured via methods other than sea angling are not readily publicly available. However, the UK MRF sector is thought to be dominated by recreational sea angling (Armstrong *et al.*, 2013; Hyder *et al.*, 2017). Therefore, while it is accepted that there will likely be some variability in the diversity of species captured by location, year, and capture method, we are using the species list published by Armstrong *et al.* (2013) to be representative of the most targeted or important species for MRF in the UK. From this assessment, Armstrong *et al.* (2013) highlighted 14 species which were commonly captured by recreational sea anglers. While no value is assigned to these species the following individually accounted for >5% of the overall fish captured within MRF: Mackerel (*Scomber scombrus*), Whiting (*Merlangius merlangus*), Bass (*Dicentrarchus labrax*), Dogfish (*Scyliorhinus sp.*), Dab (*Limanda limanda*), and Cod (*Gadus morhua*) (Figure 2).

Across the offshore, inshore, and recreational fisheries, 12 finfish species have been identified as economically important. Some species are captured across all fisheries, however due to differences in fishing techniques and equipment, and the dis-

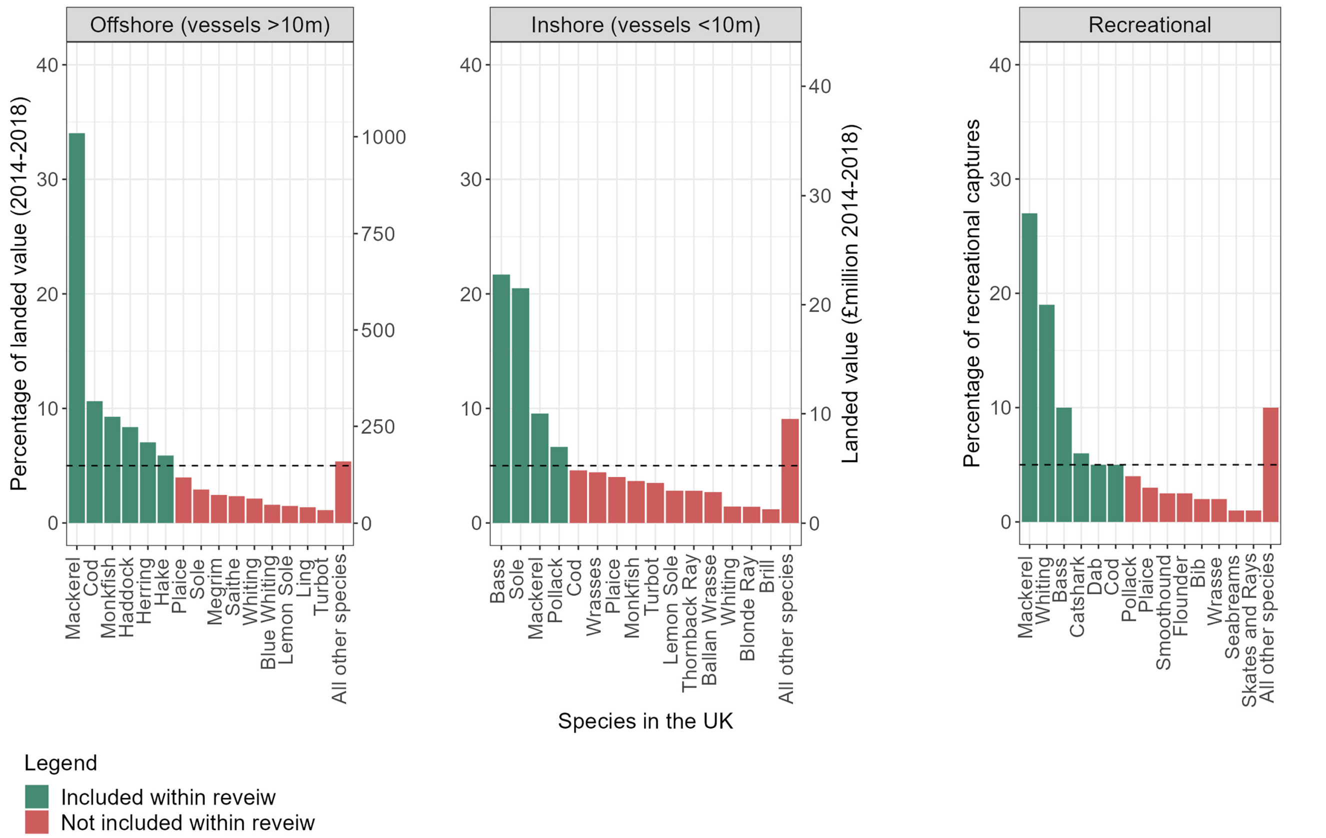

Figure 2. Economic value of finfish species which account for >5% of the total landed value within the inshore and offshore commercial fishing fleet 2014–2018, or >5% of captures within the recreational fishery. Black dashed line represents 5% of landings value (commercial fisheries) or 5% of recreational fisheries captures. All species which individually account for >5% of the landings value or recreational captures highlighted green, species <5% highlighted red (Data source: MMO, 2020 and Armstrong, 2013).

tribution of targeted fish within inshore or offshore environments, the relative importance of each species varies among the respective fisheries (Figure 2).

Estuary use by economically valuable species/taxa

For all selected 12 finfish species (green, Figure 2), a google scholar search was conducted during December 2018 which included: "Species/taxa name" + "Estuary" + "Nursery". From this search 72 peer reviewed papers were summarized and referenced within Table 1 (includes studies across each species geographic range). On average seven studies were reviewed for each species, however this varied from two (Mackerel, Pollack, and Dab) due to a scarcity research, to 17 (Herring, Whiting, or Sole). Seven (58%) of the selected 12 species (Table 1) were identified as using estuaries during their life cycle, usually in combination with other shallow coastal habitats e.g. coastal embayments. Notably, Bass (*Dicentrarchus labrax*), Sole (*Solea solea*), Whiting (*Merlangius merlangus*), and Herring (*Clupea harengus*) were often identified as being common/dominant components of estuarine fish assemblages. Further, a significant evidence base suggested that estuaries represent important "nursery habitat" for these species (Table 1)—habitats which promote recruitment and therefore maintain the adult the population, via provision of high food availability and shelter from predation (Mendes *et al.*, 2020). With the exception of Herring, literature searches suggested many of the species captured within the offshore commercial fleet, such as Mackerel, Monkfish, or Haddock, are not regularly recorded within estuaries. Whereas Bass, Sole, and Whiting are identified as being highly significant for the inshore and recreational fisheries (Figure 2), suggesting estuaries may provide a significant role in supporting the inshore commercial fleet and recreational fisheries (Meynecke *et al.*, 2007).

Within the reviewed literature, there was specific reference of European bass and Herring high utilization of intertidal habitats such as saltmarsh and/or mudflats (Laffaille *et al.*, 2001; Rochette *et al.*, 2010; Green *et al.*, 2012; Fonseca *et al.*, 2011). This is evidenced by high residency (Green *et al.*, 2012) or feeding rates (Laffaille *et al.*, 2001; Fonseca *et al.*, 2011) within vegetated habitats e.g. European bass capable of consuming 8% of body weight within 1–2 h tidal submersion of saltmarsh (Laffaille *et al.*, 2001). When these fish do not have direct access to these habitats, their diet may also be supplemented by prey species who are themselves dependent on detritus from vegetated habitats (Laffaille *et al.*, 2001; Green *et al.*, 2012). Furthermore, evidence suggests that when intertidal habitats are disturbed by human activity it may negatively affect the feeding rate of estuarine fish species, and have a corresponding influence on factors such as growth and survival (European bass: Laffaille *et al.*, 2000).

Intertidal and estuarine habitat loss

Estuaries are highly dynamic environments, which experience a wide range of environmental and anthropogenic stressors (Attrill *et al.*, 1999; Ladd *et al.*, 2019). Fluctuations in sediment supply (Ladd *et al.*, 2019), hydrology (Cui *et al.*, 2016), and sea level rise (Nicholls *et al.*, 1999; Adam, 2002; Hay *et al.*, 2015; Lawrence *et al.*, 2018) can influence the extent of intertidal and subtidal habitats e.g. saltmarsh or biogenic reefs. Introduction of alien and/or harmful substances (Kelly, 1988; Jennings, 1990; Ogburn *et al.*, 2007) or human activities such as construction of "hard" sea defences (Dixon *et al.*, 1998; Morris *et al.*, 2004; Lawrence *et al.*, 2018), and farming on intertidal habitats (Laffaille *et al.*, 2000) can also negatively affect estuarine water quality and habitat extent. The cumulative (and possibly interactive) effects of natural environmental variability and negative anthropogenic activities are likely to impact the habitats that support fish populations within estuaries (Chesney *et al.*, 2000).

Another major issue cited within the peer-reviewed literature is historic land-claim, which is the process of humans converting intertidal habitat into terrestrial habitat, typically for agricultural or industrial purposes (Lotze *et al.*, 2006). It is estimated that as much as 85% of estuaries in the UK have been impacted by historic land claim (Davidson, 2016). Whilst locally variable, this has resulted in substantial intertidal habitat loss across UK estuaries; for example, within the Forth and Thames estuaries, it is estimated that 50% (Mclusky *et al.*, 1992) and 64% (Attrill *et al.*, 1999) of the intertidal habitat has been lost, respectively. The full scale of intertidal habitat loss is hard to quantify, as limited historical records exist to show pristine estuarine environments prior to human development. However, as part of the Water Framework Directive: 2000/60/EC (WFD) Transitional and Coastal Waters angiosperm: Saltmarsh assessment, historic intertidal habitat extent is estimated using Light Detection And Ranging (LiDAR). Areas of historic intertidal habitat are identified, by detecting coastal land which is below the highest astronomical tide but located behind an artificial flood defence (Best, 2007 and WFD UKTAG, 2014).

The results from the most recent publically accessible intertidal habitat loss assessment have been summarized herein (Assessment conducted by Environment Agency. FOI: NR73435). To highlight spatial variability across the UK and aid visualization at a national scale, ESRI shapefiles of the estimated intertidal habitats loss across England and Wales (provided by the Environment Agency) were converted to 100 km^2 grid cells (Figure 3a). To highlight broad scale regional differences, the total estimated habitat loss across coastal Nomenclature of Territorial Units for Statistics (NUTS) regions in England and Wales has been calculated (Figure 3b). The results of the WFD assessment indicate widespread historic intertidal habitat loss since 1843 across England and Wales. Loss of intertidal habitat was however spatially variable, with 1728 km^2 (67%) occurring within NUTS regions along the east coast of England, notably: East England, East Midlands, Yorkshire, and the Humber. Within the remaining NUTS regions (London, Wales and south east, south west and north west England) a total of 755 km^2 (33%) of intertidal habitat is estimated to have been historically lost. When combined, it is estimated that 2483 km^2 of intertidal habitat has been historically lost (since 1843) from these regions. When put into context, this is an area larger than modern day London (1572 km^2) or roughly approximate to the area of Luxembourg (2586 km^2).

Historic saltmarsh habitat loss

It is uncertain which specific intertidal habitats have been historically degraded or lost from England and Wales e.g. saltmarsh, mudflat, or reef, however as part of the Water Framework Directive (WFD) historic intertidal habitat loss assessment, the historic extent of saltmarsh across England and Wales was also estimated. The "first epoch" Ordinance Survey (OS) maps were digitized (1843–1893) areas identified as "Saltmarsh", "Saltings", or "Grazing marsh" were then spatially defined as "Historic saltmarsh" (Best, 2007).

When comparing the total current extent of saltmarsh (405 km^2—Environment Agency, 2020) to the estimated historic extent (>1843) of saltmarsh (1123 km^2), it is estimated that 708 km^2 of saltmarsh habitat has been cumulatively lost within England and Wales. The worst affected estuaries and embayments from which the estimated historic saltmarsh habitat loss is highest include: the Wash, plus associated estuaries (24 km^2), the Blackwater and Colne estuaries (45 km^2), the Thames estuary (133 km^2), and the Medway estuary (147 km^2) (Figure 4). These four sites account for 349 km^2 (31%) of the historical saltmarsh habitat loss across the England and Wales. The remaining 774 km^2 (69%) of historic saltmarsh habitat loss is distributed widely across the coastline of England and Wales.

There is considerable uncertainty surrounding the WFD intertidal habitat loss estimates presented within this review. For example, Ladd *et al.* (2019) argue that saltmarsh habitat extent can vary both temporally and spatially in some regions of the UK, e.g. in the Solent, Southampton, saltmarsh habitat extent has increased by 158% from 1846 to 2016 (Saltmarsh extent increase = ∼158ha to ∼ 500 ha). Furthermore, a lack of historical records detailing intertidal habitat (prior to the commencement of ordinance surveys—1843) mean that land claim estimates derived from LiDAR data cannot be validated (WFD-UKTAG, 2014). Despite these caveats, the results presented here combined with high levels of coastal flood defence across many regions in the UK (Dixon *et al.*, 1998 Morris *et al.*, 2004; Lawrence *et al.*, 2018) suggest substantial loss of historic intertidal habitat has cumulatively occurred across England and Wales.

Implications for fisheries management

The cumulative impacts of the variety of natural and anthropogenic stressors on estuarine ecosystems, and their associated fish communities is not currently well understood (Chesney *et al.*, 2000; Sundblad *et al.*, 2014; Swadling *et al.*, 2022). There are however numerous studies which highlight the importance of estuaries for fish, notably juveniles may use shallow vegetated habitats (e.g. saltmarsh) to seek refuge from predation (Kelley, 1988; Paterson and Whitfield, 2000) or for feeding (Kelley, 1988; Laffaille *et al.*, 2001; Hampel and Cattrijsse, 2004, 2002; Fonseca *et al.*, 2011; Green *et al.*, 2012; Cambiè *et al.*, 2016; Swadling *et al.*, 2022). Other studies have also demonstrated a correlation between estuarine habi-

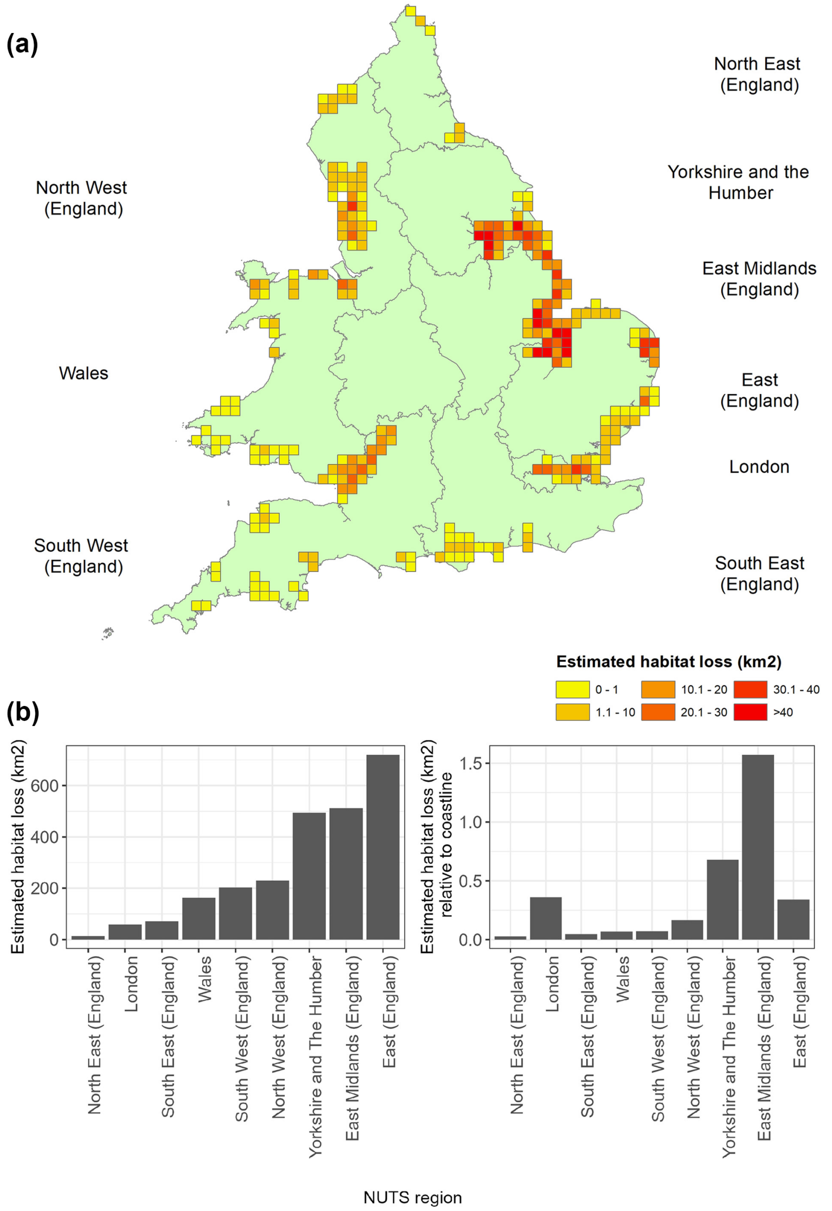

Figure 3. (a) Estimated habitat loss per 100 km^2 grid cell and (b) Total and proportional (Habitat loss km^2/coastline length km) habitat loss per coastal NUTS region. Data source: Best (2007) and WFD UKTAG (2014).

tat extent to local fish production (Mclusky *et al.*, 1992; Rochette *et al.*, 2010; Sundblad *et al.*, 2014; Swadling *et al.*, 2022).

Assessment of fish-habitat associations within estuaries is however logistically and technologically challenging, as well as financially expensive (Mullin, 1995). As a result, for many commercially and recreationally important fish species while there is evidence that estuaries are utilized, information on how they interact with, or are dependent on, estuarine or wider coastal habitats is often lacking (Vasconcelos *et al.*, 2007; Seitz *et al.*, 2014). This is particularly problematic, as it is estimated that 85% of coastline across Europe is at high or moderate risk for unsustainable coastal construction and development (Seitz *et al.*, 2014). It is possible that some fish species will be unaffected by coastal development; for example, Chesney *et al.* (2000) highlighted the stability of fisheries landings within Louisiana, USA, despite an estimated loss of 80–117 km^2 of intertidal marsh per year. However, without a better understanding of how commercially and recreationally important fish species exploit estuarine habitats, there could be unknown negative consequences on the these fisheries because of continued anthropogenic pressure on these ecosystems. Furthermore, since many important fish species may have specific habitat preferences (Fodrie and Levin, 2008; Seitz *et al.*, 2014) or localized movement behaviour (Green *et al.*, 2012), decreased habitat availability (in particular for juvenile life stages) may introduce population bottlenecks (Seitz *et al.*, 2014; Sundblad *et al.*, 2014). Estuarine fish populations are also exposed to several other anthropogenic threats which may impact survival, feeding, and growth (Vasconcelos *et al.*, 2007). Anthropogenic threats to estuarine fish populations may include but are not limited to: Continued habitat loss

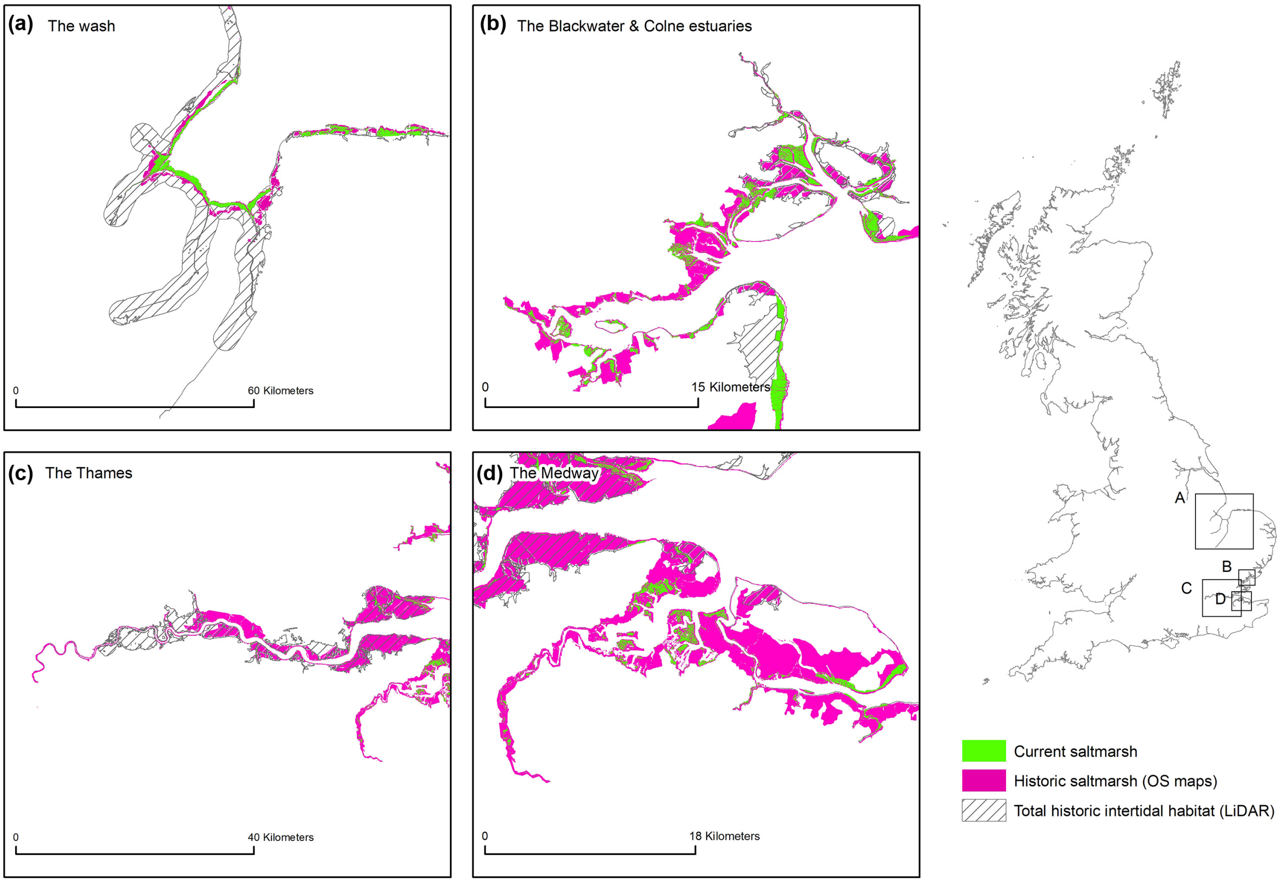

Figure 4. Estimated estuarine intertidal habitat loss and historic saltmarsh extent compared to current extent of saltmarsh within four locations in England and Wales, UK. Data provided by Environment Agency, UK, through Freedom of Information Request: NR73435 and an Open Government License. UK high water boundary shapefile sourced from Edina Digimap (Ordinance survey, 2005).

(Airoldi *et al.*, 2008; Sundblad *et al.*, 2014), Channel adaptation (e.g. channelization or dredging) (Reise, 2005), Industrial water abstraction (Greenwood, 2008), Sewage effluent (Kelley, 1988), and Uptake of persistent contaminants (Hardisty *et al.*, 1974; Dallinger *et al.*, 1987; Elliott *et al.*, 1990).

It was highlighted by Seitz *et al.* (2014) that 44% of ICES stock assessment species, utilize/exploit estuarine or coastal habitats to complete their life cycle. Similar results have also been reported by Swadling *et al.* (2022), which highlighted that estuaries directly support numerous commercially and recreationally important species in Australia. Sundblad *et al.* (2014) also found that as much as 48% of the variability in adult densities for two fish species in the Baltic sea can be explained by juvenile/nursery habitat availability. The results from the literature and the current study therefore highlight that limited access or degradation of Essential Habitat has an important role in regulating fish populations.

Conclusions and recommendations

The results presented here suggest that 58% of the most economically important finfish to the UK commercial fishing industry and recreational sector, highly utilize estuaries or estuarine habitats at a variety of life stages. However, the spatial extent of estuarine habitats that these species are dependent upon are likely to be highly reduced when compared to historical benchmarks. Whilst estuarine habitat degradation and decline is widely cited in the peer reviewed literature (Kennesh, 2002; Lotze *et al.*, 2006; Airoldi and Beck, 2007; Vasconcelos *et al.*, 2007), this review has published evidence of substantial habitat alteration throughout estuaries in the UK (WFD-UKTAG, 2014), and the associated relationship with the fish populations they support. Here, we suggest that holistic fisheries management policies should be implemented that both sustainably manage fisheries landings, but also account for the habitat requirements of the fishery (Roberts and Hawkins, 2012).

Incorporation of habitat management within fisheries is not a novel concept; for example, since 1996, Essential Fish Habitat (EFH) has been incorporated into US fisheries management through an amendment to the Magnuson–Stevens Fishery Conservation and Management Act (Chesney *et al.*, 2000). This amendment is based on the premise that some fish species are dependent on specific habitats during their life cycles, and therefore, fisheries managers should widen their remit to ensure fishery-dependent habitats remain "healthy" and be able to support sustainable fisheries (Rosenberg *et al.*, 2000; Sundblad *et al.*, 2014; Swadling *et al.*, 2022). Sundblad *et al.* (2014) furthers these statements by highlighting that in areas where access to essential habitats is highly restricted, interventions such as habitat protection or restoration are likely to have a beneficial impact on local fish production. Under Article 8 of the reformed Common Fisheries Policy (enacted in 2014), it is proposed that EU member states establish a network of marine reserves known as “Fish Stock Recovery Areas”. These areas are proposed to protect habitats, which provide essential ecosystem services to commercially and recreationally important fish and shellfish species, with particular reference to the protection of spawning and nursery grounds (Roberts and Hawkins, 2012). The UK fisheries Bill (2020) also specifically mentions an Ecosystem Approach to Fisheries Management, other international definitions of which (e.g. Magnuson-Stevens Fishery Conservation and Management Act, 2010) define protection of Essential Fish Habitat as an important component. However, as mentioned previously in this review little practical uptake has occurred to designate sites for the purposes of protecting EFH across European seas.

Due to the high economic and social value of commercially and recreationally exploited fisheries, and the evidence that numerous species are dependent on estuarine habitats, it is imperative that further research and management attention is given to identifying the habitat requirements for fish which provide an important ecological and/or economic role. Here, we specifically call for further research into the following:

- The spatial ecology of fish, in particular those with known associations with estuaries. This should include evidence on inter- and intra-specific differences and temporal trends; movement and habitat use characteristics; and home range and oncogenic shifts.
- Fisheries benefits of estuarine habitat restoration e.g. managed re-alignment schemes.
- Further understanding on how the spatial ecology of fish overlap with existing conservation and fisheries management policies e.g. Special Areas of Conservation or Marine Conservation Zones.

The outputs from these research areas would allow statutory bodies to identify important habitats for a range of species, and assess the relative merits of spatially protecting and/or restoring essential habitats. If designation/protection of EFH is adopted, assessing overlap between EFH and existing conservation measures would potentially ease the administrative burden of designating and protecting EFH as this may already be designated under other conservation measures.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Author contributions statement

All supervisors provided logistical and academic support: E. West, T. Robbins, S. Plenty, M. Attrill, and E. Sheehan.

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