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RESEARCH ARTICLE

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Sea bed disturbance increases flat oyster recruitment for low to moderate stock densities

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Abstract

1. It has long been suggested by commercial fishing interests that the sea bed benefits from being trawled or disturbed. Evidence to support increased benthic food web productivity in areas disturbed by trawling has suggested that this is the case, and that some mobile consumers can benefit from this increased productivity.
2. The same hypothesis has been put forward for shellfish recruitment, that disturbance of the sea bed, e.g. 'harrowing', increases the exposure of suitable settlement substrates for shellfish larvae. This is an approach often taken in shellfish mariculture in private fisheries, and has led to calls for support of expanding such activities into publicly managed areas to promote shellfish recovery and restoration.
3. Increased seabed disturbance, however, may not align with conservation policy or societal objectives for natural recovery of the seabed landscape. Furthermore, evidence for increased shellfish recruitment from seabed disturbance is mixed, and many attempts to elucidate whether relationships exist receive criticism for operating at small spatial and temporal scales.
4. An analysis is presented from 3 years of data (2016–2018) from a stock survey of a private European flat oyster, *Ostrea edulis*, fishery operating in the Blackwater estuary, Essex, UK. Using data for adult and recruit oyster abundance and distribution in 2018, with 'harrowing' effort from 2016–2018, it is asked whether oyster recruitment was related to disturbance effort.
5. It was found that oyster recruitment is positively related to increased seabed disturbance, but only up to intermediate adult oyster abundance equivalent to 60 oysters/100 m dredge, beyond which harrowing results in recruitment declines. This has implications for approaches to oyster fishery recovery, but also for restoration projects seeking evidence-led guidance on which ways may be appropriate to kick-start natural recovery in historical oyster areas that are habitat limited.

KEYWORDS
disturbance, fishery, local ecological knowledge, management, recruitment, restoration, shellfish

1 | INTRODUCTION

The European flat oyster, *Ostrea edulis*, has been traditionally grown and harvested since Roman times, remaining a culturally significant species to this day (Gunther, 1897; Allison et al., 2020). Throughout the industrial revolution European flat oysters suffered huge declines in their abundance and as a result a reduction in the extent of the structurally complex habitats (known as reefs or beds) that they help create (Farinas-Franco et al., 2018). This decline is due to a range of factors including disease, non-native species introduction, over fishing and pollution. *Ostrea edulis* is now listed as threatened or a declining habitat by OSPAR with the UK listing *O. edulis* as a Biodiversity Action Plan Species and Habitat, updated to a 'Priority Species' in the UK post-2010 Biodiversity Framework (Laing, Walker & Areal, 2006; JNCC & DEFRA, 2012). Building on this recognized loss and need for protection, native oyster restoration initiatives are gaining momentum throughout Europe, with an international alliance now formed under the name NORA (the Native Oyster Restoration Alliance), in addition to national and regional based restoration groups (e.g. Native Oyster Network UK & Ireland; Essex Native Oyster Restoration Initiative). This momentum led to the first marine conservation zone specifically for the protection and recovery of flat oysters and flat oyster beds being designated in Essex in 2013 (Allison et al., 2020).

Best practice on how to undertake flat oyster restoration is still debated, with restoration and population recovery success restricted by distinct site-specific limitations. These limitations may include the presence of non-native species, a lack of adult broodstock, widespread disease or local restrictions preventing the use of certain survey gear types for setting baselines and monitoring recovery and intervention techniques for kick-starting recovery (Laing, Walker & Areal, 2006; Helmer et al., 2019; Pogoda et al., 2019). Nonetheless, certain aspects of the restoration of *O. edulis* are widely agreed upon, such as that juvenile native oysters (spat) require suitable substrate to settle on to when transitioning from the larval to sessile life stages (Laing, Walker & Areal, 2006; Bromley et al., 2016; Smyth et al., 2018). These substrates are usually dead shells and gravels. Lack of suitable substrates for juvenile oyster settlement is a problem for many restoration sites with historical flat oyster distributions, such as the Solent or the Blackwater in Essex, but which are also highly turbid, muddy estuaries where high silt levels can quickly settle over any fresh shell and gravel. Even in the event of large numbers of larvae in the water column, high silt loads can prevent settlement, leading to a poor recruitment. Traditionally, oyster growers combat this by laying fresh shell (or cultch) in the days and weeks leading up to reproduction events, or by 'cleaning' the silt from existing shell within the sediment (Bromley et al., 2016). The latter is referred to as harrowing and is often preferred owing to the barriers of costs and logistics associated with high-volume shell and gravel deployment at sea. Harrowing is the deployment of a net of metal chains trawled along the seafloor, normally as the tides ebbs, to promote the transport of sediments away from the areas being modified. The chains are also referred to by oyster producers as being useful for breaking up chains of non-native slipper limpets and via their mortality contributing to the seafloor dead shell budget. Other approaches to harrowing can include the use of an oyster ladder dredge, but with the catch bag removed. The debate over the effectiveness of harrowing to improve habitat availability for oyster spat to settle is not new, with disagreements dating back to the fourteenth century arguing that oyster dredges destroy spat of oysters (Airoldi & Beck, 2007). Conversely some areas, such as the River Blackwater, have historically used harrowing, which remains to this day (Bromley et al., 2016). The effectiveness of this practice has previously been investigated, with harrowed grounds indicating higher dead shell abundance than non-harrowed plots but with effects only visible for weeks (KEIFCA, 2019). The impact of this on recruitment of *O. edulis*, however, remains unclear, primarily owing to a lack of recruitment in the years of investigation (Bromley et al., 2016) or studies that are too short lived (KEIFCA, 2019). The practice is also controversial as harrowing involves deliberate disturbance of the sea bed, which even if it does improve settlement and recruitment of a single species, is likely to have significant effects on biodiversity or conflicts with competing conservation objectives, i.e. associated species recovery or carbon capture in marine sediments (zu Ermgassen et al., 2020; Sala et al., 2021). Given the uncertainty in its effectiveness, and the likelihood of effects on marine biodiversity, a greater understanding of the implications of this method is needed before any recommendations can be made as to its use as a tool to stimulate the restoration of oysters. This study therefore aimed to better understand how harrowing effort impacts the recruitment of juvenile flat oysters across a gradient of existing adult oyster densities in a large-scale field experiment.

2 | METHODS

2.1 | Study area

The Tollesbury and Mersea Several Order area (T&M SO) in the River Blackwater, Essex, UK was selected for this study (Figure 1; see also Lown et al., 2021). This site has a history of the use of harrowing, with oyster growers often claiming its significance in oyster culture (Bromley et al., 2016). The site is situated on the east coast of the UK within the Blackwater, Crouch, Roach and Colne Estuary Marine Conservation Zone (BCRC MCZ). The BCRC MCZ was first designated in 2013 for the protection of native oysters and native oyster beds and consists of a 284 km^2 area with native oysters and their beds concentrated in two main areas: one in the south near the Ray Sand at the mouth of the River Crouch estuary and another at the north bank of the mouth of the River Blackwater estuary. The T&M SO is a smaller zone further upstream in the main body of the River Blackwater estuary in which oyster mariculture and harvesting may occur under the Sea Fisheries (Shellfish) Act, 1967 (SeaFisheries, 2019; Figure 1; see also Lown et al., 2021). The Blackwater estuary has a high sediment loading routinely above 50 mg/L (Moffat, 1995) with some measures as high as 122 mg/L (Ladd et al., 2019), which makes it an ideal system within which to test the effectiveness of harrowing.

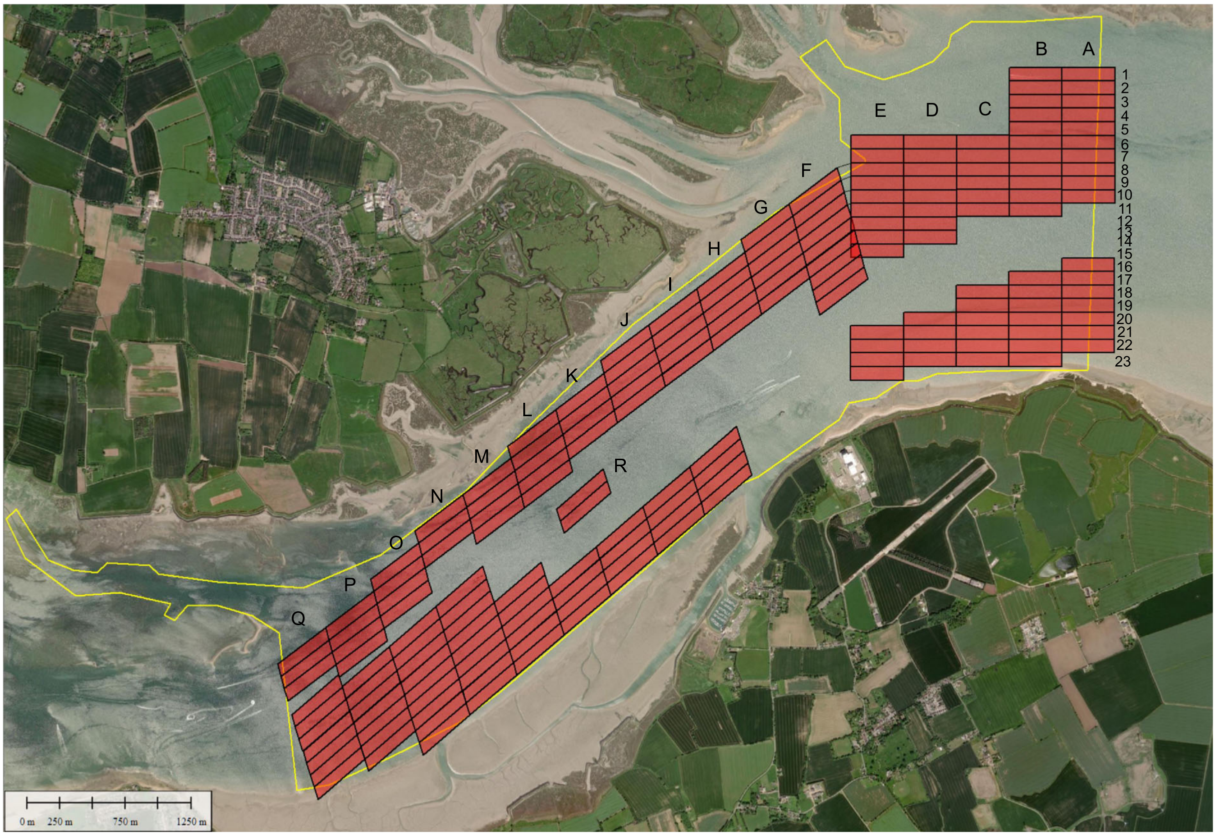

FIGURE 1 Approximate 4 ha survey boxes across the Tollesbury & Mersea Oyster Company. Several Order (boundary in yellow). This survey approach was first determined for a 1997 stock survey and reused in 2018. The number of boxes in each column changes in response to the width of the river and associated change to the legal boundary of the Several Order. The distribution of oyster abundance is not provided to protect the locations of the stock. Image created by J Pullen.

2.2 | Survey

An *O. edulis* stock survey was undertaken in the Blackwater estuary, Essex, UK in late September 2018. This consisted of a repeat of a stock survey undertaken in 1997 where the T&M SO was divided into rectangular boxes of just over 4 ha each. While some boxes were excluded on the survey day by direction of the T&M Oyster Company, samples were collected by dredge in 159 out of 185 of these boxes (Figure 1). Sampling was undertaken by boat (vessel name *Native* (10 m, 95 hp), skipper Ross Wey) and a deck team consisting of Allan Bird, Graham Baker, Jane Dixon (all Tollesbury & Mersea Oyster Company) and either Tom Cameron (TC) or Russell Smart (RS).

A 1.2 m ladder oyster dredge with a 45 mm ring size was used to sample down the centre of each 4 ha box on the grid parallel to the estuary bank (see Figure 1). Dredge distances were aimed to be 100 m by taking into account speed, how full the dredge felt and wetting time. The start and end point of each dredge was also recorded using GPS (Garmin© eTrex (differential enabled)) linked to Timezero© (Maxsea; www.mytimezero.com) so that the actual dredge length could be calculated afterwards. Dredge length ranged from 99 to 341 m – but dredges were never so full as to reduce the efficiency in capturing oysters.

Oysters were first sorted by hand by AB and GB as to whether they were live, then into one of four decreasing size classes 1–4. Size class 1 represented larger adult oysters of ≥70 mm height (umbo to outer margin), size class 2 were adults of 60–69 mm, size class 3 were 50–59 and size class 4 <50 mm. This was first judged by eye by Bird and Baker, then checked, size measured and recorded by TC and RS.

The harrowing effort was quantified through the use of fishing vessel tracking, with the records of all oyster fishing vessels working in the area to undertake pre-spawning harrowing obtained between 2016 and 2018 included in this study. These data were recorded by the company for calculating individual boat effort and wages and the data were not *a priori* intended to be used for estimating the harrowing effort – it is an independent measure of the time spent undertaking harrowing activities in each location as a sum of all harrowing activities across 2016–2018. Harrowing was performed by the T&M Oyster Company using either open dredges or chains. Harrowing was undertaken in different areas Several Order for different reasons, sometime to stimulate oyster recruitment and at other times to improve recruitment to areas where oysters were already known to be doing well. This resulted in varying levels of harrowing effort in the different boxes of the T&M SO.

To quantify the level of effort invested in cleaning over the study period, vessel tracks were converted into point tracks, with one point for each time a vessel logged its location. The time between each point varied between vessels ranging from one log point every 1–10 s. The number of log points per box was multiplied by the time interval for the corresponding individual vessel track, with each box summed for all vessels and all years to provide a total number of seconds of harrowing effort invested in each box over the 3 years prior to the oyster stock survey in September 2018. Owing to the sensitive nature of the precise distribution data of a target species within a private fishing ground of both economic and conservation value, exact location data are not presented.

2.3 | Analysis

For the purposes of studying recruitment in a fishery context, oysters that were aged one to three seasons were classed as recruits. These are individuals in size classes 3 and 4 and represent a size range of 28–59 mm measured from the umbo to the outer edge (i.e. shellfish height). These two smallest size classes could already be sexually mature males but will be considered recruits to the juvenile or subadult stage until they have reached sizes where they could have reproduced once as female or be of legal landable size. Adults were therefore all other larger individuals in size classes 1 and 2.

A correlation matrix plotted using the 'GGally' extension to 'GGplot2' in R was used to assess correlations between the variables used in this study (juvenile abundance vs. adult abundance, juvenile abundance vs. effort and adult abundance vs. effort) with box and whisker plots used to highlight differences in oyster abundance between north and south banks.

To investigate how adult abundance and level of harrowing effort are associated with recruit abundance, a single model was created, including the use of north vs. south bank as a predictor variable owing to the significant differences in oyster abundance between banks. Owing to the spatial nature of these data, they were first assessed for the presence of spatial autocorrelation. To achieve this, data were modelled in a non-spatial Poisson generalized linear model to assess how the presence of adult oysters, the cleaning effort between 2015 and 2018, the interaction between these two predictors, and the bank of the river (i.e. north/south bank of the channel) were associated with the abundance of recruits. Residuals from this model were then tested for spatial autocorrelation using DHARMa Moran's I test for spatial autocorrelation, assuming the centre point of each survey dredge as the single point reference for the sample. Spatial autocorrelation of the residuals were observed (observed $= 0.0678516$, expected $= -0.0063291$, SD $= 0.0166885$, $p < 0.001$); therefore a spatial mixed-effect model (spam) was used to model the abundance of recruited oysters associated with adult abundance, fishing effort and the riverbank placement (Rousset & Ferdy, 2014; Rousset, 2022). A Poisson distribution was selected with the model initially incorporating a fully factorial design with interactions on all terms. The three-way interaction between adult oyster abundance, effort and river bank was subsequently removed from the spatial aspect of the model owing to non-significance, resulting solely in interaction terms between adult abundance and harrowing effort, adult abundance and bank, and harrowing effort and bank. The resulting minimum adequate model was then used to predict recruit abundance based on a dummy dataset ranging in estimated oyster abundance from 0 to 100 adult oysters in a 100 m dredge sample, 0–8000 s effort recorded within each survey box, and north vs. south banks of the river Blackwater.

All statistical analyses were performed in RStudio 1.2.5042© and R-4.0.0© (R Core Team, 2020; RStudio Team, 2020). All GIS analysis was completed in QGIS 3.10.2© with GRASS 7.8.2© (QGIS, 2022).

3 | RESULTS

There was a significant and positive correlation between seabed disturbance effort and the number of recruits across both the north ($p = 0.51$) and south bank ($p = 0.31$) areas of Several Order (Figure 2). However, large amounts of variation remain unexplained, particularly in the north bank area, that are probably due to spatial correlation between adult oyster and recruit locations. Given this positive relationship between abundance of adult oysters and recruits across the site, the relationship between adult oysters, disturbance effort and recruitment in space was examined further, while confirming that spatial autocorrelation was present and significant.

3.1 | Spatial model

Spatially autocorrelated mixed models within the spaMM package in R indicate a significant effect of adult oyster abundance on the abundance of recruits ($F = 75.697$, d.f. $= 1$, $p < 0.001$), but in addition significant effects of harrowing effort and bank were also observed ($F_{EFFORT} = 32.167$, d.f. $= 1$, $p < 0.001$; $F_{BANK} = 27.142$, d.f. $= 1$, $p < 0.001$). Significant interactions affecting recruitment were observed between adult abundance and effort ($F = 14.064$, d.f. $= 1$, $p < 0.001$), adult abundance and bank ($F = 12.453$, d.f. $= 1$, $p < 0.001$) and effort and river bank ($F = 11.363$, d.f. $= 1$, $p < 0.001$). A quantile-quantile plot of residuals indicates a good model fit (KS test, $p = 0.33522$; dispersion test, $p = 0.408$; outlier test, $p = 1$) with the DHARMa non-parametric dispersion test via standard deviation of residuals fitted vs. simulated indicating no difference in simulated values (p (two sided) $= 0.408$) and no outliers in the residuals (Figure S1).

This spatial correlation corrected model was then used to predict how oyster recruitment, that is the abundance of recruits, would respond to harrowing based on a dummy dataset in order to better visualize model interactions (Figure 3). In areas of low adult flat oyster abundance, i.e. 0–50 adults oysters per dredge, the model predicts increased recruitment with increased harrowing effort for both north and south banks. These predictions of increasing recruitment with increasing disturbance are suppressed in areas with more than

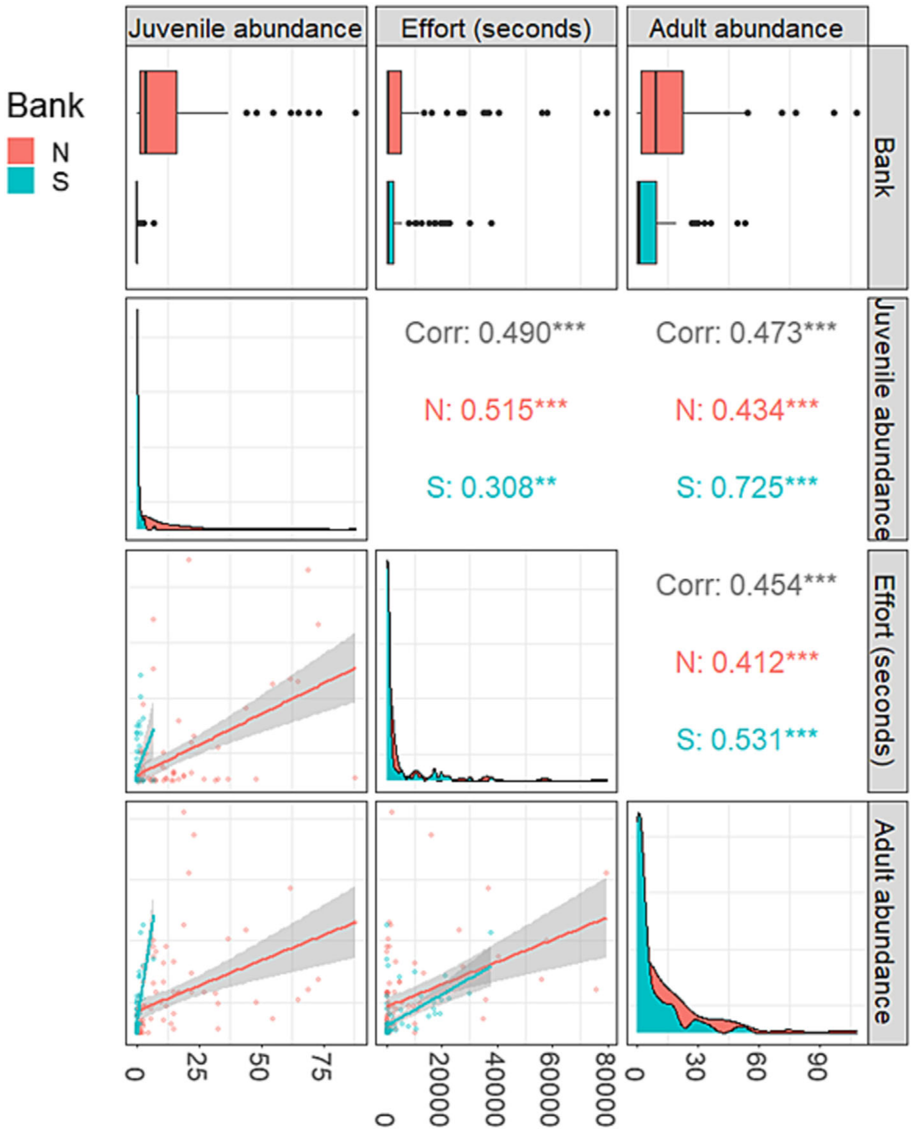

FIGURE 2 Juvenile recruit and adult oyster abundance (numbers per 100 m dredge) and sea bed harrowing effort (seconds) on the north (N) and south banks (S) of Several Order (top row). The relationship between each variable is shown including estimates of the correlation (remaining rows). Note the positive non-zero slopes of relationship between effort and juvenile abundance, but lots of variation unexplained (left column, third from top).

70 adult oysters per dredge sample, with adult abundance of 80 oysters per dredge and above indicating increased juvenile abundance with lower levels of harrowing disturbance.

4 | DISCUSSION

This study has identified increased recruitment of oysters with increasing harrowing effort in areas of low adult oyster density in a highly sedimented estuary system. This recruitment benefit of ground cleaning is increasingly suppressed and eventually reversed in areas of high adult oyster density, suggesting that once a specific density of adult oysters is achieved, oyster beds become self-sufficient in dealing with sediment, providing or somehow associated with suitable habitat for offspring to settle. This is based on multi-annual data on harrowing effort recorded by oyster producers, and highlights the wealth of information already available to assess how mariculture, fishery management and conservation goals could be informed by methods from traditional oyster growing techniques.

In the highly sedimented coastal system of the southern North Sea, with total suspended sediment values routinely above 50 mg/L (Moffat, 1995) and average annual (non-algal) suspended sediment being some of the highest in UK coastal waters (>30 mg/L; CEFAS, 2016), the deposition of high volumes of sediment is common. These depositions can occur on areas known for shellfish settlement, and were up to 8 cm deep over oyster beds off West Mersea, Essex, UK after the 2018 storm ‘Beast from the East’ (Lown, 2019). Sediment deposition can reduce the survival of shellfish and bury the habitats that they create on different timescales (Berghahn & Ruth, 2005; Bromley et al., 2016; Allison et al., 2020; Sander et al., 2021). It is widely recognized that harrowing of the seabed to disturb these sediments is a globally common practice despite a lack of strong peer-reviewed evidence of its effectiveness (Waugh, 1972; Bromley et al., 2016).

Here we show that disturbance of the sea bed in areas otherwise known for shellfish settlement across three potential recruitment seasons can have a positive effect on flat oyster recruitment. Specifically, in areas with moderate adult oyster abundance of

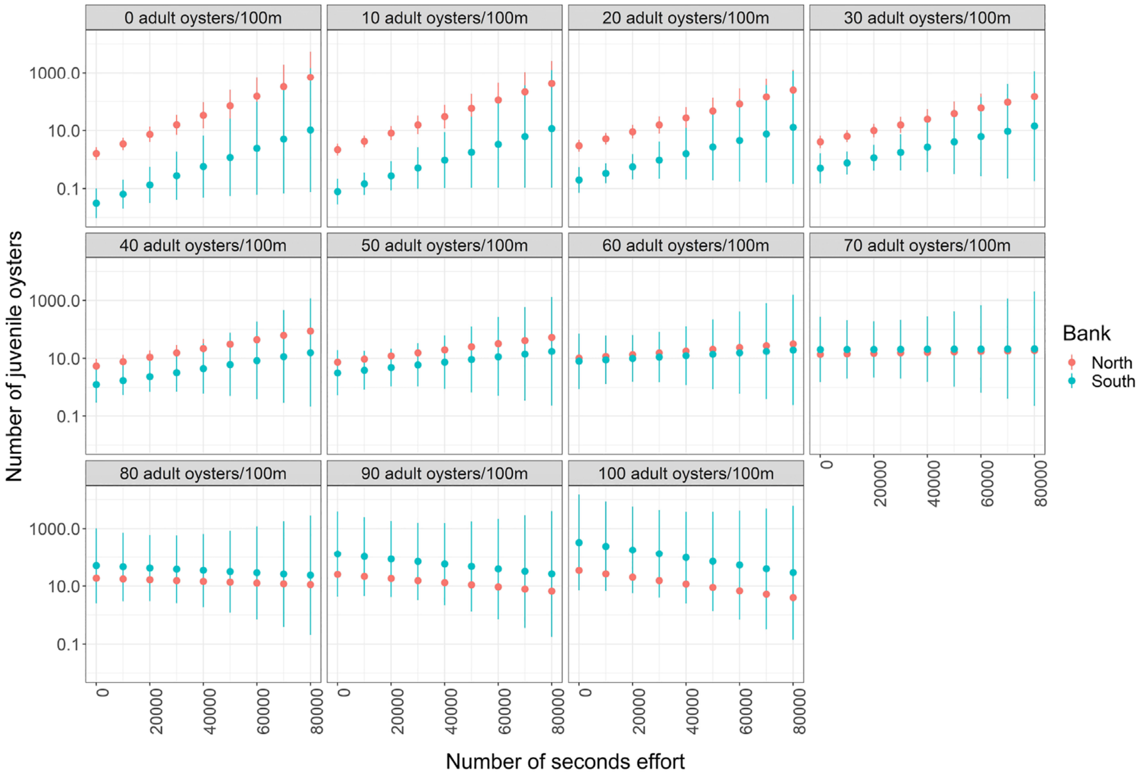

FIGURE 3 Predictions on number of juvenile oyster recruits (*y*-axis) found in a 100 m dredge in 2018 based on the number of adult oysters (top band) in a 100 m dredge and number of seconds effort fishing/cleaning (*x*-axis) between 2016 and 2018.

30 oysters per 100 m dredge, up to 40 min of harrowing effort per year in the weeks prior to predicted shellfish spawning can increase the number recruits from approximately five oysters to 100 oysters per 100 m dredge.

However, there were limits to this positive effect of harrowing on recruitment. Where there are already aggregations of live adult oysters in place, and it is assumed associated dead shell or other hard substrate communities, harrowing effort does not increase recruitment and may actually hinder it. For example where there are already 60–70 adult oysters per 100 m dredge, the positive effects of seabed disturbance on recruitment begin to decline and eventually reverse. If 60 adult oysters per 100 m dredge is the switch point, with a 10% ladder dredge efficiency (Cameron et al., in press), this is equivalent to five adult oysters per m^2 (60/120 m^2 $\times$ 10(%)). However, gains from harrowing effort would start to diminish above this density. At the higher adult oyster densities, any harrowing or cleaning intervention is predicted to have minimal or even negative effects on juvenile oyster recruitment, perhaps through damage to younger fragile oysters in a dredge when the abundance of adult oysters and associated cultch material is high (Airoldi & Beck, 2007).

Previous studies investigating the efficacy of harrowing at sites in Ireland found harrowing to increase the abundance of clean shell. In addition, harrowing was found to alter the benthic species assemblages present (Bromley et al., 2016). However, there was no difference in the number of oyster spat observed, with no live spat observed in either treatments in 2012 and 2013, and 12 spat recorded in 2014 on non-harrowed plots with three on harrowed plots, showing that harrowing made no difference to spat settlement (Bromley et al., 2016). As flat oysters can display high interannual variation in both spatfall timing and abundance (van den Brink et al., 2020), the authors point out their result could be down to bad luck in working in poor spat years, but it could also be that the shelf budget was not limiting oyster spatfall success in this system.

A smaller scale study by Kent and Essex Inshore Fisheries and Conservation Authority across six 150 × 500 m plots located in public seabed areas at the mouth of the Blackwater estuary and on the Ray Sand near the River Crouch estuary found that surface stone and shell content were increased by harrowing effort in only one site in 1 year – Ray Sand (KEIFCA, 2019). However the effect was very short-lived and the effects of harrowing were unobservable via sidescan sonar after only 1 week (compared with 6 weeks in the mud-based Blackwater; KEIFCA, 2019). The harrowing in this study, while over many hours, was not timed to coincide with certain tides, times of year for spatting or sustained by short visits over many weeks as oystermen do on their private grounds and so it has been suggested it was not a good test of harrowing effectiveness for increasing oyster recruitment.

Working of the ground or harrowing is often claimed by Essex oyster growers as essential to ensure the availability of shell and gravel for settlement of juvenile oysters. The results presented here demonstrate that in areas of low adult flat oyster abundance, harrowing can increase recruitment success. While this is mainly a test of a controversial fishery management tool, this method could be used to support conservation objectives via 'kick-starting' enhanced recruitment of the European native oyster in areas where its densities are low and costs constrain other interventions such as large volumes of cultch relaying or bought stock enhancement.

However, in areas of sufficient adult oyster densities, harrowing effort led to reduced oyster recruitment. This finding provides guidance on when harrowing interventions in either fishery management or as a kick-starting conservation measure to increase flat oyster recruitment would be counterproductive. While this tipping point between potential benefits and neutral or negative effects on oyster recruitment in this study is at approximately 60 oysters per 100 m dredge (approximately five oysters per square metre with 10% dredge efficiency), this study remains untested at other sites; therefore caution should be taken to use this specific density as an absolute tipping point. This study has highlighted the effectiveness of harrowing in driving increased oyster recruitment in areas of particularly low adult oyster density in a muddy estuary where recruitment is regularly occurring, but where conditions differ from this there is no guarantee that harrowing would deliver increased recruitment.

This study does not assess any other effects of harrowing on marine biodiversity or habitat structure. Harrowing and otherwise disturbing the seabed can cause changes to the seabed and this includes in terms of species richness and ecological community composition (Thrush & Dayton, 2002; Bromley et al., 2016). In a highly modified estuary system with very high invasive and non-native species abundance as is found in many southern UK estuary sites (Reise, Gollasch & Wolff, 1998; Stiger-Pouvreau & Thouzeau, 2015; Lown, 2019; Lown et al., 2021), one could argue that small-scale harrowing is inconsequential for biodiversity relative to other threats. Indeed maximum oyster densities and associated species richness have been found to be similar in the managed and unmanaged oyster beds in the Blackwater estuary (Lown et al., 2021). Such an argument does not consider that if the sea bed was left alone to recover from disturbance the potential for recovered habitat complexity and resulting biodiversity including increased resilience for non-native species could provide us with a new baseline (Villas & Norkko, 2011; Plumeridge & Roberts, 2017). For example, an oyster bed habitat that has been kick-started using harrowing methods but then left to recover for 20+ years may achieve a different structural and species complexity than a managed oyster area that is kick-started then harrowed every 2–3 years, and dredge harvested every 3–5 years. While both habitats are likely to be associated with greater species richness than surrounding shellfish free sediments (Lown et al., 2021), it would be important to recognize that they are not equally supportive of biodiversity-linked ecosystem services. While recognizing that seabed areas restored for fisheries vs. those restored for biodiversity ecosystem services and conservation objectives may not be equal, they are also not mutually exclusive at appropriate spatial scales. For example with flat oyster population sizes approaching several million in the BCRC MCZ, viable fisheries can be maintained with a very small fraction of biomass harvested (1–2%) and area impacted (Lown et al., 2020).

5 | IMPLICATIONS FOR CONSERVATION

The potential for using a seabed disturbing method to improve recruitment of a species of fishery and conservation concern, the European flat oyster *O. edulis*, has been demonstrated. Harrowing of highly sedimented systems where there is an expectation of juvenile flat oyster spatfall has the potential to be a conservation intervention to 'kick-start' oyster population recovery that is much more accessible to community groups and oyster growing associations than the expense, project planning and biosecurity risks required for importing hundreds of tonnes of shell and gravel material and/or new broodstock. While it would be considered a short-term intervention, any potential benefits to single species shellfish recruitment would have to be considered against potential costs to the seabed and existing marine biodiversity.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest in the work being presented. All data analysis and writing of the text were carried out independently of the Tollesbury and Mersea Oyster Company.

DATA AVAILABILITY STATEMENT

The data used in this study belong to the Tollesbury and Mersea Oyster Company and were not made available for publication. Requests for use should be directed to Tollesbury and Mersea Oyster Company.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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