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Contribution to the Supplement: '*Effects of Fishing on Benthic Fauna, Habitat and Ecosystem Function*'

Review

The physical impact of towed demersal fishing gears on soft sediments

F. G. O'Neill[1]* and A. Ivanović[2]

[1]*Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen AB11 9DB, UK*
[2]*School of Engineering, Kings College, University of Aberdeen, Aberdeen AB24 3UE, UK*

**Corresponding author: tel: +44 1224 876544; fax: +44 1224 295511; e-mail: oneillb@marlab.ac.uk*

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An improved understanding of the physical interaction of towed demersal fishing gears with the seabed has been developed in recent years, and there is a clearer view of the underpinning mechanical processes that lead to the modification and alteration of the benthic environment. The physical impact of these gears on soft sediments can be classified broadly as being either geotechnical or hydrodynamic in nature: penetration and piercing of the substrate, lateral displacement of sediment, and the influence of the pressure field transmitted through the sediment can be considered geotechnical, whereas the mobilization of sediment into the water column can be considered hydrodynamic. A number of experimental and numerical approaches have been used to gain better insights of these physical processes. These include small-scale modelling in towing tanks and sand channels; large-scale modelling in the field; measurements behind full-scale towed gears at sea; numerical/mathematical modelling of sediment mechanics; and numerical/mathematical modelling of hydrodynamics. Here, we will review this research, and that in associated fields, and show how it can form the basis of predictive models of the benthic impact of trawl gears.

Keywords: fishing gears, geotechnical, hydrodynamic, physical impact, review, sediment mobilization, soft sediments.

Introduction

Most of our understanding of the impact of fishing on the benthic environment comes from either studies across fishing gradients where data are collected from similar habitats with different levels of fishing effort (e.g. Thrush *et al.*, 1998; Hinz *et al.*, 2009; Mangano *et al.*, 2014; Palanques *et al.*, 2014) or from Before-After Control-Impact (BACI) type experiments where data are collected from both before and after an impact and compared with an undisturbed control site (Kenchington *et al.*, 2006; Pitcher *et al.*, 2009). These approaches have been very revealing and have highlighted the nature and the extent of the impacts of towed fishing gears; however, they often do not demonstrate a statistically significant effect (assuming it exists). For fishing gradient trials, there may be uncertainty in relation to fishing effort data, fishing gear descriptions, and technical creep (Shephard *et al.*, 2010; Eigaard *et al.*, 2014) and, as many fisheries use a range of gear types, it may also be difficult to identify gear-specific effects. In BACI experiments, there can be difficulties associated with detecting differences between impacted and control sites/samples above the high degree of natural variation that exists on the seabed (Løkkeborg, 2005). Furthermore, even when significant impacts can be demonstrated, the results will pertain only to that gear on the given substrate and it is often difficult to make general inferences regarding these impacts and/or extend the results to other gears on different sediments (Hughes *et al.*, 2014).

To address these issues and to synthesis and generalize the results of individual studies, a number of meta-analyses have been carried out. These analyses usually categorize towed gears as being otter trawls, beam trawls, or dredges, and have identified, to this level of resolution, the taxa and habitat types on which fishing impact is greatest (e.g. Schratzberger and Jennings, 2002; Kaiser *et al.*, 2006). They have been very informative and can be used to assess broad-scale changes of ecosystem functions, such as productivity and availability of food to the demersal system, under, for example, different levels of fishing effort (Hiddink *et al.*, 2006). There is not, however, sufficient contrast in the underlying studies or resolution in the meta-analyses to use them to investigate between-gear differences within a gear category. To distinguish between gears and to design and develop gears of reduced impact, it would be necessary to consider their impact at the level of the individual gear components (i.e. trawl doors, sweeps, groundgear element, beam trawl shoe, etc.) on a range of sediment types. The design and weight of these components, how they are rigged and fished and how they interact with each other, will influence the impact they have on the benthic environment. Given the variety of gears, individual components and elements that exist, and the range of sediments and habitats they are fished on, it is clear that it is not feasible to rely solely on the collection of empirical data.

An alternative approach is to develop more deterministic methodologies based on an understanding of the basic processes at work. The initial impact that a gear has on the benthic substrate is physical. Hence, to develop such an approach, we first need to understand these physical processes and subsequently relate them to their environmental and ecological effects. Restricting our attention to soft sediments, the physical interactions of a fishing gear with the seabed can be classified as being either (i) geotechnical or (ii) hydrodynamic. Geotechnical interactions refer to the mechanical interaction of the gear components with the seabed and, in particular, the penetration into the sediment, the lateral displacement of the substrate, and the associated shearing and pressure forces. The hydrodynamic interactions are associated with the generation of turbulence and the pressure drop in the wake of gear components and also the resulting mobilization of sediment (Figure 1).

In recent times, we have begun to get a much better understanding of these interactions. A range of acoustic and optical technologies have been used to observe the physical impacts of fishing gears on soft sediments; experimental trials and laboratory-based studies have been carried out at both sea and sand channels; and empirical and numerical models of these processes have been developed. Here, we review these advances and those in related fields, and demonstrate that we are now in a position to develop predictive models of the benthic impact of trawl gears.

Geotechnical impacts on soft sediments

The engineering behaviour of cohesive and granular sediments is extremely complex. This is especially the case when dealing with sediment-structure problems and problems close to or at a sediment surface. When a solid object impacts a sediment, there can be compression, shearing, and displacement of the sediment. Depending on the mechanical properties of the sediment and the weight and geometry of the object, there may be a build-up of a sediment in front of the object, and following its passage, there may be alteration to the sediment surface which can range from superficial scouring to a trench with well-defined edges, possibly berms either side, and backfilling of sediment which settles at a characteristic angle.

Some of most important properties defining the mechanical behaviour of a sediment are the shear strength characteristics. They identify the point at which a sediment fails and adjacent surfaces within the sediment shear. Failure and shearing are common behaviours of granular materials. In front of a penetrating object being towed along the seabed, there may be alternating episodes of resistance and sediment failure where sediment is displaced forwards and upwards along the failure surfaces forming a frontal spoil, which may be deposited along the edges (Figure 2).

Observations of the alteration of the seabed following the passage of towed fishing gears have been made by both acoustic and optical methods. Sidescan sonar has been used to identify the occurrence and estimate the density of trawling (Fonteyne *et al.*, 1998; Schwinghamer *et al.*, 1998; Thrush *et al.*, 1998; Tuck *et al.*, 1998; Friedlander *et al.*, 1999; Malik and Mayer, 2007; Smith *et al.*, 2007; Lucchetti and Sala, 2012; Palanques *et al.*, 2014); it has also been used to estimate the depth of penetration of otter doors into the seabed and has more recently been used by Lucchetti and Sala (2012) to observe both gear and impacts during the fishing operation. The seabed classification system (RoxAnn) has been employed by Fonteyne *et al.* (1998), Schwinghamer *et al.* (1998), Tuck *et al.* (1998), and Humborstad *et al.* (2004) to measure "texture" of the seabed following trawling as a means to quantify the extent to which the sediment layer has been mixed; multibeam echosounders have been used by Depestele *et al.* (2016) to measure the alteration to the seabed in the wake of beam trawls and by Malik and Mayer (2007) to identify the impact of scallop and clam dredges. Optical methods, such as sediment profile imagery (SPI) and camera and laser systems mounted on towed bodies, sledges, ROVs, and drop frames or operated by divers, have been used to assess modifications to the seabed by a range of

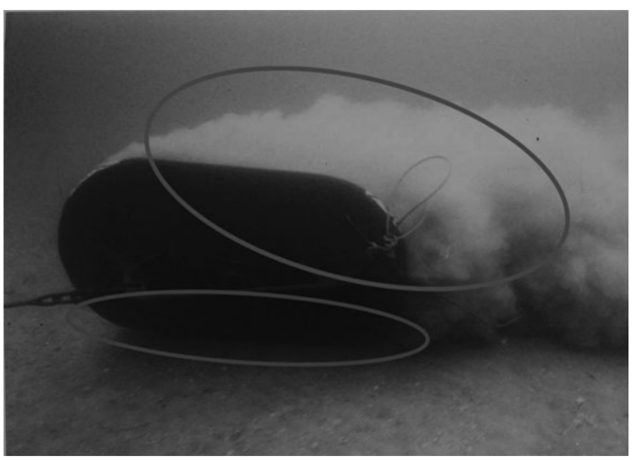

Figure 1. The physical interactions of a fishing gear with the seabed can be classified as being either (i) geotechnical or (ii) hydrodynamic. Geotechnical interactions refer to the mechanical interaction of the gear components with the seabed (lower oval). The hydrodynamic interactions are associated with the generation of turbulence and the mobilization of sediment (upper oval).

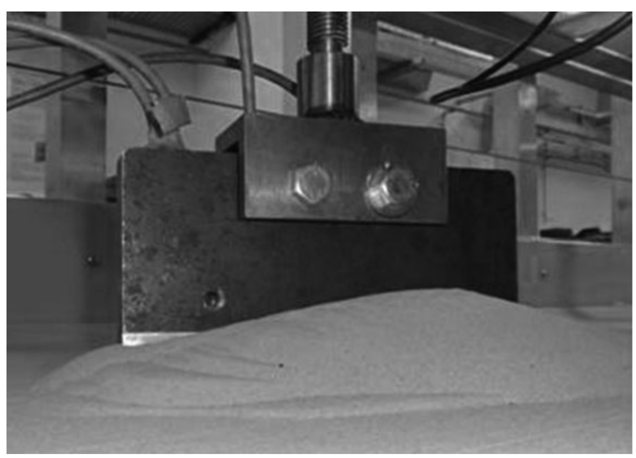

Figure 2. A demonstration of sediment failure in front of a towed penetrating object in a sand channel where there are alternating regions of resistance separated by failure surfaces.

fishing gears (Paschen *et al.*, 2000; Collie *et al.*, 2000; Dellapenna *et al.*, 2006; O'Neill *et al.*, 2009, 2013a; Puig *et al.*, 2012; Boulcott *et al.*, 2014; Martín *et al.*, 2014).

More focused geotechnical studies have taken place under laboratory conditions in sand channels. Generally, these studies are of small-scale gear components, attached to a mobile carriage and towed over a sandy sediment (Figure 3). Depending on the instrumentation available, measurements can be made of the three-dimensional force acting on the component, the depth of penetration of the component into the sediment, and the morphology of the sediment surface following the passage of the component. These studies have concentrated on developing a better understanding of the basic processes; developing small-scale modelling rules, so results from channel experiments can be transferred to the full scale; and providing data to validate numerical models. Paschen *et al.* (2000) performed the first of these studies and examined the contact forces between ropes and chains and sand in a sand channel, and they have subsequently been extended by Enerhaug *et al.* (2012), Ivanović and Casanovas Revilla (2013), and Esmaeili and Ivanović (2014) to consider groundgears, doors, and roller clumps. In one of the few laboratory studies to examine directly the link between physical impact and the associated biological implications, Gilkinson *et al.* (1998) investigate the damage to infaunal bivalves from a full-scale trawl door in a sand channel.

Numerical models of the geotechnical interaction of fishing gears with the seabed have also been developed. The simplest of these models predict the contact forces between a gear component and the seabed, and do not allow for any deformation or penetration of the sediment (Prat *et al.*, 2008). Igland and Søreide (2008) subsequently study the contact forces between a roller clump and marine pipelines where the seabed is deformable but impenetrable. Rességguier *et al.* (2009) try a different approach and investigate the vertical drop of trawl doors into soils of various strengths by analysing the absorption of kinetic energy; however, they do not examine the case of the door being towed across the seabed. Ivanović *et al.* (2011) develop a finite element approach using a constitutive sediment model to investigate the impact of a trawl door and a roller clump on fully saturated muddy sediment. Ivanović and O'Neill (2015) apply this approach to study the influence that the dimensions, the weight, the cross sectional geometry, and the soil material properties have on penetration and drag of truncated rigid cylinders (Figure 4). Esmaeili and Ivanović (2014) improve the numerical methods of Ivanović *et al.* (2011) to better account for the large deformations of the seabed that are associated with trawling activities and validate their approach by comparing their predictions with laboratory experiments where a segment of a rock-hopper groundgear is towed in a sand channel.

There are also related geotechnical problems in many engineering applications. One of the main topics of contact mechanics is the interaction between an object and a deformable body (Johnson, 1985), and the particular problem of determining the reaction force acting on a towed object and the deformation of the medium on which it is towed is of major interest. There have been both laboratory and numerical modelling studies related to soil cutting and ploughing processes (Nouguier *et al.*, 2000), iceberg interaction with seabed (Yang and Poorooshasb, 1997; Barrette, 2011), vehicle mobility assessment (Bekker, 1969; Wong, 2001), and the indentation and rolling of wheels on both cohesive and frictional soils associated with off-road vehicles (Hambleton and Drescher, 2008, 2009a). Hambleton and Drescher (2009b) employ a similar model to that of Ivanović and O'Neill (2015) to carry out two- and three-dimensional simulations of wheels on a cohesive sediment. The numerical modelling of these sediment contact problems is also an active area of research; typically, there is a need to identify constitutive stress/strain relationships (which characterize the mechanical behaviour of the sediment at the infinitesimal level) and develop accurate and efficient numerical methods.

Hydrodynamic impacts on soft sediments

As explained by O'Neill and Summerbell (2011), the interaction of towed fishing gear components, the seabed, and the ambient water produces a region of high velocity, high turbulence, high shear bed stress, and a pressure drop all of which may contribute to entrainment and mobilization of sediment behind the gear component in

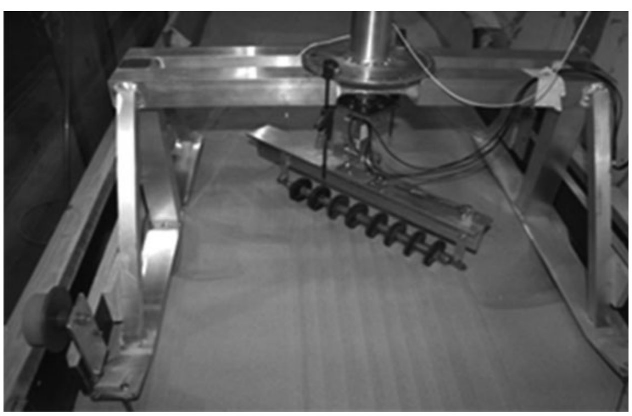

Figure 3. A small scale model of a segment of a rockhopper groundgear attached to a mobile carriage and towed over a dry sandy sediment in a sand channel.

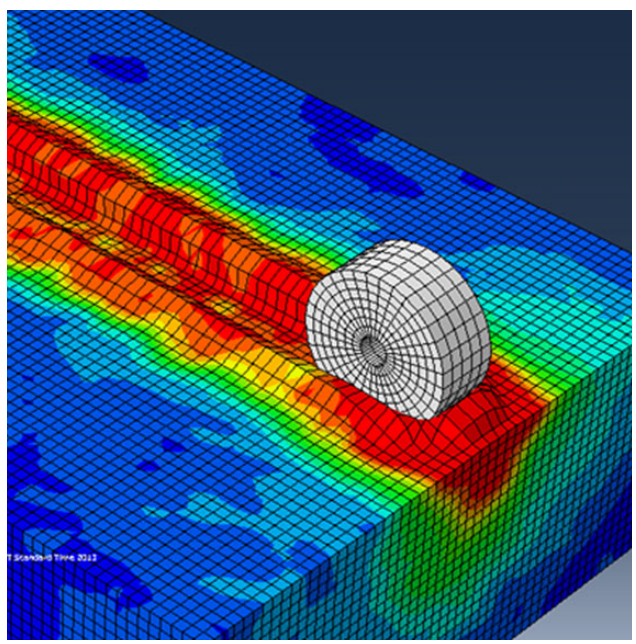

Figure 4. A graphical description of the model predictions for a circular cylinder on a muddy sand sediment, showing a build-up of a sediment in front of the cylinder, a trench with well-defined edges and berms either side and where the 'warmer' colours identify regions of higher stress (Ivanović and O'Neill, 2015).

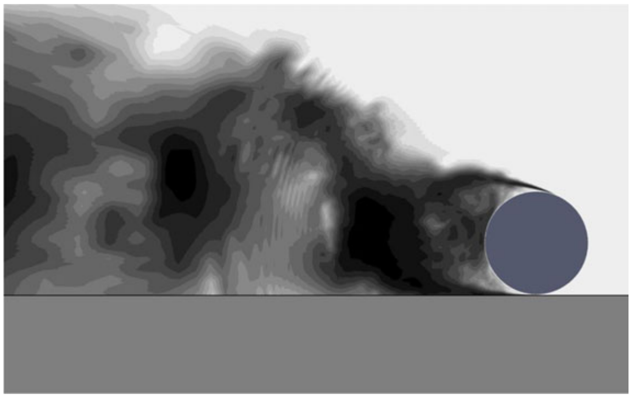

Figure 5. A schematic of the instantaneous flow behind a cylinder towed across the seabed where the darker shading identifies regions of high velocity, high turbulence, high shear bed stress and a pressure drop all of which may contribute to entrainment and mobilization of sediment. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

contact with the seabed (Figure 5). The entrained sediment will have a vertical profile that depends on the turbulence and particle size. Its concentration will decrease with distance from the gear component as turbulence decays and the sediment settles and as the sediment plume diffuses. The transport, diffusion, and subsequent settlement of sediment are relatively well understood and have been studied extensively in the context of coastal engineering and the extraction of marine mineral deposits. However, to make use of our understanding of these processes and to assess the environmental and ecological impact of sediment mobilization by towed fishing gears, it is necessary to be able to quantify how much sediment is put into the water column in the first instance.

Acoustic and optical technologies have been used to investigate the mobilization of sediment in the wake of towed gears, both to identify the extent of the problem and to estimate the amount of sediment mobilized. Lucchetti and Sala (2012) have shown how observations of the sediment plume behind a hydraulic dredge, a Rapido trawl, and demersal otter trawls can be made using sidescan sonar. Durrieu de Madron *et al*. (2005) have used the backscatter signal from an acoustic Doppler current profiler to quantify the sediment mobilized by a trawler in the NW Mediterranean, and O'Neill *et al*. (2013b) use a multibeam echosounder to measure the concentration of sediment put into the water column by an otter door and a twin-trawl roller clump. Optical backscatter sensors have been used by Black and Parry (1999) to measure turbidity behind "Peninsula" scallop dredges in southeastern Australia, and a number of authors have used transmissometers and particle size analysers to measure sediment concentration and particle size distribution behind towed gears and individual gear components (Durrieu de Madron *et al*., 2005; Dellapenna *et al*., 2006; O'Neill *et al*., 2013a, b). Direct sampling from the sediment plume has also taken place. Pranovi *et al*. (2004) used a submerged pump to sample the wake of a clam harvesting gear called the "rusca" in the Venice Lagoon, and the sediment put into suspension behind commercial and survey demersal trawls has been investigated by Dounas (2006) and Dounas *et al*. (2007) in Greek waters, using 2 l water sampler bottles.

Changes to the particle size distribution of the sediment and the settlement of sediment in areas next to trawling have also been measured. Depending on the local hydrographic conditions, a winnowing process can occur whereby the finer sediments which remain in suspension longer are transported from the trawled area leading to a gradual coarsening of the sediment that remains (Pranovi and Giovanardi, 1994; Palanques *et al*., 2014).

We are not aware of any laboratory experiments to investigate the sediment mobilized by towed bodies. However, in addition to the measurements and observations at sea behind full-scale gears, there have been experiments at sea to evaluate the sediment put into the water column by specific gear components. Dounas (2006) simulates the disturbance caused by a trawl groundrope by pushing one ahead of a benthic sledge and samples the sediment plume using water bottles. O'Neill and Summerbell (2011) use a particle size analyser on a similar type of sledge to systematically investigate the particle size distribution and concentration of the sediment mobilized by a trawl door and different types of groundgear on sediments ranging from sandy mud to sand.

O'Neill and Summerbell (2011) demonstrate empirically that the quantity of sediment mobilized behind a gear component is related to the hydrodynamic drag of the component, and that the finer the sediment the more that is mobilized. This, they explain, is because for a body in a steady flow, the energy associated with overcoming the hydrodynamic drag acting on a gear component manifests itself as turbulence in the wake, which will give rise to a pressure drop and a shearing action, both of which can cause sediment to mobilize. Hence, the greater the hydrodynamic drag, the greater the turbulence in the wake, and the greater the quantity of sediment put into the water column. One implication of sediment mobilization being a hydrodynamic process and related to hydrodynamic drag is that it depends on the towing speed and frontal area of the component causing the disturbance rather than the weight and penetration of the component. This conclusion is supported by recent trials where the sediment mobilized behind a range of gear components was measured and the weight and the towing speed of the component could be varied (FGO'N, pers. comm.).

The mobilization of sediment by turbulent flows is an important topic in many other environmental and engineering contexts. There has been a great deal of research directed at the transport of sediment by current flows and waves as well as the scouring and removal of sediment behind static objects such as pipelines, vertical cylinders, bridges, and piers. More recently, there have been studies in areas such as the mobilization of sediment by ship-generated wakes and propeller wash (Ji *et al*., 2014; Liao *et al*., 2015), the uplift and suspension of sediment particles under rotary blades (Milluzzo and Leishman, 2010), and the dust clouds behind terrestrial vehicles (Gillies *et al*., 2005). Detailed experimental and numerical investigations have taken place in these and related fields making use of particle image velocimetry (PIV), acoustics and computational fluid dynamic (CFD) modelling, and these techniques and methods could also be applied to investigations of the sediment mobilized in the wake of towed demersal fishing gears.

Demonstration of physical impact models

To illustrate the potential for the modelling approaches mentioned above and the role they could play in the development of a deterministic methodology to investigate the environmental and ecological impacts of towed demersal gears, we consider the predictions of the geotechnical model of Ivanović and O'Neill (2015) and those of the empirical sediment mobilization model of O'Neill and Summerbell (2011). We demonstrate how these models can be used to estimate the extent to which gear components penetrate the seabed and mobilize sediment into the water column and also how some relatively simple design modifications to the components can cause these estimates to vary.

Geotechnical model

Ivanović and O'Neill (2015) investigate the influence that the design parameters and the sediment properties have on the geotechnical impact of truncated rigid cylinders towed on fully saturated muddy sediments. They use a numerical model that assumes that the sediment behaves in a linear elastic manner when it is subject to shear stresses below a threshold known as the yield stress, and that it behaves plastically when it is subject to stresses greater than this threshold. This type of model has been widely used in solving geomechanical problems for sediments in undrained conditions and can predict the penetration depth, soil displacement, and drag force associated with towing individual gear components across the seabed. They demonstrate that over the parameter ranges examined there is a non-linear increase in penetration and drag as the weight increases; a decrease in penetration and an associated reduction of drag as the yield stress increases; and, for a given weight, a decrease in penetration and drag as the radius and/or length of the cylinder increases.

They also examine the non-dimensional form of the problem and demonstrate that the predicted penetration and drag values can be summarized (at least to a first order of approximation) by two curves, respectively, which are dependent solely on the non-dimensional weight. Given the fact that these simulations are very computationally expensive, this is very significant, as it means that over the large range of radius, length, weight, and yield stress values they examine, the penetration and drag of a truncated cylinder on fully saturated muddy sediments can be predicted. The expression for penetration, in dimensional form, is

$$\delta = r\left(0.0605\left(\frac{W}{Ybr}\right) - 0.1748\left(\frac{W}{Ybr}\right)^2 + 0.2057\left(\frac{W}{Ybr}\right)^3 - 0.0433\left(\frac{W}{Ybr}\right)^4\right), \quad (1)$$

where δ is the penetration, W is the weight per unit width, b is the width of the cylinder, r is the radius, and Y is the yield stress.

Hydrodynamic model

O'Neill and Summerbell (2011) develop an empirical model with sediment concentration data they collect behind a range of groundgear components and a trawl door. They use a particle size analyser to measure the particle size distribution and concentration of the sediment mobilized into the water column by the different components, and for each of the four sediments on which the trials take place, they relate the amount of sediment added to the water column to the hydrodynamic drag of the component. Here, we reanalyse these data and regress the amount of sediment mobilized on to a bilinear function of the hydrodynamic drag and the proportional silt fraction of the sediment (% of sediment <63 μm). The resulting expression for the quantity of sediment put into the water column is

$$m = 2.602s_f + 1.206 \times 10^{-3}H_d + 1.321 \times 10^{-2}s_f H_d, \quad (2)$$

where m is the mass of sediment put into the water column per m^2 swept, s_f is the silt fraction, and H_d is the hydrodynamic drag per metre width of the gear component ($N\,m^{-1}$). This expression permits the estimation of the amount of sediment put into water column in the wake of towed bodies on sediments with silt fractions ranging from 0.02 to 0.69. This curve and the respective datasets are plotted in Figure 6, for the four sediments on which the trials took place.

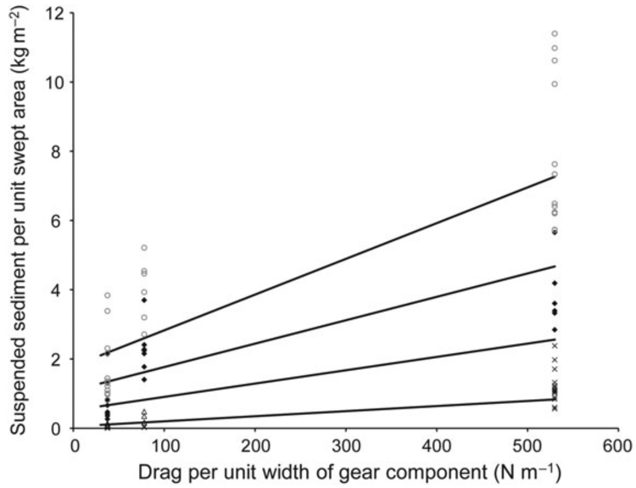

Figure 6. The predictions of the sediment mobilization model [equation (2)] at the four silt fraction sediments on which the trials took place and the corresponding data of O'Neill and Summerbell (2011).

Prediction of geotechnical and hydrodynamic impacts

To demonstrate how Equations (1) and (2) can be used in either a design or assessment context, we show how some relatively simple modifications to the design of a cylindrical twin-trawl clump cause the corresponding predictions of penetration and mass of sediment mobilized to vary. The clump is designed to distribute the towing force of the central warp between the two nets of a twin trawl and to have sufficient weight to ensure that the nets maintain contact with the seabed. It is one of the heaviest individual components of a trawl gear and is expected to have a large physical impact on the seabed. We use Equation (1) to estimate the penetration depth of the clump weights and Equation (2) to estimate the amount of sediment mobilized. To estimate, H_d, the hydrodynamic drag of a clump we use

$$H_d = 0.5\rho U^2 0.67rb,$$

which is the hydrodynamic drag of a cylinder with radius to width $r/b > 0.25$ (Hoerner, 1965). Figure 7a presents the case where r is increasing, and the width, b, and the weight, W, are kept constant. Hence, as r increases, the weight per unit area, W/br, and consequently, penetration decrease. There is also an increase of frontal area, leading to an increase of hydrodynamic drag and sediment mobilization. In Figure 7b, we have the case where as r increases, b is kept constant, and W increases in relation to the increase of volume (i.e. density of clump remains the same). Thus, the weight per unit area increases with r and penetration increases. The frontal area of the clump also increases with r, leading to a greater hydrodynamic drag and more sediment being mobilized. In Figure 7c, as r increases, W is constant, and the width, b, decreases in such a way that the volume of the cylinder is kept constant. Thus, $b \sim 1/r^2$, and the

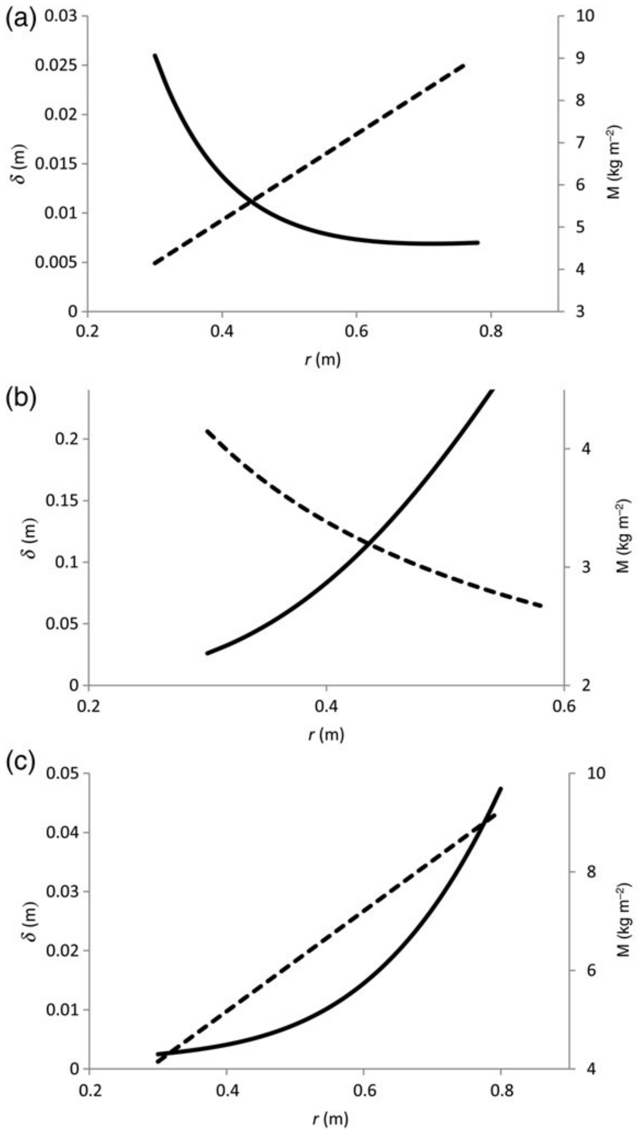

Figure 7. Predictions of the penetration (solid lines) and the mobilization of sediment (dashed lines) caused by a cylindrical clump as the radius *r* increases. In (a) the width, b, and the weight, W, are kept constant (1.0 m and 10 kN respectively). In (b) b = 1.0 ms − 1 and W increases in relation to the increase of volume (ie the density of clump remains the same). In (c) W = 10 kN, and b decreases in such a way that the volume of the cylinder is kept constant. In all cases the towing speed, U = 1.5 ms^{-1}, the yield stress, Y = 25 kPa and the silt fraction is 0.42.

weight per unit area increases with *r* and penetration increases. However, the frontal area decreases with *r*, leading to a reduction in hydrodynamic drag and sediment mobilization.

Figure 8 shows how the physical impact may vary as the silt fraction in the sediment increases while the weight, dimensions, and towing speed of the clump remain constant. Although this example is speculative, insofar as it assumes a linear relationship between yield stress and the silt fraction based on just two measurements (Ivanović *et al*., 2011), it illustrates how, as the sediment becomes finer and goes from sand to muddy sand, the clump penetrates more and larger quantities of sediment are put into the water column.

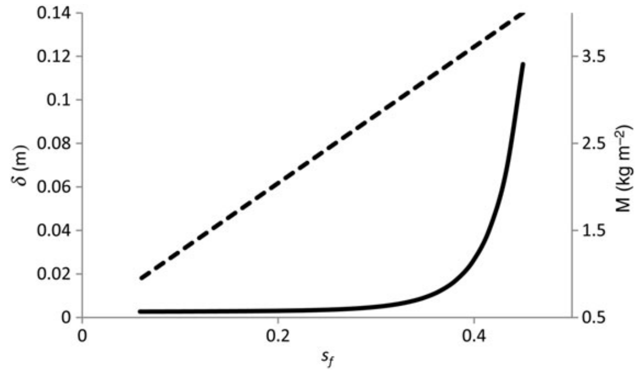

Figure 8. Predictions of the penetration (solid line) and the mobilization of sediment (dashed line) caused by a cylindrical clump as the silt fraction in the sediment increases while the weight, dimensions and towing speed of the clump remain constant.

Assessing physical impacts at a gear level

These models permit the estimation of the physical impact of fishing at the level of individual gear components, which have to be combined to estimate the impact at the level of a particular fishing gear. O'Neill and Summerbell (2011) performed such an analysis to estimate the sediment put into the water column behind the trawl components that are in contact with the seabed by calculating the hydrodynamic drag of the doors and the different groundgear sections. Here, we performed a similar analysis and portray in Figure 9 the distribution of sediment put into the water column across the swept width of a typical 1000–1400 hp Scottish whitefish demersal trawl by estimating the amount mobilized by the doors, the groundgear, and the lower netting panels on a sediment with a 0.2 silt fraction using Equation (2). We assume that the sweeps and the turbulent flow generated by the upper netting panels do not contribute to the remobilization of sediment. The formulae for hydrodynamic drag of the trawl doors and the groundgear sections are the same as those used by O'Neill and Summerbell (2011), and the hydrodynamic drag of the netting panels uses the expressions of Reid (1977). The highest value per metre squared swept is behind the doors, but this is concentrated over a very small area, and overall, the contribution of the groundgear and the net is about 3.5 times that of the doors. Figure 10 contains the average quantity of sediment mobilized per unit area swept between the doors and shows how it increases with towing speed and as the sediment becomes finer.

There has been much research into the development of low impact trawl gears. The general approach has been to reduce pressure on the bottom of various trawl components and to minimize the impacted area (Valdemarsen *et al*., 2007; He and Winger, 2010) and includes modifications to trawl rigging, design changes, the use of lighter gear components, and the reduction in the number of contact points between the gear and the seabed (e.g. Fonteyne and Polet, 2002; Sterling and Eayrs, 2006; Rose *et al*., 2013). The ability to predict the physical impacts at the gear level will allow the quantitative assessments of these modifications at the design stage and permit an evaluation of the extent to which physical impacts can be mitigated.

Assessing physical impacts at a fleet/fishery level

To address ecological and environmental concerns and to contextualize anthropogenic physical disturbance by comparing it to that

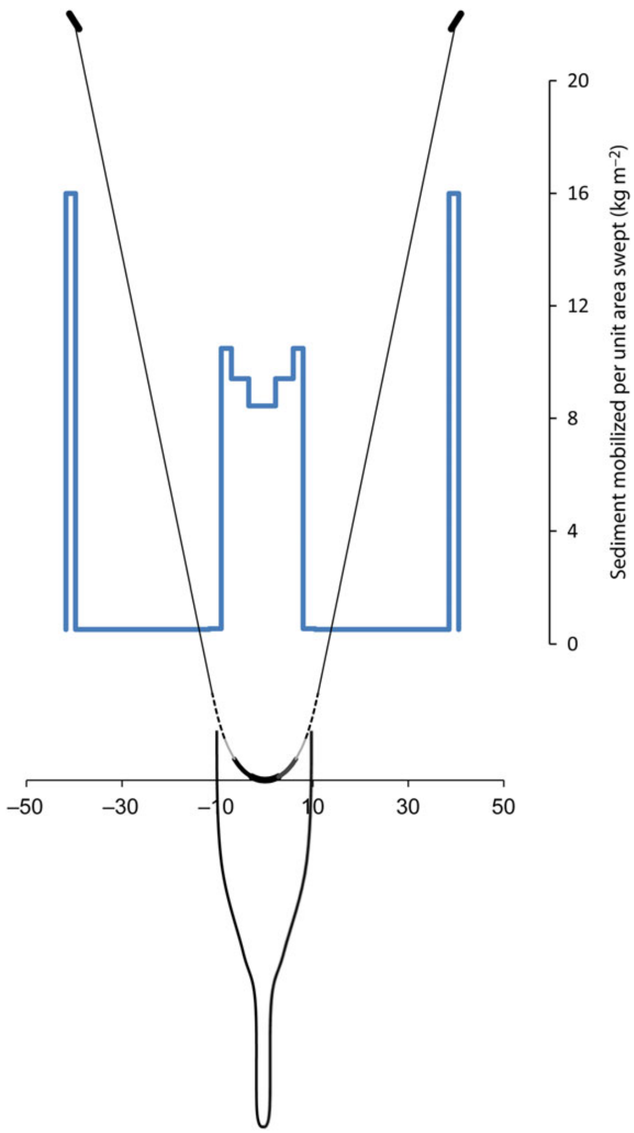

Figure 9. A schematic of a typical 1000 – 1400 hp Scottish whitefish demersal trawl. Superposed is an estimate of the distribution of sediment put into the water column across the swept width assuming a sediment silt fraction of 0.2 and a towing speed of 1.5 ms^{-1}. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

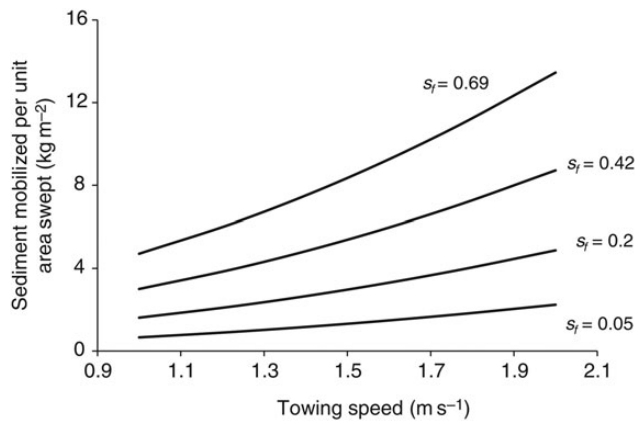

Figure 10. The average quantity of sediment mobilized per unit area swept as predicted by equation (2), showing how the amount put into the water column increases with towing speed and as the sediment becomes finer. The silt fractions used correspond to the four sediments on which trials of O'Neill and Summerbell (2011) took place.

which occurs naturally (Hall, 1994), a broader analysis will generally be required, and impacts will need to be considered at the fleet or fishery level and/or at a range of spatial and temporal scales (Hinz *et al*., 2009; Lambert *et al*., 2014; van Denderen *et al*., 2015).

A number of authors have carried out these sorts of investigation where the physical impact of towed gears has been scaled up by combining fishing effort data with estimates of the area impacted by a particular gear or considered at spatial and temporal scales consistent with current driven flow and individual to multiple tidal cycles. Churchill (1989) models the amount and settlement of sediment after trawling on the Middle Atlantic Bight shelf by making certain assumptions regarding the rate of mobilization and the nature of the settlement decay function. He compares his predictions with estimates of mean concentrations of sediment put into suspension by currents, and finds that sediment resuspended by trawls can make a sizeable contribution to the total suspended sediment load in heavily fished areas where storm-related bottom stresses are weak. Dale *et al*. (2011) investigate the sediment remobilized by scallop dredges in a highly dispersive environment in the West of Scotland and predict that the principle risk to reef habitats is from settling sand particles when dredge tracks approach within tens of metres of a reef, but that the cumulative effect of dredging (at the recorded fishing effort levels) is not expected to significantly modify suspended silt concentrations.

More recent studies estimate fishing effort from vessel monitoring system (VMS) data. These are high-resolution data that all EU fishing vessels >15 m must transmit every 2 h giving their position, speed, and heading (Lee *et al*., 2010), and which have been interpolated in an attempt to recreate the trawl path (Hintzen *et al*., 2010) or enumerated into grids of a given size to estimate the proportional area trawled (Piet and Quirijns, 2009). Diesing *et al*. (2013) compare the impact of fishing with natural disturbance in the English sector of the North Sea and the English Channel using VMS data to estimate the trawled area in a 12 × 12 km^2 grid cell and quantify natural disturbance as the number of days in a year the seabed is disturbed by tides and waves. While there are some concerns as to how well the different interpolation procedures reflect the true trawl path and there are issues regarding the spatial scale on which point effort data are enumerated (Lambert *et al*., 2012; Gerritsen *et al*., 2013), these data often offer a spatial and temporal resolution greater than that of our knowledge of the benthic component under consideration.

These advances in defining fishing effort have not, in general, been matched with improvements defining the physical impact. It is usually assumed that a generic gear is deployed, and that it makes an impact of a given severity over a specified area of the trawl path. Little attention has been given to the variation that exists between gears within a fishery, the in-year variation of fishing effort and natural disturbance, and the variability of seabed type. Eigaard *et al*. (2016), when looking at seabed penetration, address some of these issues by considering the impact of individual gear components in contact with the seabed and relating gear type to fishery and gear size to vessel size. It is clear, however, that all of these studies could be further enhanced by having more detailed descriptions of the physical impacts, and that these could be supplied by the predictive models of the types described above. This would allow a level of investigation consistent with the variation of gear type and design and at spatial and temporal scales consistent with the available fishing effort and sediment type data.

Discussion

The work that has taken place in relation to the observation, the quantification, and the estimation of the immediate physical impacts of trawl gears on soft sediments comprises a combination of remote observations, experimental trials, laboratory-based studies, and empirical and numerical modelling. These have led to a much better understanding of the underlying physical processes and to the development of models that capable of predicting the impacts of towed gears at the gear component, fishing gear, and fishery level, and which can be used in either a design or assessment context. The physical impacts have been classified as being either geotechnical or hydrodynamic in nature, and while this is generally the case (at least to a first-order approximation), it must also be recognized that there will be some interaction. For example, the passage of the gear elements in contact with the seabed may alter the integrity of the upper sediment layers making them more likely to be mobilized or the penetration of an element into the seabed may expose deeper layers to mobilization. Furthermore, we have not considered the fluidization of the seabed that is related to the use of hydraulic dredges, nor have we discussed explicitly the hydrodynamic processes associated with pore water pressure.

The investigation of these geotechnical and hydrodynamic processes is an active area of research both within fisheries and in related engineering areas, and it must be emphasized to keep up to date with developments as it is clear that some of the techniques and approaches being applied elsewhere could also be applied directly to the problems examined here. Different constitutive stress/strain relationships are being explored to characterize the geotechnical response of a broader range of sediment types, which in relation to the impact of towed gears need to include both sandier and more clay-like sediments. Improvements to the accuracy and efficiency of the numerical methods are also being investigated. In relation to sediment mobilization, the empirical model will need to be updated and possibly reassessed as new experimental data are collected. Furthermore, there is particular scope for using PIV to gain a more detailed description of the mechanisms governing sediment mobilization and CFD modelling to develop deterministic models of this process. There are also difficulties in measuring the mechanical parameters used to characterize the geotechnical response of sediments which need to be resolved. These parameters are difficult to measure *in situ*, and those measured from samples taken from the seabed do not always reflect their *in situ* response.

The longer term aim of developing models to predict the physical impact on soft sediments is to be able to assess and quantify the environmental and ecological impact of towed gears. To achieve this, the physical impacts need to be related directly to the resulting geochemical, biological, and environmental effects such as nutrient enhancement and benthic mortality. A few studies have investigated some of these relationships. The rate of dissolved and particulate nutrient release behind groundropes has been measured by Dounas *et al*. (2007). The damage to infaunal bivalves from a trawl door have been examined by Gilkinson *et al*. (1998), and the mobilization of phytoplankton cysts and copepod eggs behind gear components and of inhabiting infauna behind scallop dredges have been studied by Brown *et al*. (2013), O'Neill *et al*. (2013), and Drillet *et al*. (2014). Meta-analysis of studies undertaken into the mortality of benthos in the passage of towed gears (Kaiser *et al*., 2006) have related mortality by different fishing gears to biological characteristics, and research is ongoing to further refine these models to relate mortality with biological traits, such as life history, morphology, and behavioural characteristics.

The development of such a hierarchy of models would provide management tools to direct fishing effort, identify and establish closed areas, and develop environmentally friendly fishing techniques. With sufficient spatially and temporally refined fishing effort data and spatially refined data on seabed typology, it will be possible to assess the impact of fishing at the fleet level and hence permit a comparison with the environmental and ecological impact of other anthropogenic activities or naturally occurring events such as storms and tidal currents.

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