Environmental Pollution 170 (2012) 232–241

Contents lists available at SciVerse ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Bottom trawling resuspends sediment and releases bioavailable contaminants in a polluted fjord

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ARTICLE INFO

Article history:
Received 12 March 2012
Received in revised form
11 June 2012
Accepted 14 June 2012

Keywords:
Sediment resuspension
Bottom trawling
Contaminant
Bioavailability
Blue mussel
SPMD

ABSTRACT

Sediments are sinks for contaminants in the world's oceans. At the same time, commercial bottom trawling is estimated to affect around 15 million km^2 of the world's seafloor every year. However, few studies have investigated whether this disturbance remobilises sediment-associated contaminants and, if so, whether these are bioavailable to aquatic organisms. This field study in a trawled contaminated Norwegian fjord showed that a single 1.8 km long trawl pass created a 3–5 million m^3 sediment plume containing around 9 t contaminated sediment; ie. 200 g dw m^{-2} trawled, equivalent to c. 10% of the annual gross sedimentation rate. Substantial amounts of PCDD/Fs and non-ortho PCBs were released from the sediments, likely causing a semi-permanent contaminated sediment suspension in the bottom waters. PCDD/Fs from the sediments were also taken up by mussels which, during one month, accumulated them to levels above the EU maximum advised concentration for human consumption.

1. Introduction

Bottom sediments are considered sinks for many contaminants entering the marine environment. Many contaminants associate readily with sediment particles and to particulate organic matter, organic molecules, colloids and black carbon in sediments (Cornelissen et al., 2005; Olsen et al., 1982; Schwarzenbach et al., 2003). However, if sediment is disturbed, for example by waves, currents, bioturbation, boat wash, dredging or bottom trawling, these particle-associated contaminants can be resuspended into the overlying water (e.g., Hedman et al., 2009; Jonas and Millward, 2010; Nelson et al., 1987; Olsen et al., 1982).

Laboratory experiments have shown that changes in chemical equilibrium may also lead to desorption of contaminants from the particulate to the dissolved phase, depending on the properties of the sediment (Cantwell et al., 2008; Latimer et al., 1999) or the overlying water (Atkinson et al., 2007), resuspension time (Feng et al., 2008; Friedman et al., 2011), contaminant concentrations and contaminant chemical properties such as K_{OW} (Friedman et al., 2011).

Particle-associated and dissolved contaminants that are suspended or released from sediments may be available for uptake by organisms, either through particle uptake or through transport across membranes (Eggleton and Thomas, 2004). Bioavailability and uptake depends on the type, chemical form and partitioning of the contaminant, physico-chemical properties of the sediment and water, and habitat and feeding mode of the organisms (Luoma, 1983). Dredging operations have been shown to enhance uptake of PAHs and metals (Bocchetti et al., 2008) and PAHs and PCBs (Bellas et al., 2007) to caged mussels in the field, but the majority of work in this area is also based overwhelmingly on laboratory studies (Roberts, 2012). The general applicability and relevance of these lab investigations to field conditions is uncertain, since, although there is a large body of data concerning contaminant concentrations in field sediments and organisms from monitoring studies, these data are rarely collected in the context of field measurements of contaminated sediment resuspension, release of contaminants from such sediments, and bioavailability of these contaminants to organisms (Roberts, 2012). Bottom trawling as an agent of contaminated sediment resuspension is particularly under-investigated.

Bottom trawling for fish and invertebrates, mostly for human consumption, is a globally important economic activity. An area half the size of the world's continental shelf is trawled every year (Watling and Norse, 1998), mainly on soft substrates. Most bottom fishing gears disturb the seabed, often deliberately in order to cause benthic organisms to swim up into the net. Despite the well-documented impacts of bottom fishing on benthic communities

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http://dx.doi.org/10.1016/j.envpol.2012.06.019

(e.g., Bradshaw et al., 2002; Jennings and Kaiser, 1998; Thrush and Dayton, 2002), there is surprisingly little information on the importance of disturbance of the seabed by trawling on resuspension and/or remobilisation of sediment-associated contaminants and nutrients, or on the implications of this for the ecosystem. From the few studies that have been carried out, it is clear that bottom-contacting fishing gears disturb sediments (e.g., Durrieu de Madron et al., 2005; Floderus and Pihl, 1990; O'Neill and Summerbell, 2011; Palanques et al., 2001), disrupt geochemical processes on the seafloor (Falcão et al., 2003; Pilskaln et al., 1998; Trimmer et al., 2005), and increase nutrient efflux (Durrieu de Madron et al., 2005; Falcão et al., 2003; Krost, 1990; Percival et al., 2005; Warnken et al., 2003). Resuspension may also alter pollutants' chemical forms and thus their bioavailability and toxicity (Cotou et al., 2005) and/or enhance the transfer of organic pollutants in the benthic food chain, through the mobilisation of contaminated particles (Charles et al., 2005). Given that bottom trawls disturb the sediment surface to depths of at about 20 cm (Hiddink et al., 2006) and that trawling activity is so extensive, it is highly likely that large quantities of sediment, and potentially contaminants, are resuspended by trawling activities.

This study provides new data to help fill this knowledge gap by quantifying i) the suspension of sediment immediately after the passage of a bottom trawl in a contaminated Norwegian fjord and ii) the release to the bottom water, bioavailability and uptake of sediment-associated contaminants during one month in the same fjord, using semi-permeable membrane devices (SPMDs) and a model marine organism, the blue mussel *Mytilus edulis*.

2. Methods

2.1. Study site

Eidangerfjord is one of five branches of the Grenlandfjords system in southern Norway. It is a typical fjord with a U-shaped cross-section under water, maximum depth of c. 118 m, a sill at the mouth (at 50 m water depth) and a stratified water column. Residence time for the bottom water is 5–8 months, typically with a stagnation period between May and October (Molvær and Stigebrandt, 1991). In 1951, Norsk Hydro established a magnesium production plant in a neighbouring branch, Frierfjord. As part of the production process, by-products (dioxins and other chlorinated organic contaminants) were released into Frierfjord, leading to high concentrations of dioxins in the Grenlandfjords ecosystem. During the mid-1970s and late 1980s restrictions and improved effluent treatment reduced this contaminant discharge, but contaminant concentrations remained high in water, sediment and biota (Knutzen et al., 2003; Persson et al., 2002; Schlabach et al., 1998). The plant was closed in 2002, but the legacy of contamination remains, particularly in the sediments of Frierfjord, and to a lesser degree in Eidangerfjord. PAHs are also released into the Grenlandfjords, mainly from a ferro-manganese plant (Næs, 1999), though discharges have decreased by 90% since 2000. Due to the continued high contaminant load, Norwegian authorities recommend not to consume eel, herring, mackerel and crabs from Eidangerfjord. However, there is a small prawn fishery in the fjord (1–2 trawls per week). Around 2–4 boats fish are active, mainly when bad weather prevents them fishing further afield. They use small otter trawls; e.g., the one used in this experiment was a demersal shrimp trawl with two 170 kg, 1.6 × 0.8 m wooden otter boards each with an iron shoe, which were attached to the sweeps by 3–4 m (12 kg) of chain. The trawl door spread was 25 m. The 35 mm mesh net was equipped with a 60 m long groundrope, and the headrope was 48 m long. Fishing boats usually trawl Eidangerfjord in a several km long loop that runs parallel with the fjord sides (Fig. 1b).

2.2. Field experiment to quantify sediment suspension caused by bottom trawling

The experiment was carried out in Eidangerfjord between 2 and 4 June 2008. Trawling took place four times during the experiment (twice on 3 June, twice on 4 June) by the prawn trawler *Tine Marlin* using standard fishing gear (see Section 2.1) along a c. 1800 m long track. The tracks passed between two pairs of fixed measuring stations (N and S, Fig. 1b), c. 1200 m from each other and with c. 125 m between the paired buoys, where pairs of Aanderaa RCM9 current meters were deployed 2 m above the seabed (Fig. 1a). The instruments measured water current speed and direction and turbidity once a minute during deployment to provide spatio-temporal information on the spread of the sediment plume. To describe the vertical profile of the plume in more detail, turbidity measurements were also taken behind the trawler using three CTDs (one Falmouth CTD and 2 SEACAT Seabird) with Seapoint turbidity meters deployed from *R/V Trygve Braarud* and mounted on a Rosette water sampler. Vertical turbidity profiles were taken with the CTDs measuring continuously from just above the seabed to c. 15 m above the seabed, at a distance of c. 500 m from the trawler (c. 350 m from the otter boards; Fig. 1d), directly in, and at 30 m and 60 m to each side of the trawl track (Fig. 1e). These five profiles took just over 10 min to complete. In addition, 27 Rosette water samples were taken close to (mainly within 5 m of) the seabed in parallel with these turbidity measurements and total suspended material (TSM) determined in order to provide data for calculation of TSM from turbidity. The particle size distributions were also measured in seven of these samples using a Coulter counter.

The sinking rate of suspended particles was calculated using Stokes' law:

$$V = \frac{d^2(\rho_s - \rho_w)g}{18\mu}$$

where: V = sinking rate of particles in the water (m s^{-1}); d = particle diameter (m); g = 9.81 m s^{-2}; ρ_s = particle density (kg m^{-3}); ρ_w = water density (kg m^{-3}); μ = dynamic viscosity of water (kg m^{-1} s^{-1}). For field conditions during the experiment (salinity of 34.5, 6 °C), ρ_w is 1027 kg m^{-3}; μ is $1.6 \cdot 10^{-3}$ kg m^{-1} s^{-1} ρ_s is taken as 2600 kg m^{-3}.

Basic characteristics of the bottom sediment (% <63 μm by weight, water and total organic carbon content) were measured in the top 2 cm of two sediment cores taken with a Gemini gravity corer (0.005 m^2) at station 2 (Fig. 1b) in May 2009.

2.3. Field experiment to evaluate longer term (1 month) effects of bottom trawling

Semi-permeable membrane devices (SPMDs; from Exposmeter AB) were deployed in the field to measure the amount of dissolved organic contaminants in the water column. The SPMDs were of standard size and design; 92 cm-long and 2.5 cm-wide lay-flat low density polyethylene tubing filled with 1 ml triolein. SPMD site control samplers were used during deployment and retrieval of the samplers to evaluate potential contamination from the air and handling of the devices and to measure the initial concentrations of performance reference compounds (PRCs). To measure the total bioavailable amount (dissolved and particulate) of contaminants in the water column, caged blue mussels, *Mytilus edulis*, (c. 40 per cage, fresh from Scanfjord AB mussel farm, Lysekil, Sweden) were used. Since these were destined for human consumption, we assume that contaminant levels before deployment were low or below the detection limit.

The SPMDs and mussels were deployed on three ropes placed as close as possible to the trawl tracks in the deep basin of the fjord (water depth 90–100 m) (Fig. 1b and c), with the lower set of samplers c. 1.5 m above the seabed (referred to as BW (bottom water) stations in the following text). It was assumed that these were exposed to sediment resuspended during trawling (see Section 3.1). Another set of samplers (referred to as OW; open water) were placed c. 19 m above the seabed, and were thus not exposed to resuspended sediment, but were well below the halocline/thermocline and the level of the fjord sill. Both OW and BW were in the same water layer within the stratified fjord and therefore exposed to the same oxygen concentration, temperature, salinity, water pressure and water exchange processes. The samplers were left in place from 4 June to 7 July 2008. During this period, one fishing boat was in operation, and trawled on five occasions; 13th, 17th, 20th, 24th June and 2nd July. Water temperature at the sampling depth during this period was constant at c. 6 °C. After one month all samplers were retrieved, but one OW mussel sample was later lost due to handling error. Two sediment samples were taken with a Gemini gravity corer (0.005 m^2) at station 2 (Fig. 1b) in May 2009 and the top 2 cm used for contaminant analysis.

Ideally, similar samplers would have been placed in control areas for comparison. However, suitable control areas with similar physical characteristics, similar contaminant loads, and most importantly, lack of fishing impacts (including export of resuspended sediment from trawled areas) could not be found. We therefore decided to use a 'weight of evidence' approach, focussing on the differences in concentrations between OW and BW and interpreting them in the context of a) the spatio-temporal quantification of suspended sediment (as described in Section 2.2) and b) data from towed SPMDs (Allan et al., 2011) where short-term pre- and post-trawl concentrations are available.

2.4. Analysis of contaminants in samples

SPMDs were analysed for four perdeuterated performance reference compounds (PRCs; acenaphtene-d_{10}, pheneanthrene-d_{10}, fluoranthene-d_{10} and chrysene-d_{10}), polychlorinated dibenzo-*p*-dioxins and -furans (PCDD/Fs), non-ortho polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). Sediments were analysed for PCDD/Fs, PCBs and PAHs and blue mussels for PCDD/Fs and PCBs. PCDD/F and PCB analyses were conducted at the Norwegian Institute for Air Research (NILU) while those for PAHs and PRCs from the SPMDs were done at the Norwegian Institute for Water Research (NIVA). SPMDs were extracted by dialysis with hexane (2 × 24 h extraction). Extracts were reduced and split into two fractions for analyses of a) PAHs and PRCs and b) PCDD/Fs and PCBs.