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Effects of bottom trawling on ecosystem functioning

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ABSTRACT

By combining field observations with data from controlled mesocosm experiments this study demonstrated that bottom trawling has the potential to cause long-term impacts on sediment nutrient fluxes. Field observations confirmed that trawling reduced the density of important bioturbators in the study area, but revealed only weak effects of trawling on nutrient fluxes. The importance of the decline in bioturbators was demonstrated in the mesocosm experiments where the density of four key bioturbators (*Brissopsis lyrifera*, *Nuculana minuta, Calocaris macandreae* and *Amphiura chiajei*) showed significant correlations with nutrient flux. All four species caused an increase in the rate at which silicate was released from the sediment, but their effect on nitrogen cycling were species specific. Bioturbators that bulldoze through the sediment (*B. lyrifera* and *N. minuta*) increased the loss of dissolved inorganic nitrogen (DIN) from the sediment, whereas those that irrigate burrows within the sediment (*C. macandreae* and *A. chiajei*) caused increased uptake of DIN. This shows that the activities of the species present can determine whether the seabed acts as a source or a sink of nitrogen nutrients. By combining these experimental results with field observations of bioturbator abundances, we demonstrate the potential impacts of trawling on benthic ecosystem function. Due to the worldwide extent of intensive bottom-trawling, such effects may be globally significant and affect the nutrient balance especially in continental shelf and coastal areas.

1. Introduction

Soft-sediment ecosystems cover almost 70% of the earth's surface and have a fundamental role in the functioning of marine systems, both for remineralization of organic carbon and nutrients and as food producers for larger macrofauna and fish. In recent years, there has been growing awareness that physical disturbance caused by bottom trawling may be one of the most important sources of anthropogenic disturbance to soft-sediment benthic communities and habitats (Dayton et al., 1995; Jennings and Kaiser, 1998; Collie et al., 2000; Pauly et al., 2002; Kaiser et al., 2006). Recent articles and correspondence led by the late Professor John Gray have shown that this is still a very highly topical area of research (Gray, 2000; Gray et al., 2006, 2007a,b). Over the last decades trawlers in the North Sea have used heavier gears and over 90% of the sea floor is trawled at least once, and in some areas six times a year (Jennings et al., 2001). The effects of trawling on structurally complex habitats and fauna have been compared to the effects of forest clear-cutting (Watling and Norse, 1999). The world fleet of trawlers sweep up to 15 million km^2 of seabed annually – an area 150 times greater than that of the forests cleared each year (Malakoff, 1998). As nets, beams, trawl doors, chains and dredges pass over the seabed, the sediment surface is disturbed and a large proportion of the resident biota (e.g. bivalves, burrowing crustaceans, tube-building polychaetes and echinoderms) is damaged or removed (Craeymeersch et al., 1997; Jennings and Kaiser, 1998; Kaiser et al., 2006). Whilst it is generally accepted that bottom trawling changes the structure of benthic communities, with trawled areas being dominated by small-bodied, opportunistic species at the expense of species that are large, long-lived and potentially fragile, few studies have considered the implications of trawling on ecosystem processes (Duplisea et al., 2001; Thrush and Dayton, 2002; Tillin et al., 2006). Large parts of most shelf seas have been intensively exploited by bottom trawlers for decades. Assessing the long-term and large-scale impact of chronic bottom trawling on ecosystem functioning should therefore have priority in studies of the impact of bottom trawling (Tillin et al., 2006). In order to fully study the effects of trawling investigations should consider impact on both structure and function (de Juan et al., 2007).

Function can be defined as specific processes within an ecosystem that change the rates and properties in the system. Important ecosystem functions in soft-sediment environments are biogeochemical processes associated with remineralization of organic material and regeneration of nutrients and nutrient fluxes. Organic material produced in the pelagic and shallow benthic zones and from terrestrial runoff is deposited at the sediment surface (eg. Aller, 1982; Hall et al., 1996). Once the particles reach the sediment, the material will be

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mineralized and transported as solutes across the sediment-water interface into the water column or buried in the sediment (Aller, 1982; Ståhl et al., 2004; Norling et al., 2007). The remineralization process, through fluxes of nutrients, ultimately fuels new algal production in the euphotic zone. In the surface sediment system the macrofauna is an important component for the benthic-pelagic coupling in terms of transport and exchange of solids and solutes in sediment and water through deposition and recirculation (Graf, 1992; Aller, 1988, 1994).

Organic matter remineralization in sediments is performed mostly by the micro-organisms, both in the oxic and anoxic part of the sediments. Benthic macrofauna inhabiting the surface sediments markedly influence these processes through bioturbation that alters the habitat by reworking the sediments (e.g. Gray, 1974; Rhoads, 1974; Rhoads and Boyer, 1982). These macrofauna activities have a large impact on organic matter remineralization, transformation of nitrogen and mobilization of phosphate and silicate (Aller, 1982, 1988; Hooper et al., 2005). Through burrowing, feeding, ventilatory and locomotory behaviour, the infauna disproportionately influence biogeochemical and diagenetic reactions within the interstitial porewater and promote the vertical and lateral redistribution of sediment particles above and/or below the sediment-water interface (Solan et al., 2004). Bioturbation also directly enhances microbial activity (Aller and Yingst, 1985).

Without macrofauna in the sediments to stimulate these processes the breakdown of organic matter would be based on diffusion within the sediment and across the sediment-water interface. These processes are slow, but are greatly enhanced (2–10 times) by macrofaunal activities in the surface sediments (e.g. Rutgers van der Loeff et al., 1984; Aller and Yingst, 1985; Helder and Andersen, 1987). Overall, bioturbation by macrofauna is one of the most important functions that regulate process rates and pathways during organic matter mineralization in marine environments (Rhoads, 1974; Aller, 1982; Norling et al., 2007). Based on the knowledge we already have on the impacts of trawling we must expect it will interfere with these functional processes in coastal and shelf areas, where benthic-pelagic coupling often is tight. Studies of indirect effects of trawling on nutrient fluxes, through impact on the macrobenthic communities, are therefore important. A key to understanding the effect of trawling disturbance on the functioning of benthic ecosystems is the relationship between the function of species and their vulnerability to trawling disturbance (Larsen et al., 2005; Tillin et al., 2006).

In the present study field investigations were performed to describe sediment nutrient fluxes in trawled and non-trawled sea beds. Sediment cores were collected for determination of field fluxes of oxygen and nutrient species. Simultaneously a mesocosm experiment was designed to investigate the effects of larger, bioturbating infauna on sediment-water fluxes and quantify relations between nutrient fluxes and densities of several large, trawl sensitive species commonly found in the study area. In the experiments we manipulated the density of 7 large, naturally occurring, species of macrofauna which were considered potentially vulnerable to trawling (S. Jennings, pers. comm., Table 1). The selected species were added to experimental buckets with natural sediments with inherent communities of micro-organisms, meiofauna and other macrofauna, which is important to mimic the seabed environment (Widdicombe and Austen, 1998; Widdicombe et al., 2004).

The 7 species of bioturbators selected for this study were the sea urchin *Brissopsis lyrifera* (Forbes, 1841), the bivalves *Nuculana minuta* (Müller, 1776) and *Astarte sulcata* (da Costa, 1778), the thalassinid shrimp *Calocaris macandreae* (Bell, 1846), the brittle star *Amphiura chiajei* (Forbes, 1843) and the polychaetes *Nephtys caeca* (Fabricius, 1780) and *Aphrodita aculeata* (L., 1758). These species are abundant in the Oslofjord and represent a range of bioturbation, bio-irrigation and burrow-formation mechanisms, as well as a range of trait profiles including feeding strategies that are potentially vulnerable to trawling. For a more complete description of these species, see Widdicombe et al. (2004). The selected bioturbating species also occur in many other areas throughout the North Sea, Irish Sea and English Channel, where trawling disturbance is absent or low. They are functionally similar to other species common in many soft-sediment habitats. The benthic fauna of the study area has been described as typical of that found in other sites in Western Europe and probably also of large areas of the European continental shelf (Mirza and Gray 1981; Valderhaug and Gray, 1984).

2. Materials and methods

2.1. Selection of field sites

The area of investigation was the outer Oslofjord, a northern branch of the Skagerrak in the North Sea, where a very large part of the seabed deeper than 60 m is regularly visited by shrimp trawlers. Their target organism is the edible shrimp *Pandalus borealis* (Krøyer, 1838), with a by-catch of demersal fish. The sediment type is mainly muddy sand, a habitat shown to be surprisingly vulnerable to trawling and with predicable recovery times measured in years (Kaiser et al. 2006; Allen and Clarke, 2007). Four areas subjected to commercial otter trawling were identified for study. These areas are visited by trawlers between 50 and 100 times per year, and based on the size of the trawls and the boat speed, each part of these areas are trawled on average 2–3 times per year. Each of the areas were surveyed using a remotely operated vehicle (ROV) equipped with an autonomous positioning system, a digital video recorder and a ROV-mounted side-scan sonar to locate trawled and non-trawled sites within each area. Trawling leaves 10–20 cm deep furrows in the seabed, which were visible on the side-scan images (Fig. 1).

Based on furrow frequencies determined from the sonar- and video-images, one trawled site and one non-trawled control site were chosen within each area (8 sites altogether, Fig. 2). Control sites were placed in areas with wrecks or areas with rocks on the bottom, which are avoided by the fishermen to prevent destruction of gear.

Table 1
The seven bioturbating species used for density manipulations in mesocosm experiment

Bioturbating species	Organism type	Organism characteristics	Low density	High density
Nuculana minuta	Bivalve	Sub-surface “bulldozing” deposit feeder	8	32
Astarte sulcata	Bivalve	Medium sized, suspension feeder, sits near sediment surface with upper edge of shell protruding slightly into the water column	3	12
Amphiura chiajei	Brittle star	Lays buried in the sediment with its disc at 4—6 cm depth. One or two arms are stretched up above the sediment to collect food at the surface, other arms may be extended deeper into the sediment below the disc.	7	28
Aphrodite aculeata	“Sea mouse” Polychaete	Large, oval bodied, active, mobile predator operates close to or actually on the sediment surface.	1	4
Nephtys caeca	Polychaete	Highly mobile, predatory worm, 15—25 cm long, creates non-permanent burrows to a depth in excess of 15 cm.	1	4
Brissopsis lyrifera	Heart urchin	Non-selective, infaunal, “bulldozing” deposit feeder, burrows to 10 cm depth.	1	4
Calocaris macandreae	Burrowing shrimp	Constructs deep, complex burrows with multiple surface openings, rarely emerges onto sediment surface	1	4

Type of organism, short description of feeding, and treatment densities (individuals per bucket, 0.1 m^2).