ELSEVIER
Journal of Experimental Marine Biology and Ecology 339 (2006) 251 – 259
Journal of EXPERIMENTAL MARINE BIOLOGY AND ECOLOGY
www.elsevier.com/locate/jembe

A new apparatus for the direct measurement of the effects of otter trawling on benthic nutrient releases

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Received 10 June 2006; received in revised form 2 July 2006; accepted 25 July 2006

Abstract

An innovative Towed Trawl Simulator Sledge (TTSS) which has been tested in the field is described. The new instrument, which incorporates six water sampling bottles and video observation equipment, is designed to simulate the effects of the passage of otter trawl groundropes over seafloor sediments. The TTSS is towed from a surface vessel at speeds similar to those of commercial trawls and the water bottles, triggered simultaneously by electrical or acoustic signals, collect water samples in the plume of disturbed sediment behind the groundrope. The TTSS has been tested in the continental shelf fishing grounds of Heraklion Bay (Eastern Mediterranean) where quantitative measurements of the physical (sediment resuspension) and chemical (nutrient release) effects on surface sediments caused by the passage of otter trawl groundrope typical of that used in the Cretan fishery trawling were performed. The performance of the TTSS is also validated against an instrumented full-scale trawl. It is suggested that the TTSS should be used for the study and modelling of the effects of otter trawling and similar fishing processes on nutrient supply from seafloor sediments and the resulting ecosystem responses.

Keywords: New method; New sampling apparatus; Nutrient releases; Sediment resuspension; Trawling impact

1. Introduction

The use of towed gear by the fishing industry can have a variety of effects on the benthic ecosystem. Such effects are expressed by changes in the biology, sediment structure and biogeochemistry of the benthic environment and the intensity of the final impact depend on factors such as substrate type, type of fishing gear, and frequency of disturbance (Lindeboom and de Groot, 1998). The greater part of research conducted on the benthic effects of towed fishing gears has been concerned with impacts on faunal communities (e.g. Jones, 1992; Watling and Norse, 1998; Jennings and Kaiser, 1998). Observations of the effects on the sediment itself have generally been restricted to the depth of disturbance by the fishing gear (Churchill, 1989; Hall, 1999; Palanques et al., 2001). Bottom trawling is expected to affect both the timing (in a seasonal sense) and the instantaneous rate of nutrient fluxes to the water column, introducing a much more episodic pattern to the releases (Pilskaln et al., 1998). The study of the effects of trawling on nutrient recycling and the resulting biological response requires the development of new field methodologies and sampling techniques (Churchill, 1998). These methodologies must enable quantification of the rate at which trawls resuspend sediment and disperse particulate and dissolved materials, including nutrients.

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0022-0981/$ - see front matter
doi:10.1016/j.jembe.2006.07.022

The main structural elements of otter trawls are: the doors (keeping the mouth of the net open), the groundrope (ensuring contact of the full width of the mouth opening of the net with the seabed) and a funnel-shaped net (retaining the catch). The doors plough the sediment to a depth of a few centimeters and create turbid clouds of resuspended sediment that herd the fish into the net (Main and Sangster, 1981, 1983; Wardle, 1983). The groundrope exerts less pressure on the sediment, though over a much wider swath of seafloor. In some cases the groundrope accounts for more than 90% of the contact area of the trawl gear with the seabed (Lindeboom and de Groot, 1998; Ragnarsson and Steingrimsson, 2003), and is sufficient to disrupt the biologically, and geochemically, critical benthic boundary layer between the sediment and the overlying water (Mayer et al., 1991; Watling et al., 2001). Research conducted in Heraklion Bay, Crete has shown that almost all the biologically active compounds at the sediment surface are resuspended by a single passage of the trawl groundrope, which implies that the upper extremely thin layer of sediments contains a considerable reservoir of dissolved and particulate nutrients in concentrations that are much higher than in the immediately underlying surface sediment layers (Dounas et al., 2005). In this paper the design of a new field equipment is described, which is used to simulate the disturbance of seafloor sediments by trawl groundropes, and at the same time allows direct sampling of water to be carried out in the plume of the disturbed sediment behind the groundrope.

2. Materials and methods

2.1. Technical description of the towed trawl simulator sledge (TTSS)

The TTSS is developed on the frame of an existing towed benthic sledge (Shand and Priestley, 1999) that had previously been employed as a vehicle for underwater video cameras. The design allows the combined use of underwater video and water sampling bottles (triggered by acoustic or electrical release systems) at adjustable distances above the seabed as sampling tools (Fig. 1).

The sledge is a robust construction made of saltwater-resistant (grade HE 30) aluminium tubing, 60 mm diameter and 5 mm wall thickness in the lower section and 38 mm diameter and 3 mm wall thickness in the upper section. Welded to the bottom of the sledge are two steel runners to protect the aluminium tubes from abrasion. A buoyancy tank is mounted near the top to keep the sledge upright in the water whilst being deployed. The sledge has a total length of 2.24 m, 1.27 m width, and 1.52 m height. Its weight with camera equipment mounted is about 127 kg in air and 55 kg in water.

The TTSS carries one or more 1.5 m lengths of otter trawl groundrope in contact with the seabed. The

Fig. 1. General aspect of the towed trawl simulator sledge (TTSS).

groundrope is supported freely by two light-weight metal arms 1.5 m in length (adjustable from 1.2 to 1.8 m) attached to the sides of the sledge, held in position by a transverse 1.5 m long metal rod connecting the two arms to prevent changes in the curvature of the groundrope during operation of the gear (Fig. 2B). Six water bottles (2-l Hydrobios horizontal water samplers, 10 cm internal diameter) are mounted in metal sub-frames fixed internally to the front and sides of the sledge and arranged in three rows above the seabed surface (Fig. 2A, B). The position of the bottles can be adjusted to any height up to 50 cm above the seabed. The bottles are fired at will through a specially developed electromechanical system. The battery package and the electronic controller are held in the pressure housing mounted on the upper part of the sledge (Fig. 2A, B). One electromagnet is mounted on each bottle and holds both end closures in the open position (armed) against pre-tensioned springs. All electromagnets are equipped with magnetic switches and are connected to the controller. The controller is connected with the surface towing vessel through the umbilical cable of the sledge that also supplies power to the lights and ensures the return of signals from the underwater camera. On command from the surface, the electromagnets are turned off, closing all six water samplers simultaneously. A video camera located in the upper part of the sledge (Fig. 2A) visually records the performance of the whole underwater apparatus (groundrope, metal arms, sledge and water bottles). The camera is an Osprey (OE1362 Osprey Electronics, now Kongsberg-Simrad) low light-sensitive color camera, mounted on the sledge looking obliquely forward with 2 wide angle 500 W underwater lighting units (Versabeam, Deep Sea Power and Light). The camera has a fixed focal length lens and a calibrated field of view of 1 m. The umbilical cable is a multi-core electric cable attached to a 10 mm towing wire. The electric cable is deployed by hand and attached every 5 m for the first 20 m and thereafter every 20 m using a slip knot (Shand and Priestley, 1999). Floatation is added to the warp at the sledge end of the cable to prevent the towing cable from disturbing the sediment in front of the sledge. The overall performance of the apparatus has been tested successfully in depths up to 300 m, restricted only by the length of the available umbilical cable.

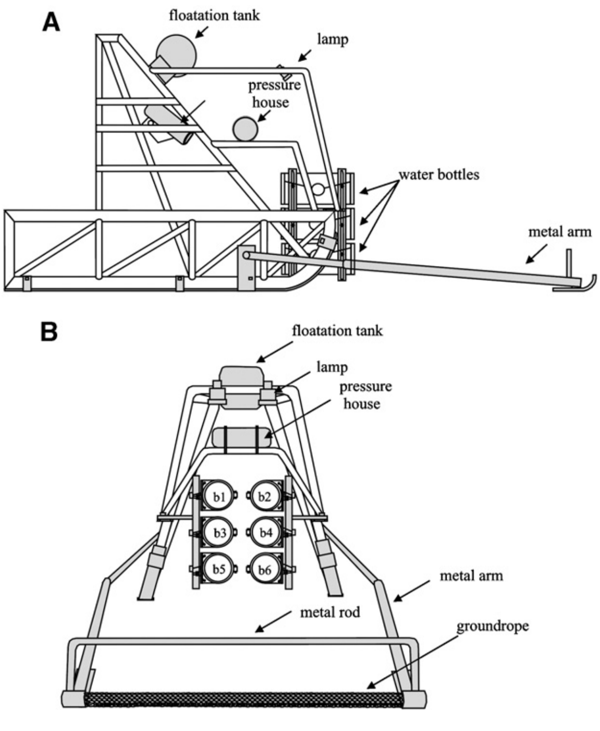

Fig. 2. Lateral (A) and front (B) schematic view of the TTSS (b1–6: water bottles).

The TTSS can be used for the direct measurements of the amount of particulate material raised into suspension and the dissolved nutrients released per groundrope track length, or seabed surface unit. These fluxes are calculated from the inventories of resuspended material measured from the sets of three water samples after corrections for undisturbed (reference) conditions were made using the same apparatus without the groundrope. Total inventory of material raised in the sediment plume by the trawl groundrope may be expressed as quantities resuspended per area of disturbed sediment. Furthermore, application of the towing speed allows the rate of resuspension of materials per unit of trawling time to be calculated.

2.2. Experimental site

The experiments were carried out during the period of 20–24 September 2001 just before the opening of the 8-month trawling season on the continental shelf of Heraklion Bay, located on the north coast of Crete (Eastern Mediterranean). All samples were collected from an area of 1000 m × 100 m along the isobath of 50 m centred on 35°21.72′N–25°06.04′E (Fig. 3). In this area the sediments are classified as mud, consisting of clay minerals (kaolinite, chlorite, illite and a mixed layer of smectite–illite), quartz and feldspar, together with some coarser shell fragments and other biogenic debris (Chronis et al., 2000). Reported mean annual inorganic nutrient concentrations over the continental

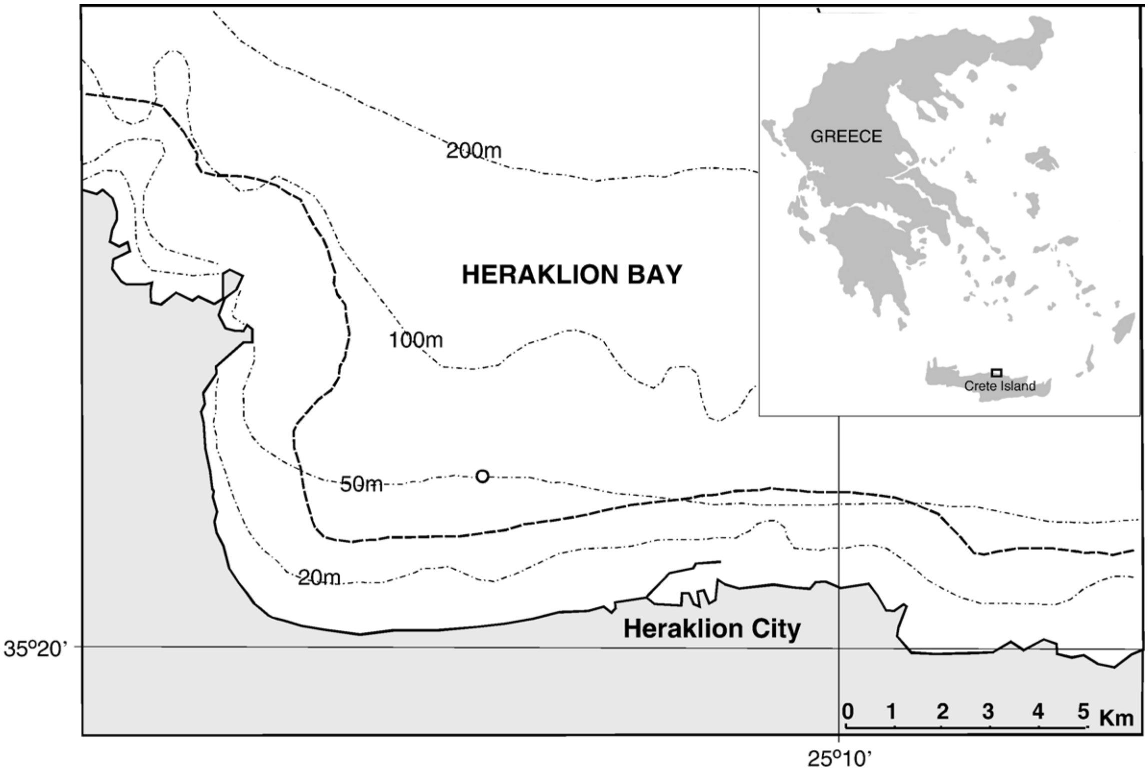

Fig. 3. Map of Heraklion Bay (Crete Island, Greece, Eastern Mediterranean) showing the location of the station occupied during this study (bold dashed line shows the 1 NM trawling limit according to the Greek Fisheries Legislation).

shelf of Heraklion Bay and low levels of chloroplastic pigments, POC, and PON in the euphotic zone are all indicative of an oligotrophic ecosystem (Tselepides et al., 2000). Depth integrated rates of primary productivity averaged seasonally reach 220 (±64.3) mg C/m^2/day with an annual gross primary productivity of 80 g C/m^2/year (Psarra et al., 2000).

2.3. TTSS validation experiments

For the TTSS validation experiments, the bottles were arranged in three pairs: the first at 2.5 cm, the second at 17.5 and the third at 30 cm above the seabed, 1.5 m behind the groundrope, in front of the disturbance caused by the sledge, and in the middle of the sediment cloud caused by the groundrope. *RV Philia* towed the sledge at a normal trawling speed (2.2 NM/h). The groundrope used had a diameter of 6.5 cm and a weight of 3.2 kg/m (2 kg/m in water). Monitoring by video camera attached to the sledge showed that resuspension ahead of the sampling bottles was caused solely by the groundrope, and the sediment cloud was always lower than the 30 cm sampling bottle (the lower height of the third pair of bottles).

In the absence of any other apparatus capable of carrying out comparable simulation and sampling, the performance of the TTSS was validated in field experiments using a modified full-scale otter trawl operating under normal fishing conditions (Fig. 4). The net used was a Greek commercial bottom trawl with 26 mm cod-end (stretched mesh) equipped with the same type of groundrope as that previously tested by TTSS. A metal frame (70 × 40 × 120 cm) was tied securely with ropes at an internal-central position at the bottom of the trawl net. It was equipped with two pairs of horizontal Hydrobios water bottles held in a horizontal position at 2.5 cm and 17.5 cm above the surface of the net, 1.5 m behind the groundrope. The bottle openings were located in a frontal position in order to avoid any potential sediment disturbance which might be caused by other parts of the apparatus. Floats were attached to the upper part of the frame so that the whole apparatus was neutrally buoyant. In this special rig, the sampling bottles were triggered by a MORS acoustic release (type AR701AE) located behind the bottle arrays, and activated by a MORS low frequency telecommand transmitter (type TT301-A) operated from the ship. All water bottles closed simultaneously and

Fig. 4. General aspect of the metal frame used in a full-scale trawling rig for the validation of the new method: (A) view of the frame equipped with two pairs of water bottles with doors connected with an acoustic releaser, (B) attachment of the frame inside the trawling net at a distance of 1.7 m behind the groundrope, (C) recovery of the trawling net on the vessel's deck, (D) recovery of the water samples collected.

were recovered with the trawl. The trawl was towed at a speed of 2.2 NM/h and the ratio of the wire paid out to depth was 3:1. Upon recovery of the trawl, the net must be ripped off at the area of the bottles in order to collect the water samples (Fig. 4). This is a time-consuming procedure especially if the need for restoration of the trawl net prior to its reuse is taken into consideration.

Six trawls were performed at a depth of 50 m. Chemical analyses of water and sediment samples were compared with samples from the same number of TTSS tows using the same groundrope in the same area. Three additional tows of TTSS without the groundrope were also performed and collected samples were used as reference. Finally, 5-l Niskin bottles were used to sample the water column at standard depths (1, 10, 20, 30, 40, 49 m) before the start of the experiments. Upon recovery, all water samples were filtered through Whatman GF/F glass fiber filters in order to estimate chlorophyll *a*, phaeopigments, particulate organic carbon (POC), and particulate organic nitrogen (PON), as well as solids concentrations measured by routine oceanographic methods. Water sub-samples (200 ml) were collected from the filtrate for nutrient analysis (PO_4, SiO_2, NH_4, NO_2, NO_3), frozen immediately, and stored at −20 °C until analysis upon return to the laboratory. Chlorophyll *a* and chloroplastic pigment equivalent (CPE) were determined according to the fluorometric method of Yentsch and Menzel (1963), using a Turner 112 fluorometer. The POC and PON concentrations were analyzed using a Perking Elmer CHN 2400 analyzer, and nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), phosphate (PO_4), and silicate (SiO_2) concentrations were determined using a Beckmann DU65 spectrophotometer and standard manual oceanographic colorimetric methods (Strickland and Parsons, 1972). The Mann–Whitney's *U*-test was used to assess statistically the significance of differences between total net releases of the various nutrient compounds derived from the application of TTSS and the trawl.

3. Results and discussion

The averaged concentrations of the different dissolved and particulate elements produced by the two experimental methods used in this study, as well as water column reference concentrations measured either by using TTSS without the groundrope or by using Niskin bottles (averaged concentrations at 1 to 49 m above

Table 1
Mean values of artificially resuspended and reference inorganic and particulate nutrient concentrations and solids measured at several distances above the seabed (TTSS: water samples collected with the trawl simulating apparatus, TRAWL: water samples collected from a commercial trawling rig, REF: reference water samples collected with TTSS omitting the groundrope and Niskin bottles)

Parameter	Samples	Distance above seabed (cm)			
		0–15	15–30	30–45	100–4900
Total inorganic nitrogen (μM/l)	TTSS	6.49±0.89	3.30±0.93	2.00±0.47	–
	TRAWL	6.11±0.69	3.34±0.63	–	–
	REF	1.89±0.10	1.83±0.08	2.11±0.29	1.80±0.81
Total inorganic phosphate (μM/l)	TTSS	0.37±0.07	0.19±0.06	0.06±0.03	–
	TRAWL	0.39±0.08	0.23±0.07	–	–
	REF	0.06±0.05	0.05±0.01	0.04±0.04	0.04±0.05
Total inorganic silicate (μM/l)	TTSS	5.70±3.81	3.15±1.34	1.74±0.21	–
	TRAWL	6.72±2.61	4.50±2.16	–	–
	REF	1.57±0.26	1.33±0.30	1.39±0.27	1.35±0.42
Total particulate carbon (mg/l)	TTSS	11.08±1.33	2.83±2.76	0.80±0.22	–
	TRAWL	9.45±1.16	4.27±1.50	–	–
	REF	0.48±0.09	0.26±0.06	0.22±0.04	0.23±0.05
Total particulate nitrogen (mg/l)	TTSS	1.56±0.20	0.38±0.37	0.11±0.03	–
	TRAWL	1.25±0.16	0.53±0.20	–	–
	REF	0.05±0.01	0.03±0.01	0.03±0.01	0.02±0.01
Chlorophyll *a* (μg/l)	TTSS	10.26±1.20	1.60±2.27	0.05±0.02	–
	TRAWL	6.80±1.99	4.15±1.92	–	–
	REF	0.07±0.02	0.05±0.01	0.04±0.02	0.13±0.06
Phaeopigments (μg/l)	TTSS	4.97±1.18	1.02±1.05	0.04±0.03	–
	TRAWL	4.25±1.84	2.44±0.97	–	–
	REF	0.06±0.06	0.06±0.03	0.06±0.03	0.04±0.01
Total solids (g/l)	TTSS	1.51±0.22	0.34±0.37	0.06±0.01	–
	TRAWL	1.28±0.24	0.55±0.20	–	–
	REF	0.05±0.01	0.05±0.01	0.05±0.01	0.04±0.01

seabed), are presented in Table 1. It should be noted that all averaged reference concentrations measured are very similar throughout the water column. Furthermore, nutrient concentrations above the sediment plume (0.30 to 0.45 m above the seabed) measured with TTSS at a distance of 1.5 m behind the groundrope were always similar to water column reference concentrations measured without the groundrope at the same height above the seabed. Comparison of the net fluxes produced at the sediment plume section from 0 to 0.15 and from 0.15 to 0.30 m above the seabed as well as the total net fluxes per square meter of seabed disturbance measured by using the two sampling methods is shown in Fig. 5. The data for almost all the measured fluxes suggest that the trawl net resuspends about 10% more sediment at the superior plume section (0.15–0.30 m above seabed). This discrepancy might be attributed to the influence of the trawl net (in addition to the groundrope) and/or to the resistance to water flow of the water sampler parts (floats, metal frame) used in the otter trawl. Nevertheless, application of the Mann–Whitney *U*-test in total fluxes of all dissolved and particulate substances estimated by using the two sampling methods showed no significant differences ($p>0.05$) between the two sets of data.

The groundrope is the component of trawl gear that is directly attached to the lower leading edge of the net and in contact with the seabed. The bridles connect the trawl doors with the trawl net and may well be in contact with the seabed for at least part of their length. They are constructed similarly to the groundrope, with a cable or chain covered with protective material (Rose et al., 2000). The total length of both groundrope and bridles that come in contact with the seabed may vary from 20 to 40 m (average 30 m; Lindeboom and de Groot, 1998; Hall, 1999). On the other hand, otter boards are rigid structures that use hydrodynamic forces to depress the trawl to the seabed and to spread it horizontally. The furrow width of both otter boards is estimated to vary from 1.8 to 2.7 m (average 2.4 m; Ragnarsson and Steingrimsson, 2003). Consequently, it appears that the area of the seabed disturbed by the groundrope per haul is about 12.5 times greater than with the otter boards.

Previous experimental results from the same area by using different types of groundrope settings (e.g. weight, structure, diameter) have shown that almost all the biologically active compounds at the sediment surface are resuspended by a single passage of the simulating gear (Dounas et al., 2002, 2005). These

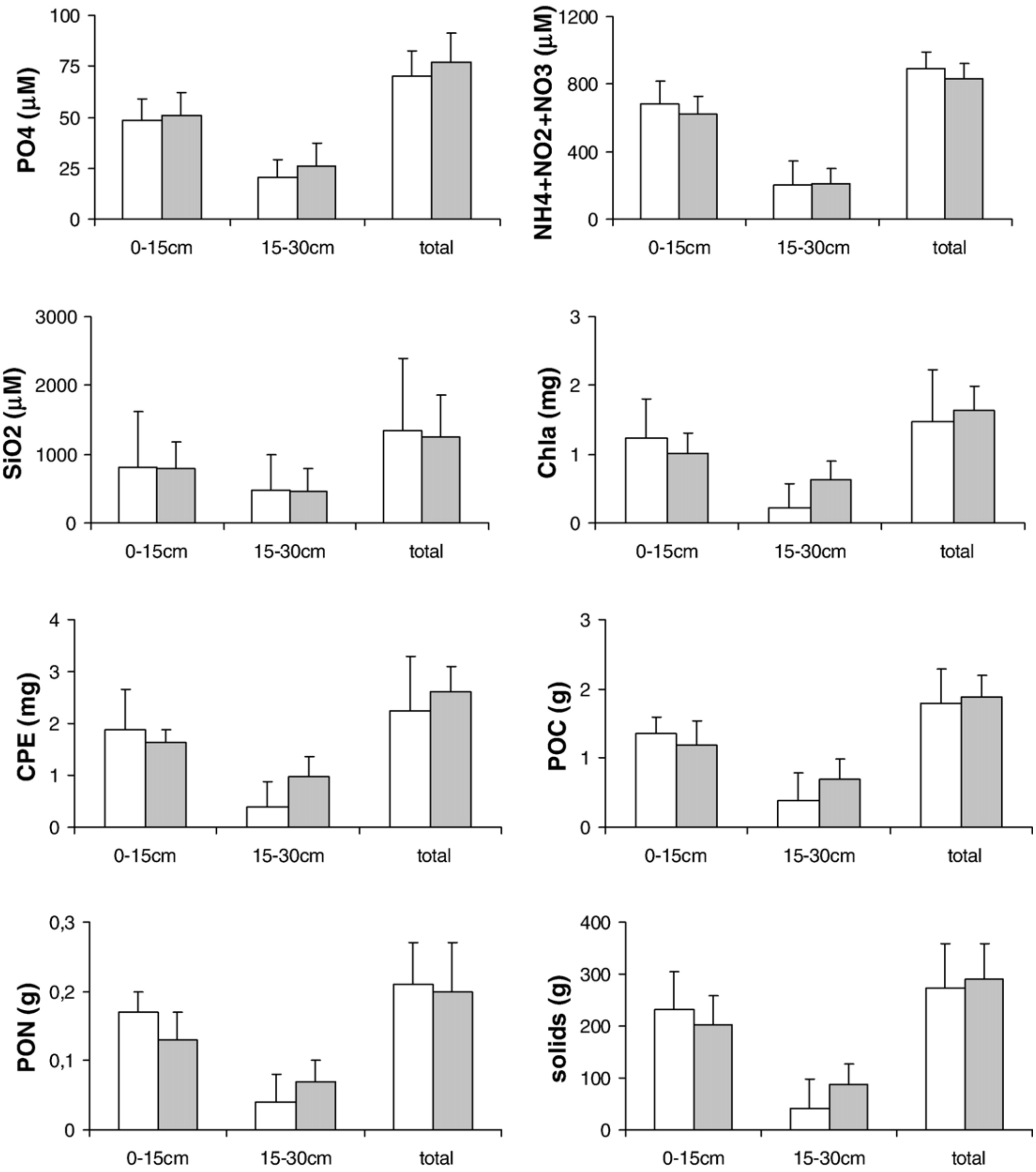

Fig. 5. Comparison of net fluxes of inorganic phosphate, total nitrogen, silicate, chlorophyll *a*, CPE, POC, PON and solids produced by the TTSS and a full-scale otter trawl rig in different levels above seabed.

observations implied that the sediment–water interface, in non-permeable seabeds, may contain a considerable reservoir of dissolved and particulate nutrients in concentrations that are much higher than in the immediately underlying surface sediment layers. Consequently, other parts of the trawl rig, e.g. the doors, presenting a very limited swept area in comparison with the groundrope are not expected to contribute significantly to the amounts of inorganic nutrient and chlorophyllous particulate substances resuspended by the groundrope.

The fluxes of both particulate and dissolved material from the sediment to the overlying water measured by using TTSS are equivalent to the effects of sediment disturbance by full-scale otter trawls when both gears are equipped with the same type of groundrope. The combined use of underwater video equipment, trigger release systems and water sampling bottles in experimental gear (such as TTSS that simulates otter trawls) can allow direct measurements to be made of the amount of sediment and nutrient concentrations put into suspension per track length or per unit area of seabed. The TTSS opens up opportunities for the study of the effects of otter trawling and similar processes on nutrient supply from seafloor sediments and on the resulting ecosystem responses in open continental shelf and upper slope areas where most trawling activity is concentrated. Furthermore, TTSS, as a modular apparatus can be easily transformed on board to a hyperbenthic sledge simply by replacing the water bottles with nets in order to provide direct quantitative measurements of the effects of otter trawling mainly on the small epibenthic and hyperbenthic animals of soft sediments (Koulouri et al., 2003, 2005; Eleftheriou and Moore, 2005). Future modifications of TTSS will allow the study of heavier (e.g. beam trawl) or more disruptive (e.g. toothed dredge) fishing gears. Further applications of this new experimental method may allow measured environmental effects to be ascribed to particular gear type, gear component or even characteristic of a specific component. Such knowledge should be useful to researchers of fishing gear technology in order to continue improving our understanding of the mechanisms by which fishing gear components affect sedimentary environments and may be applied for the evaluation and further development of gear-specific measures to mitigate such effects. Full drawings of the TTSS are available from the author at kdounas@her.hcmr.gr.

Acknowledgments

This work was carried out in the framework of the project "Development of a new method for the quantitative measurement of the effects of otter trawling on benthic nutrient fluxes and sediment biogeochemistry" financed by the European Commission (DG. XIV, Studies for the support of CFP). The author would like to thank A. Eleftheriou and M. Eleftheriou for the critical reading of the manuscript, C. Christodoulou for his technical support as well as the officers and crew of RV Philia for their assistance in the operational aspects of the new apparatus.**[SS]**

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