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Methodological assessment of vertical export fluxes during an eight-month sediment trap deployment off the central coast of Peru (12°S)

Evaluación metodológica de los flujos verticales de exportación durante un despliegue de ocho meses de una trampa de sedimento frente a la costa central del Perú (12°S)

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Abstract.- Although the export of surface production to seabed is widely recognized, few studies have addressed methodological aspects related to its quantification. The objective of this study was to assess vertical fluxes off the central coast of Peru (12°S), measured in 2020 over 239 days of sediment trap deployment, and to evaluate the associated methodological approach. Using a Folsom split subsampler and successive aliquots, total mass fluxes ranged from 240.6 to 1122.0 mg m^{-2} day^{-1}. The mean flux of 634.5 ± 155.9 mg m^{-2} day^{-1} was lower than values reported for other comparable upwelling systems. The methodology applied represents an improved approach, as it minimizes potential sources of error and ensures more consistent and reliable estimates.

Key words: Vertical flux, sediment traps, Peru upwelling, Northern Humboldt Current System

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Introduction

Following the early concept of a "detrital rain" connecting surface ocean biological production with deep-sea communities (Agassiz 1888), research on the vertical transport of organic matter has become critical to understanding production processes within marine ecosystems (Müller & Suess 1979, Ming *et al.* 2022). Sinking particles have been extensively studied as a means of quantifying benthic-pelagic coupling using sediment traps. Since the early 1970s, much attention has been given to these procedures because they expanded the study of nature and dynamics of sinking particles (Berger 1971, Honjo 1976). Although the export of surface production to the seafloor is well-documented, only a few studies have explored how to measure sedimentation rates and which methodologies to use (Chen *et al.* 1998, Buesseler *et al.* 2007, Bhattacharya *et al.* 2021). In the Eastern Pacific, the deployment of sediment traps is challenging due to persistent organic-rich particle plumes associated with upwelling, which result in highly concentrated samples requiring complex post-recovery processing (Pace *et al.* 1987). In this highly productive upwelling system (3-4 g C m^{-2} day^{-1}) (Calienes *et al.* 1985, Chavez *et al.* 1989), sediment inputs also include terrigenous material transported by river plumes during El Niño events (Velazco *et al.* 2021). Despite the complex interactions among the processes influencing total mass flux to the seafloor, standardized procedures for handling highly concentrated material from this ecosystem remain limited. Recent efforts have focused on developing appropriate methods for the removal of swimmers and fecal pellets, as well as improving splitting accuracy during extreme El Niño events (Mendoza *et al.* 2022). In this context, the present study analyzed fluxes measured over a prolonged sediment trap deployment (*i.e.,* several months), with emphasis on the implications for the pre-treatment of particle-rich samples. The *ad hoc* methodological approach applied was also evaluated in comparison with other procedures.

Materials and methods

A research campaign was carried out in an upwelling region off the coast of central Peru, near Callao, 12°S. A mooring array was deployed at a depth of 40 m from the R/V IMARPE VI through a total period between March 14 and December 18 (279 days), 2020, close to San Lorenzo Island off Callao Bay (Fig. 1). A 6-sample Multi Sediment Trap fixed at 30 m depth was used. This study analyzed a 239-days resolution flux signal between April 23 and December 18 in only one of the samples (S5), providing an opportunity to test *ad hoc* procedures.

For S5, a procedural test for sample splitting and swimmer removal was initially conducted following Mendoza *et al.* (2022). The efficiency of the Folsom splitter was determined gravimetrically based on the volume fraction obtained after splitting. To evaluate splitter performance, a test was conducted using distilled water mixed with 1 g of surface sediment collected from the study area. In each trial, a total volume of 500 mL, equivalent to twice the capacity of the sampling bottle (250 mL), was divided into eight equal fractions, as splitting errors tend to increase with the number of subsamples generated per split (Heussner *et al.* 1990). To prevent filter clogging, the procedure was continued through successive dilutions up to 1/64 aliquots (Fig. 2). The mean and standard deviation of the Folsom splitter efficiency were calculated, and the coefficient of variation (CV, expressed as a percentage) was determined as the ratio between the standard deviation and the mean. Subsequent ignition and filtration procedures followed the protocols described by Grasshoff *et al.* (1983), Strickland & Parsons (1972), and Miquel *et al.* (2015). Whatman GF/F glass fiber filters (47 mm diameter) were pre-combusted at 450 °C for 5 h, cooled in a desiccator, and weighed using a Sartorius analytical balance with a resolution of 0.0001 g (initial filter weight, W1). The 1/64 aliquots were filtered using a Whatman filtration system, applying vacuum suction with a pump operating at 0.2 bar (Boxhammer *et al.* 2016). Filters were then dried at 75 °C for 30 min using aluminum foil as a support, stored in a desiccator, and reweighed using the analytical balance (final filter weight, W2). The difference between W1 and W2, after correction using the mean blank value, was considered the final sample mass. Total mass flux (TMF, mg m^{-2} day^{-1}) was calculated using the following equation:

$$TMF = (F \times \alpha) / (A \times \gamma)$$

Where, F: dilution factor; α: particulate matter mass (mg); A: trap mouth area (0.080384 m²); γ: number of days.

To analyze the present results, the TMFs values were assumed as two sets of related observations (S5-sourced observations).

The normality of the distributions of the two sets of S5-derived observations (n= 8 per set) was assessed separately using the Shapiro-Wilk test. The null hypothesis of normality was rejected for set 1 ($P = 0.0249$) but was not rejected for set 2 ($P = 0.7995$), using $\alpha = 0.05$. Addressing this, the non-parametric Wilcoxon test for two dependent samples was employed to analyze the null hypothesis of no difference (in terms of central tendency) between sets using TMF.

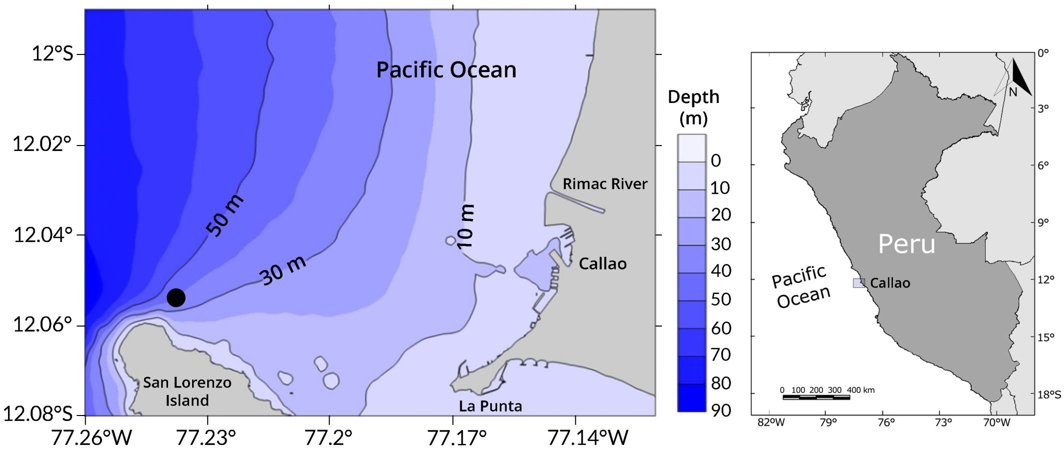

Figure 1. Bathymetric map of the study area and location of the sediment trap mooring (black circle) in Callao Bay (12°S), Peru / Mapa batimétrico del área de estudio y ubicación del anclaje de la trampa de sedimento (círculo negro) en la bahía del Callao (12°S), Perú

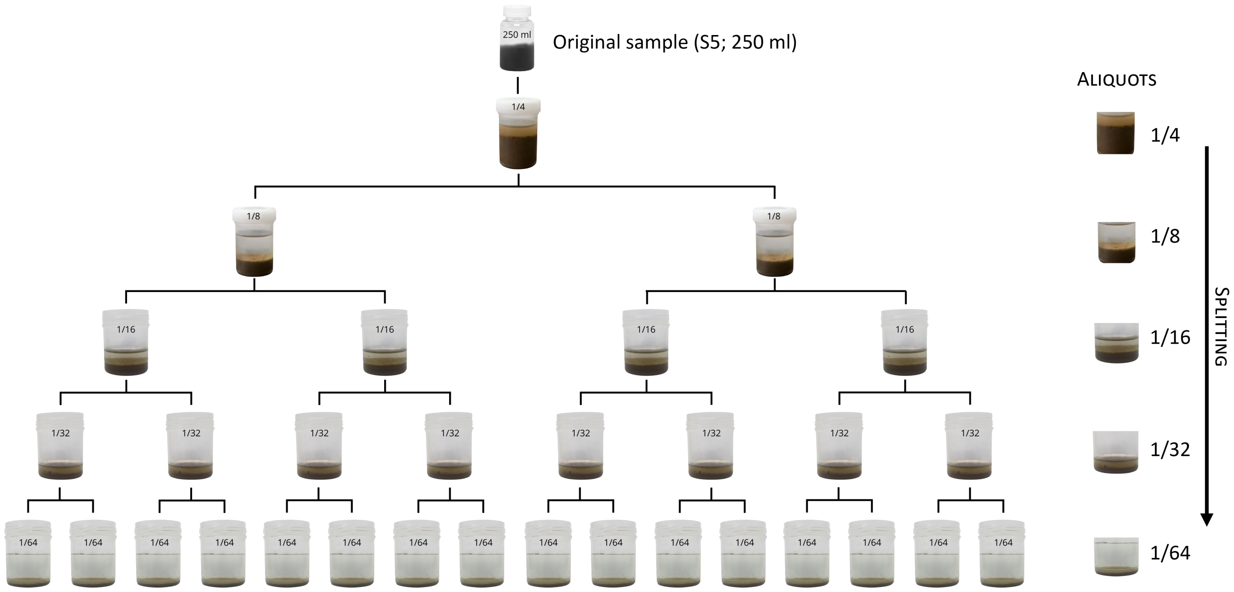

Figure 2. Scheme of the splitting process using a Folsom plankton splitter and Whatman filtration equipment applied to the original sample (S5) / Esquema del proceso de fraccionamiento utilizando un divisor Folsom de plancton y equipo de filtración Whatman aplicado a la muestra original (S5)

Results and discussion

Sediment traps are rarely deployed for prolonged periods, as their main use is to investigate short-term variability in vertical fluxes or to characterize seasonal patterns. In this study, an unexpectedly prolonged deployment resulting from a sediment trap malfunction provided a unique opportunity to evaluate methodological approaches and examine flux data at a lower temporal resolution.

A key methodological aspect evaluated in this study was the splitting test. The test performed to determine the efficiency of the Folsom splitter resulted in an overall CV of 12.39%, which was higher than the values reported by Mendoza *et al.* (2022). This CV was also higher than the 5-6% range reported for a Folsom splitter used by Chiarini *et al.* (2014) with low-particle-content material from the Antarctic region, suggesting that splitting precision may vary depending on sample characteristics and material concentration. Nevertheless, the results indicate that the Folsom splitter provides an adequate approach for processing highly concentrated samples from productive upwelling systems, supporting its application for similar environmental conditions and particle-rich materials.

For the filtration process, different types of filters have been used in previous methodologies, including the quartz-fiber membrane filter used by Miquel *et al.* (2015) and the GF/C-grade glass-fiber filter recommended by Strickland & Parsons (1972). In the present study, Whatman GF/F glass-fiber filters were used. GF/F filters have also been employed by Grasshoff *et al.* (1983) and Boxhammer *et al.* (2016) for the processing of sediment-trap material.

Different pre-combustion conditions reported in the literature were evaluated, including 450 °C for 2 h (Grasshoff *et al.* 1983), 450 °C for 6 h (Boxhammer *et al.* 2016), and 105 °C for 1 h (Szmytkiewicz & Zalewska 2014). In this study, the pre-combustion condition selected for this study was 450 °C for 5 h. Higher temperatures or longer combustion times caused irreversible wrinkling of the filters, increasing their susceptibility to cracking during handling.

During the filtering process, suction pump pressure tests were conducted at 0.27, 0.5, and 0.2 bar, referencing Grasshoff *et al.* (1983), Strickland & Parsons (1972), and Boxhammer *et al.* (2016), respectively. The suction pump pressure used in this study was set at 0.2 bar, as higher pressures led to noticeable pellet rupture. This procedure is in accordance with Grasshoff *et al.* (1983), who noted that a higher pressure gradient may result in cell rupture causing loss of material.

The filter drying stage showed the greatest variability compared with previous studies, likely due to the high amount of material retained on the filters after the extended sediment trap deployment. Szmytkiewicz & Zalewska (2014) dried filters at 105 °C for 2 h, Strickland & Parsons (1972) at 75 °C for 1 h, and Boxhammer *et al.* (2016) at 60 °C overnight. In this study, the procedure described by Grasshoff *et al.* (1983) was adapted by drying filters at 75 °C for 30 min and periodically moving them every 10 min to prevent adhesion to the aluminum foil and avoid cracking during removal, which could lead to sample mass loss.

The mean TMF obtained from aliquots 1 to 8 of S5 (first batch) was 744.8 ± 170.3 mg m^{-2} day^{-1}, which was higher than the mean obtained for the second batch (524.2 ± 174.7 mg m^{-2} day^{-1}) (Table 1). All samples were processed by the same analyst to minimize potential analytical bias. It is important to note that one aliquot from the second batch showed a relatively low value (240.6 mg m^{-2} day^{-1}) compared with the remaining estimates. When evaluating data consistency, the Wilcoxon test did not reject the null hypothesis ($P = 0.1484$), indicating no statistically significant difference between the two batches. This is consistent with most values reflecting a similar environmental flux signal, though it does not rule out batch-specific differences. In terms of TMF distributions, the violin plot showed that batch 1 was concentrated toward higher values, with greater density at the upper end, whereas batch 2 displayed a more symmetrical distribution around the mean (Fig. S1).

Year-round wind-driven upwelling is the main mechanism regulating seasonal primary production and, consequently, particle export and food availability in the Peruvian marine system (Kämpf & Chapmann 2016). The annual time series obtained from the same sediment trap under neutral oceanographic conditions showed seasonal variability, with a maximum peak (860.9 mg m^{-2} day^{-1}) during austral summer in Callao Bay (Leigh *et al.* 2023). The analysis of the 16 S5 aliquots collected over 239 days resulted in a mean TMF of 634.5 ± 155.9 mg m^{-2} day^{-1}. This mean value was lower than those reported for other shallow coastal systems (30 m depth), including northern Chile (400 ± 1100 mg m^{-2} day^{-1} in Mejillones) (Cerda *et al.* 2010) and central Chile (300 ± 4600 mg m^{-2} day^{-1} in Concepción) (Farias *et al.* 1996), both during the austral summer. Seasonal variability has been reported at Walvis Ridge, within the Benguela Coastal Current, where a distinct bimodal flux pattern was recorded by an upper sediment trap (599 m) during a year-round observation (Wefer & Fischer 1993). Due to the lower particle flux captured by deeper sediment traps (1648 m), the 216-day collection period (79.9 mg m^{-2} day^{-1}) showed limited capacity to resolve temporal variability. The deepest trap, with an 18-day sampling resolution, captured only the first peak, which closely matched the values observed in the upper trap. Overall, the results of the present study, although lower than the austral summer peak values reported for other systems, encompassed the expected range of seasonal variability. By controlling potential sources of error during the splitting and filtration procedures, this study provides a consistent methodological framework for estimating export fluxes in the Humboldt Current System.

Table 1. Table 1. Mass measurements and total mass flux calculated from 1/64 aliquots of sample 5 (S5) / Pesos y flujo de masa total calculados a partir de las alícuotas 1/64 de la muestra 5 (S5)

Set (batch)	Aliquot sample	W1 Dry weight of empty filter (g)	W2 Dry weight of filter + sample (g)	W2 - W1 Dry weight of the sample (mg)	Corrected weight by the blank (mg)	Total mass flux (mg m^{-2}day^{-1})
1	1	0.1314	0.3752	243.8	243.7	812.2
	2	0.1308	0.3574	226.6	226.5	754.9
	3	0.1310	0.3231	192.1	192.0	639.9
	4	0.1302	0.4670	336.8	336.7	1122.0
	5	0.1291	0.3146	185.5	185.4	618.0
	6	0.1301	0.3113	181.1	181.0	603.6
	7	0.1325	0.3600	227.4	227.3	757.9
	8	0.1303	0.3254	195.0	194.9	649.9
Mean						744.8
SD						170.3
2	9	0,1288	0.2542	125.4	125.3	417.5
	10	0.1261	0.2696	143.5	143.4	477.8
	11	0.1271	0.2916	164.4	164.3	547.4
	12	0.1241	0.1964	72.3	72.2	240.6
	13	0.1270	0.3592	232.2	232.1	773.3
	14	0.1262	0.3478	221.6	221.5	738.0
	15	0.1256	0.2541	128.5	128.4	427.8
	16	0.1280	0.2996	171.6	171.5	571.4
Mean						524.2
SD						174.7

W1: weight 1, W2: weight 2, SD: standard deviation

Statements

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Author contributions

U.M. and B.L. contributed to study conceptualization, experimental design, validation, formal analysis, investigation, and data curation. B.L. contributed to software and visualization. U.M., F.V., and P.A. contributed resources, while U.M., B.L., and M.C. contributed to the original draft. All authors reviewed and edited the manuscript. M.G. and U.M. contributed to supervision and project administration, and M.G. was responsible for funding acquisition.

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Data availability statement

All data are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no conflict of interest.

Use of AI tools

The authors declare that no generative artificial intelligence (AI) tools were used in the study or in the preparation of the manuscript.

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Supplementary material

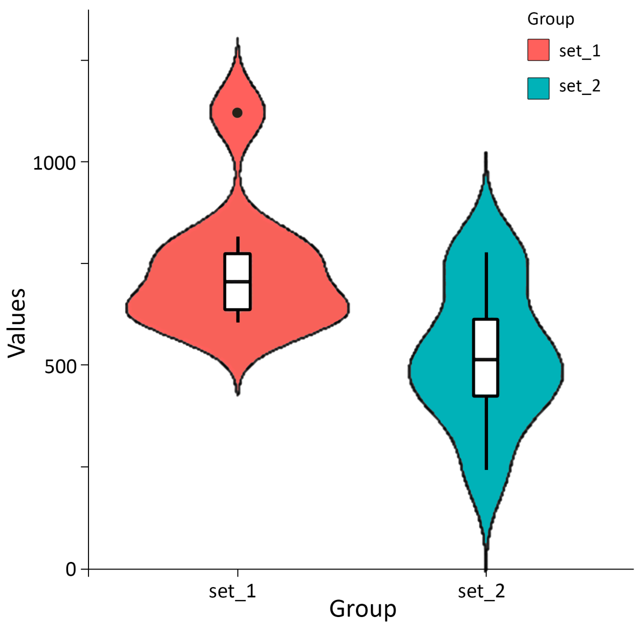

Figure S1. Violin plot comparing total mass flux (TMF) between set 1 (aliquots 1-8) and set 2 (aliquots 9-16) obtained from the original sample (S5) / Diagrama de violín que compara el flujo de masa total (TMF) entre el subconjunto 1 (alícuotas 1-8) y el subconjunto 2 (alícuotas 9-16) obtenidos de la muestra original (S5)