



Elemental and isotopic constraints on zooplankton-mediated carbon fluxes in Ryder Bay, Western Antarctic Peninsula

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Abstract. Zooplankton faecal pellets are recognised as a key pathway for particulate organic carbon export in the Southern Ocean, yet their elemental and isotopic composition remains poorly characterised, limiting understanding of how zooplankton-mediated processing and particle type shape the chemical signatures of sinking material. Here, we present moored sediment trap observations from Ryder Bay, Western Antarctic Peninsula, quantifying particulate organic carbon and nitrogen fluxes for total sediment trap material and isolated faecal pellets, alongside measurements of POC:PN ratios and the stable isotopic compositions of carbon and nitrogen. Cylinder faecal pellets dominated summer particulate organic carbon flux, reaching up to 100% of the total flux, which was concentrated in a brief but intense pulse consistent with episodic changes in zooplankton community composition. POC:PN ratios in both the total sediment trap material and cylinder faecal pellets were substantially elevated above Redfield, reaching values of up to 27, well beyond the range previous reported for inshore Western Antarctic Peninsula environments, whereas round pellets retained near-Redfield stoichiometry. This particle-type specific contrast indicates that the elemental composition of exported material is primarily governed by the dominant fluxing particle type rather than directly reflecting system-wide environmental conditions. Stable isotopic signatures are most consistent with post-production modification of organic matter, including preferential nitrogen remineralisation and trophic reworking, including benthic feeding, rather than directly reflecting primary production signals. Together, these findings suggest the organic matter exported across the WAP shelf break may carry a chemically distinct signature, with implications for tracing the contribution of shelf-derived carbon to broader-scale export budgets.

1 Introduction

The Southern Ocean plays a disproportionate role in global carbon cycling, acting as a major sink for atmospheric CO₂ (Gruber et al., 2023) and contributing significantly to the biological carbon pump (BCP) (Volk and Hoffert, 1985). The BCP transfers carbon from the surface ocean to depth through multiple pathways, including the gravitational settling of particles and the physical transport of particulate and dissolved organic matter via mixing and subduction processes (Stukel and Ducklow, 2017; Boyd et al., 2019). Strong seasonal variability in the Southern Ocean drives intense phytoplankton blooms during the spring-summer period, resulting in pronounced pulses of particle flux (Thomalla et al., 2023). However, the magnitude and efficiency of carbon export are highly variable and depend strongly on the interplay between ecosystem structure (Bianchi



25 et al., 2013; Cavan et al., 2017; Treguer et al., 2018), food web interactions (Schmitz and Leroux, 2020; Pinti et al., 2022), particle composition (Le Moigne, 2019), and physically mediated transport processes (Boyd et al., 2019).

Particle flux is mediated by a range of biological pathways and particle types, reflecting strong spatial and temporal variability in ecosystem structure, resulting in varying particle compositions. Phytoplankton aggregates (González et al., 2009; Roca-Martí et al., 2017), zooplankton faecal pellets (FPs), zooplankton carcasses (Gleiber et al., 2012; Manno et al., 2015; 30 Belcher et al., 2017), zooplankton exuviae (Manno et al., 2020), diatom resting spores (Rembauville et al., 2015, 2016), and Acantharea (Belcher et al., 2018) have all been shown to form dominant contributions to particulate organic carbon (POC) flux in the Southern Ocean. While aggregates can drive substantial export following bloom development, their contribution to vertical flux is modulated by upper ocean processing, including microbial degradation and zooplankton grazing (Cavan et al., 2017). Zooplankton-mediated processes, particularly FP production, represent a key link between surface production and ver- 35 tical particle transfer, as grazing converts phytoplankton biomass into rapidly sinking FPs that can efficiently transport organic matter through the water column (Cavan et al., 2017). This transformation includes both recycling and export components, with a portion of ingested material respired or retained in the upper ocean, and the remainder repackaged into sinking particles (Turner, 2015). However, while the contribution of FPs to export has been widely recognised (Cavan et al., 2015, 2017; Karakuş et al., 2021; Perhirin et al., 2025; Turner, 2015), their elemental and isotopic composition remains comparatively 40 under-characterised, limiting our understanding of how trophic processing impacts the chemical signatures of sinking material.

Coastal and inshore regions of the Western Antarctic Peninsula (WAP) are characterised by high biological productivity and strong seasonal variability, with Antarctic continental shelves exhibiting some of the highest area-normalised primary production rates in the Southern Ocean (Henley et al., 2018). Primary production is tightly regulated by the seasonal sea ice cycle and upper ocean stratification, which together control light availability and mixed layer dynamics (Henley et al., 45 2019). On-shelf intrusion of circumpolar deep water (CDW) (Klinck, 1998), which is altered by both mixing with on-shelf surface waters (Brearley et al., 2017), and by sediment fluxes (Sherrell et al., 2018) to form modified CDW (mCDW), supplies macronutrients (Martinson et al., 2008; Annett et al., 2017), alongside substantial inputs of trace micronutrients such as iron from glacial melt (Annett et al., 2015; Bown et al., 2017, 2018; Monien et al., 2017). As a result, up to approximately 50 % of surface primary production may be exported from the upper ocean in these environments (Henley et al., 2018).

50 Observations across the West Antarctic Peninsula (WAP) reveal a deficit between estimates of new production and measured gravitational particle flux, indicating that additional export pathways must play a substantial role in closing regional carbon budgets (Stukel and Ducklow, 2017). Physically mediated processes, including vertical mixing and subduction, can transport organic matter along isopycnal and diapycnal pathways, redistributing carbon in three dimension rather than solely through vertical settling (Boyd et al., 2019). In the WAP, cross-shelf exchange is further facilitated by glacially carved troughs, such as 55 Marguerite Trough, which acts as a conduit for both the on-shelf transport of mCDW (Brearley et al., 2017) and the offshore export of shelf-modified waters in the form of eddies (Brearley et al., 2019), driving export of organic matter to the ocean interior via the eddy subduction pump (Boyd et al., 2019).

Despite the recognised importance of these processes, traditional observations of particle flux typically only considered two dimensional flux (Boyd et al., 2019). As a result, the contribution of physically mediated transport pathways to carbon



60 export cannot be directly constrained using these approaches. A possible approach could be to characterise the composition of
particulate organic matter from different locations, with the aim of identifying signatures that reflect its origins and processing
history. In this context, the elemental and isotopic composition of sinking particles may offer a means of linking organic matter
to the biological and environmental processes that produced and modified it, and of distinguishing between material derived
from different regions or pathways (Boyd and Trull, 2007; Buesseler and Boyd, 2009; Boyd et al., 2019). However, substantial
65 understanding of the controls on these compositions must be developed before they could be considered as tracers of organic
material origin.

The elemental and isotopic composition of particulate organic matter, including particulate organic carbon to particulate
nitrogen (PN) ratios (POC:PN) (Redfield, 1960), and stable isotopic signatures such as $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$, is shaped by pro-
cesses operating across stages of the BCP. During primary production, phytoplankton stoichiometry and isotopic signatures are
70 influenced by environmental conditions, including nutrient availability (Copin-Montégut, 2000; Gervais and Riebesell, 2001;
Schneider et al., 2003; Bidigare et al., 1999; Wada and Hattori, 1978), CO_2 concentrations (Popp et al., 1999), and community
composition (Popp et al., 1998; Trull and Armand, 2001; Tuerena et al., 2019). Subsequent trophic processing, particularly
zooplankton grazing and FP production, can further modify these signatures through selective assimilation and metabolic
fractionation (Gerber and Gerber, 1979; Checkley and Entzeroth, 1985; Morales, 1987; Mayor et al., 2011; Atkinson et al.,
75 2012; Rembauville et al., 2015; Peterson and Fry, 1987; Altabet and Small, 1990; Kim et al., 2015). Finally, remineralisation
and recycling processes preferentially alter elemental ratios and isotopic compositions during particle degradation (Rosenfeld,
1981; Hedges et al., 1986; Ganeshram et al., 1999; Arndt et al., 2013; Copin-Montegut and Copin-Montegut, 1983; Martin
et al., 1987; Treguer et al., 1990; Anadón et al., 2002; Minagawa and Wada, 1984; Montoya, 2007; Volkman et al., 2008; Fu
et al., 2022). In coastal Antarctic systems, these biological signals may be further modified by the incorporation of non-marine
80 material, including glacial and terrigenous inputs (Banse, 1974; Müller, 1977; Ratmeyer et al., 1999; Hebel and Karl, 2001;
Schneider et al., 2003; Wefer et al., 1988). Together, these processes may generate distinct biogeochemical signatures reflecting
the origin and history of organic matter.

Ryder Bay, located within the inshore WAP, provides a well-characterised example of a high-productivity (Venables et al.,
2023), high-recycling (Weston et al., 2013) coastal Antarctic system. It exhibits pronounced seasonality, with summer sea ice
85 retreat supporting elevated primary productivity (Venables et al., 2013; Venables and Meredith, 2014) and active zooplankton
communities (Clement et al., 2026), alongside substantial recycling and modification of organic material within the water
column (Weston et al., 2013). The combination of strong biological activity and physically mediated transport processes makes
Ryder Bay an ideal setting in which to investigate how zooplankton mediated pathways influence the composition of sinking
material, and how these signatures may reflect broader processes or organic matter transformation and redistribution.

90 Here, we investigate the contribution of zooplankton FPs to summer particle flux in Ryder Bay using moored sediment trap
observations. POC and PN fluxes are quantified for both bulk material and isolated FPs, alongside measurements elemental
ratios and stable isotopic compositions ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$). By integrating biogeochemical flux measurements with elemental
and isotopic analyses, we aim to (1) quantify the contribution of FPs to the total particulate carbon and nitrogen, (2) char-
acterise differences in elemental and isotopic composition of carbon and nitrogen between FP and total particulate material,



95 and (3) evaluate the extent to which primary production, trophic processing and remineralisation, and coastal environmental processes influence the observed signatures. In doing so, this study provides insight into the mechanisms governing particle flux and transformation in a coastal Antarctic system, and identifies biogeochemical signatures representative of organic matter produced on the WAP shelf.

2 Methods

100 2.1 Study area

The study was conducted in the Ryder Bay on-shelf environment of the Western Antarctic Peninsula (WAP). This is the site of the oceanographic mooring associated with the Rothera Time Series (RaTS) long term monitoring program which provides long-term, high frequency sampling to quantify and understand seasonal, interannual, and decadal impacts to the region across physical, biogeochemical, and biological parameters (Venables et al., 2023).

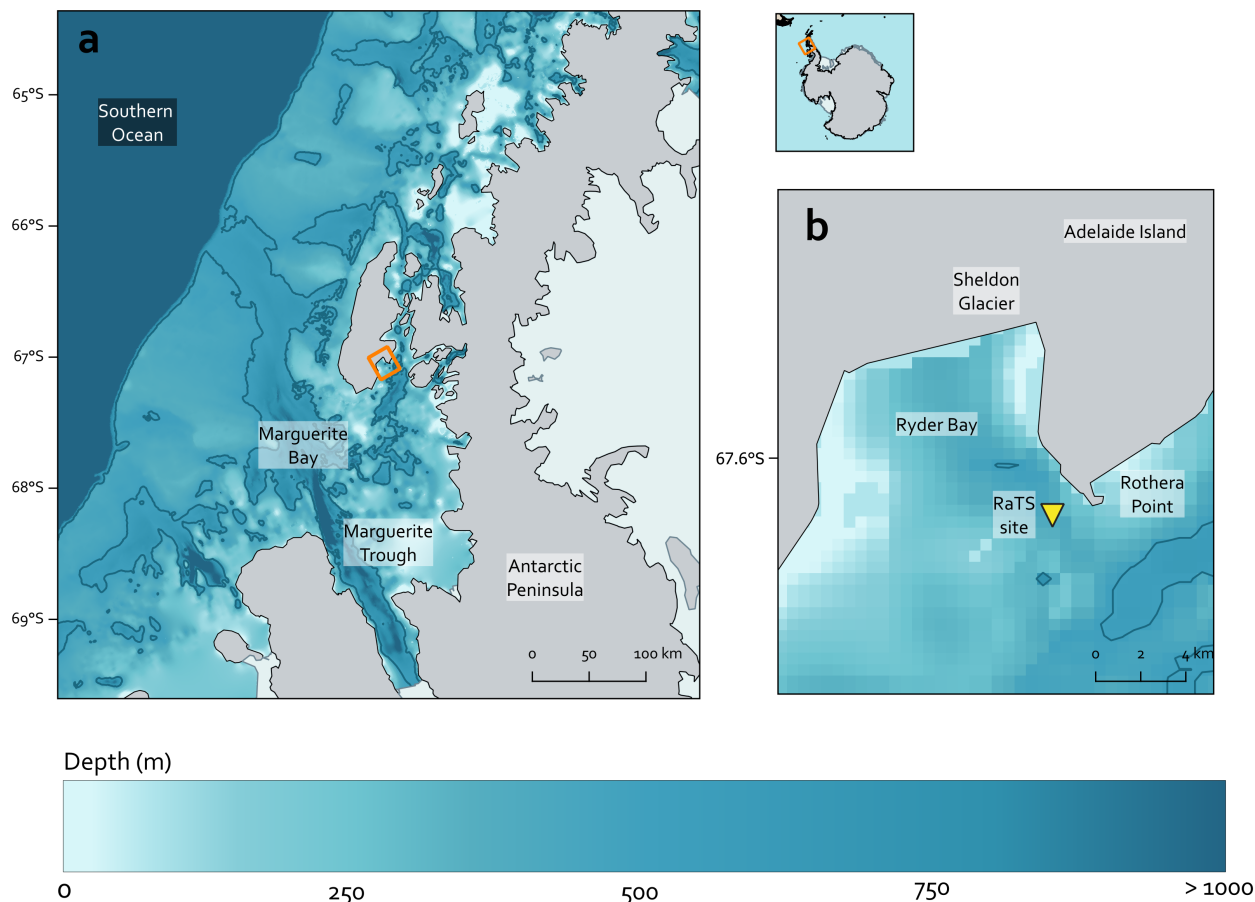


Figure 1. (a) Overview map of Marguerite Bay and the Western Antarctic Peninsula, showing bathymetry from IBCSO v2 ?. The 500 m isobath is shown, and the orange box indicates the location of panel (b). (b) map showing the location of the RaTS sampling site.

105 2.2 Sediment trap deployment

The sediment trap was deployed on the mooring array in Ryder Bay to collect sinking particulate material. The mooring was deployed on 12th January 2020 during research cruise JR19002 aboard the RRS James Clark Ross and recovered on 18th February 2022. The site was located at 67.5808° S, 68.1556° W, east of Adelaide Island, at a water depth of 400 m.

The sediment trap (McLane Parflux Mark 78H; 0.5 m² surface collecting area; McLane Research Laboratories Inc., Fallmouth, MA, USA) was positioned at 368 m and fitted with 21 sample bottles. Each bottle was pre-filled with a formosaline preservative solution consisting of filtered seawater spiked with 2 % v/v formalin, 0.025 % w/v sodium tetraborate (BORAX), and 0.5 % v/v sodium chloride to inhibit biological degradation. A baffle mounted at the top of the collection cone prevented entry of large organisms into the sample bottles.



The carousel was programmed to rotate at intervals of 12-31 days, with shorter sampling periods during the austral summer
115 and longer periods during winter. Upon recovery, it was determined that the carousel did not complete its programmed rotation
due to a power supply failure. As a result, only four bottles contained samples, representing the period from 14th January to 11th
March 2020. Instrument records indicate that these four sampling intervals were completed successfully and that the failure
occurred during rotation to the fifth bottle. These four sampling intervals are hereafter referred to as periods 1–4, corresponding
to consecutive sampling periods between 14th January to 11th March 2020, spanning from austral summer to the beginning of
120 austral autumn.

2.3 Trap sample processing

Upon recovery, sediment trap sample bottles were removed from the instrument and stored at 4 °C for transport to the laboratory
at the British Antarctic Survey, Cambridge, UK. The supernatant was carefully removed using a syringe, and each sample was
passed through a 500 µm mesh to remove swimmers (zooplankton presumed to have entered the trap alive). Swimmers were
125 excluded from flux calculations. Exuvia were retained, analysed, and considered part of the passive flux. The screened material
was examined under a dissecting microscope, and large particles contributing to the passive flux (e.g. large faecal pellets and
aggregates) were returned to the sample.

Each sample was homogenised and split into multiple aliquots using a McLane rotary splitter. Two aliquots were retained
from each sample for analysis of organic carbon and nitrogen in the full sediment trap material. From a separate aliquot, FPs
130 were isolated under a dissecting microscope for organic carbon and nitrogen analysis. For each sample, two sets of cylinder (n
= 15) and round (n = 15) pellets were selected and photographed prior to further processing.

Aliquots of either isolated FPs or full sediment trap material were filtered onto pre-combusted (450 °C, 6 hours) 25 mm
GF/F filters and rinsed with Milli-Q water. Filters were air dried, fumigated for 24 hours with 37 % HCl in a desiccator, and
subsequently oven dried at 50 °C for 24 hours.

135 2.4 Organic carbon and nitrogen

Filters and filter blanks were placed in sterile tin capsules prior to analysis. POC and PN were quantified using a CE Instru-
ments NA2500 elemental analyser. The instrument was calibrated with acetanilide standard (71.09 % C and 10.36 % N), and
calibration standards were interspersed regularly throughout each run to monitor and correct for instrumental drift. Analytical
precision was better than 1.0 % for POC and 1.1 % for PN.

140 Stable isotope ratios ($\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$) were determined using a Thermo Finnigan Delta-V Advantage isotope ratio
mass spectrometer in line with the elemental analyser. Isotope values are reported in delta notation (‰) relative to international
standards, calculated as:

$$\delta X(\text{‰}) = 10^3(R_{\text{sample}}/R_{\text{standard}} - 1)$$

Where R represents the ratio of $^{13}\text{C}/^{12}\text{C}$ for carbon or $^{15}\text{N}/^{14}\text{N}$ for nitrogen. R_{sample} denotes the isotopic ratio of the sample, and
145 R_{standard} corresponds to the appropriate international reference material: Vienna Pee Dee Belemnite (V-PDB) for carbon and



atmospheric nitrogen (AIR) for nitrogen. Analysis of the certified reference material PACS-2 marine sediment was repeated multiple times, giving a reproducibility of 0.2 ‰ for both carbon and nitrogen. This uncertainty is substantially smaller than the reported isotopic uncertainty associated with organic compounds in formalin preservatives (± 1 ‰ for carbon and ± 1.5 ‰ for nitrogen; (Mincks et al., 2008) and references therein).

150 2.5 Flux calculations

The total mass of POC or PN in each sample was calculated by multiplying the measured POC or PN mass in the analysed aliquot by the fraction of the total sample represented by that aliquot. POC and PN fluxes ($\text{mg C or N m}^{-2} \text{ d}^{-1}$) were calculated as:

$$F = m \div (A \times D)$$

155 Where m is the total mass of POC or PN in the sample bottle (mg), d is the sampling duration (12-31 days), and A is the surface area of the sediment trap opening (0.5 m^2). Two replicate aliquots were analysed from each bottle, and the mean and standard deviation are reported.

The total number of FPs in each sample was estimated by counting pellets in a known aliquot and scaling by the corresponding fraction of the full sample. Pellets were categorised as large cylinder, small cylinder, oval, or round, to assess contributions from different zooplankton groups. Based on published classifications, cylinder pellets are typically associated by euphausiids and large calanoid copepods (González, 1992), tabular pellets with salps (Accornero et al., 2003), ovoid and ellipsoidal pellets with pteropods, chaetognaths, cyclopoids, small copepods, and larvaceans (González, 1992; Manno et al., 2010; Yoon et al., 2001; Gorsky and Fenaux, 1998; González and Smetacek, 1994), and round pellets with small copepods, crustacean nauplii, and amphipods (González, 1992; Yoon et al., 2001).

165 Pellet dimensions were measured from dissecting microscope images using ImageJ, and volumes were calculated using the geometric formulae appropriate to each shape (cylindrical or spherical) (González et al., 2000). In addition to pellets isolated for chemical analysis, a further 139-162 cylinder and round pellets per sample were measured to characterise size distributions. For each sample, mean pellet volume was calculated for each shape (total $n = 169 - 192$ per shape per sample) and multiplied by the corresponding total pellet count to estimate total FP volume. The fraction of the total sample represented by the analysed FP aliquot was determined by dividing the aliquot FP volume by the total FP volume for that shape. This fraction was then used to calculate faecal pellet carbon (FPC) and faecal pellet nitrogen (FPN) fluxes using the equation above. Finally, the percentage contribution of each FP category to total POC and PN fluxes was calculated.

Partially degraded pellets (“faecal fluff”) were difficult to quantify; therefore, the contribution of faecal pellet carbon to total flux may be underestimated.

175 2.6 Statistical analysis

One-way analysis of variance (ANOVA) was used to assess differences among samples and sample types (cylindrical FPs, round FPs, and bulk sediment trap material) for %POC, %N, POC and PN fluxes, POC:PN ratios, $\delta^{13}\text{C}_{\text{POC}}$, and $\delta^{15}\text{N}_{\text{PN}}$. Prior



to analysis, data were evaluated for normality and homogeneity of variances using Levene's test. Where significant differences were detected, Tukey's honest significant difference (HSD) post hoc tests were applied to identify pairwise differences among
180 groups. Statistical significance was accepted at $P < 0.05$.

3 Results

3.1 POC and PN fluxes

The mean POC flux from the sediment trap was $131.01 \pm 61.10 \text{ mg C m}^{-2} \text{ d}^{-1}$. Although POC flux appears elevated in period 3, there is no significant variations between the time periods ($F_{3,4} = 6.04$, $p = 0.057$).

185 Cylinder FPs contribute a mean FPC flux of $92.49 \pm 75.17 \text{ mg C}^{-2} \text{ d}^{-1}$, a value which is not significantly different from that of the overall POC flux ($p = 0.370$). However, there is significant variation in cylinder FPC flux between the time periods ($F_{3,4} = 71.93$, $p < 0.001$), where two discrete groups form, with periods 2 and 3 being significantly higher than periods 1 and 4, with a 3.6 fold increase from period 1 to period 2.

FPC flux from round FPs is around two orders of magnitude smaller than that of the total flux ($p < 0.001$), and that from
190 cylinder FPs ($p = 0.010$), with a mean of $0.94 \pm 0.64 \text{ mg C m}^{-2} \text{ d}^{-1}$. There is also significant variation in round FPC flux between the time periods ($F_{3,4} = 15.73$, $p = 0.011$), with significantly higher FPC flux in periods 2 and 3 than period 4 ($p = 0.029$, $p = 0.011$), and higher FPC flux in period 3 than period 1 ($p = 0.047$).

Cylinder FPs contribute from 4.48 % (period 4) to ~ 100 % (period 2) of the total POC flux. Round FPs contribute from 0.22 % (period 4) to 0.96 % (period 2) of the total POC flux.

195 The mean PN flux from the sediment trap was $10.58 \pm 7.83 \text{ mg N m}^{-2} \text{ d}^{-1}$. There is significant variation in the total PN flux across the study period ($F_{3,4} = 18.68$, $p = 0.008$), with period 3 increasing to more than 2.5 x the flux of period 2 ($p = 0.021$).

Cylinder FPs contribute a mean FPN flux of $4.55 \pm 3.44 \text{ mg N m}^{-2} \text{ d}^{-1}$, which is not significantly different from the total PN flux ($p = 0.058$). There is significant variation in the cylinder FPN flux across the study period ($F_{3,4} = 94.40$, $p < 0.001$), where two discrete groups form, with periods 2 and 3 being significantly higher than periods 1 and 4, with a three-fold increase from
200 period 1 to period 3.

FPN flux from round FPs is around 20-fold lower than from cylinder FPs, with a mean of $0.20 \pm 0.12 \text{ mg N m}^{-2} \text{ d}^{-1}$. There is no significant variation in round FPN flux across the study period ($F_{3,4} = 6.08$, $p = 0.057$).

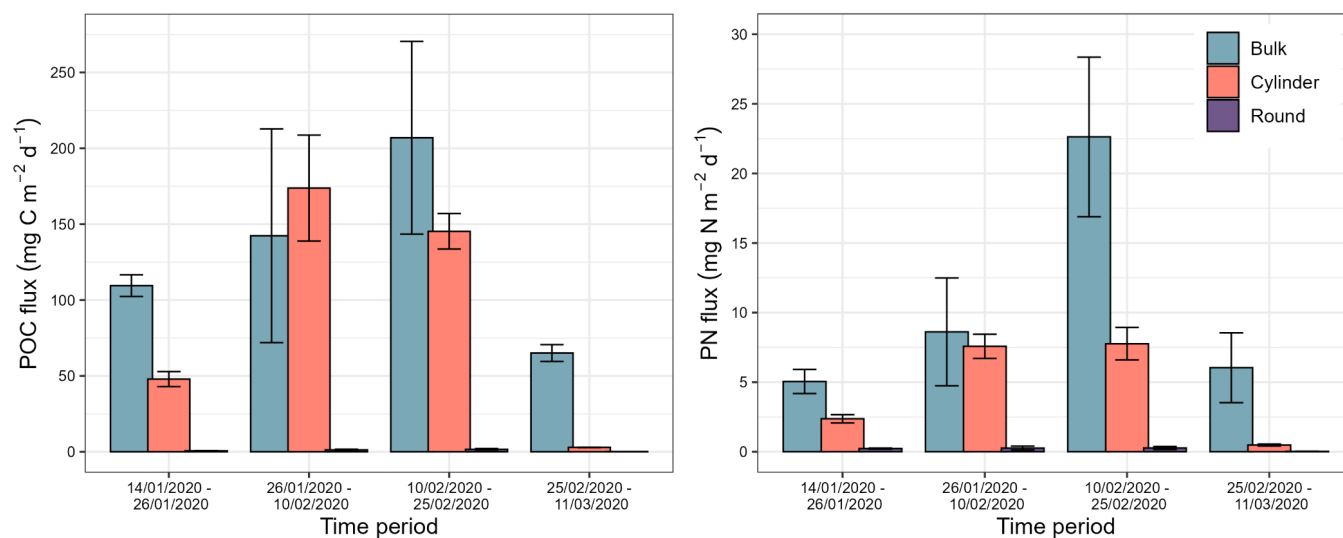


Figure 2. POC flux ($\text{mg C m}^{-2} \text{d}^{-1}$) (a) and PN flux ($\text{mg N m}^{-2} \text{d}^{-1}$) (b) across four time periods. Bars represent mean fluxes for bulk sediment trap material (blue), cylinder faecal pellets (pink), and round faecal pellets (purple) within each time period. Error bars indicate $\pm 95\%$ confidence intervals.

3.2 Carbon and nitrogen contents

Mean %POC in the sediment trap material is $6.73 \pm 2.90\%$. %POC differed significantly between the four sampling periods ($F_{3,4} = 235.35$, $p < 0.001$), forming two discrete groups where periods 1 and 4 have around half the %POC of periods 2 and 3.

The mean carbon content of cylinder FPs ($0.041 \pm 0.005 \text{ mg mm}^{-3}$) was significantly higher than round FPs ($0.031 \pm 0.005 \text{ mg mm}^{-3}$) (two-samples t-test, $p = 0.002$), with no significant variation across time periods for either shape ($F_{3,4} = 3.78$, $p = 0.116$; $F_{3,4} = 0.41$, $p = 0.758$).

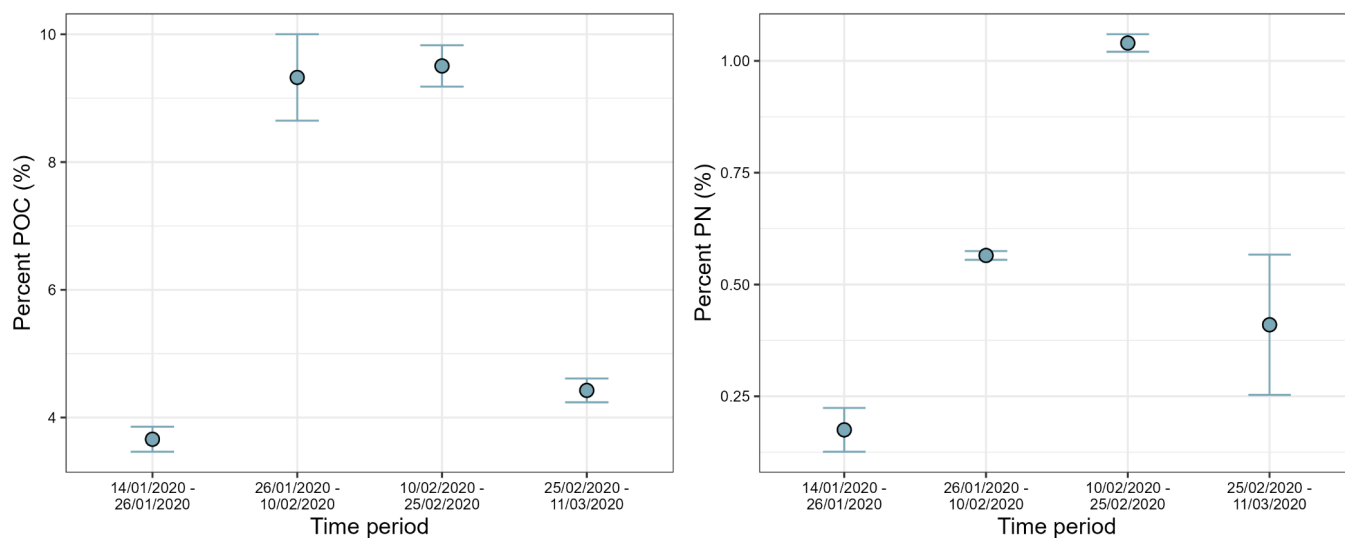


Figure 3. Percent contribution of POC (a) and PN (b) to the total sediment trap material for each of the four time periods. Error bars indicate $\pm 95\%$ confidence intervals.

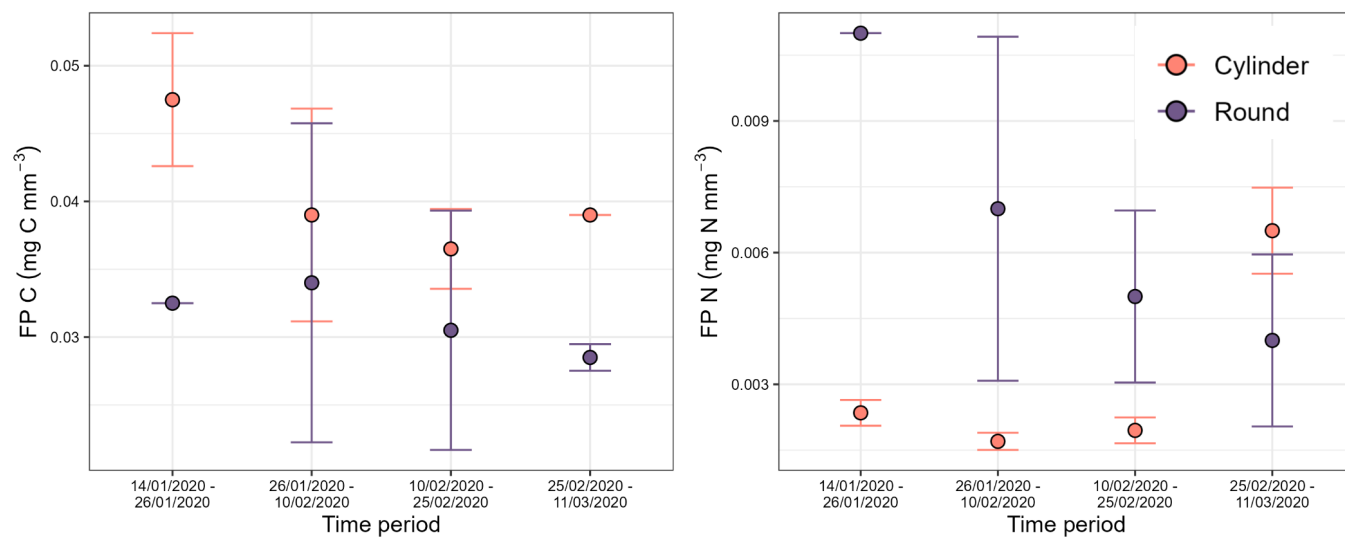


Figure 4. Percent contribution of carbon (a) and nitrogen (b) to faecal pellet volume across the four time periods. Points represent cylinder faecal pellets (pink) and round faecal pellets (purple) within each time period. Error bars indicate $\pm 95\%$ confidence intervals.

Mean %PN in the sediment trap material is $0.55 \pm 0.34\%$. %PN differed significantly between the four sampling periods ($F_{3,4} = 74.69$, $p < 0.001$), with period 2 increased above period 1 ($p = 0.010$), and period 3 higher than periods 1 ($p < 0.001$), 2 ($p = 0.005$), and 4 ($p = 0.002$), reaching almost double the %PN of period 2, and almost 6 times that of period 1.



The mean nitrogen content of cylinder FPs ($0.0031 \pm 0.002 \text{ mg mm}^{-3}$) was less than half that of round FPs ($0.0068 \pm 0.003 \text{ mg mm}^{-3}$, $p = 0.017$). Period 4 had over three times the cylinder FP nitrogen content of the other time periods ($F_{3,4} = 67.33$, $p < 0.001$), reaching a maximum of $0.0065 \text{ mg mm}^{-3}$. There was no significant variation in the nitrogen content of round FPs
215 across the study period.

3.3 POC:PN ratio

The mean POC:PN ratio of the sediment trap material over the study period was 17.11 ± 6.52 . There was significant variation in POC:PN across the study ($F_{3,4} = 12.20$, $p = 0.018$), with a higher POC:PN in period 1 (25.57 ± 4.35) than periods 3 (10.64 ± 0.42 , $p = 0.018$) and 4 (13.05 ± 3.13 , $p = 0.033$).

220 There was no significant difference in the mean POC:PN ratio between the total sediment trap material and that of the cylinder FPs (FPC:FPN) ($p = 0.663$), with a mean FPC:FPN of 19.92 ± 8.62 . Cylinder FPC:FPN varied significantly over the study period ($F_{3,4} = 12.06$, $p = 0.018$), where the lowest value in period 4 (7.04 ± 0.76) is significantly lower than those of period 1 (23.60 ± 0.38 , $p = 0.033$), 2 (27.02 ± 6.13 , $p = 0.017$), and 3 (22.04 ± 3.67 , $p = 0.046$).

225 The mean FPC:FPN of round FPs is significantly lower than both the total sediment trap material ($p = 0.009$) and the cylinder FPs ($p = 0.001$), with a mean value of 6.45 ± 2.82 , within the range of the canonical Redfield ratio. There is no significant variation in the FPC:FPN of round FPs across the study period ($F_{3,4} = 1.84$, $p = 0.281$).

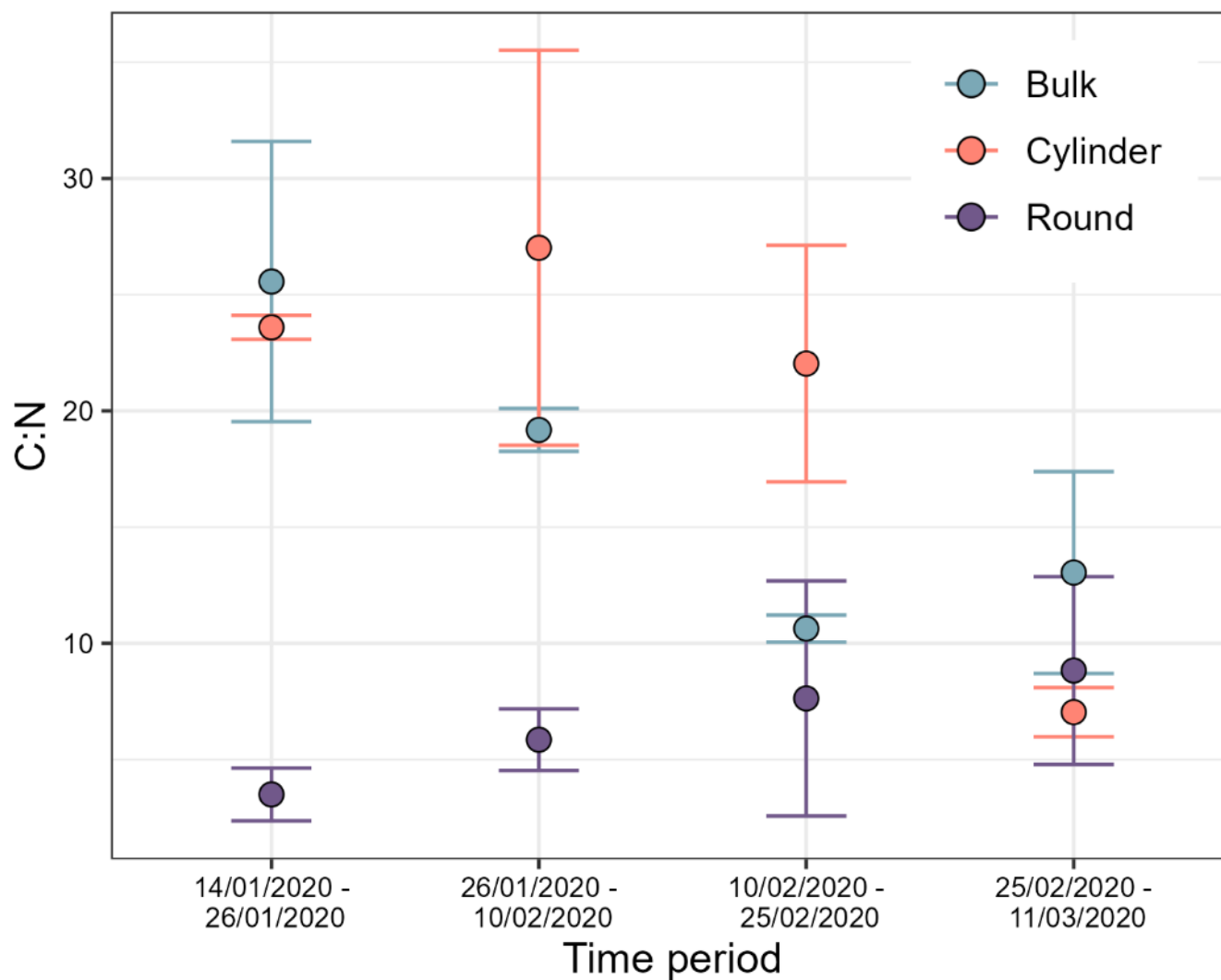


Figure 5. POC:PN (mol:mol) across four time periods. Points represent mean POC:PN for bulk sediment trap material (blue), cylinder faecal pellets (pink), and round faecal pellets (purple) within each time period. Error bars indicate $\pm 95\%$ confidence intervals.

3.4 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

The mean $\delta^{13}\text{C}_{\text{POC}}$ of the total sediment trap material was $-23.54 \pm 2.45\text{‰}$. $\delta^{13}\text{C}_{\text{POC}}$ varied significantly across the study period ($F_{3,4} = 32.73$, $p = 0.003$) with significantly higher $\delta^{13}\text{C}_{\text{POC}}$ in period 2 than periods 1 ($p = 0.010$), 3 ($p = 0.002$), and 4 ($p = 0.010$).



The mean $\delta^{13}\text{C}_{\text{FPC}}$ of cylinder FPs was significantly lower than that of the total sediment trap material ($-26.34 \pm 1.46 \text{‰}$, $p = 0.031$), and did not vary significantly across the study period ($F_{3,4} = 0.85$, $p = 0.533$). There was a mean difference in $\delta^{13}\text{C}_{\text{POC}}$ between the total sediment trap material and the cylinder FPs of $+3.00 \text{‰}$.

In contrast, the mean $\delta^{13}\text{C}_{\text{FPC}}$ of round FPs ($-20.55 \pm 2.07 \text{‰}$) was significantly higher than both the total sediment trap material ($p = 0.020$) and the cylinder FPs ($p < 0.001$), and also did not vary significantly across the study period ($F_{3,4} = 2.45$, $p = 0.204$).

The mean $\delta^{15}\text{N}_{\text{PN}}$ of the total sediment trap material was $1.75 \pm 0.61 \text{‰}$. $\delta^{15}\text{N}_{\text{PN}}$ varied significantly across the study period ($F_{3,4} = 27.56$, $p = 0.004$), with significantly higher $\delta^{15}\text{N}_{\text{PN}}$ in period 2 ($2.62 \pm 0.23 \text{‰}$) than periods 1 ($1.45 \pm 0.16 \text{‰}$, $p = 0.009$), 3 ($1.13 \pm 0.03 \text{‰}$, $p = 0.003$), and 4 ($1.81 \pm 0.20 \text{‰}$, $p = 0.032$).

The mean $\delta^{15}\text{N}_{\text{FPN}}$ was significantly higher in the cylinder FPs than the total sediment trap material ($3.81 \pm 0.62 \text{‰}$, $p < 0.001$), and did not vary significantly between the study periods ($F_{3,4} = 3.38$, $p = 0.135$). The mean difference between the total sediment trap $\delta^{15}\text{N}_{\text{PN}}$ and that of the cylinder FPs was $+2.06 \text{‰}$.

The mean $\delta^{15}\text{N}_{\text{FPN}}$ of round FPs ($2.46 \pm 0.42 \text{‰}$) was significantly higher than the total sediment trap material ($p = 0.048$) but significantly lower than that of the cylinder FPs ($p < 0.001$). The mean difference between the total sediment trap $\delta^{15}\text{N}_{\text{PN}}$ and that of round FPs was $+0.71 \text{‰}$.

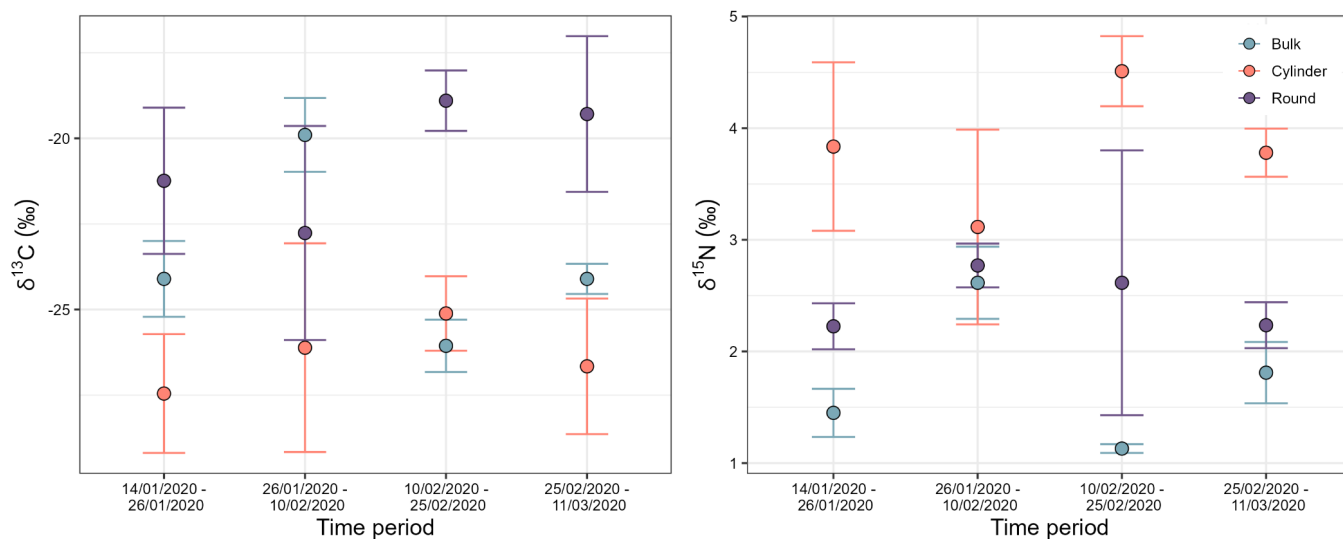


Figure 6. $\delta^{13}\text{C}_{\text{POC}}$ (‰) (a) and $\delta^{15}\text{N}_{\text{PN}}$ (‰) (b) across four time periods. Bars represent mean values for bulk sediment trap material (blue), cylinder faecal pellets (pink), and round faecal pellets (purple) within each time period. Error bars indicate $\pm 95 \text{‰}$ confidence intervals.



4 Discussion

4.1 High levels of zooplankton mediated carbon flux

The magnitude of summer POC flux observed in this study (up to $206.97 \text{ mg C m}^{-2} \text{ d}^{-1}$) is comparable to that reported in an earlier Ryder Bay study (Weston et al., 2013), which documented fluxes of up to $150 \text{ mg C m}^{-2} \text{ d}^{-1}$ at a similar depth. These values are also consistent with summer POC fluxes measured across the wider inshore WAP where trap and bottom depths are similar (Weston et al., 2013; Ducklow et al., 2008; Smith et al., 2008; Gleiber et al., 2012; Ducklow et al., 2015), which typically span $12\text{-}200 \text{ mg C m}^{-2} \text{ d}^{-1}$. Taken together, these results confirm that summer POC fluxes in Ryder Bay reflect the high seasonal productivity and strong carbon cycling characteristic of inshore WAP environments (Henley et al., 2018).

The POC flux in Ryder Bay is dominated by FPs, with cylinder pellets accounting for the majority of flux through most of the study period. Previous studies across the WAP have reported substantial heterogeneity in the contribution of FPs to the total summer POC flux, ranging from small contributions to cases where FPs comprise 100 % of the measured POC flux (Gleiber et al., 2012; Ducklow et al., 2015; Pauli et al., 2021). In contrast, the contribution of round FPs in Ryder Bay remains consistently low, contributing less than 1 % of the total POC flux, which is lower than values reported in other studies including comparable FP shape classifications (Gleiber et al., 2012; Manno et al., 2015). This dominance of cylinder FPs suggests that carbon flux in Ryder Bay is primarily mediated by zooplankton taxa that produce cylinder FPs, namely euphausiids and large calanoid copepods (Manno et al., 2015; González, 1992).

The near-total contribution of FPs during the period of elevated POC flux indicates that organic carbon flux was primarily grazer-driven, with phytodetrital aggregation playing only a minor role. Such FP dominance is consistent with the view that top-down processes exert substantial control on carbon export in productive inshore regions of the WAP, where larger zooplankton act as a major conduit for carbon transfer from the euphotic zone to depth through the production of dense, cohesive faecal material with high sinking velocities (Gleiber et al., 2012; Pauli et al., 2021; Gleiber et al., 2016; Henley et al., 2019).

Cylinder FPC flux peaked during periods 2 and 3, with substantially lower fluxes in periods 1 and 4, indicating a brief but intense flux event spanning up to four weeks. Such pulses are consistent with episodic increases in FP-mediated POC export reported elsewhere in the Southern Ocean during the spring-summer season, often associated with temporary increases in the abundance of key grazing taxa (Gleiber et al., 2012; Pauli et al., 2021; Manno et al., 2015; Belcher et al., 2019; Cavan et al., 2015). In Ryder Bay, this pattern is consistent with the transient presence of a swarming migratory zooplankton such as krill (Siegel et al., 2013), which are known to produce large cylindrical faeces similar to the ones dominating these samples (González, 1992).

Changes in FP nitrogen content and size distribution over the study period further suggest relatively rapid, week-scale temporal variability in the zooplankton community mediating export. Following the peak in cylinder FPC flux during periods 2 and 3, FP nitrogen content increased three-fold in period 4, coinciding with a marked reduction in FP flux. Supplementary analyses (Table A1) indicate a shift in FP size class, from dominance by large cylinder pellets (0.2 to 0.4 mm diameter) in periods 1 and 2, to a higher proportion of small cylinder pellets (0.1 to 0.2 mm diameter,) in periods 3 and 4. The increase in relatively small cylinder pellets in period 3 coincided with a 2.5-fold increase in PN flux relative to period 2, potentially



280 reflecting a shift in the dominant FP-producing taxa from larger euphausiids to smaller euphausiids or large calanoid copepods (González, 1992). Such changes in FP size and producing species could influence FP stoichiometry through differences in diet and gut passage processes; however, this effect is not clearly reflected in the temporal pattern of FP nitrogen content relative to FP size class.

4.2 Non-Redfield elemental composition of C and N

285 POC:PN ratios in this study consistently exceed the canonical Redfield ratio (C:N = 6.6 : 1) (Redfield, 1960; Geider and La Roche, 2002), reaching values as high as 25.57 in the total sediment trap material. While elevated C:N ratios are common in sediment trap material globally (Schneider et al., 2003), values of this magnitude have not been previously documented in Ryder Bay, where the mean POC:PN at a similar depth was found to be 9.3, only a little above Redfield (Weston et al., 2013), or for the wider WAP in shallow inshore environments during summer, where C:N ratios of 5.5 to 16.4 have been observed
290 (Smith et al., 2008; Weston et al., 2013; Ducklow et al., 2008; Anadón et al., 2002; Baldwin and Smith, 2003; Ducklow et al., 2015; Mincks et al., 2008). A pronounced temporal evolution is evident, with POC:PN decreasing by more than 10 between the earliest sampling period and later periods, bringing ratios closer to Redfield as the season progressed. In contrast, the isotopic composition of the fluxing material lies within established Southern Ocean ranges: $\delta^{13}\text{C}_{\text{POC}}$ values fall at the heavier end of the regional distribution, which is typically centred around -28 ‰ and rarely exceeds -20 ‰ (Verwega et al., 2021),
295 while remaining comparable to previous summer sediment trap measurements in Ryder Bay (-20.3 to -24.7 ‰ at 200-512 m) (Henley et al., 2012). Similarly, $\delta^{15}\text{N}_{\text{PN}}$ values fall within the broad Southern Ocean range of -6.09 to 10.80 ‰ (St John Glew et al., 2021).

Elevated C:N ratios may reflect deviations from Redfield stoichiometry during primary production, preferential remineralisation of nitrogen relative to carbon during trophic processing and microbial remineralisation, or the incorporation of non-marine
300 material with inherently higher C:N ratios (Schneider et al., 2003). These processes are associated with different responses in the isotopic composition of organic matter (McMinn et al., 1999; Venturini et al., 2020; St John Glew et al., 2021; Berg et al., 2011; Riebesell et al., 1993; Brault et al., 2018; Volkman et al., 2008; Middelburg, 2018; Altabet and Small, 1990; Peterson and Fry, 1987); consequently, $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$ provide important constraints for evaluating the mechanisms responsible for the elevated POC:PN ratios observed here, which are considered in turn in the following sections.

305 4.2.1 Phytoplankton production

Phytoplankton production can generate organic matter with elevated C:N ratios when growth occurs under conditions that favour carbon fixation relative to nitrogen assimilation (Schneider et al., 2003), such as nutrient stress (Copin-Montégut, 2000; Gervais and Riebesell, 2001). In such cases, the isotopic composition of particulate organic matter largely reflects the processes operating during primary production, allowing the accompanying $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$ signatures to be used to assess whether
310 the observed stoichiometry could originate in surface-derived material (McMinn et al., 1999; St John Glew et al., 2021; Berg et al., 2011; Riebesell et al., 1993; Zhang et al., 2014; Brault et al., 2018; Munro et al., 2010).



Although nitrate limitation can elevate phytoplankton C:N ratios (Copin-Montégut, 2000; Gervais and Riebesell, 2001), it is unlikely to have been a dominant driver in Ryder Bay. Observations indicate that macronutrients generally do not limit primary productivity in this system, although transient nitrate limitation may occur (Henley et al., 2018). Consequently, while
315 short-lived periods of nitrate stress could influence phytoplankton stoichiometry, it is unlikely that the observed value reflects a sustained signal of nitrate-limited production.

A more plausible production-related explanation is production of sea-ice associated phytoplankton. Sea-ice algae frequently exhibit elevated C:N ratios, with reported values ranging from near-Redfield up to ~ 20 , where $C:N > 7.7$ is considered indicative of nitrogen stress (Henley et al., 2012; Gradinger, 2009; McMinn et al., 1999; Ugalde et al., 2014; Cota and Sullivan,
320 1990; Lizotte and Sullivan, 1992). During the study period, satellite observations show a rapid decline in sea-ice coverage, from 60-80 % in mid-January to near zero by early March (Figure A2). Peaks in $\delta^{13}C_{POC}$ and $\delta^{15}N_{PN}$ during period 2 coincide with maximum chl- α concentrations and enhanced POC and PN fluxes, suggesting a surface production signal consistent with contributions from sea-ice associated phytoplankton. Ice-associated production could therefore contribute organic matter with elevated C:N ratios to the sinking flux, potentially mediated through zooplankton grazing on ice-derived phytoplankton.
325 However, the highest sediment trap POC:PN values observed here (25.57) exceed the upper range typically reported for sea-ice algae, indicating that this mechanism alone is unlikely to account for the full magnitude of the deviation.

Transparent exopolymeric particles (TEP) may provide an additional carbon-rich component to sinking material. TEP, produced by diatoms and bacteria in the Antarctic marine environment, particularly in sea ice, can exhibit very high C:N ratios of up to ~ 26 , and may aggregate with or adhere to sinking particles, increasing their carbon content (Henley et al., 2012; Passow,
330 2002; Nichols et al., 2005; Meiners et al., 2004). While this process could contribute to elevated C:N ratios in sediment trap material, TEP was not directly measured in this study, and its potential role remains speculative. TEP therefore represents a possible secondary contributor rather than a primary driver of the elevated C:N ratios observed.

4.2.2 Remineralisation

Elevated C:N ratios attributed to preferential remineralisation of nitrogen have been widely reported in sediment trap stud-
335 ies, reflecting progressive degradation of sinking organic matter (Anadón et al., 2002; Copin-Montegut and Copin-Montegut, 1983; Gordon, 1971; Martin et al., 1987; Treguer et al., 1990). In the Southern Ocean and along the Antarctic Peninsula, this mechanism has been invoked to explain increases in particulate C:N with depth, with reported values reaching up to 16.4 in sediment trap material (Anadón et al., 2002). While such observations demonstrate that post-production degradation can substantially modify elemental stoichiometry, the magnitude of C:N ratios observed in this study, particularly in the total sediment
340 trap material and in cylinder FPs where values exceed 20, lies beyond the upper range reported for this region. This suggests that while preferential nitrogen remineralisation likely contributes to elevated C:N ratios in the fluxing material, degradation alone is insufficient to account for the most extreme values observed, and additional zooplankton-mediated or particle-specific processes must also be considered.

The elevated C:N ratios observed in bulk sediment trap material are closely reflected in the composition of cylinder FPs,
345 whose mean FPC:FPN ratios do not differ significantly from those of the total collected material. Cylinder pellets also represent



a major fraction of the total POC flux during the first three sampling periods, indicating that these particles exert a strong control on the bulk stoichiometric signal, as suggested by the positive correlation previously reported between FP abundance and total sediment trap C:N ratio (Rembauville et al., 2015; Gerber and Gerber, 1979; Checkley and Entzeroth, 1985; Morales, 1987). In contrast, round FPs exhibit C:N ratios close to Redfield. This particle-specific expression of elevated C:N suggests that the anomaly is intrinsic to the dominant fluxing particles rather than arising from uniform post-production modification of all material in the sediment trap. The presence of highly elevated C:N ratios within intact cylinder FPs further constrains the role of degradation during sinking. FPs typically exhibit higher C:N ratios than suspended particulate matter, reflecting selective assimilation of nitrogen by zooplankton, but reported values generally fall within the range of 4-13.2 (Atkinson et al., 2012). The much higher values observed here, reaching 27.02, would require extensive preferential nitrogen remineralisation after pellet formation. This appears unlikely given that most cylinder pellets recovered from the trap were intact and enclosed within peritrophic membranes, which can inhibit microbial degradation during sinking (Turner, 2015). A more plausible explanation is that the zooplankton producing these pellets were feeding on organic matter that had already undergone substantial degradation and nitrogen loss, thereby propagating an elevated C:N signature into the FPs themselves. This interpretation is consistent with the observation that round FPs retain C:N ratios close to Redfield, suggesting differences in feeding substrates or trophic pathways rather than uniform post-formation degradation of all pellet types.

Benthic feeding by large zooplankton provides a mechanism linking elevated C:N ratios with the isotopic characteristics of cylinder pellets. Krill have been shown to forage on the seabed in both on- and off-shelf environments, particularly under conditions of reduced surface feeding success or food limitation (Schmidt et al., 2011). Antarctic shelf sediments are recognised as a persistent “food bank” or labile organic material (Mincks et al., 2008), where preferential remineralisation of particulate nitrogen can result in substantial increases in C:N ratios during early diagenesis, with increases of up to ~ 30 % reported in benthic sediments (Kristensen, 1994). Detrital material that has interacted with the seafloor is commonly enriched in $\delta^{15}\text{N}_{\text{PN}}$ due to nitrification and cumulative metabolic processing (Middelburg, 2018). Zooplankton feeding on benthic material would therefore be expected to produce FPs with both elevated C:N and higher $\delta^{15}\text{N}_{\text{PN}}$ relative to pellets produced by zooplankton consuming freshly produced phytoplankton. The enrichment in $\delta^{15}\text{N}_{\text{PN}}$ observed in cylinder compared to round pellets is consistent with this interpretation, suggesting benthic coupling and feeding on reworked material as an important contributions to elevation of C:N ratios in the fluxing material.

4.2.3 Non-marine inputs

Non-marine material associated with lithogenic particles can influence particulate C:N ratios in coastal sediment trap samples (Schneider et al., 2003; Wefer et al., 1988). In shelf environments, marine particles may incorporate material derived from aeolian dust, terrestrial runoff, or resuspended sediments (Banse, 1974; Müller, 1977; Ratmeyer et al., 1999; Hebel and Karl, 2001), and increasing lithogenic contributions to the particle flux have been associated with elevated C:N ratios in sediment trap material (Schneider et al., 2003). This reflects the typically high C:N ratios of terrestrial organic matter, which substantially exceed Redfield values; organic soils can reach C:N ratios of 50-60 (Schneider et al., 2003), and terrestrial organisms generally exhibit C:N ratios above 12 (Venturini et al., 2020; Meyers, 1994; Fabiano and Pusceddu, 1998; Lamb et al., 2006). In Ryder



380 Bay, lithogenic material constitutes a substantial fraction of total sediment trap material ($\sim 60 - 80 \%$; (Weston et al., 2013)),
with similar proportions recorded in both the upper and lower sediment traps of this study, suggesting that vertical rather
than lateral resuspension fluxes dominate lithogenic inputs (Weston et al., 2013). The high summer meltwater fluxes from
glaciers and snowbanks characteristic of this coastal setting further enhance the potential for lithogenic and terrestrial material
to enter the particle flux (Annett et al., 2015). Lithogenic or terrestrial organic material could therefore plausibly contribute
385 to the elevated C:N ratio in the trap material, either through aggregation in the water column or via benthic feeding by
zooplankton and subsequent propagation into FPs (Schneider et al., 2003). However, the bedrock geology of Adelaide Island
is predominantly volcanic and volcanoclastic (Riley et al., 2011), and therefore low in organic content, rendering a significant
lithogenic contribution to the organic fraction of sediment trap material unlikely.

The stable isotope composition of the sediment trap material provides further evidence against a dominant non-marine
390 contribution to the observed elemental signatures. In the Southern Ocean, proximity to land has been associated with higher
 $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$ values in particulate material (St John Glew et al., 2021), and the elevated $\delta^{13}\text{C}_{\text{POC}}$ values observed in
this study may in part reflect the near-shore location of the sediment trap in Ryder Bay. At the same time, terrestrial organic
matter is generally depleted in both ^{13}C and ^{15}N relative to marine organic matter (Venturini et al., 2020), with mean $\delta^{15}\text{N}$
values of approximately 0.4 ‰ and variable but often lower $\delta^{13}\text{C}$ signatures. Specific terrestrial sources that can adhere to
395 lithogenic material, such as mosses and lichens colonising ice-free substrates in areas of glacial retreat, exhibit distinct $\delta^{13}\text{C}$
signatures (e.g. -23 ‰ for mosses around King George Island and -21.1 to -18.4 ‰ for lichens in Admiralty Bay) (Boy et al.,
2016; Cipro et al., 2011), and could potentially influence local particulate $\delta^{13}\text{C}$ values. However, in coastal settings, terrestrial
influence is also associated with higher $\delta^{15}\text{N}$ values in the range of $3-10 \text{ ‰}$ (St John Glew et al., 2021), which is not consistent
with the lower $\delta^{15}\text{N}$ values observed in this study. While a terrestrial or lithogenic contribution to particulate matter in Ryder
400 Bay cannot be conclusively excluded, the combined $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$ signatures provide limited support for a dominant
non-marine control on the elevated C:N ratios.

5 Conclusions

Ryder Bay exhibits high summer POC flux that is strongly dominated by cylinder faecal pellets, indicating that carbon flux
in this coastal Antarctic system is primarily mediated by zooplankton grazing rather than by phytodetrital aggregation. The
405 pronounced contribution of cylinder faecal pellets, together with marked short-term variability in flux magnitude and compo-
sition, suggests a dynamic export regime governed by episodic changes in the activity and composition of large zooplankton
communities.

Faecal pellet-mediated export exerts a strong influence on the chemical composition of sinking particulate material. Substan-
tially elevated POC:PN ratios in Ryder Bay sediment trap material are present in cylinder faecal pellets, but not round pellets,
410 suggesting that particle type specific variability, rather than system-wide environmental conditions, is the primary control on
the elemental composition of exported organic matter. $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PN}}$ further constrain the origin of elevated POC:PN
ratios, with patterns most consistent with modification of organic matter post-production through processes such as preferential



nitrogen remineralisation and biologically mediated transformation during faecal pellet production and degradation, rather than being primarily generated during primary production.

415 These findings suggest that organic matter transported across the Marguerite Bay shelf break may carry a distinct chemical signature compared to organic matter produced off-shelf. However, the processes through which this signature is generated are both temporally variable and not well quantified. Further progress will require improved constraints on local isotopic endmembers, alongside development of complementary tracers less susceptible to modification during degradation and trophic processing, in order to constrain the contribution of shelf-derived particulate organic carbon to broader-scale carbon export.

420 *Data availability.* Observational data used in this study is available from the UK Polar Data Centre (DOI pending confirmation from PDC). Previously published datasets are cited in the text and figure captions.

Appendix A: Appendix

A1 Current speed at the sediment trap

425 The mean current velocity at the sediment trap was $0.04 \pm 0.02 \text{ m s}^{-1}$, with maximum current speed reaching 0.10 m s^{-1} . There were two periods with current elevated substantially above the mean which each lasted less than one day in duration, peaking at 0.10 m s^{-1} and 0.06 m s^{-1} (Figure A1). These peak current velocities are relatively low, and thus are unlikely to have biased particle collection during the study (Buesseler et al., 2007).

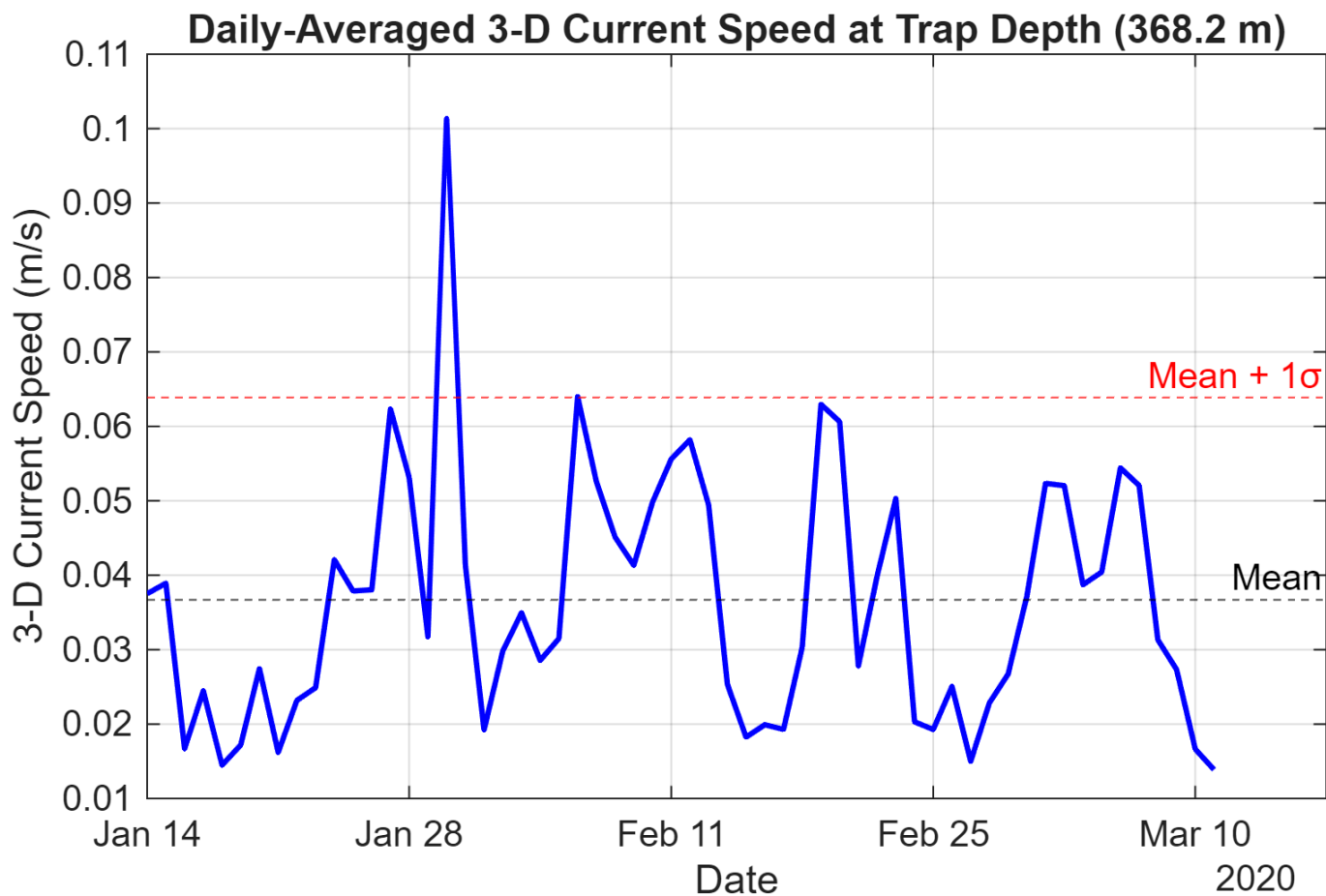


Figure A1. Daily-averaged 3-D current speed (m s^{-1}) measured at the sediment trap deployment depth over the study period. The black dashed line indicates the time-averaged mean current speed and the red dashed line indicates the mean plus one standard deviation.



A2 Sea ice cover

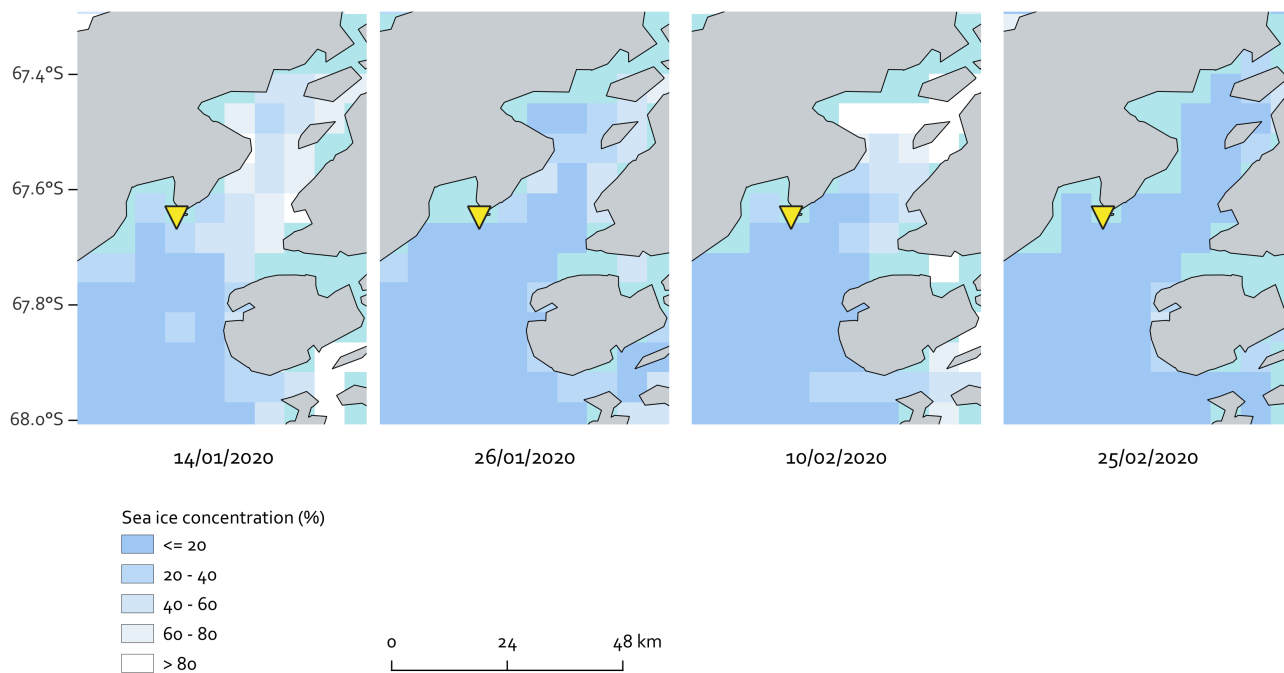


Figure A2. Sea ice concentration (%) in Ryder Bay, Antarctic Peninsula, at the start of each sampling period. Sea ice concentration was derived from AMSR2 passive microwave satellite data at 6.25 km resolution, obtained from the University of Bremen Sea Ice Remote Sensing database (<https://data.seaice.uni-bremen.de/databrowser/>). The yellow triangle denotes the mooring location.



A3 Faecal pellet size classes

Time period	No. oval	No. round	No. small cylinder (0.1 - 0.2 mm)	No. large cylinder (0.2 - 0.4 mm)
1	15500	10750	33000	90500
2	68500	20000	190000	750000
3	102500	31250	812500	306300
4	6630	8125	25380	37500

Table A1. Estimated total counts of faecal pellets by morphological shape, and size class for cylinder pellets, for each sampling period. Classes are defined as oval, round, small cylinder (0.1 - 0.2 mm), and large cylinder (0.2 - 0.4 mm).

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