Seasonal variations in the nitrogen isotopic composition of settling particles at station K2 in the western subarctic North Pacific

Yoshihisa Mino[1], Chiho Sukigara[2], Makio C. Honda[3], Hajime Kawakami[3], Kazuhiko Matsumoto[3], Masahide Wakita[3], Minoru Kitamura[3], Tetsuichi Fujiki[3], Kosei Sasaoka[3], Osamu Abe[2], Jan Kaiser[4], Toshiro Saino[3]

[1]Institute for Space-Earth Environment Research, Nagoya University, Nagoya, Japan

[2]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

[3]Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan

[4]Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich, UK

Corresponding author: Yoshihisa Mino (kuro@hyarc.nagoya-u.ac.jp)

Abstract

Intensive observations using hydrographical cruises and moored sediment trap deployments during 2010 and 2012 at station K2 in the North Pacific western subarctic gyre (WSG) revealed seasonal changes in $\delta^{15}N$ of both suspended and settling particles. Suspended particles (SUS) were collected from depths between the surface and 200 m; settling particles by drifting sediment traps (DST; 100-200 m) and moored sediment traps (MST; 200 and 500 m). All particles showed higher $\delta^{15}N$ values in winter and

lower in summer, contrary to the expected by isotopic fractionation during phytoplankton nitrate consumption. We suggest that these observed isotopic patterns are due to ammonium consumption via light-controlled nitrification, which could induce variations in δ^{15}N(SUS) of 0.4-3.1 ‰ in the euphotic zone (EZ). The δ^{15}N(SUS) signature was reflected by δ^{15}N(DST) despite modifications during biogenic transformation from suspended particles in the EZ. δ^{15}N enrichment (average: 3.6 ‰) and the increase in C:N ratio (by 1.6) in settling particles suggests year-round contributions of metabolites from herbivorous zooplankton as well as TEPs produced by diatoms. Accordingly, seasonal δ^{15}N(DST) variations of 2.4-7.0 ‰ showed a significant correlation with primary productivity (PP) at K2. By applying the observed δ^{15}N(DST) vs. PP regression to δ^{15}N(MST) of 1.9-8.0 ‰, we constructed the first annual time-series of PP changes in the WSG. This new approach to estimate productivity can be a powerful tool for further understanding of biological pump in the WSG, even though its validity to be examined carefully.

Keywords nitrogen isotopes; suspended and settling particles; nitrogen recycling; nitrification; primary productivity, western subarctic North Pacific

1. Introduction

The nitrogen isotopic composition of marine organic and inorganic nitrogen species changes depending on their biogeochemical transformations and associated isotopic fractionations (Wada and Hattori 1991). In the euphotic zone (EZ), in particular, the

isotope delta of particulate nitrogen, δ^{15}N(PN), is governed by both the δ^{15}N of substrates and isotopic fractionation during PN formation (i.e. the incomplete utilization of dissolved inorganic nitrogen by phytoplankton). Thus, δ^{15}N(PN) is thought to record nitrate availability and utilization in the EZ in the case that preformed nitrate supplied to the upper ocean is the main nitrogen source for PN formation. Negative correlations have been found between δ^{15}N(PN) and the concentration of nitrate (NO_3^-) in the upper mixed layer of several eutrophic regions (Saino and Hattori 1985; Rau et al. 1991; Wu et al. 1997; Altabet et al. 1999; Thunell et al. 2004). Thus, the δ^{15}N of settling particles incorporated into sediments has often been used to reconstruct paleo-nutrient conditions and biological productivity (Calvert et al. 1992; Francois et al. 1992, 1993; Altabet and Francois 1994b; Farrell et al. 1995; Francois et al. 1997; Teranes and Bernasconi 2000; Brunelle et al. 2010).

There are, however, other nitrogen sources for PN formation by phytoplankton, such as ammonium (NH_4^+) and molecular nitrogen (N_2), which have δ^{15}N values that are distinct from preformed NO_3^- (5-7 ‰) supplied from below the euphotic zone (EZ) (Wada and Hattori, 1991). N_2 incorporated by marine nitrogen fixers adds nitrogen with a lower δ^{15}N (-2 to 0 ‰) to the PN pool (Minagawa and Wada, 1984). There are diverging views on the δ^{15}N of the NH_4^+ pool in the upper ocean, which is affected by a variety of processes, including zooplankton excretion, bacterial ammonification, assimilation by phytoplankton and heterotrophic bacteria, pH, air-sea gas exchange as well as bacterial and archaeal nitrification. Checkley and Miller (1989) reported that NH_4^+ excreted by zooplankton has relatively low δ^{15}N, and as a nitrogen source this

NH_4^+ tend to lower the $\delta^{15}N$ of the suspended PN pool (Altabet 1988; Mino et al. 2002). On the other hand, studies by Yoshikawa et al. (2005) and Wankel et al. (2007) suggested that relatively high $\delta^{15}N(NH_4^+)$ values due to preferential ^{14}N consumption by nitrifiers could increase $\delta^{15}N(PN)$ via subsequent assimilation by phytoplankton. The $\delta^{15}N$ of organic nitrogen in the EZ can also be altered during heterotrophic transformations of particles such as metabolism, degradation, and trophic transfer in the water column (Saino and Hattori 1980; Minagawa and Wada 1984; Fry, 1988; Aita et al. 2011). Thus, careful consideration is required to unravel the effects of different processes on $\delta^{15}N(PN)$, such as PN formation in the EZ and its transport to the deep ocean, which controls the efficiency of biological pump.

The western subarctic gyre (WSG) of the North Pacific is regarded as an atmospheric CO_2 sink and a more efficient exporter of particulate organic carbon (POC) than other oceanic regions (e.g., Honda et al. 2002; Buesseler et al. 2007; Honda and Watanabe 2010; Kawakami et al. 2014). This is especially true in the early summer when diatoms are dominant (Fujiki et al. 2014; Kawakami et al. 2015), organic carbon produced in the EZ is exported quickly to the ocean interior (Honda et al. 2006). Relative high values of export ratio (*e*-ratio), 46 to 55%, have been found in summer in the WSG (Kawakami and Honda 2007). Summer productivity in the WSG including station K2 exhibited the highest peaks among seasons, but phytoplankton growth was limited by both light and iron availabilities in the stratified waters (Tsuda et al. 2003; Matsumoto et al. 2014; Fujiki et al. 2014). Especially productivity was often attenuated by reductions of light availability due to dense sea fog in this season. Meanwhile, knowledge is still scarce on

how the subsequent particle dynamics respond to seasonal variations of productivity with such large fluctuations in summer, which is required for predicting future CO_2 sequestration in the WSG.

The "K2S1 project" was conducted between 2010 and 2013 to obtain a comprehensive understanding on the seasonal and intra-seasonal variability of ecosystem dynamics and biogeochemical cycles in the western North Pacific (Honda et al. this volume). The project involved repeated hydrographical cruises combined with mooring system deployments and satellite data analysis. As part of our studies, we examined $\delta^{15}N$ time-series of settling particles collected by a moored sediment trap (MST) at depths of 200 and 500 m at station K2 (47º N, 160º E) in the WSG during 2010 to 2012. In addition, seasonal variations of $\delta^{15}N$ for both suspended and settling particles in the upper ocean (0-200 m) were examined during five cruises that were undertaken contemporaneously with the trap deployments and recoveries. These data sets allowed us to investigate: 1) the temporal variations of $\delta^{15}N$(PN) due to nitrogen recycling and PN formation and 2) the transformation of particles settling in the water column, essential to understand ocean particle dynamics in the WSG. Factors controlling the seasonal variations of primary productivity is also discussed based on this data.

2. Materials and Methods

2.1 Collection of settling particles by a moored sediment trap (MST)

Moored sediment trap (MST) time-series experiments were conducted three times

during February 2010 to June 2012, in which conical traps were deployed at ca. 200 and 500 m, to examine fluxes, chemical composition as well as $\delta^{15}N$ of settling particles. Before deployment, collecting cups were filled with seawater containing 10 % buffered formalin as a preservative. The sampling interval was set to between 6 and 16 days, depending on the planned deployment period of the traps. Following trap recovery, samples were stored in a refrigerator on board until pretreatment (water sieving, swimmer elimination, splitting, filtration, drying, and pulverization) on shore. The dry weight of trapped particles less than 1 mm was measured to estimate total mass fluxes (TMF). Concentrations of organic carbon and nitrogen were measured with a CHN/O elemental analyzer. Those of Al, Si, and Ca were measured with an inductively coupled plasma atomic emission spectrometer. These data were used to estimate the concentrations of organic material, biogenic opal, $CaCO_3$ and lithogenic materials. Full details of sample preparation and chemical analysis have been described elsewhere (e.g. Honda et al. 2002, 2013). The fluxes of each component were calculated from both TMF and their concentrations in the trapped particles. Subsamples were used to measure the $\delta^{15}N$ of MST particles (section 2.4).

2.2 Collection of suspended particles (SUS) and water samples for $\delta^{15}N$ of nitrate

Samples for $\delta^{15}N$ of suspended particles were collected during five cruises (MR10-06, late October 2010; MR11-02, February to March 2011; MR11-03, April 2011; MR11-05, July 2011; and MR12-02, June 2012) on board R/V *Mirai* (JAMSTEC). 20 to 80 liters of seawater were collected by CTD/Carousel Water Sampling system with Niskin

bottles and a bucket at depths from the surface to 200 m (500 m during MR12-02), and filtered through pre-combusted GF/F filters (Whatman). The filters were kept frozen until analysis on shore. In addition to particle collections, water samples for $\delta^{15}N$ of NO_3^- were also taken during cruise MR10-06. Samples were collected into 50 mL polypropylene bottles at depths between 5 and 1000 m, and then kept frozen until analysis.

2.3 Collection of settling particles by a drifting sediment trap (DST)

During the cruises mentioned above, we conducted short-term, 3 to 4 day-drifting sediment trap (DST) experiments. Cylindrical traps were filled with high-salinity filtrated seawater (S = 39, adjusted by addition of NaCl) and deployed on drifter moorings at approximate depths of 60, 100, 150, and 200 m during all cruises, and at 500 m during MR12-02. More details of these deployments have been described elsewhere (Honda et al. 2015). Particles settled to the bottom of the traps were collected on pre-combusted GF/F filters, and then frozen immediately after swimmers on the filters were removed with tweezers. Concentrations of major components in the DST particles were measured using the methods used for MST particles, as well as $\delta^{15}N$ (section 2.4).

2.4 Isotopic analysis

In the laboratory on shore, finely powdered MST samples and DST and suspended particles collected on to pre-combusted filters were exposed overnight to HCl fumes to

remove carbonates, dried in vacuum, and then pelletized with a tin disk. Mass fractions of particulate organic carbon and nitrogen (POC, PN) and δ^{15}N(PN) in the pellets were measured with an elemental analyzer combined with a continuous flow isotope-ratio mass spectrometer (EA1112-Delta Plus, Thermo Fisher Scientific). The precision for PN and POC mass fractions analysis were better than 3 % and 5 %, respectively. δ^{15}N(PN) values of samples were calibrated against IAEA-N-1. The precision was better than 0.2 ‰, estimated from repeated measurements of laboratory standards (Amino Standard, SI science) along with the samples. δ^{15}N of NO_3^- was determined using the denitrifier method following Casciotti et al. (2002) and Kaiser et al. (2007), calibrated against IAEA-NO-3. The repeatability was 0.08 ‰, which was derived from the average standard deviation of duplicate analyses. Noted that nitrite was not removed from samples prior to isotopic analysis. Therefore, our results indicate δ^{15}N of (nitrate + nitrite) although nitrite concentration was quite smaller than nitrate (see the section 3.2).

2.5 Other measurements

Water samples for nutrient and chlorophyll *a* concentrations (Chl *a*) analyses were collected by Niskin bottles during each cruis. Concentrations of NO_3^-, nitrite (NO_2^-) and NH_4^+ were measured on board with a continuous flow analyzer (QuAAtro 2-HR system, BL-Tech). Chl *a* was measured in the particles collected on GF/F filters. Chl *a* on the filters was extracted in N,N-dimethylformamide in the dark at -20 °C for 24 h and then measured in a Turner fluorometer (model 10-AU, Turner Designs), calibrated against a pure chlorophyll *a* (Sigma-Aldrich Co.).

Daily photosynthetic photon flux density (PPFD) and sea surface temperature (SST) were estimated during the trap deployments from 2010 to 2012 by averaging data acquired by the MODIS satellite over an 11 × 11 pixel square (approximately 100 km × 100 km) centered at station K2. Both estimates were averaged for the sampling interval for MST particles to be analyzed with time-series variations of δ^{15}N(MST).

Results

3.1 Characteristics of particles collected by the moored sediment trap (MST)

This study revealed temporal variations over 2.5 years in particulate organic carbon (POC) flux and the nitrogen isotope delta (δ^{15}N(MST)) of the settling particles collected by sediment traps moored at 200 and 500 m (Fig. 1). For unknown reasons, more than 70 % of trapping cups at 200 m did not collect any particles. We therefore discuss mainly the characteristics of the settling particles at 500 m.

POC flux averaged over the 2.5-year long deployment was 8.1±8.5 mg m^{-2} d^{-1} (in carbon (C) equivalents) at 500 m. High POC fluxes (>15 mg m^{-2} d^{-1}) were found during May and July to August 2010, July and September to October 2011, and April 2012 (Fig. 1). During these periods, markedly higher fluxes of >30 mg m^{-2} d^{-1} occurred during May 2010 and September to October 2011. Meanwhile, lower values (<5 mg m^{-2} d^{-1}) were found during winter to early spring.

δ^{15}N(MST) at 500 m ranged from 1.9 to 8.0 ‰, with winter maxima and summer minima (Fig. 1). Despite the limited amount of data, a similar seasonal trend was found for δ^{15}N(MST) at 200 m (4.0 to 8.3 ‰), but with slightly enriched by average

1.1±1.1 ‰ (n = 14). δ^{15}N(MST) at 500 m was correlated weakly with POC flux (r = -0.50, p <0.001, Table 1, Fig. 2a). More significant correlations were also found with the organic carbon-to-nitrogen mole ratio (n(C):n(N) ratio, R(C:N); r = -0.67, p <0.001, Table 1 and Fig. 2b). δ^{15}N(MST) was only weakly correlated with the biogenic opal mass fractions, w(opal), and the opal to calcium carbonate mole ratio, R(opal:$CaCO_3$) = n(opal):n($CaCO_3$), of MST particles (r = -0.32 and -0.44, respectively; Table 1). Moreover, significant negative correlations were found with satellite based-daily PPFD as well as SST (r = -0.65 and -0.38, respectively; Table 1). The flux-weighted average δ^{15}N(MST) for the experimental period was 4.1 ‰ at 500 m. This is slightly lower than the δ^{15}N value of NO_3^- (5 to 6 ‰) reported previously for intermediate and deep waters of the Pacific (e.g. Tanaka and Saino, 2002; Sigman et al. 2009).

3.2 Seasonal variation of nitrogen compounds in the water and particles at the upper layer

Five repeat observations between 2010 and 2012 revealed seasonal changes in water density, Chl *a* and nutrients concentrations, δ^{15}N and C:N mole ratio of particles in the upper layer (0-200 m) at K2 (Fig. 3). Mixed layer depth (MLD), determined based on a potential density difference of 0.125 kg m^{-3} from the near-surface (10 m) value (Suga et al. 2004), reached >100 m on February and April 2011 and shoaled to 27 and 39 m on July 2011 and June 2012, respectively (Fig. 3f, k, p, u). The depth of the euphotic zone (EZ), defined as the 0.1 % of surface PPFD level, was around 50 m (39 to 64 m). Depth-average Chl *a* concentrations in the EZ varied from 0.4 mg m^{-3} during

winter/spring to 1.2 mg m^{-3} in early summer (Fig. 3c, h, m, r, w).

The maximum NO_3^- concentration (25.5 μM) in the EZ was found in April 2011, associated with the deepest mixed layer (Fig. 3k). During mixed layer shoaling in summer, NO_3^- concentrations decreased as a result of phytoplankton consumption and attained a minimum value of 11.4 μM in late October 2010 (Fig. 3a). As compared to NO_3^-, concentrations of regenerated nutrients, NH_4^+ and nitrite (NO_2^-), showed different seasonal concentration variations. They were found mostly in the upper 100 m for the entire period, and their concentrations were inversely correlatd to MLD (Fig. 3b, g, l, q, v). In early summer (July 2011, June 2012), distinct NH_4^+ concentration peaks of 1.10 μM were found at the base of the EZ; maximum NO_2^- concentrations of 0.71 μM were found deeper (Fig. 3q, v). It is notable that, during the MR12-02 cruise (June 2012, Fig. 3v), average NH_4^+ concentrations in the EZ increased from 0.35 to 0.65 μM, during a three day-interval between casts. $\delta^{15}N$ of nitrate, $\delta^{15}N(NO_3^-)$ observed in October 2010 during MR10-06 cruise was relatively constant around 5.5 ‰ below the depth of 200 m and increased up to 9 ‰ with decreasing water depth, concomitantly with as nitrate concentrations (Fig.4a), which is attributed to phytoplankton assimilation (e.g. Sigman et al. 1997; Tanaka and Saino 2002). Noted that the $\delta^{15}N(NO_3^-)$ reported here might be underestimated since the nitrite (NO_2^-) with lower $\delta^{15}N$ in samples was not removed (Casciotti and McIlvin, 2007). However, the corrected $\delta^{15}N(NO_3^-)$ for a nitrite influence were only 0.3 ‰ higher than the measured values in the upper 25 m, based on that concentrations of NO_3^- and NO_2^- are 11.4 and 0.3 μM, respectively, and assuming the $\delta^{15}N$ difference of 14.4 ‰ between nitrate and nitrite (as found in the oxygen minimum

zone in the eastern tropical north Pacific, Buchwald and Casciotti 2013).

Concentrations of suspended POC (Fig. 3c, h, m, r, w) were higher in the upper layer and decreased with depth to a nearly constant value (1.1±0.2) μM below 150 m. EZ-averaged concentrations ranged from 2.6 μM in winter to 9.0 μM in summer (Jun 2012), which followed the seasonal variation of chlorophyll *a* concentration. The δ^{15}N of suspended particulate nitrogen, δ^{15}N(SUS), exhibited lower values (-0.3 to 3.5 ‰) within the EZ while higher values (3.6 to 10.4 ‰) were found below the EZ (Fig. 3d, i, n, s, x). The PN-weighted average δ^{15}N(SUS) integrated over the EZ exhibited the highest values of 3.1 ‰ in February and the lowest value of 0.4 ‰ in July 2011 (Table 2). The C:N mole ratio of suspended particles, R_{SUS}(C:N), showed a near constant value of around 6 within the EZ during all seasons and increased to between 7 and 10 at greater depths (Fig. 3e, j, o, t, y, Table 2).

Results from DST experiments showed the highest POC flux (75-90 mg m^{-2} d^{-1}) during the productive summer season and lower fluxes (22-27 mg m^{-2} d^{-1}) in winter/spring (Honda et al. 2015). The δ^{15}N value of settling particles collected by DST, δ^{15}N(DST), ranged from 2.1 to 7.4 ‰, and showed distinct seasonal variations (Fig. 1) with little vertical fluctuation from 100 to 200 m (Fig. 3d, i, n, s, x). Depth averaged δ^{15}N(DST) showed the highest values of 7.0 ‰ in February and April 2011 and the lowest value of 2.4 ‰ in June 2012 (Table 2). The C:N mole ratio of DST particles, R_{DST}(C:N), was generally >7.0 (Fig. 3e, j, o, t, y), and the average R_{DST}(C:N) from 100 to 200 m showed the highest value of 9.1 in April 2011 and the lowest of 7.2 in February 2011 (Table 2).

Scatter plots of δ^{15}N against R(C:N) (Fig. 5) indicate obvious differences for the suspended particles in the EZ and the underlying water (100-200 m): the latter had higher values both for δ^{15}N and R(C:N). In addition, a negative correlation (r = -0.76, p = 0.01, n = 11) between them was found for DST particles, except for the MR11-03 cruise (April 2011). This negative correlation was also observed for MST particles at 500 m depth (Fig. 2) implying that similar particles were collected by both DST and MST.

DISCUSSION

4.1 Seasonal variation in δ^{15}N of suspended particles and its relation to nitrogen cycle in the mixed layer

The EZ-averaged concentrations of suspended POC at station K2 varied closely with those of Chl *a* resulting in average POC:Chl *a* ratio (*w*/*w*) of 88±13 (n = 6). The typical C:Chl *a* ratio for *in situ* living phytoplankton in the northwestern North Pacific, estimated from both Chl *a* and POC production has been reported as 67 by Obayashi and Tanoue (2002). This suggests that on average 77 % (63 to 92 %) of the POC pool in the EZ is made up of organic matter freshly contributed by autotrophic particles. This observation is also supported by the R_{SUS}(C:N) of around 6 observed in each season (Table 2, Fig. 5), close to the Redfield value of 6.6, implying a negligible contribution of highly degraded organic matters. On the basis of these observations, we can discuss the observed variations of δ^{15}N(SUS) in the EZ with the assumption that it predominantly reflects δ^{15}N of phytoplankton, which in turn is influenced by changes in

nitrogenous substrates and their availability for phytoplankton growth.

Previous studies have reported an inverse relationship between δ^{15}N(PN) and nitrate concentrations in the upper layer in various oceanographic regions (Saino and Hattori, 1985; Rau et al., 1991; Altabet and Francois, 1994a), except for oligotrophic regions where N_2 fixation occurs (e.g. Dore et al. 2002). This δ^{15}N behavior has been explained to result mainly from an increase of δ^{15}N of nitrate caused by preferential $^{14}NO_3^-$ uptake during photosynthesis (Miyake and Wada, 1967). However, such a relation was not found in this study (Fig. 7a). The average δ^{15}N(SUS) value within the EZ (0-50 m) varied seasonally by ca. 3 ‰ (Fig. 6c, Table 2): highest (3.1 ‰) and lowest (0.4 ‰) δ^{15}N values corresponded to higher (1.1 moles m^{-2}) and lower (0.9 moles m^{-2}) nitrate inventories (depth-integrated (0-50 m) nitrate concentration) in winter and in summer, respectively (Fig. 6a).

The vertical profile of δ^{15}N of nitrate observed in October 2010 showed an increase of $\delta^{15}N(NO_3^-)$ with decreasing nitrate concentration, $c(NO_3^-)$ (Fig. 4a). Such an increase of $\delta^{15}N(NO_3^-)$ was attributed to seasonal nitrate consumption by phytoplankton with ^{15}N fractionation, implying that $\delta^{15}N(NO_3^-)$ would be higher and lower during summer/autumn and winter/spring, respectively, in contrast to δ^{15}N(SUS). Applying a Rayleigh fractionation framework, the isotopic fractionation during nitrate removal, $^{15}\varepsilon(NO_3^-)$, can be derived by linear regression of the equation $\delta^{15}N(NO_3^-) = \delta^{15}N(NO_3^-, \text{initial}) + {}^{15}\varepsilon \ln[c(NO_3^-)/c(NO_3^-, \text{initial})]$, where $\delta^{15}N(NO_3^-, \text{initial})$ and $c(NO_3^-,\text{initial})$ correspond to the δ^{15}N and concentration of the initial nitrate pool (we set it as the nitrate found at 100 m), and $\delta^{15}N(NO_3^-)$ and $c(NO_3^-)$ correspond to the profile values.

The derived isotopic fractionation is $^{15}\varepsilon(NO_3^-)$ = –(3.4±0.1) ‰ (Fig. 4b). Then, using both $\delta^{15}N(NO_3^-)$ and the $\delta^{15}N$ of PN synthesized using it, i.e. ($\delta^{15}N$(new PN) = $\delta^{15}N(NO_3^-)$ + $^{15}\varepsilon(NO_3^-)$), in the EZ during each cruise were computed (see caption to Fig. 6). The results indicated lower $\delta^{15}N$ (6.2 to 6.7 ‰ for $\delta^{15}N(NO_3^-)$; 2.8 to 3.3 ‰ for $\delta^{15}N$(new PN)) result in winter/spring and maxima (9.2 for $\delta^{15}N(NO_3^-)$; 5.8 ‰ for $\delta^{15}N$(new PN)) occur in autumn (Fig. 6a). The $\delta^{15}N$(new PN) computed showed higher values than $\delta^{15}N$(SUS) during any cruise and its variation contradicted the observed variation of $\delta^{15}N$(SUS) (Fig. 6a, c). In all likelihood, this suggested that algal uptake of regenerated nutrients such as NH_4^+, which would add PN with lower $\delta^{15}N$ to the suspended PN pool throughout the year. Alternatively N_2 fixation by diazotrophs can provide for a low $\delta^{15}N$ signal, but the contribution of diazotrophs is most unlikely in the WSG, where seasonal drawdowns of nitrate and phosphate occur with their ratios near the Redfield stoichiometry (ca. 16) and N_2 fixation rate in the surface waters is very low (Shiozaki et al. 2010; Yasunaka et al. 2014).

Shipboard incubation experiments using ^{15}N tracer techniques to access DIN uptake by phytoplankton were conducted during four cruises during 2010 to 2011, which provided an opportunity to deduce seasonal variations of $\delta^{15}N$ of PN formed using NH_4^+ ($\delta^{15}N$(reg. PN)). The results showed that the *f*-ratio (*f*, the fraction of primary production fuelled by NO_3^-) depended on ambient NH_4^+ concentrations ($c(NH_4^+)$) and ranged from 0.4 to 0.8 for $c(NH_4^+)$ <0.4 μM, and from 0.1 to 0.4 for $c(NH_4^+)$ ≥0.4 μM in the surface waters (Matsumoto et al. unpublished data). Here, we compute $\delta^{15}N$(reg. PN) assuming a typical *f*-ratio of 0.6 and 0.3 during winter and summer, respectively, based on the

averaged $c(NH_4^+)$ in the upper 50 m (ca. 0.1 and 0.5μM). These *f*-ratio are consistent with the results of simulation experiments at K2 (0.6-0.8 and 0.3-0.5, respectively in Sasai et al. 2016). And δ^{15}N(new PN) value of 3.3 and 3.9 ‰, as well as δ^{15}N(SUS) value of 3.1 and 0.4 ‰, respectively (during MR 11-02 and MR11-05 in Fig. 6a,c), and a simple mass balance equation: $\delta^{15}N(SUS) = f\ \delta^{15}N(\text{new PN}) + (1\text{-}f)\ \delta^{15}N(\text{reg. PN})$ were assumed. This computation gives a higher value of δ^{15}N(reg. PN) of 2.8 ‰ in winter and a lower value of -1.1 ‰ in summer, making ca. 4 ‰ difference. This indicates significant seasonal variation of δ^{15}N(reg. PN) as well as its contribution (1-*f*) in controlling δ^{15}N of bulk PN produced in the EZ (i.e. phytoplankton PN).

Unfortunately, no data exist for this study for δ^{15}N of NH_4^+ that would affect δ^{15}N(reg. PN). As described above, however, concentrations of regenerated nutrients (NH_4^+ and NO_2^-) showed unique, distinct seasonal changes (Fig. 3b, g, l, q, v). Within the EZ (0-50 m) the NH_4^+ inventory in stratified periods (summer) was about five times higher than in mixing periods (winter/spring) (Fig. 6b). Similarly, the $c(NH_4^+)$:$c(NO_2^-)$ ratio was about four times higher in summer. Such seasonal changes can hint at the behaviors of recycled nitrogen and their δ^{15}N characteristics (as illustrated in Fig. 8). In general, recycled nitrogen (NH_4^+) in the EZ mainly comes from both bacterial ammonification (Hollibaugh and Azam 1983, Stepanauskas et al. 1999) and zooplankton excretion (Jawed 1973; Hernandez-Leon et al. 2008) (the process iv in Fig. 8). We observed a 1.6-times increase of the NH_4^+ inventory (by 12.3 mmol m^{-2}) within three days during MR12-02 (Fig. 3v and 6b), indicating active production of NH_4^+ occurred within the EZ in summer as reported by Elskens et al. (2008). Interestingly, we also found a

concurrent decrease in the Chl *a* inventory by 24.3 mg m^{-2} (Fig. 3w), which assuming an algal C:Chl *a* ratio (*w*/*w*) of 67 and the Redfield C:N mole ratio of 6.6 corresponds to 20.6 mmol m^{-2} (N equivalents). Even though this loss of Chl *a* was rather large relative to the observed increase in the NH_4^+ inventory, these concurrent short-term changes imply that NH_4^+ can be regenerated quickly via decomposition of phytoplankton cells. In addition, given the dependency of the heterotrophic prokaryotic production on both temperature and DOC availability at station K2 reported by Uchimiya et al. (2015), NH_4^+ production via DON degradation would be enhanced in summer with high primary productivity. The $\delta^{15}N$ of NH_4^+ regenerated in the upper oxic water is inferred to be relative low (<-1 ‰) as a consequence of the kinetic isotope effect during remineralization of organic nitrogen (-1 to -8 ‰, Macko and Estep 1984; Bada et al. 1989; Checkley and Miller 1989; Silfer et al. 1992; Möbius 2013; Knapp et al. 2012). Additionally such ^{15}N depleted NH_4^+ is reassimilated by phytoplankton with even larger isotope fractionation (-6.5 to -27 ‰, Montoya et al. 1991; Pennock et al. 1996; Waser et al. 1998 etc.), which has been proposed as the mechanism for lowering the $\delta^{15}N$ value of "bulk" suspended particles (Altabet et al. 1988; Mino et al. 2002; Knapp et al. 2011; Treibergs et al. 2014).

On the other hand, NH_4^+ produced in the upper layer was consumed not only by phytoplankton (v in Fig. 8) and heterotrophic bacteria (Kirchman 1994), but also by ammonium-oxidizing bacteria and archaea (Ward and Carlucci 1985; Könneke et al. 2005) (vi in Fig. 8). In general, nitrification rate is low in the surface layer and increases to maximum at the base of, or just below the EZ, which contributes the primary nitrite

maximum (Ward et al. 1982; Dore and Karl 1996; Ward 2005; Beman et al. 2012; Santoro et al. 2013). Such a decline in nitrification in the EZ has been attributed to the light inhibition (Olson, 1981 etc.) and the competition for NH_4^+ with phytoplankton (Smith et al. 2014: Fripiat et al. 2014). Consequently, photosynthesis is the process responsible for consuming NH_4^+ in the sunlit layer while nitrification takes over in the dimly-lit or aphotic layer where phytoplankton growth is light-limited, as seen in Fig. 8. Also nitrification (i.e. NH_4^+ oxidation to NO_2^-) can decrease the $c(NH_4^+)$:$c(NO_2^-)$ ratio effectively. Thus, higher NH_4^+ inventories (20 to 30 mmol m^{-2}) and the high $c(NH_4^+)$:$c(NO_2^-)$ ratio (>2.3) found in summer (Fig. 6b) most likely result from suppressed nitrification within the bright, upper stratified water, as well as enhanced NH_4^+ production by heterotrophs activities (Fig. 8b). In winter/spring, meanwhile, the competition with phytoplankton for NH_4^+ is reduced (thereby NH_4^+ consumption by nitrifiers was enhanced) by deep mixing across the base of the EZ (Fig. 8a), which would reduce both NH_4^+ inventory and the $c(NH_4^+)$:$c(NO_2^-)$ ratio to the values of 4.4 to 7.9 mmol m^{-2} and 0.6 to 0.8, respectively) as seen in Fig. 6b.

During nitrification, NH_4^+ is subjected to isotopic fractionation of -38 ‰ (Casciotti et al. 2003), which can be larger than that associated with NH_4^+ uptake by phytoplankton (-27 ‰, Waser et al. 1998). Therefore, preferential $^{14}NH_4^+$ oxidation by nitrifiers in the deeply mixed water would cause higher $\delta^{15}N$ of the NH_4^+ pool in winter/spring than that in summer when nitrification was suppressed (Fig. 8). Similar change in $\delta^{15}N$ of NH_4^+ pool in the upper layer of station K2 was simulated in the ecosystem model including nitrogen isotopes (Yoshikawa et al. 2015). Furthermore, this speculation is consistent

with our computed variation of δ^{15}N(reg. PN) with higher (2.8 ‰) and lower (-1.1 ‰) values in winter and summer, respectively. That is, such enriched ^{15}N signal of NH_4^+ via nitrification was imprinted on phytoplankton PN by subsequent photosynthetic uptake (i.e. regenerated production), which would result in the observed higher δ^{15}N(SUS) values in winter/spring relative to summer. Moreover, enhanced heterotrophic breakdown of DON can provide more NH_4^+, that is possibly depleted in ^{15}N due to isotope fractionation (Knapp et al. 2012), which partly contribute to the lower δ^{15}N(SUS) in summer. These hypotheses are partly supported by the apparent trend of the higher δ^{15}N(SUS) with the lower $c(NH_4^+)$:$c(NO_2^-)$ ratio in the EZ and vice versa (Fig. 7b), given that this ratio indicates the relative importance of NH_4^+ oxidation in the N cycle in the upper mixed layer (more contribution by nitrification with lower $c(NH_4^+)$:$c(NO_2^-)$ ratio).

As another factor altering δ^{15}N(SUS), seasonal change of phytoplankton community structure should be considered given a taxonomic δ^{15}N differences. Fawcett et al. (2011) reported that eukaryotes had higher δ^{15}N than prokaryotes at the Sargasso Sea. Karsh et al. (2003) found higher δ^{15}N values for large-size particles than small-size ones in the Southern Ocean, and attributed it to less isotope fractionation during nitrate uptake by large diatoms. However, at station K2, cyanobacteria was a minor component throughout the year (accounted for <8 % of total Chl *a*) and large diatoms dominated in the summer bloom period (Fujiki et al. 2014) even when lower δ^{15}N(SUS) was found. Therefore, we did not confirm a significant effect of taxonomic δ^{15}N differences on δ^{15}N(SUS) in our limited data.

All in all, we speculated that seasonal variations of NH_4^+ consumption via nitrification, which are controlled by light condition within the upper mixed layer, would mainly determine δ^{15}N(reg. PN) and thereby derive the observed variation of δ^{15}N(SUS) values with higher in winter and lower in summer.

4.2 Formation of sinking particles and their behavior

δ^{15}N of DST particles, δ^{15}N(DST), exhibited little vertical fluctuation (from 100 to 200 m) while δ^{15}N(SUS) increased with depth in all season (Fig. 3d, i, n, s, x). This was also true for C:N ratios of DST particles (R_{DST}(C:N)) (Fig. 3e, j, t, y) except for data with a vertical increase found in MR11-03 cruise (Fig. 3o). In this section, we evaluate seasonal variations of $\delta^{15}N_{DST}$ and R_{DST}(C:N) by comparing them with those of suspended particles within the EZ (~50 m) and in the underlying layer (100-200 m) in order to discuss the formation processes of DST particles as well as the behavior of particles during their settling.

δ^{15}N(DST) and R_{DST}(C:N) were always higher than those of suspended particles in the EZ (mainly contributed by autotrophic particles, i.e. phytoplankton: Fig. 6c, d, Table 2), which implies biological alternation of DST particles during their formation from the photosynthesized organic matters. Such ^{15}N-enrichment in settling particles has been seen in various oceanic areas (Altabet et al. 1988; Wu et al. 1999; Pantoja et al. 2002; Casciotti et al. 2008), which is generally explained by the isotope fractionation associated with the trophic transfer (3 to 4 ‰ per trophic level), leading to higher δ^{15}N of heterotrophs than their dietary nitrogen source (DeNiro and Epstein 1981; Minagawa

and Wada 1984; Fry 1988; Aita et al. 2011). As with the body tissue of zooplankton, their fecal material also has a higher δ^{15}N value than the food ingested (Checkley and Entzeroth 1985; Altabet and Small 1990). Observed δ^{15}N difference between the settling particles and phytoplankton (Δ^{15}N(DST-SUS) = (δ^{15}N(DST) - δ^{15}N(SUS)) in this study were 1.4-2.6 ‰ and 3.8-5.4 ‰ in summer and winter/spring, respectively (Table 2). The annual average Δ^{15}N(DST-SUS) of 3.6±1.3 ‰ suggested that DST particles were formed apparently from herbivores if they were produced as a by-product of zooplankton feeding. Zooplankton communities in the western subarctic North Pacific including the station K2 were dominated by herbivorous zooplankton (Taniguchi 1973) such as copepods *Neocalanus* spp. (Mackas and Tsuda 1999; Kobari et al. 2003; Kobari et al. 2013; Kitamura et al. 2016). In fact, major copepods, such as *Neocalanus cristatus*, *Neocalanus plumchrus*, *Metridia pacifica,* had δ^{15}N values of ca. 5-7 ‰ in MR10-06, MR11-02 and MR11-03 cruises (Kitamura et al., in prep.), which were consistent with δ^{15}N(DST) values obtained in same cruises (Fig. 6c, Table 2). Noted that relative large swimmers (>1 mm), including these calanoids were eliminated by sieving prior to isotopic analyses. Alternatively, their δ^{15}N values were recorded in δ^{15}N(DST) through their metabolites such as fecal pellets trapped in the collection cups (Wilson et al. 2008; Kobari et al. 2016). Actually, Kobari et al. (2016) reported that the fecal pellets in the DST samples, mostly categorized into cylindrical shape from calanoids, accounted for 8-21 % of sinking POC flux at 150 m. Smaller mobile protozoan could be included in DST samples by evading our picking with the naked eye, but it is likely that such contributions were quite small given only modest biomass of protozooplankton relative

to metazooplankton in the western subarctic North Pacific (e.g. Yamaguchi et al. 2002). Meanwhile, Honda et al. (2015) found increased opal concentrations in DST particles during summer, which indicated that more diatoms contributed to settling particles relative to the other seasons. This is consistent with the observed decrease of Δ^{15}N(DST-SUS) (i.e. a decline of apparent trophic level of DST particles) during July 2011 and June 2012 (in MR11-05 and MR12-02) (Table 2). Consequently, we infer that, at least with respect to the nitrogen component, the DST particles would originate generally from metabolites of herbivorous mesozooplankton, however contribution of diatoms would increase in summer.

As noted above, R_{DST}(C:N) in MR11-03 cruise showed a vertical increase with higher values of >9 at deeper depth (Fig. 3o). These DST particles collected at 150 and 200 m contained markedly large amounts of lithogenic materials (LM), ca. 13-15 % in concentration, relative to others with averages of 3±2 % (Honda et al. 2015), indicating a significant input of episodic Asian aerosols including dust as well as black carbon etc (Uematsu et al. 1983). Therefore, from here on, we use the R_{DST}(C:N) value of 7.3 at 100 m during MR11-03 as the representative for this term. Average R_{DST}(C:N) from 100 to 200 m showed the lowest value of 7.2 in winter and higher values of 8.1-8.8 in summer whereas C:N of the suspended particles, R_{SUS}(C:N), in the EZ was around 6.0 for all seasons (Fig. 6d, Table 2). Thus, the difference between R_{DST}(C:N) and R_{SUS}(C:N) is larger in summer (Table 2). The C:N mole ratios of zooplankton collected by plankton nets (0.33-mm mesh) during each cruise ranged from 5 to 8 and higher values were observed in summer (Kitamura et al. 2016), which is consistent with

R_{DST}(C:N) in summer. On the other hand, zooplankton C:N mole ratios were <5.5 in fall and winter, which alone cannot explain R_{DST}(C:N) of 7.2-7.5 in the same seasons. As an additional source, contributions of transparent exopolymer particles (TEPs) formed from dissolved polymers released by phytoplankton (Alldredge et al, 1993) could raise R_{DST}(C:N). Oceanic TEPs have been known to enhance particle aggregations and their consequent settlement in various environments (Passow et al. 2001; Engel et al. 2004 etc.), which have relatively high C:N mole ratios (>20, Engel and Passow 2001; Mari et al. 2001). Therefore, it is reasonable to assume that contributions of TEPs to the DST particle formation can sustain higher R_{DST}(C:N) than R_{SUS}(C:N) in the EZ, especially given that diatoms that release TEP precursors (Passow et al. 1994) are either the primary or secondary dominant algal group at station K2 all year around (Fujiki et al. 2014). Furthermore, higher R_{DST}(C:N) values during summer could be attributed to increased contributions of organic carbon from TEPs accumulated during a diatom bloom. This enhancement in diatoms is also evident from observations of increased opal concentrations in the DST particles in summer (Honda et al. 2015).

In summary, the higher δ^{15}N and R(C:N) of DST particles as compared to phytoplankton suggests that the organic nitrogen and carbon in DST particles were composed mainly of metabolites (including fecal pellets) of herbivorous zooplanktons such as copepods as well as that of diatoms. Contributions of both diatom cells and TEPs would increase in summer, which is reflected by lower Δ^{15}N(DST-SUS) as well as a further increase in R(C:N) in summer than during other seasons. The former strengthens the seasonal δ^{15}N trend (higher values in winter and lower in summer) in the

DST particles relative to phytoplankton. The latter provides the trend of higher R(C:N) in summer. Both effects would cause the negative relationship between δ^{15}N(DST) and R_{DST}(C:N) as seen in Fig. 2b and 5.

In general, a large reduction of settling POC flux is found within the upper 500 m, which has been reported in station K2 (Buesseler et al. 2007, Honda et al. 2015). Honda et al. (2015) estimated the exponent b, represents the degree of POC flux attenuation with depth, by applying the "*Martin curve*" (Martin et al. 1987) to the POC flux data (via DST particles) at station K2 obtained during respective cruises in 2010-2012. Annual average b was 0.64±0.3 (n = 6). Relative high values of ca. 1.0 were found in MR10-06 and MR11-02, which corresponds to the attenuation by ca. 50 % of settling POC from 100 to 200 m. Assuming an ^{15}N fractionation of -4.0 ‰ during remineralization of organic nitrogen, the δ^{15}N of the PN left behind (in the DST particles at 200 m) would increases by ca. 2.9 ‰ from the original δ^{15}N (at 100 m) in the Rayleigh equation. Contrary to this expectation, only modest changes (<0.8 ‰) in δ^{15}N(DST) were found within 100 to 200 m depth in all season (Fig. 3d, i, n, s, x), which implies that the DST particles underwent less remineralization with an isotope effect during their settling, at least for those collected in MR10-06 and MR11-02. Alternatively, the observed attenuation of POC flux (losses of DST particles) resulted mainly from the fragmentation of settling aggregates (Karl et al. 1988; Banse 1995; Dilling and Alldredge 2000) as well as the direct grazing by omnivorous zooplankton (Koppemann et al 2004; Steinberg et al. 2008) since both processes had little isotopic effect. Actually, the morphological analyses of fecal pellets trapped at station K2

revealed obvious vertical reductions in volume of fecal pellets without shape composition change, implying that the fecal pellet fluxes may have been reduced by coprorhexy and coprophagy during their sinks (Kobari et al. 2016). Fragmented smaller aggregates and fecal pellets with the δ^{15}N value similar to δ^{15}N(DST) were input to the suspended particulate pool, which can partly explain the sharp increases of δ^{15}N(SUS) below the EZ as observed in this study (Fig. 3 d, i, n, s, x). Furthermore it is very likely that the fragmented particles would have been gradually remineralized during longer residence times in the upper layer of 200 m (Goldthwait et al., 2005) relative to the unfragmented DST particles. Consequently, such PN remineralization with the isotopic effect in the suspended pool might result in higher δ^{15}N(SUS) at 100 to 200 m than δ^{15}N(DST) (annual average 5.6±1.9 ‰ vs. 6.6±0.9 ‰, Table 2). Thus, based on the δ^{15}N properties of both suspended and settling particles at 100 to 200 m, the aggregates and pellets in DST particles may break down while settling, which provides a continuous supply of fresh organic material to biota below the EZ.

4.3 Implications of δ^{15}N signatures recorded in trapped materials at station K2

As described above, δ^{15}N(SUS) in the EZ exhibited seasonal change of ca. 3 ‰, which can be attributed mainly to variations of δ^{15}N(reg. PN) through its contribution (1-*f*). δ^{15}N(reg. PN) and *f*-ratio vary depending on nitrogen recycling, NH_4^+ productions and consumptions (including nitrification), then both become lower in bright, warm stratified waters while being higher in sun-lit, cold mixed waters. Consequently, δ^{15}N(SUS) would show lower and higher values in summer and winter, respectively.

These signatures are carried to the DST particles but with ^{15}N enrichments during their formation. This ^{15}N enrichment varies seasonally depending on trophic components in the DST particles, with being small in summer due to increased contribution of diatom cells when the particle aggregation is enhanced by TEP in the upper stratified waters. Accordingly, $\delta^{15}N$(DST) exhibited even larger seasonal change (~4.6 ‰) than $\delta^{15}N$(SUS), but with the same trend of lower and higher in summer and winter, respectively. Thus, $\delta^{15}N$ signature imprinted in the DST particles is inferred to vary closely associated with the vertical stability of the upper water mass (stratification vs. convective mixing) as well as the resultant photo-environment in it.

Surprisingly, $\delta^{15}N$(DST) showed a significant negative correlation (r^2 = 0.94) with the primary productivity (PP) estimated by ^{13}C tracer method during respective cruises (Matsumoto et al. 2016) as depicted in Fig. 9a. This is likely because PP also varies dependently on light condition in the surface layer at K2. Actually, Matsumoto et al. (2014) revealed a significant positive relationship between productivity and light availability in the mixed layer from seasonal shipboard observations conducted repeatedly during 2005 to 2013. They suggested that reduced and enhanced PP in winter/spring and summer, respectively are attributed to severe light limitation due to deep mixing and its relaxation by an increased insolation and a shallowing MLD. However, they also indicated that even summer PP is often attenuated by a reduction of light availability due to dense sea fog typical in this season in the WSG (Sasakawa et al. 2003). Such low-light effects on phytoplankton growth would be enhanced partly by a reduced micronutrient (iron) availability, as indicated by lowered photosynthetic

potential, F_V/F_M, during summer (Fujiki et al. 2014). Additionally, less seasonal variation of phytoplankton biomass imposed partly by the MLD-dependent grazing pressure (Evans and Parslow 1985) would enforce the apparent light influence on PP. Thus, Matsumoto et al. (2014) concluded that the light availability exerts a primary control of PP throughout the year at K2 because of its larger and more frequent (daily) variation among limiting factors.

Given that both variations of δ^{15}N(DST) and PP have strong dependencies on light condition in the upper mixed layer, it is reasonable for them to show the correlation as we found (Fig. 9a). Although their coupling is indirect, it would be maintained unless both dependencies are disturbed. We then applied this relationship to the time-series δ^{15}N value of MST particles in order to estimate seasonal variations of PP at station K2.

First, the consistency between δ^{15}N(DST) at the depth of 100-200 m and δ^{15}N(MST) at 500 m was confirmed (r^2 = 0.91, n = 4) with a small error in the mean (δ^{15}N(DST) - δ^{15}N(MST)) of +0.3 ‰ (Fig. 9b). After correction for this bias, the RMSE was 0.6 ‰. Second, monthly averages of δ^{15}N(MST) (weighted by PN flux) were calculated from daily data obtained during the entire experimental period from February 2010 to June 2012 (Fig. 10b). Monthly δ^{15}N(MST) values exhibited the maximum value of 7.5 ‰ and the minimum of 2.8 ‰ in February and July, respectively, and correlated negatively with monthly average daily PPFD (r = -0.74) as well as positively with the climatological monthly MLD (r = 0.58; Wakita et al. this volume). These results highlight the cause of δ^{15}N(MST) seasonality; increases correspond to weak insolation and deeper mixing, decreases to strong insolation and stratification, as inferred from

variations of both δ^{15}N(SUS) and δ^{15}N(DST). Finally, monthly averaged PP was calculated using the linear regression shown in Fig. 9a, which ranged from 65 to 550 mg m^{-2} d^{-1} (in carbon equivalents, Fig. 10c). The annual average of calculated PP was 343 mg m^{-2} d^{-1}, which is very close to the values obtained from seasonal PP observations (315 mg m^{-2} d^{-1}: Matsumoto et al. 2016).

As depicted in Fig. 10c, PP estimates show higher values during spring to summer (April to August) and lower values in winter (December to March), in accordance with the seasonal trend inferred from changes of underwater optical fields (Honda et al. 2009). It is somewhat surprising that relative higher PP occurs during April and May despite the relatively deep MLD of >90 m. This is partly because MLDs in early spring are deeper than the depth of actual “mixing layer” (Brainerd and Gregg 1995), in which the turbulent mixing becomes weak after atmospheric cooling subsides at the end of winter. This situation would increase the residence time of phytoplankton in the EZ thereby alleviating the severe light-limitation that occurs in winter. Concurrently, suppressed mixing would alter a micronutrient supply as well as grazing pressure by mobile heterotrophs (Evans and Parslow 1985, Saito et al., 2005) in the mixing layer, which can also influence the initiation timing and magnitude of diatom blooms. Ultimately these combined effects may derive increased productivity before the MLD shallowing, but which cannot be examined in this study. In any case, for further understanding a marine ecological response to physical forcing, the availability of seasonal measurements of PP is crucial. Year round PP measurements by traditional shipboard means are scare and methods based on satellite ocean color data are limited

by heavy cloud and dense sea fog especially in summer (Matsumoto et al. 2014). The approach that we propose, i.e. the use of continuous, time-series $\delta^{15}N$ data of MST particles variations of PP can help circumvent the perennial problem of lack of year round PP data in the WSG, even though further examinations of its validity are required.

5. Conclusions

$\delta^{15}N$ of particles trapped at the middle layer (500 m) of the WSG showed higher values in winter when more surface nitrate was available for phytoplankton, and lower values in summer when less nitrate was available. It is inferred that these $\delta^{15}N$ variations reflect mainly seasonal change of surface $\delta^{15}N(NH_4^+)$ due to isotopic fractionation by light-controlled nitrification and subsequent assimilation of ^{15}N-enriched NH_4^+ by phytoplankton. Particle $\delta^{15}N$ values are further modified by biogenic transformations during settling particle's formation. A similar $\delta^{15}N$ pattern of time-series trapped particles has been reported elsewhere in open oceans, the northeastern North Atlantic, subarctic northeastern Pacific and Southern ocean (Voss et al. 1996; Wu et al. 1999; Lourey et al. 2003), where productivity is not limited by macro-nutrients. Meanwhile, such $\delta^{15}N$ pattern is contrary to the expected by isotopic fractionation during photosynthetic nitrate consumption, demanding caution when applying $\delta^{15}N(PN)$ as a proxy of surface nitrate utilization over wide oceanographic settings. Alternatively, $\delta^{15}N$ variations for trapped particles in station K2 were significantly correlated with primary productivity, which is attributable to their respective dependencies on light condition in the upper layer. This indicates new

approach to estimate a time-series variation of productivity at least in the WSG from δ^{15}N analysis for moored trap samples although its validity should be examined carefully. Furthermore, it is feasible to estimate the export ratio by combining δ^{15}N-derived PP with measurements of organic carbon flux. These applications can be a powerful tool for further understanding of biological pump in the WSG.

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Table 1 Results of regression analysis of δ^{15}N(MST) at 500m against data (variables) for fluxes, chemical properties[a] of MST particles and surface environments.

variable	*r*	*n*	*p*
Total mass flux (mg m^{-2} d^{-1})	-0.52	55	<0.001
POC flux (mg m^{-2} d^{-1})	-0.50	55	<0.001
w(OC) (%)	0.28	55	0.037
w(opal) (%)	-0.32	55	0.018
R(opal:$CaCO_3$) (mol mol^{-1})	-0.44	55	<0.001
R(C:N) (mol mol^{-1})	-0.67	55	<0.001
Daily PPFD (E m^{-2} d^{-1})	-0.65	56	<0.001
SST (°C)	-0.38	56	0.007

[a]*w*(OC), *w*(opal) indicates mass fraction (%) of organic carbon, biogenic opal, respectively. *R*(opal:$CaCO_3$), *R*(C:N) indicates the mole ratio (*n*/*n*) of opal to calcium carbonate, and organic carbon to nitrogen, respectively.

Table 2 Averaged δ^{15}N and C:N mole ratio (R(C:N)) of suspended particles at 0-50 m (SUS, EZ), in the underlying 100-200 m layer (SUS, deep), and in settling particles (DST) collected during each cruise.

		δ^{15}N (‰)				R(C:N) (mole mole^{-1})			
Cruise	Date	0-50 m SUS, EZ	100-200 m SUS, deep	100-200 m DST	Δ^{15}N (‰) (DST – SUS, EZ)	0-50 m SUS, EZ	100-200 m SUS, deep	100-200 m DST	ΔR(C:N) (mole mole^{-1}) (DST – SUS, EZ)
MR10-06	October 2010	2.8	7.4	5.6	2.8	5.7	7.5	7.5	1.8
MR11-02	February 2011	3.1	6.5	7.0	3.8	6.0	6.6	7.2	1.2
MR11-03	April 2011	1.7	7.3	7.0	5.4	6.0	7.9	9.1 (7.3)[a]	3.2 (1.4)[b]
MR11-05	July 2011	0.4	5.3	2.9	2.6	6.0	7.0	8.1	2.1
MR12-02	June 2012	1.0	7.0	2.4	1.4	5.6	6.9	8.8	3.3
Ave. in 2010-2011		2.0	6.6	5.6	3.6	5.9	7.2	8.0 (7.5)[b]	2.1 (1.6)[b]
S.D in 2010-2011		1.2	0.9	1.9	1.3	0.1	0.5	0.8 (0.4)[b]	0.8 (0.4)[b]

Δ (DST-SUS, EZ) is the difference of properties between DST particle and SUS particle in the EZ. Both δ^{15}N and R(C:N) for SUS particles was calculated by PN-weighted meaning δ^{15}N of particles within the respective layers (EZ and deep). For DST particles, values represent the arithmetic mean for data from 100 to 200 m.

[a]R(C:N) in brackets represents the values of DST particles at 100 m from MR11-03 cruise when those at the deeper (150 and 200 m) showed relative high R(C:N) of >9 and lithogenic contents of >13 %, which was likely due to significant contributions of aeolian dust (see text). [b]Values in brackets were calculated when using R(C:N) of DST particles at 100 m as a representative during MR11-03 cruise.

Figure captions:

Fig. 1 Time series of the particulate organic carbon (POC) flux (bars) and δ^{15}N of the particles collected by moored sediment traps (δ^{15}N(MST); circles) at 200 (white bars/circles) and 500 m (grey bars/circles) depth in the station K2. Also δ^{15}N values of the particles collected by drifting trap (δ^{15}N(DST); black triangles) at 100 to 200 m during five hydrographic cruises are inserted. Cruise ID is shown on top. As for POC flux data, the bar with lower flux between 200 and 500 m was overlaid.

Fig. 2 Relationships of δ^{15}N(MST) at 200 m (white circles) and 500 m (grey circles) with (a) organic carbon flux and with (b) carbon and nitrogen mole ratio, *R*(C:N). The dashed line in (b) represents a linear fit using reduced major axis (RMA) regression of δ^{15}N(MST) versus *R*(C:N) at 500 m (r^2 = 0.45, n = 55).

Fig. 3 Vertical profiles of parameters in the upper water column observed during five cruises: MR10-06 (a-e), MR11-02 (f-j), MR11-03 (k-o), MR11-05 (p-t), and MR12-02 (u-y). Parameters are sigma theta (σ_θ, top *x*-axis) and nitrate concentrations (NO_3^-, bottom *x*-axis) in the 1st column of panels. Concentrations of nitrite and ammonium ($c(NO_2^-)$, $c(NH_4^+)$) are shown in the 2nd column; chlorophyll *a* (*c*(Chl, *a*), top *x*-axis) and suspended particulate organic carbon concentrations (*c*(POC), bottom *x*-axis) in the 3rd column; δ^{15}N of suspended (SUS) and settling (DST) particles in the 4th column; organic carbon to nitrogen mole ratio (*R*(C:N)) of particles in 5th column. Different profiles of $c(NO_2^-)$ and $c(NH_4^+)$ (panel v), *c*(Chl *a*) (panel w) during MR12-02

correspond to the data collected during earlier and later period of observation, which stresses short-term (<3 days) changes in these parameters. Horizontal solid and dotted lines indicate mixed layer depth (MLD) and the depth of euphotic zone (EZD), respectively.

Fig. 4 (a) Vertical profiles of both nitrate concentration ($c(NO_3^-)$) and $\delta^{15}N$ of nitrate at the station K2 in October 2010 (during MR10-06). (b) Nitrate $\delta^{15}N$ vs $\ln[c(NO_3^-)]$ for the profile data in (a). Dashed line represent a linear fit to the data in the upper 100 m ($r^2 = 0.997$, $n = 7$ $p < 0.001$), which gives a slope of –3.4±0.1 ‰ corresponding to the isotope effect ($^{15}\varepsilon(NO_3^-)$) for nitrate consumption by phytoplankton following the Rayleigh fractionation model (see text).

Fig. 5 Relationship between R(C:N) and $\delta^{15}N$ of both suspended and settling particles. Open and grey squares denote suspended particles within the euphotic zone (SUS, EZ) and from the underlying depth from 100 to 200 m (SUS, deep), respectively. Black triangles denote the settling particles collected by the drifting sediment traps (DST) at the depth from 100 to 200 m. Data for DST particles collected during MR11-03 are represented as open triangles. Dashed line represents a linear fit using RMA regression between $\delta^{15}N$ and R(C:N) of MST particles at 500 m seen in Fig. 2b. The properties of DST particles follow the same trend, except for those from MR11-03.

Fig. 6 The relation of PN-weighted average $\delta^{15}N$ of suspended particles within the EZ

versus (a) the NO_3^- inventory and (b) the ratio of NH_4^+ to NO_2^- inventories in the upper layer of 50 m. The error bars of NH_4^+ to NO_2^- ratio denote the standard error of the mean for respective cruises. Largest error was found during MR12-02 when a short-time increase in NH_4^+ occurred between casts (see text). The solid line indicates a linear regression between variables (r = -0.66, p = 0.22).

Fig. 7 Temporal changes in (a) depth-integrated (0-50 m) nitrate inventory (grey bars) and modeled $\delta^{15}N$ of nitrate ($\delta^{15}N(NO_3^-)$, closed circles) and PN formed from it ($\delta^{15}N$(new PN), closed squares) in the EZ. (b) depth-integrated ammonium and nitrite inventories (black and white bars, respectively) and their ratios (white circles). The PN-weighted averaged (c) $\delta^{15}N$, (d) R(C:N) of suspended particulate pool in the EZ (SUS, EZ; white squares) and the lower layer (100-200 m) (SUS, deep; grey squares) and the depth average values for settling particles (DST, black triangles) at 100-200 m. The error bars in (a) and (b) denote the standard deviation of the mean of data collected in respective cruises. Note: NO_3^-, NO_2^- and NH_4^+ inventories during MR12-02 cruise in (a) and (b) have distinct values for the earlier and later part of the cruise, as seen in Fig. 3v. But as for the ratio of NH_4^+ to NO_2^- inventories, the average values for respective cruises were plotted in (b). The time-evolution of $\delta^{15}N(NO_3^-)$ and $\delta^{15}N$(new PN) in (a) was estimated by a simple Rayleigh fractionation model assuming nitrate was consumed seasonally with $^{15}\varepsilon(NO_3^-)$ of -3.4 ‰ and using the observed ratio of surface to deeper (100 m) nitrate concentrations and $\delta^{15}N(NO_3^-$, initial) of 5.9 ‰ found at 100 m (see Fig. 4b and text).

Fig. 8 Simplified nitrogen cycling in the upper water column during (a) winter and (b) summer at the station K2. Arrows indicate fluxes: (i) NO_3^- transport due to winter convection, (ii) NO_3^- uptake by phytoplankton, (iii) PN sinking, (iv) Regeneration of NH_4^+ (ammonification by heterotrophs), (v) NH_4^+ uptake by phytoplankton, (vi) NH_4^+ oxidation by nitrifiers, (vii) NO_3^- diffusion. Dotted and dashed lines indicate depths of the euphotic layer (ELD) and the mixed layer (MLD), respectively. For fluxes (v) and (vi), the isotopic fractionations associated with them are described as ε_{ntrA} and ε_A, respectively. All nitrogen within the mixed layer ultimately originates from deep water NO_3^- supplied by wintertime vertical mixing (i). This preformed nitrate is consumed by phytoplankton (ii) to form particulate nitrogen. Part of PN is removed as sinking PN from the mixed layer (iii). Another part is remineralized to ammonium by microbial ammonification (iv). Ammonium can then be reassimilated into the PN pool by algal uptake in the euphotic layer (v) or oxidized by nitrifiers to nitrite (vi), and further oxidized to nitrate in the aphotic layer. Here we assume that NH_4^+ oxidation by nitrifiers in the euphotic layer is suppressed due to the light inhibition and the competition with phytoplankton (see text). The balance of these fluxes and the isotopic fractionations associated with them determine the $\delta^{15}N$ of each nitrogen pool. As for the ammonium pool in summer (b), it is regulated by both regeneration (iv) and re-assimilation (v) of NH_4^+ in the shallow mixed layer. Below the euphotic layer, NH_4^+ oxidation (vi) occurs but does not affect the ammonium pool within the upper mixed layer (and the euphotic layer). On the other hand, in winter (a) nitrification does affect the ammonium pool

since the MLD is deeper than the ELD. The isotopic fractionation during ammonium oxidation (ε_{ntrA}) is larger in magnitude than the isotopic fractionation during assimilation (ε_A). This can make the residual ammonium pool more enriched in ^{15}N in winter relative to that in summer.

Fig. 9 (a) Correlation between the averaged $\delta^{15}N$ value of DST particles ($\delta^{15}N$(DST)) at 100 to 200 m depth and the primary productivity measured during each cruise (Matsumoto et al. 2016). The solid line indicates a linear regression between them (r^2 = 0.94, p = 0.007). (b) Comparisons of averaged $\delta^{15}N$(DST) with $\delta^{15}N$ of MST particles ($\delta^{15}N$(MST)) at 200 and 500 m (open and closed circles, respectively). Data were used for both particles collected around the same period. The dotted line represents a 1:1 relationship. $\delta^{15}N$(MST) at 500 m correspond to$\delta^{15}N$(DST) with the mean error of 0.3 ‰, albeit the data limited (n = 4).

Fig. 10 Monthly variations in (a) daily PPFD (diamonds) (Data were acquired by the MODIS satellite), (b) climatological mixed layer depth (MLD, white squares) and $\delta^{15}N$ of the MST particles ($\delta^{15}N$(MST), black circles) at 500m depth, (c) primary productivity (PP, bars) estimated from $\delta^{15}N$(MST) (see text).

Figure 1

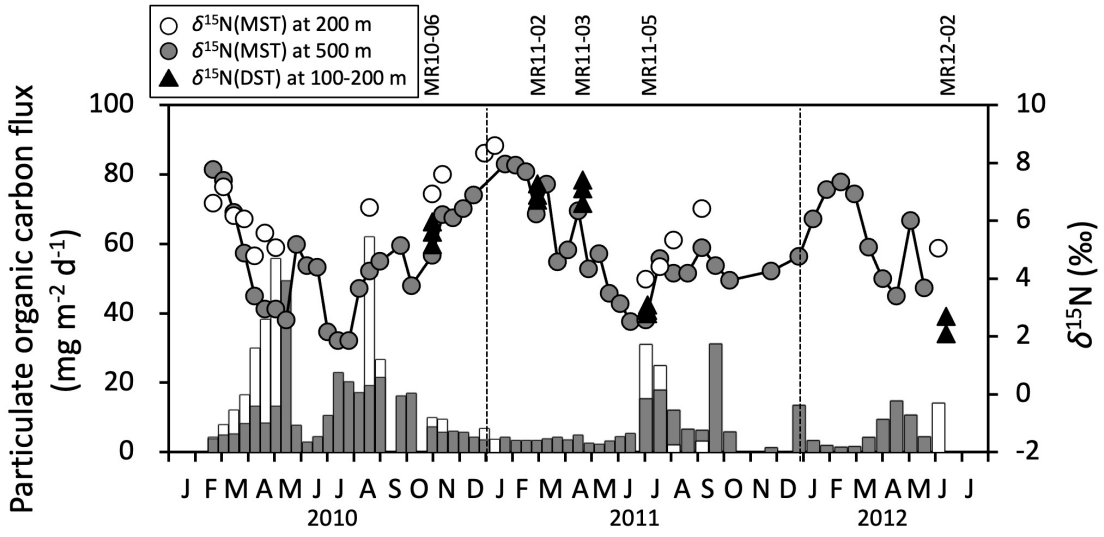

δ15N(MST) at 200 m
δ15N(MST) at 500 m
δ15N(DST) at 100-200 m
MR10-06
MR11-02
MR11-03
MR11-05
MR12-02
Particulate organic carbon flux (mg m-2 d-1)
δ15N (‰)
100
80
60
40
20
0
10
8
6
4
2
0
-2
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J
2010
2011
2012

Figure 2

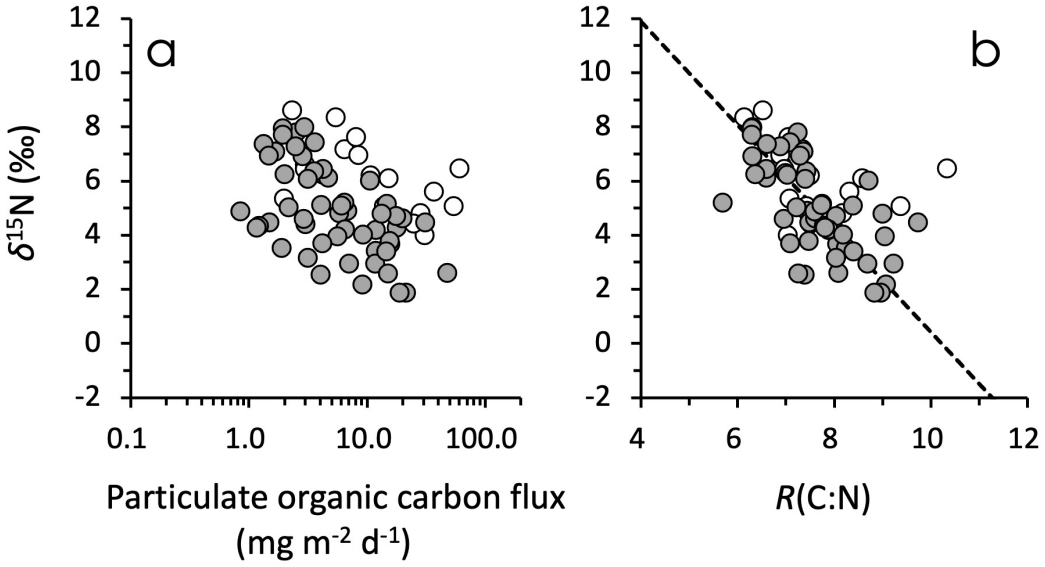

a
b
12
10
8
6
4
2
0
-2
δ^{15}N (‰)
0.1
1.0
10.0
100.0
Particulate organic carbon flux
(mg m^{-2} d^{-1})
4
6
8
10
12
R(C:N)

Figure 3

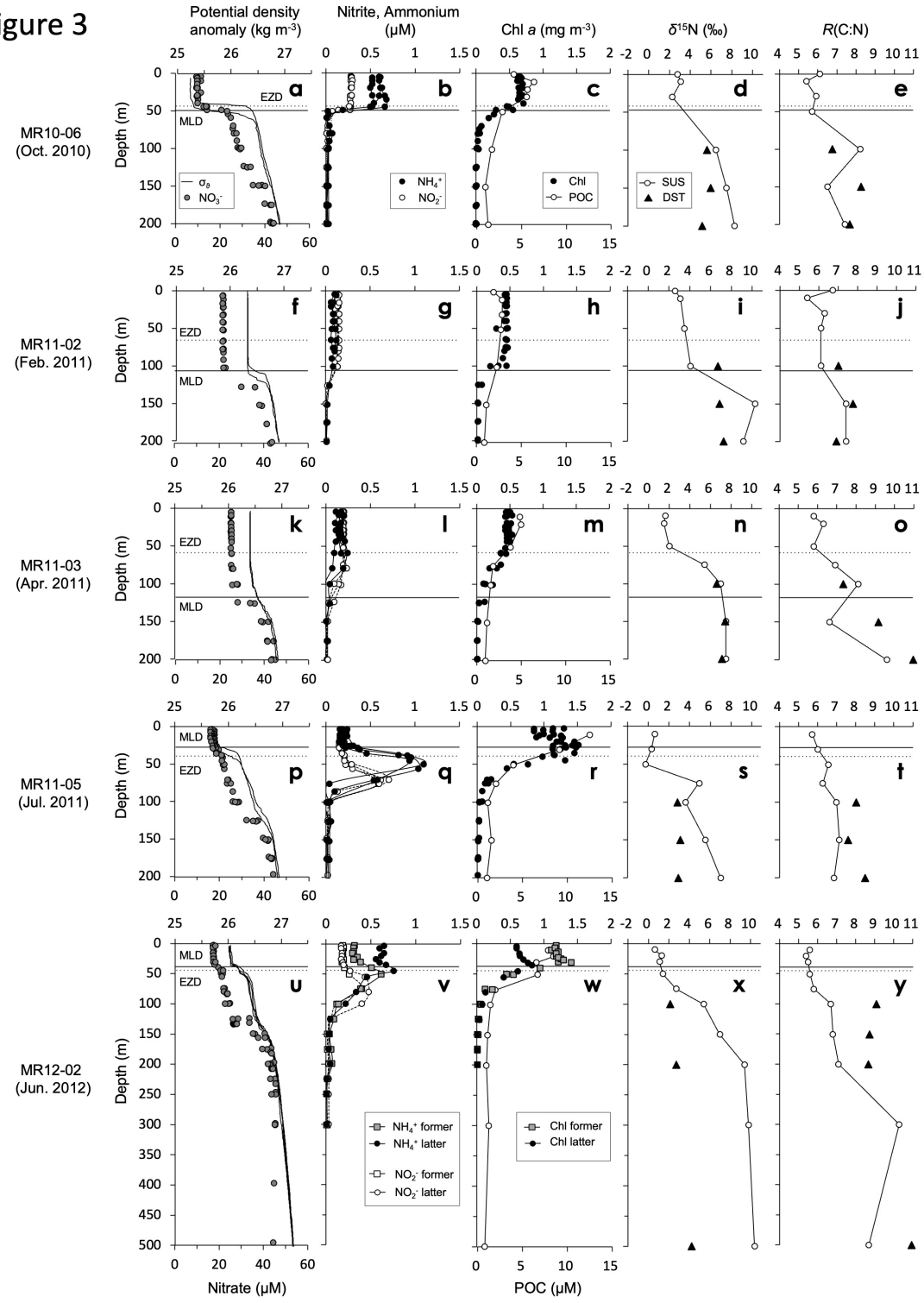

Potential density anomaly (kg m-3)
Nitrite, Ammonium (μM)
Chl a (mg m-3)
δ15N (‰)
R(C:N)
MR10-06 (Oct. 2010)
MR11-02 (Feb. 2011)
MR11-03 (Apr. 2011)
MR11-05 (Jul. 2011)
MR12-02 (Jun. 2012)
Depth (m)
EZD
MLD
σθ
NO3-
NH4+
NO2-
Chl
POC
SUS
DST
NH4+ former
NH4+ latter
NO2- former
NO2- latter
Chl former
Chl latter
Nitrate (μM)
POC (μM)

Figure 4

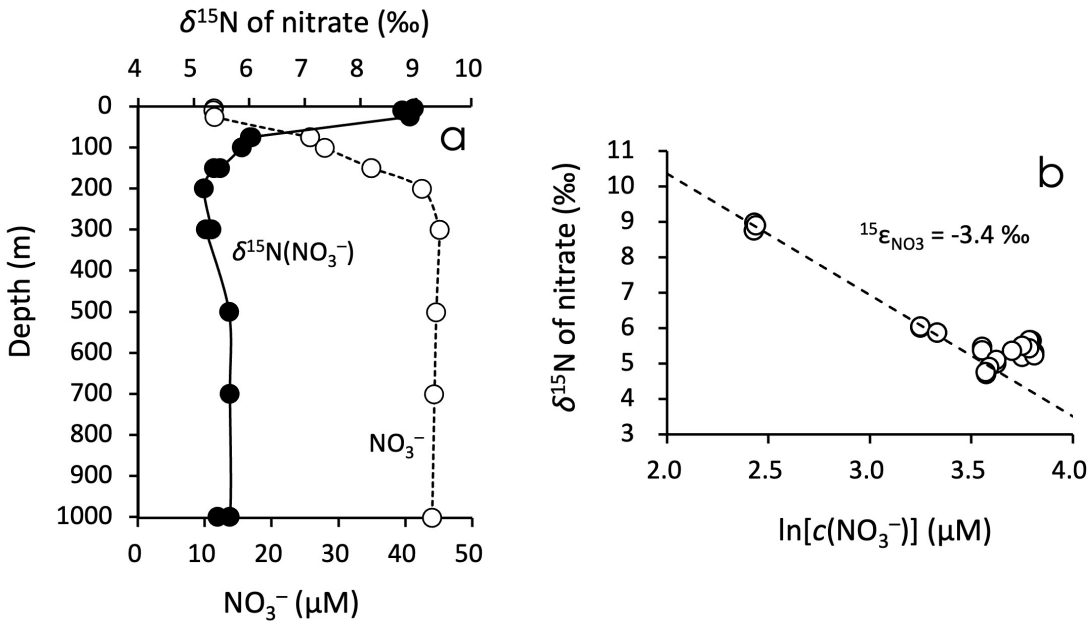

δ15N of nitrate (‰)
4 5 6 7 8 9 10
0 100 200 300 400 500 600 700 800 900 1000
Depth (m)
a
δ15N(NO3−)
NO3−
0 10 20 30 40 50
NO3− (μM)
b
15εNO3 = -3.4 ‰
δ15N of nitrate (‰)
11 10 9 8 7 6 5 4 3
2.0 2.5 3.0 3.5 4.0
ln[c(NO3−)] (μM)

Figure 5

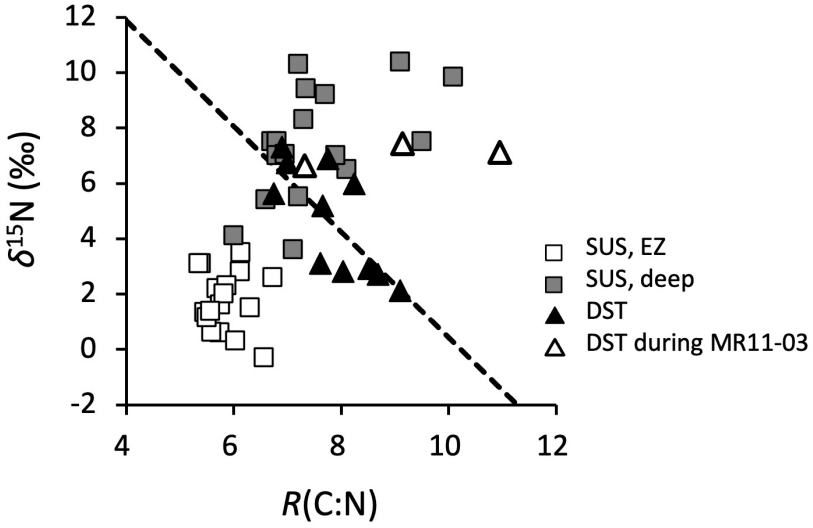

12
10
8
6
4
2
0
-2
4
6
8
10
12
δ15N (‰)
R(C:N)
SUS, EZ
SUS, deep
DST
DST during MR11-03

Figure 6

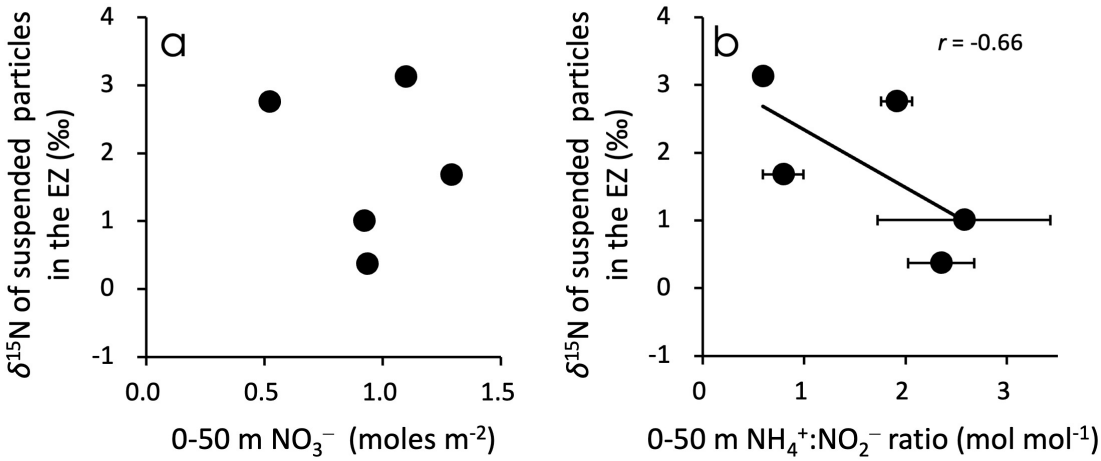

a
b
r = -0.66
δ15N of suspended particles in the EZ (‰)
0-50 m NO3− (moles m-2)
0-50 m NH4+:NO2− ratio (mol mol-1)

Figure 7

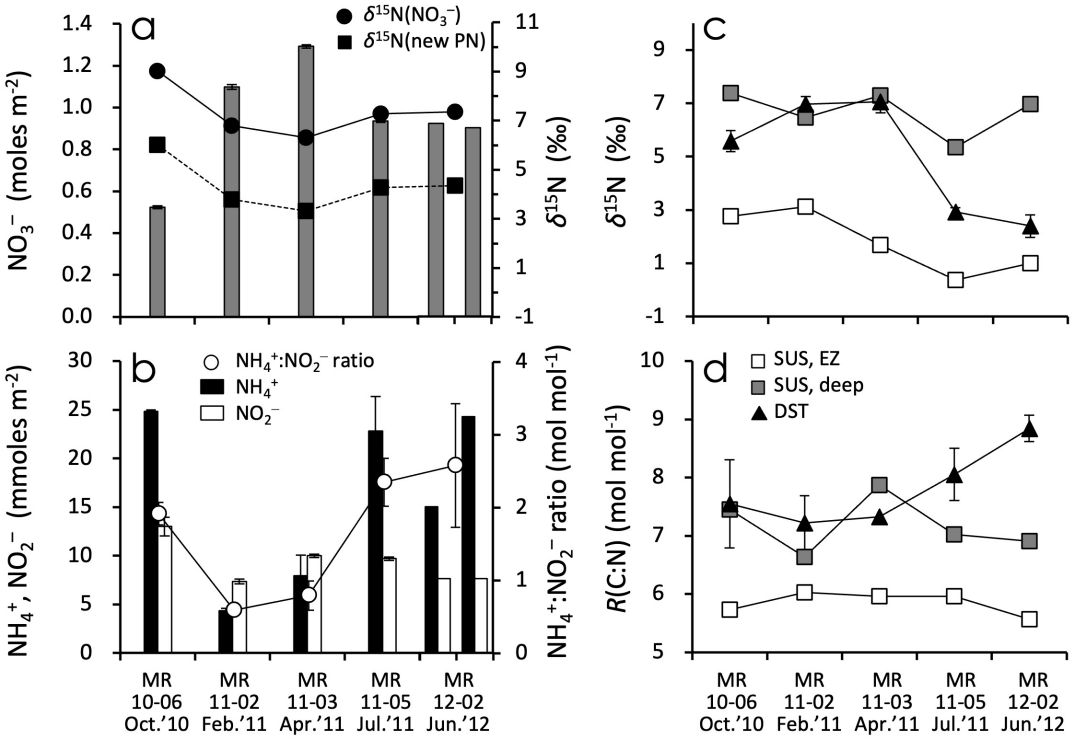

a
b
c
d
δ^{15}N(NO_3^-)
δ^{15}N(new PN)
NO_3^- (moles m^{-2})
δ^{15}N (‰)
NH_4^+:NO_2^- ratio
NH_4^+
NO_2^-
NH_4^+, NO_2^- (mmoles m^{-2})
NH_4^+:NO_2^- ratio (mol mol^{-1})
SUS, EZ
SUS, deep
DST
R(C:N) (mol mol^{-1})
MR 10-06 Oct.'10
MR 11-02 Feb.'11
MR 11-03 Apr.'11
MR 11-05 Jul.'11
MR 12-02 Jun.'12

Figure 8

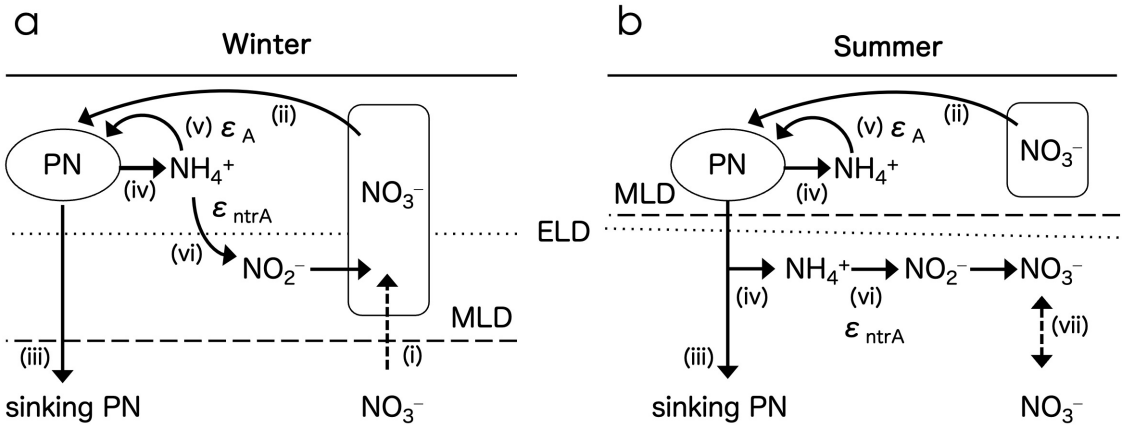

a
Winter
PN
(v) ε A
(ii)
NH4+
(iv)
NO3−
ε ntrA
(vi)
NO2−
MLD
(iii)
(i)
sinking PN
NO3−
b
Summer
PN
(v) ε A
(ii)
NO3−
NH4+
(iv)
MLD
ELD
NH4+
NO2−
NO3−
(iv)
(vi)
ε ntrA
(vii)
(iii)
sinking PN
NO3−

Figure 9

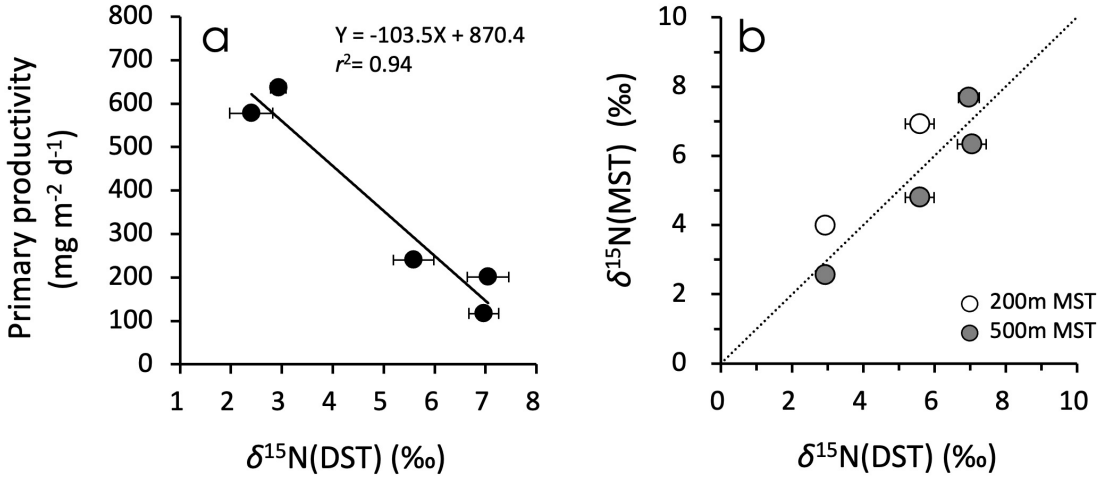
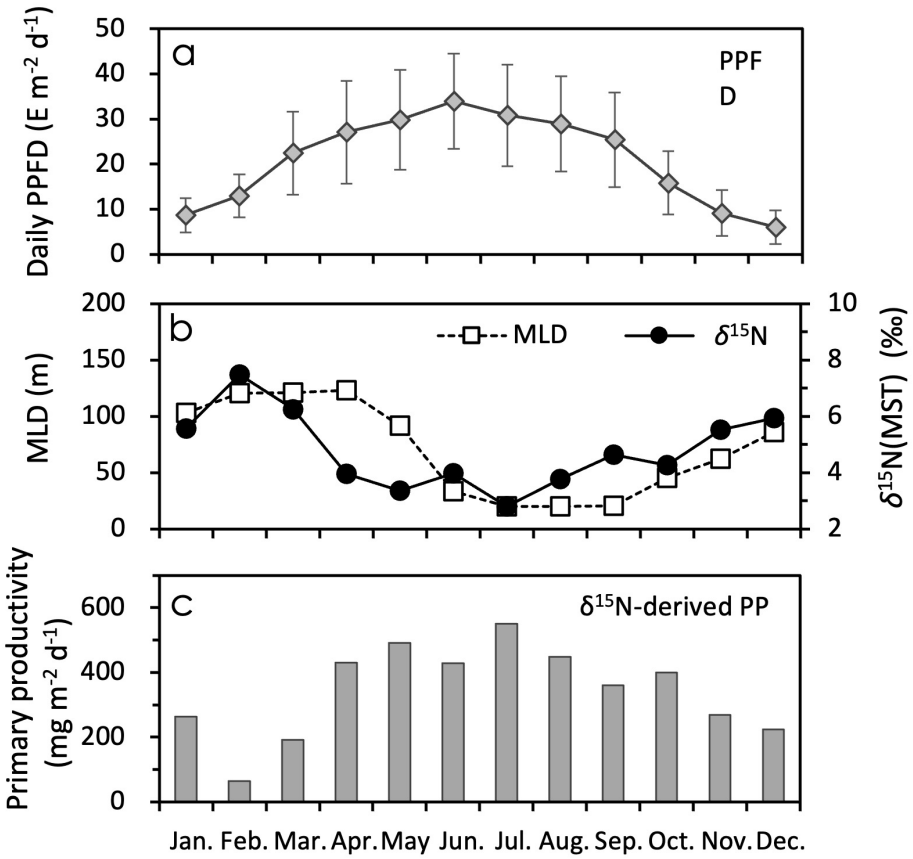

a
Y = -103.5X + 870.4
r2= 0.94
Primary productivity (mg m-2 d-1)
δ15N(DST) (‰)
b
δ15N(MST) (‰)
δ15N(DST) (‰)
200m MST
500m MST

Figure 10


a
PPF
D
Daily PPFD (E m-2 d-1)
50
40
30
20
10
0
b
MLD
δ15N
MLD (m)
δ15N(MST) (‰)
200
150
100
50
0
10
8
6
4
2
c
δ15N-derived PP
Primary productivity (mg m-2 d-1)
600
400
200
0
Jan. Feb. Mar. Apr. May Jun. Jul. Aug. Sep. Oct. Nov. Dec.