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Nitrogen cycling driven by organic matter export in the South Pacific oxygen minimum zone

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Oxygen minimum zones are major sites of oceanic nitrogen-loss, and have been expanding globally. Nitrogen-loss occurs mainly as the production of dinitrogen gas by denitrification or the so-called anammox process – the anaerobic ammonium oxidation with nitrite. Activity of anammox has been found more common in recent studies in the eastern tropical South Pacific, one of the largest oxygen minimum zones worldwide. As anammox requires substrates from multiple co-occurring nitrogen transformations, regulation of nitrogen-loss has to involve factors controlling overall nitrogen cycling, but which exactly remains unclear. Here, we present the most comprehensive nitrogen budget assessment for all major nitrogen fluxes to date for the eastern tropical South Pacific oxygen minimum zone. Extensive ¹⁵N-labelling experiments, nutrient measurements and export production modelling, together show that overall nitrogen cycling therein are tightly linked to the export of organic matter. Nitrogen-loss is most active over the productive shelf, fuelled by high rates of sinking organic matter and benthic ammonium release; then declines sharply offshore. These results highlight the importance of coastal oxygen minimum zones in oceanic nitrogen balance, and offer an empirical relationship for parameterization in biogeochemical models to more realistically assess the effects of climate change on oceanic carbon and nitrogen cycling.

Coastal upwelling of nutrient-rich deep water fuels high surface productivity at the eastern boundaries of (sub)tropical oceans. The resultant export of organic matter stimulates strong microbial respiration in the subsurface. Combined with poor ventilation, permanently O₂-deficient waters called oxygen minimum zones (OMZs) develop at mid-depths^{1,2}. Ongoing, global expansion and intensification of OMZs will expectedly continue as anthropogenic pressures on marine environments grow^{3,4,5}.

25 Although constituting only ~1% ($O_2 \leq 20 \mu\text{mol kg}^{-1}$) of global ocean volume⁶, OMZs
have a profound impact on oceanic nitrogen (N) balance as they account for ~20-40% of
global oceanic N-loss⁷. Ocean de-oxygenation might enlarge the ocean volume subject to N-
loss⁸, exacerbate N-limitation of phytoplankton, and reduce the ocean's capacity to attenuate
rising atmospheric carbon dioxide. Assessing the effects of expanding OMZs on the future
30 ocean's nutrient balance, however, remains speculative, as biogeochemical models do not
reproduce present-day global patterns of N-loss^{9,10,11}. A major deficiency of those models
appears to be the poor representation of coastal regions; whereas an increasing number of
studies indicates that N-loss in shelf OMZs^{12,13,14}, coastal-offshore OMZ water mass
exchange¹⁵ and OMZ-sediment interactions¹⁶ play more important roles on the overall N-
35 budget.

 Based on the observed accumulations of nitrite (NO_2^-) and associated N-deficits, most
N-loss in OMZ waters has traditionally been attributed to heterotrophic denitrification^{17,18,19},
the stepwise reduction of nitrate (NO_3^-) to gaseous dinitrogen (N_2). Recent studies have,
however, often failed to detect significant denitrifying activity in OMZs; rather, anammox
40 has more commonly been identified as a major N_2 -forming pathway in these
environments^{12,13,14,20}.

 The regulation of N-loss activity including anammox is not fully understood.
Anammox requires NH_4^+ and NO_2^- . Sources and sinks of both compounds have been
identified in the OMZs, including aerobic NH_3 and NO_2^- oxidation, as well as anaerobic NO_3^-
45 reduction to NO_2^- and dissimilatory $\text{NO}_3^-/\text{NO}_2^-$ reduction to NH_4^+ (DNRA)^{14,15,21,22}.
Surprisingly, O_2 sensitivity assays show that these processes in OMZ waters share a large
overlapping range of O_2 concentrations ($>0\text{-}20 \mu\text{mol L}^{-1}$) in which they can co-occur,
implying that within this range, controlling factors other than O_2 are more important^{23,24}.
Enhanced autotrophic and heterotrophic N-cycling activity in the upper OMZ^{13,14,20,21}, and

50 generally elevated anammox rates usually measured in coastal versus offshore OMZs⁶,
suggest that N-loss might ultimately be regulated by export production of organic matter.

To test this hypothesis, we conducted a large-scale survey of N-cycling rates,
functional gene abundances, chlorophyll, nutrient and O₂ concentrations, as well as modelled
export production, throughout the eastern tropical South Pacific (ETSP), one of the three
55 major OMZs in the world.

Dissolved Inorganic Nitrogen in the South Pacific Oxygen Minimum Zone

Consistent with past observations in the ETSP^{18,26}, pronounced secondary NO₂⁻
maxima were found in the offshore OMZ between 10°S and 18°S (supplementary Fig. 1),
60 extending up to 100's km westward with maximum concentrations of ~11 μmol L⁻¹. Based on
the spatial distribution of measured O₂, the lower OMZ boundary occurred at ~600 m on
average near the Peruvian shelf (Figs S1-2). Henceforth, this is used as a depth cut-off to
differentiate coastal OMZ stations, where the OMZ is in direct contact with sediments and
benthic N-fluxes (<600m), from all others that are defined as offshore OMZ stations.
65 Integrated over the thickness of the OMZ (defined by O₂ ≤ 15 μmol L⁻¹ where N-loss activity
remains detectable in O₂-sensitivity assays²⁴; Figs 1b, S2), NO₂⁻ concentrations reached >2
mol m⁻² in the offshore region (Fig. 1d). Concentrations of NH₄⁺ were low (<0.25 μmol L⁻¹)
throughout the OMZ, but could be ≥0.5 μmol L⁻¹ over the shelf and near the upper OMZ
boundary further offshore. Deeper in the offshore OMZ, plumes of elevated NH₄⁺
70 concentrations (≤~3 μmol L⁻¹) sometimes occurred (supplementary Fig. 1), resulting in high
depth-integrated values (Fig. 1e).

Offshore OMZs were characterized by severe N-deficits, expressed here as strongly
negative N* with minima from -8 μmol N L⁻¹ at 3.58°S down to -32 μmol N L⁻¹ at 16°S.
Depth-integrated values of N* (Fig. 1e) and NO₂⁻ were significantly correlated (Spearman

75 R=-0.61, $p \leq 0.001$). The southward intensification of both NO_2^- maxima and N^* minima likely reflects the accumulated effects of time-integrated microbial activity in OMZ waters that advect poleward along the continental slope with the Peru-Chile Undercurrent^{27,28}. Over the Peruvian shelf between 12°S and 14°S, extreme N-deficits (N^* down to $-60 \mu\text{mol L}^{-1}$, Supplementary Fig. 1) were detected along with the presence of hydrogen sulphide (H_2S).

80 These stations are not further considered in the remaining discussions unless otherwise indicated, as the resident microbial communities and processes profoundly differ from typical OMZ scenarios (Schunck et al. submitted.).

Sources of Nitrite

85 Nitrite in the OMZs can be generated by NH_3 oxidation, the first step of nitrification; or by the reduction of nitrate to nitrite^{6,21,22}. Ammonia oxidation has been identified as an important NO_2^- source in the Peruvian OMZ, that is active under near-anoxic conditions^{21,23,29}. Our measured rates of NH_3 oxidation generally peaked at the base of the oxycline ($\sim 90 \text{ nmol N L}^{-1} \text{ d}^{-1}$), decreased to detection limit at the stations furthest offshore,

90 and were not detectable in the core of the OMZ (Tables 1 and S2). The presence of both archaeal and bacterial ammonia-oxidizers is verified by the detection of their biomarker functional genes encoding ammonia monooxygenase subunit A (Tables 1 and S3).

Integrated over the thickness of the OMZ, NO_2^- production via NH_3 oxidation increased from undetectable at the westernmost stations to $\leq 4.7 \text{ mmol NO}_2^- \text{ m}^{-2} \text{ d}^{-1}$ near the coast (Fig. 2a; supplementary Table 1). For the entire OMZ volume examined ($\sim 5.5 \times 10^5 \text{ km}^3$), NH_3 oxidation is estimated to produce $\sim 3.8 \text{ Tg N y}^{-1}$ of NO_2^- , with 24% attributed to coastal OMZ ($\leq 600 \text{ m}$) and 76% offshore ($> 600 \text{ m}$) (Fig. 3). Although significant rates have also been reported for the surface mixed layer in the ETSP³⁰, the mixed layer was not included in the current OMZ budget.

100 Overall, NH_3 oxidation accounted for only ~7% of the total NO_2^- production. The majority came from NO_3^- reduction to NO_2^- , consistent with previous findings in the Peruvian, Namibian and Arabian Sea OMZs^{15,21,22}. Apart from its association with anammox, NO_3^- reduction to NO_2^- is the first step in denitrification and DNRA, and NO_3^- is the next preferred terminal electron acceptor after O_2 for the oxidation of organic matter. NO_3^- reduction was detected throughout the OMZ at all investigated stations; it reached a maximum ($\sim 1 \mu\text{mol N L}^{-1} \text{d}^{-1}$) over the central shelf, but dropped to $\sim 10 \text{ nmol N L}^{-1} \text{d}^{-1}$ at the westernmost offshore stations (Table 1).

Depth-integrated rates showed similarly declining trend offshore (Fig. 2c; supplementary Table 1). Integration over the whole region yields an annual NO_3^- reduction of ~49 Tg N, of which 29% occurs in the coastal OMZ and 71% offshore (Fig. 3). Like previous observations from the Peruvian²³ and the Arabian Sea¹⁵ OMZs, NO_3^- reduction significantly correlated with depth-integrated NO_2^- concentrations (Spearman $R=0.71$, $p \leq 0.001$) (Table 2), which indicates that NO_3^- reduction is a major contributor to the secondary NO_2^- maxima.

115 ***Sinks of Nitrite***

Nitrite oxidation, the second step in nitrification, was most active in the upper OMZ throughout the ETSP. Its activity was detected deeper into the OMZ than NH_3 oxidation, consistent with earlier reports^{23,29}. Nitrite oxidation rates were highest ($928 \text{ nmol N L}^{-1} \text{d}^{-1}$) over the Peruvian shelf despite low O_2 levels (Table 1), and declined sharply to $\leq 20 \text{ nmol N L}^{-1} \text{d}^{-1}$ along the furthest offshore transect. Although NO_2^- oxidation is believed to require O_2 , this process has been detected at $< 1\text{-}2 \mu\text{mol O}_2 \text{ L}^{-1}$ in the Peruvian^{23,29} and Namibian OMZs²². O_2 sensitivity assays ($\sim 1\text{-}25 \mu\text{mol L}^{-1}$) at two stations further demonstrated only a moderate attenuation by low O_2 (at most ~50% activity reduction at $< 1 \mu\text{mol L}^{-1}$)

(supplementary Fig. 3), which agrees well with observations in the Namibian OMZ²².

125 Clearly, NO₂⁻ oxidizers are well adapted to O₂-deficient environments.

NO₂⁻-supply from NH₃ oxidation, the first step of nitrification, is thought to constrain NO₂⁻ oxidation rates. Despite the significant correlation between NH₃ and NO₂⁻ oxidation rates (Spearman R=0.73, p≤0.001) (Table 2), NO₂⁻ oxidation in the ETSP OMZ exceeded those of NH₃ oxidation often by more than tenfold (Fig. 2a,b; supplementary Table 1,2).

130 Similar observations in the OMZs off Namibia²² and Peru^{23,29}, indicate a decoupling of the two steps of nitrification in O₂-deficient systems. A likely alternative NO₂⁻ source is NO₃⁻ reduction.

Based on modeled N-fluxes a NO₂⁻ “shunt”, in which 45-74% of the NO₃⁻ reduced to NO₂⁻ by “denitrifying” micro-organisms is re-oxidized by aerobic NO₂⁻ oxidizers, has been
135 proposed for the ETSP³¹. In agreement, our annual rates of NO₂⁻ oxidation for the coastal (7 Tg N y⁻¹) and offshore OMZ (23 Tg N y⁻¹) are equivalent to 51% and 65%, respectively, of NO₃⁻ reduction (Fig. 3). The strong correlation between the two processes (Spearman R=0.75, p≤0.001) (Table 2) indicates a close coupling between NO₂⁻ oxidation and NO₃⁻ reduction in the ETSP OMZ.

140 Meanwhile, only sporadic and low rates of DNRA (≤1.3 nmol L⁻¹ d⁻¹) were detected during our sampling period (Table 1). A general lack of detectable *nrfA*, a key functional gene encoding for the cytochrome *c* NO₂⁻ reductase corroborates these results (Table 1). DNRA appears to exhibit a high degree of spatio-temporal variability, with similarly low rates measured on the Namibian shelf²², but with tenfold greater rates and *nrfA* gene
145 abundance than observed in the OMZs off Peru²¹ and Oman¹⁴. Hence, we cannot exclude DNRA as a significant NO_x⁻-sink for and NH₄⁺-source in the ETSP at other times.

Nitrogen-Loss Activities

At the time of our sampling, denitrification, expressed as the production of $^{30}\text{N}_2$ from $^{15}\text{NO}_x$, was generally non-detectable. Low rates of denitrification ($\sim 2\text{-}5 \text{ nmol L}^{-1} \text{ d}^{-1}$) were measured in three samples from the Peruvian shelf OMZ (Tables 1, S2). Substantially higher rates were detected in few samples containing measurable amounts of H_2S (Fig. 2e; supplementary Tables 1,2), suggesting a coupling with H_2S oxidation (ref. 32; Schunck et al. submitted). In contrast to the conclusion drawn by a recent study³³, water-column denitrification was only of minor importance ($\ll 1\%$ total N-loss) for the overall N-budget in the ETSP OMZ (supplementary information).

N_2 production attributed to anammox was detected at all stations except the two furthest offshore, consistent with previous studies in the ETSP^{13,20,34}. Anammox activity was often enhanced in the upper OMZ and markedly elevated in the bottom waters over the shelf and upper continental slope. Rates were highest ($\leq \sim 225 \text{ nmol N L}^{-1} \text{ d}^{-1}$) over the central shelf ($10^\circ\text{S}\text{-}16^\circ\text{S}$) and declined by two orders of magnitude westward (Table 1). The presence of anammox bacteria was verified by the detection of their characteristic hydrazine (N_2H_4) oxidoreductase genes (*hzol* and 2) throughout the OMZ; whereas denitrifier-*nirS*, encoding for the cytochrome *cd₁*-containing NO_2^- reductase, was generally not detectable (Tables 2, S3).

Depth-integrated anammox rates were $>10 \text{ mmol N m}^{-2} \text{ d}^{-1}$ on the central shelf, similar to previous findings¹³, and $<1 \text{ mmol N m}^{-2} \text{ d}^{-1}$ at the furthest offshore stations (Fig. 2d; supplementary Table 1). Altogether, anammox accounts for an annual N-loss of $\sim 10 \text{ Tg}$ in an area of $1.2 \times 10^6 \text{ km}^2$, which is at the lower end of earlier estimates for the ETSP ($9\text{-}26 \text{ Tg N y}^{-1}$)^{13,18,23,35}.

Flux measurements of dissolved inorganic nitrogen and N_2 made just prior to our sampling demonstrate that the sediments underlying the OMZ are additional sites of N-loss¹⁶. Combined with reaction-diffusion modeling, anammox and denitrification were shown to be

active N-sinks in the Peruvian coastal sediments. Based on the reported sedimentary NO_x^- fluxes and NO_x^- partitioning between anammox, denitrification, and DNRA¹⁶, we estimate a loss of 1 Tg N y^{-1} from sediments in contact with the OMZ bottom waters (Fig. 3).

Conventionally, the accumulation of NO_2^- in OMZ waters has been interpreted as signs of active N-loss, and thus, is targeted by most field-sampling campaigns^{17,18,19,20,23,26,29}. Our data contradict this interpretation. Unlike NO_2^- , depth-integrated anammox rates did not reveal any meridional trends, but decreased from shelf to offshore. Depth-integrated anammox rates and NO_2^- concentration were only moderately correlated (Spearman $R=0.64$, $p<0.001$) (Table 2). Furthermore, significant correlations between volumetric rates and NO_2^- concentrations were only observed for the shelf OMZ (Spearman $R=0.72$, $p<0.001$) and not offshore (Spearman, $p>0.5$). NO_2^- accumulation offshore probably resulted from a greater persistence of NO_3^- reduction to NO_2^- compared to other NO_2^- -consuming processes in a poorly ventilated region, where the net NO_2^- gain was about five times higher compared to the coastal OMZ (11.4 and 2.2 Tg N y^{-1} , respectively).

Ongoing water column N-loss cannot be deduced simply from the intensity of N^* minima, as shown by the lack of significant correlation (Spearman $p>0.05$) between anammox activity and N^* (Table 2). While the depth-integrated N-deficit is strongest (most negative N^*) offshore, anammox activity is highest over the shelf and upper continental slope. Though comprising only 10% of the area covered and merely 4% of the sampled OMZ volume, coastal OMZ waters contribute as much as 30% of the total N-loss (Fig. 3). Meanwhile, N-deficits in coastal OMZ waters amount to only 5% (4 Tg N) of the total N-deficit (71 Tg N). Hence, the large N-deficit offshore most likely results from horizontal advection of N-deficient shelf waters²¹ that accumulate due to a long residence time in the offshore OMZ ($\sim 10 \text{ y}$ based on N^* and measured N-loss). This is analogous to recent observations made in the Arabian Sea: substantial NO_2^- accumulation and low N-loss activity

in the central basin, compared to the rapid N-loss over the adjacent productive Omani
200 shelf^{14,15}.

Sources of Ammonium

N-loss driven by anammox requires NH_4^+ , which usually does not accumulate in
OMZs. Ammonium concentrations can be kept low by a tight coupling between NH_4^+
205 production and consumption processes, while the NH_4^+ released at the reported
reminerzalization rates may already be sufficient to fuel anammox. Major sources of NH_4^+ are
water-column organic matter remineralization and sedimentary NH_4^+ release.

DNRA and organic matter ammonification are active benthic NH_4^+ sources off the
coast of Peru. During two preceding cruises (M77-1 and 2) to the ETSP¹⁶, large NH_4^+ fluxes
210 ($\sim 0.5\text{-}4 \text{ mmol m}^2 \text{ d}^{-1}$) from sediments into the overlying OMZ waters were measured on a
cross-shelf transect at 11°S . The often enhanced anammox activity in the coastal OMZ
bottom waters suggests a strong influence from NH_4^+ diffusing out of the sediments^{13,36}.
Assuming an average benthic NH_4^+ flux of $\sim 2 \text{ mmol m}^{-2} \text{ d}^{-1}$ and a typical anammox rate of
 $\sim 4 \text{ mmol NH}_4^+ \text{ m}^{-2} \text{ d}^{-1}$ for the Peruvian coastal waters, the underlying sediments could supply
215 $\sim 50\%$ of the NH_4^+ needed for the anammox rates observed. Clearly, additional NH_4^+ sources
are necessary to fulfil the remaining requirements for anammox, especially in offshore OMZ
waters, which are spatially decoupled from the sediments.

Based on the measured NO_3^- reduction rates, subsequent ammonification of
Redfieldian organic matter generates 65% and 73% of the NH_4^+ needed for anammox in the
220 coastal and offshore OMZs, respectively (Fig. 3). These are likely underestimates,
considering the observed preferential N-degradation of organic matter via NO_3^- respiration
under suboxic conditions³⁷. Whether the reduction of NO_3^- is directly coupled to the

oxidation of organic matter, or indirectly via a recently proposed cryptic sulphur cycle³⁸, could not be discerned at this point.

225 Remineralization of sinking organic matter and subsequent NH_4^+ release is usually enhanced near the upper OMZ boundary, and would support the high anammox and NH_3 oxidation activity observed^{13,14,15,20,21,23}. On average, ~40% of their combined NH_4^+ demands are supplied by NO_3^- reduction, with the remainder possibly coming from microaerobic organic matter remineralization²⁰. The activity of O_2 -dependent nitrification at non-detectable
230 O_2 concentrations in OMZs indicates that microaerobic respiration proceeds even at nanomolar O_2 levels, in accordance with an apparent half-saturation coefficient of $<20 \text{ nmol L}^{-1}$ previously reported for microaerobic respiration in these waters³⁹. High O_2 consumption rates, mainly attributable to heterotrophic respiration, and genes encoding for terminal respiratory oxidases with high O_2 -affinities were detected in the ETSP on the same
235 expedition (Kalvelage et al. unpubl.). While there are suggestions that O_2 is efficiently depleted down to the limits of microaerobic respiration in the OMZ core⁴⁰, regular intrusions of more oxygenated surface waters or mixing events, such as those related to eddies⁴¹, may sustain aerobic microbial activity in the upper OMZ.

240 ***Linking Surface Productivity and Sub-surface Nitrogen Cycling***

Depth-integrated anammox rates correlated strikingly well with NO_3^- reduction, NO_2^- oxidation and NH_3 oxidation (Spearman $R=0.88$, 0.86 and 0.75 , respectively; $p \leq 0.001$), indicating a common controlling factor for their concerted activity. Our data suggest that N-cycling processes in the OMZ are tightly coupled to the export of organic matter.

245 Export of organic matter at the base of the euphotic zone was estimated from net primary production (NPP)⁴² and the ratio of export-to-total primary production (*ef*-ratio)⁴³. At the time of sampling, NPP was up to $\sim 3 \text{ g organic C (C}_{\text{org}}) \text{ m}^{-2} \text{ d}^{-1}$ near the coast and

decreased to $<0.5 \text{ g C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ further offshore, values typical for the Peruvian upwelling system⁴⁴. Computed *ef*-ratios ranged from 0.16 (low-NPP sites) to 0.42 (high-NPP sites). The
250 resulting N-export production rates (converted from measured C:N=7.2 of surface particulate organic matter) were $>10 \text{ mmol organic N (N}_{\text{org}}) \text{ m}^{-2} \text{ d}^{-1}$ over the shelf and in the order of $\sim 1 \text{ mmol N}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ at the stations furthest offshore (Fig. 2f; supplementary Table 1). Export production was highly correlated to depth-integrated rates of anammox, NO_3^- reduction and NO_2^- oxidation (Spearman $R=0.79, 0.75$ and 0.60 , respectively, $p \leq 0.001$) as well as NH_3
255 oxidation (Spearman $R=0.56$, $p \leq 0.01$) (Table 2). This suggests that the lateral distribution of N-cycling activity, including anammox, is mainly determined by the export of organic matter, which is the ultimate source of the required reactive substrates NH_4^+ and NO_2^- in the OMZ.

Overall, we estimate NPP of 12 and 47 Tg N y^{-1} in the coastal and offshore surface waters, respectively, which appear reasonable at a net lateral supply of 88 $\text{Tg NO}_3^- \text{ y}^{-1}$ to the
260 upwelling region (Fig. 3). The corresponding export fluxes are 4.4 and 9.9 $\text{Tg N}_{\text{org}} \text{ y}^{-1}$. Taking organic matter sedimentation and export to the deep ocean into account, our results show that the export production to the OMZ is sufficient as an N-source to support the measured N-fluxes.

In summary, extensive sampling and experimentation throughout the ETSP OMZ
265 shows that the activity of anammox and N-linked processes is highly correlated with export production. High productivity over the shelf and upper slope, as well as sedimentary NH_4^+ release, drive high rates of tightly coupled N-cycling processes and thus N-loss via anammox in the shallow coastal OMZ compared to the offshore OMZ.

While the globally expanding OMZs might increase the oceanic volume conducive to
270 N-loss, N-loss would only continue to rise as long as there is sufficient nutrient supply for primary production in the euphotic zone, and nutrient supply is not hampered by intensified stratification (i.e. reduced upwelling) due to ocean warming. These positive and negative

feedbacks are important considerations for biogeochemical models, which at present do not adequately reproduce the observed spatial patterns of N-loss in OMZs. In light of our results, 275 the activities of N-loss via anammox appear to be directly linked to export production rates in biogeochemical models using the following empirical relationship: $\text{anammox} = 0.7 \times N_{\text{org}}$ export (supplementary Fig. 4). This may facilitate a realistic assessment of the short- and long-term impacts of ocean de-oxygenation and changing productivity on N-cycling in OMZs, as well as their effects on neighbouring water masses.

280

Materials & Methods

Physico-chemical and N-cycling rate measurements

Large-scale distributions of chemical and biological variables were determined during the cruises M77-3 and 4 from December 2008 to February 2009 onboard R/V Meteor. 285 Seawater was collected with either a conductivity-temperature-depth (CTD) rosette system fitted with 10-L Niskin bottles or a pump-CTD system (depth range: ~375 m). Continuous vertical profiles of chlorophyll-*a* were obtained fluorometrically and calibrated against discrete values derived from acetone extraction. Oxygen was measured with a Seabird sensor, a conventional amperometric microsensor and a highly sensitive STOX (Switchable Trace amount Oxygen) sensor³⁹ (detection limit: 50 nmol L⁻¹). Dissolved inorganic N and PO₄³⁻ 290 concentrations were analyzed using standard protocols^{45,46}. Nitrogen deficits were calculated as N* following Gruber & Sarmiento⁴⁷. Rates of microbial N-cycling (NH₃ and NO₂⁻ oxidation, NO₃⁻ reduction, anammox, denitrification and DNRA) were determined in short-term, time-series incubation experiments with various combinations of ¹⁵N-labeled and 295 unlabelled compounds as described in Füssel et al.²² and Holtapples et al.⁴⁸. Oxygen sensitivity assays for NO₂⁻ oxidation were conducted as previously described²². Consistent rates for anammox were calculated from the various ¹⁵N-incubation experiments

($^{15}\text{NH}_4^+ \pm ^{14}\text{NO}_2^-$, $^{15}\text{NO}_2^- \pm ^{14}\text{NH}_4^+$, $^{15}\text{NO}_2^- \pm ^{14}\text{NH}_4^+$) for coastal OMZ stations; whereas more variability was associated with offshore OMZ stations. Although the possibility of substrate stimulation due to $^{15}\text{N}/^{14}\text{N}$ -amendments cannot be fully eliminated, marine microbes including anammox and nitrifying bacteria^{13,22} are often associated with particles, and thus can experience substrate concentrations several orders of magnitude greater than the ambient water⁴⁹ such that our measured rates could also be substantially underestimated. In order to examine whether the export production is sufficient to support these measured rates of various subsurface N-cycling processes and ultimately N-loss, the maximum potential rates for anammox from the various isotope-amendments (Supplementary Table 2) were used in budget calculations. Based on our combined rate measurements, nutrient inventories and subsequent modeling, the N-fluxes are sufficient to support all measured rates of N transformation. Hence, the here-presented measured rates may not be too far from reality.

310

Molecular ecological analyses

Water samples for nucleic-acids-based analyses were collected onto polyethersulfone membrane filters (0.2 μm ; Millipore) and immediately frozen at -80°C until further analysis. Nucleic acids were extracted using a Qiagen DNA/RNA All prep Kit following the manufacturers protocol with minor modifications⁵⁰. Functional genes for archaeal and bacterial (β -/ γ -proteobacterial) NH_3 oxidation (arch-*amoA* and β -/ γ -*amoA*, respectively), anammox (*hzo1* and 2), denitrification (denitrifier-*nirS*) and DNRA (*nrfA*) were PCR-amplified as described in Löscher et al.⁴⁹. Standards for quantitative PCRs were obtained from: *Nitrosococcus oceani* NC10 and *Nitrosomonas marina* NM22 and NM51 (γ - and β -*amoA*, respectively), an environmental clone (GenBank accession number JF796147; arch-*amoA*), *Candidatus* “*Scalindua profunda*” (*hzo1* and 2), *Pseudomonas aeruginosa* PAO1 (denitrifier-*nirS*) and *Escherichia coli* K12 (*nrfA*).

320

Modeling of export production

325 Export production was calculated from estimates of net primary production and the
ratio of export production to total primary production (*ef*-ratio). Net primary production
(NPP) at the time and location of our experimental stations was computed from measured
chlorophyll-a concentrations and satellite-based (MODIS ocean color data) estimates of
photosynthetic available radiation using the Vertically Generalized Production model⁴². *Ef*-
330 ratios were calculated from NPP and measured surface temperatures after Laws et al.⁴³.

Author contributions

TK, GL and MK designed the study. TK, GL, SC and AP performed ¹⁵N-labeling
335 experiments. TK, GL and PL analyzed the data. CL carried out functional gene analyses.
LA and AO modelled export production rates. LS provided CTD and ADCP data. TK, GL,
PL and MK wrote the manuscript.

The authors declare no competing financial interests.

340

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Table 1 | Abundance of selected N-functional genes and N-conversion rates in the ETSP during cruise M77-3.

Functional genes and N-conversion rates were not always determined at the same station and/or depths but with a comparable latitudinal and longitudinal as well as vertical resolution.

		N-functional gene abundances (10^2 copies mL ⁻¹)							N-conversion rates (nmol N L ⁻¹ d ⁻¹)					
		arch-amoA	β -amoA	γ -amoA	hzo1	hzo2	den-nirS*	nrfA	NH ₃ ox.	Anammox	Denitri- fication	DNRA	NO ₂ ⁻ ox.	NO ₃ ⁻ red.
Coastal OMZ (≤ 600 m)	N:	63 (64)	8 (49)	0 (64)	8 (64)	42 (64)	0 (63)	0 (64)	27 (33)	33 (33)	3 (33)	7 (33)	27 (32)	27 (32)
	Range:	0.16-2773	0.05-1056	-	0.05-0.09	0.14-12.8	-	-	0.22-48.8	2.84-227	2.21-5.42	0.48-1.74	8.48-928	3.79-1010
	Mean:	676	135	-	0.07	4.45	-	-	8.24	43.4	4.19	1.14	172	203
	Median:	90	5.0	-	0.06	3.77	-	-	3.40	21.2	4.94	1.10	65.4	101
Offshore OMZ (> 600 m)	N:	67 (71)	2 (33)	0 (72)	4 (71)	43 (72)	2 (72)	1 (72)	17 (40)	33 (40)	0 (40)	3 (40)	27 (40)	25 (34)
	Range:	0.04-2332	0.15-1.36	-	0.01-0.09	0.06-14.7	0.06-1.98	0.11	0.51-88.8	0.71-46.9	-	0.33-1.31	4.58-186	4.53-77.4
	Mean:	352	0.75	-	0.08	3.15	1.02	0.11	20.9	6.14	-	0.82	40.6	32.1
	Median:	89.5	0.75	-	0.08	1.51	1.02	0.11	5.79	3.01	-	0.83	30.2	22.3

N = number of samples in which N-functional genes/N-processes were detected; in parenthesis: number of samples analyzed.

*denitrifier-nirS.

Table 2 | Spearman rank correlation of depth-integrated nutrients and N-cycling rates as well as modelled export productions.

	NH₃ oxidation	NO₂⁻ oxidation	NO₃⁻ reduction	Anammox	Export Production
NH₄⁺	0.51*	0.31	0.08	0.30	0.29
NO₂⁻	0.46*	0.49*	0.71***	0.64**	0.10
N*	-0.08	-0.20	-0.05	-0.02	-0.02
Export Production	0.56*	0.60**	0.75***	0.79***	
Anammox	0.75***	0.86***	0.88***		
NO₃⁻ reduction	0.49*	0.75***			
NO₂⁻ oxidation	0.73***				

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Presented values are correlation coefficients with significant values denoted by * (p≤0.05), ** (p≤0.01) and *** (p≤0.001).

Figure legends

Figure 1 | Maps of sampling locations and nutrient distributions in the ETSP

OMZ. a, Sampling sites during M77-3 (●) and M77-4 (●) and ¹⁵N-experimental stations (●). **b,** vertical extent of the OMZ (in m) as defined by $O_2 \leq 15 \mu\text{mol L}^{-1}$. **c-f,** concentrations of NO_3^- , NO_2^- , NH_4^+ and N^* (in mol m^{-2}) integrated over the thickness of the OMZ. Red line in panel **a.** denotes the 600m-isobath that was used demarcate the coastal OMZ from offshore OMZ.

Figure 2 | Depth-integrated N-cycling rates in the ETSP OMZ. a,b, the two steps

of the aerobic nitrification, NH_3 oxidation and NO_2^- oxidation. **c,** NO_3^- reduction to NO_2^- . **d,e,** N-loss due to anammox as well as denitrification coupled to the oxidation of H_2S during a sulfidic event on the Peruvian shelf. **f,** modelled export of organic N from the euphotic zone to the OMZ. All rates in $\text{mmol N m}^{-2} \text{d}^{-1}$.

Figure 3 | N-fluxes and nutrient inventory of the ETSP OMZ. Black numbers

indicate inventories of dissolved inorganic nitrogen (in Tg N). They were derived from the depth-integrated values over the OMZ thickness shown in Figs. 1-2, and then based on the 600 m seafloor depth cut-off for coastal versus offshore OMZs, the depth-integrated values were further integrated over the areal extents of the two types of OMZs. Fluxes (in Tg N y^{-1}) within the OMZ or across its boundaries are given in colour and white, respectively. A detailed description of the flux calculations is included in the supplementary information.





