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Enrichment and Molecular Detection of Denitrifying Methanotrophic Bacteria of the NC10 Phylum

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Anaerobic methane oxidation coupled to denitrification was recently assigned to bacteria belonging to the uncultured phylum NC10. In this study, we incubated sediment from a eutrophic ditch harboring a diverse community of NC10 bacteria in a bioreactor with a constant supply of methane and nitrite. After 6 months, fluorescence in situ hybridization showed that NC10 bacteria dominated the resulting population. The enrichment culture oxidized methane and reduced nitrite to dinitrogen gas. We assessed NC10 phylum diversity in the inoculum and the enrichment culture, compiled the sequences currently available for this bacterial phylum, and showed that of the initial diversity, only members of one subgroup had been enriched. The growth of this subgroup was monitored by quantitative PCR and correlated to nitrite-reducing activity and the total biomass of the culture. Together, the results indicate that the enriched subgroup of NC10 bacteria is responsible for anaerobic methane oxidation coupled to nitrite reduction. Due to methodological limitations (a strong bias against NC10 bacteria in 16S rRNA gene clone libraries and inhibition by commonly used stopper material) the environmental distribution and importance of these bacteria could be largely underestimated at present.

Atmospheric concentrations of methane have risen 2.6-fold since preindustrial times (10). After several years of stagnation, there was again a clear increase in the methane concentration in 2007 (29). Currently, it is uncertain whether an increase in the number of sources and production or a decrease in the number of sinks and consumption is responsible for this reversal of the trend.

Freshwater habitats like natural wetlands and rice fields are a major source (38% [9]) of atmospheric methane. In the absence of other documented electron donors, aerobic methane oxidation is assumed to be the most important sink in these habitats, but the role of alternative electron donors is not well understood (19, 30). Anaerobic methane oxidation coupled to denitrification is energetically favorable, but evidence that it occurs is scarce. In marine, methane-containing sediments, nitrate and nitrite are usually not quantitatively important electron acceptors; in freshwater sediments the denitrifying and aerobic zones are in close proximity (3, 22, 35), possibly masking the process from detection. To our knowledge, concomitant methane and nitrate profiles of sediments have never been published.

So far, methane oxidation coupled to denitrification has received the most attention in the field of hydrogeology. In groundwater, contamination with nitrate and nitrite occurs frequently, whereas electron donors are limiting. Methane plumes often form around landfills, and their attenuation has sometimes been attributed to denitrification (2, 37). So far, a single previous study unambiguously demonstrated anaerobic oxidation of methane coupled to denitrification in a contaminated freshwater aquifer (32). The first in vitro observation of anaerobic methane oxidation coupled to denitrification came from a laboratory-scale sludge digestor (11). The use of a laboratory enrichment culture also eventually resulted in identification of the organisms involved; bacteria of the NC10 phylum and archaea of the order Methanosarcinales dominated a mixed culture carrying out anaerobic methane oxidation coupled to denitrification (27). This culture was enriched from a freshwater canal sediment after 1 year of continuous supply of methane and nitrite. Subsequently, the archaea were shown to be dispensable, as they disappeared after prolonged incubation of the same culture (7). Mass balance calculations showed that methane oxidation was coupled to the reduction of nitrite with a 3:8 stoichiometry, in accordance with theoretical expectations. The bacteria that dominated the mixed culture and apparently oxidized methane anaerobically are members of the NC10 phylum, one of the many phyla having no members in pure culture (8, 28). The 16S rRNA gene sequences of such organisms, however, have been found in a number of environmental surveys of aquatic environments; e.g., the most closely related sequences have been found in aquifers (1, 23) and lake sediments (13, 17). Sequence similarity and phylogenetic affiliation may indicate similar metabolic capacities of organisms, but by itself this is not sufficient to infer similar metabolism (5). This is especially true for denitrifying methanotrophs, because only a single enrichment culture has been described so far (7, 27).

The objective of the present study was to generalize the previous finding that NC10 bacteria were associated with an-
aerobic methane oxidation, a necessary step forward in addressing the significance of this poorly understood process as a methane sink in freshwater habitats.

MATERIALS AND METHODS

Sampling and enrichment. Sediment samples (upper 5 cm) were obtained in July 2006 from four ditches draining agricultural land in the Oostpolder (51°50′N, 5°54′E), a floodplain of the River Rhine in The Netherlands. The samples were transported to the lab within 1 h and mixed with ambient water to obtain a homogeneous slurry (2 liters) used for inoculation.

The sediment was incubated in a 16-liter glass bioreactor (Applikon, Schiedam, The Netherlands), which was operated aseptically in a sequencing-batch dam, The Netherlands), which was operated aseptically in a sequencing-batch process. After 6 months, the cycle was shortened to 22.5 h of supply of medium, draw off liquid from above the settled sediment and biomass. As activity in the enrichment culture after 6 months and stored at 4°C.

The samples were transported to the lab within 1 h and mixed with ambient water to obtain a homogeneous slurry (2 liters) used for inoculation. The minimum liquid volume of the enrichment culture was kept at 10 liters by means of a level controller, and the maximum volume at the end of a filling period was 13 liters. The culture vessel was wrapped in black foil, and black tubing with low oxygen permeability (Viton and Norprene; Cole Parmer, United States) was attached to the culture vessel to prevent entry of air during drawing off. The KHCO₃ and NaNO₂ contents of the medium were varied depending on the activity increase, after 6 months the cycle was shortened to 22.5 h of supply of medium, 1 h of settling, and 30 min of drawing off of liquid. During the supply period, the culture was stirred gently at 100 rpm, sparged with CH₄/CO₂ (95:5, vol/vol) to maintain anoxic conditions and contained the following components (per liter): KHCO₃, 0.5 to 1.5 g (see Results); NaNO₂, 0.25 to 0.3 g (see Results); MgSO₄, 0.3 g; CuSO₄, 0.095 g NiCl₂ 6H₂O, 0.068 g ZnSO₄ 7H₂O, 0.068 g ZnSO₄ 7H₂O, 0.068 g CuSO₄ 5H₂O, 0.32 g CuSO₄ 5H₂O. The alkaline (10 mM NaOH) trace element solution contained (per liter) 0.067 g FeSO₄ 7H₂O, 0.068 g ZnSO₄ 7H₂O, 0.12 g CoCl₂ 6H₂O, 0.5 g MnCl₃ 4H₂O, 0.5 mg CuSO₄ 5H₂O, 0.05 g MgSO₄ 7H₂O, 0.2 g NaNO₃, 0.425 g (5 mM); NaNO₃, 0.0345 to 1.38 g (0.2 to 50 mM) (see Results); an acidic trace element solution, 0.5 ml; and an alkaline trace element solution, 0.2 ml. The acidic (100 mM HCl) trace element solution contained (per liter) 2.085 g FeCl₃ 6H₂O, 0.068 g ZnSO₄ 7H₂O, 0.12 g CoCl₂ 6H₂O, 0.5 g MnCl₃ 4H₂O, 0.5 mg CuSO₄ 5H₂O, 0.05 g MgSO₄ 7H₂O, 0.2 g NaNO₃, 0.425 g (5 mM); NaNO₃, 0.0345 to 1.38 g (0.2 to 50 mM) (see Results); an acidic trace element solution, 0.5 ml; and an alkaline trace element solution, 0.2 ml.

TABLE 1. Primers and PCR conditions for the 16S rRNA gene libraries

<table>
<thead>
<tr>
<th>Clone library</th>
<th>Designation Forward primer</th>
<th>Sequence (5′-3′)</th>
<th>Reverse primer</th>
<th>Annealing temperature (°C)</th>
<th>Amplicon positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ino-nFR</td>
<td>202F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>GAC CAA AGG GGG CGA GCG</td>
<td>1043R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>TCT CCA CGC TTC CTT GCG</td>
<td>69</td>
</tr>
<tr>
<td>Ino-Ra</td>
<td>8F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>AGA GTT TGA TMY TGG CTC AG</td>
<td>1043R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>TCT CCA CGT TTC CTT GCG</td>
<td>57</td>
</tr>
<tr>
<td>Ino-Rb</td>
<td>8F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>AGA GTT TGA TMY TGG CTC AG</td>
<td>1043Rb&lt;sup&gt;a&lt;/sup&gt;</td>
<td>GGT TAC CTT GTC ACG ACT T</td>
<td>57</td>
</tr>
<tr>
<td>Ino-F</td>
<td>202F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>GAC CAA AGG GGG CGA GCG</td>
<td>1492R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>TCT CCA CGC TTC CTT GCG</td>
<td>59</td>
</tr>
<tr>
<td>Enr-Ra</td>
<td>8F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>AGA GTT TGA TMY TGG CTC AG</td>
<td>1043R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>TCT CCA CGT TTC CTT GCG</td>
<td>58</td>
</tr>
<tr>
<td>Enr-Rb</td>
<td>8F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>AGA GTT TGA TMY TGG CTC AG</td>
<td>1043R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>TCT CCA CGT TTC CTT GCG</td>
<td>58</td>
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<td>Enr-F</td>
<td>202F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>GAC CAA AGG GGG CGA GCG</td>
<td>1492R&lt;sup&gt;a&lt;/sup&gt;</td>
<td>GGT TAC CTT GTC ACG ACT T</td>
<td>60</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on previously described FISH probes (27).
<sup>b</sup> See reference 12.
<sup>c</sup> See reference 21.
<sup>d</sup> The positions are based on the gap-free sequence of the NC10 bacterial clone D-BACT (GenBank accession no. DQ369742), starting at E. coli position 8.

DNA quality was checked by agarose gel electrophoresis, and the DNA concentrations of samples for qPCR were measured at 260 nm with a Spectrace 3000 spectrophotometer (Bio-Rad).

(ii) Phylogenetic analysis. To assess the diversity of bacteria affiliated with the NC10 phylum, 16S rRNA gene libraries were constructed after PCR amplification of DNA isolated from the inoculum (library Ino) and the enrichment culture (library Enr) after 6 months of incubation. One library (library Ino-nFR) was obtained using a nested PCR approach: a PCR with a general bacterial primers 8F and 1545R (12) was followed by a second amplification using a specific primer pair and a high annealing temperature. The other libraries were obtained with combinations of a specific primer with a general primer and relatively low annealing temperatures (Table 1). PCR products were amplified in Escherichia coli with the pGem-T Easy cloning vector (Promega, United States). Plasmids were isolated from 10 to 15 randomly selected clones per library using a Genelute miniprep kit (Fermentas, Lithuania). Sequencing was performed at the DNA Diagnostics Center of Nijmegen University Medical Center using both the M13 forward and reverse primers. The quality of sequences was checked with the FinchTV program, and a BLAST search was performed to obtain related sequences (>90% similarity) from GenBank (http://www.ncbi.nlm.nih.gov [GenBank/ accessed October 2008]). Additionally, all sequences assigned to the NC10 phylum by the taxonomies of Hugenholtz and Pace (http://genegenes.ibl.gov [August 2008]) were added. To cover the full NC10 phylum, short sequences (minimum length, 548 bp) were also included. Three species of Acidobacteria, a closely related phylum (8), served as an outgroup. The sequences were aligned with the MUSCLE algorithm (6) and imported into the MEGA4 software (36), where the alignment was manually checked and trimmed. Phylogenetic trees were calculated on basis of 1,394 and 800 aligned positions (positions containing alignment gaps and missing data were eliminated only in pairwise sequence comparisons) with the MEGA’s neighbor-joining, maximum parsimony, and minimum evolution (Fig. 1) methods, which yielded the same overall topology. The robustness of tree topology was also tested by bootstrap analysis (1,000 replicates).

Evolutionary distances were computed with the Tajima-Nei correction. The phylum was divided into four well-supported groups (groups a to d).

(iii) qPCR. Based on the 16S rRNA gene sequences obtained from the enrichment culture, the sequence of a previously enriched bacterium (27), clone D-BACT (GenBank accession no. DQ369742), and closely related sequences (DQ837241, DQ837250, and AF351217), two primer pairs for qPCR were designed: qPF (5′-GGG CTT GAC TAT CCA CGA ACC TG-3′) and qPR (5′-CCG CCT TCT CCT CCA GCT TGA CGC-3′) amplify positions 1001 to 1201, and qPF (5′-GGG CTT GAC TAT CCA CGA ACC TG-3′) and qPR (5′-GCT CAC ACG GCT TTC GAG TAC AG-3′) amplify positions 108 to 128. The primers and their optimal annealing temperature were tested with the enrichment culture (8) and the qPCR products obtained with the oligo mass calculator, vers. 1.3 (http://library.med.utah.edu/masspec/mongo.htm) and the plasmid concentration determined by spectrophotometric measurement with a Spectrace 3000 (Bio-Rad) at 260 nm. qPCR for the standard curves and the samples was performed with the Bio-Rad iQ5™ cycler and real-time detection system using
IQTM SYBR green Supermix (Bio-Rad, United States), 800 nM forward primer, and 800 nM reverse primer. An initial denaturing step of 95°C for 3 min was followed by 40 cycles of 95°C for 1 min, 63°C for 1 min, and 72°C for 1 min. After a final extension for 5 min at 72°C, a melting curve analysis was carried out at temperatures from 60°C to 95°C, increasing at a rate of 0.5°C/30 s. The calculated efficiency was 100% for both primer pairs. The copy numbers in samples were calculated based on comparison with the threshold cycle values of the standard curve, taking into account the dilution and the liquid volume of the bioreactor during sampling.

(iv) FISH. Biomass from the enrichment culture was harvested monthly, fixed, stored, and subjected to fluorescence in situ hybridization (FISH) as described previously (7), using a concentration of 40% formamide. The following probes were used: S-*-DBACT-0193-a-A-18 and S-*-DBACT-1027-a-A-18 for domi-

Activity measurements. For batch incubation, biomass was transferred aero-

Analysis of nitrogen compounds, methane, and protein. The nitrite concent-

with Ar-CO₂ (95:5), followed by 5 min of flushing with Ar-CO₂, leaving an overpressure of 0.5 × 10⁻⁵ Pa. Methane was added to final headspace concentra-

tions of 2.5 to 10%. Samples were incubated on a magnetic stirrer at 30°C. To assess formation of gaseous N compounds, twofold-concentrated samples were preincubated anaerobically with methane until the residual nitrite and nitrate were exhausted, and [¹⁵N]nitrite (99.6% ¹⁵N; Isotec, United States) was used as the sole electron acceptor.

FIG. 1. Phylogenetic tree of the NC10 phylum with Acidobacteria as the outgroup. The sequences obtained from the inoculum of the enrichment culture (libraries Ino-nFR, Ino-F, Ino-Ra, and Ino-Rb) are indicated by an open star, and the sequences obtained from the enrichment culture after 6 months (libraries Enr-F, Enr-Ra, and Enr-Rb) are indicated by a filled star. The tree was calculated using the minimum evolution method and the Tajima-Nei correction. Bootstrap support values greater than 50% (n = 1,000) are indicated at the nodes, and the branches supported by all treeing methods (see Materials and Methods) are indicated by a circle.
Enhanced MSD Chem Station (version E.02.00.493; Agilent). Calibration was performed with standards consisting of $^{28}\text{N}_2$ in helium. Additionally, the initial and final concentrations of $\text{N}_2$ and $\text{N}_2\text{O}$ were verified by gas chromatography as described previously (7).

Nucleotide sequence accession numbers. The sequences of 16S rRNA genes have been deposited in the GenBank database under accession no. FJ621531 to FJ621562.

RESULTS AND DISCUSSION

Using previously described FISH probes (27) as primers in a nested PCR approach, we screened several freshwater sediments for the presence of phylum NC10 sequences. Of those, sediments from a ditch draining agricultural land in a floodplain of the River Rhine yielded an amplicon of the correct length. The sequences obtained after cloning (library Ino-nFR) (Table 1 and Fig. 1) were related to the bacterium dominating an enrichment culture performing anaerobic methane oxidation coupled to denitrification (27) and fell into two distinct groups (groups a and b) of the NC10 phylum. However, these bacteria were not detected in the sediment with FISH using the same probes. Because of the strong background fluorescence of sediment particles, only a few bacteria were visible, and no archaea could be detected.

The sediments were subsequently used to inoculate an anaerobic continuous culture bioreactor. The culture was sparged with $\text{CH}_4$/$\text{CO}_2$ as the sole carbon sources and supplied with mineral medium containing nitrite and nitrate as electron acceptors. In the first 3 weeks, the nitrite-reducing activity in the culture decreased from 4.6 mmol day$^{-1}$ to zero (Fig. 2). After a 110-day period without measurable activity, nitrite reduction resumed, and methane oxidation activity, although still low, could be measured in a batch experiment with the whole culture from day 136 to day 142 (Fig. 2) (methane oxidation activity, 0.18 mmol min$^{-1}$ mg protein$^{-1}$, as determined using previously described methods [7]). Until day 217, nitrite reduction increased in a roughly linear fashion up to a maximum of 33.5 mmol day$^{-1}$ (Fig. 2). During this period, the nitrite concentration in the medium could be increased from 0.5 to 20 mM with nearly complete consumption by the culture. The KHCO$_3$ concentration was decreased from 15 to 0.5 mM to compensate for H$^+$ consumption associated with denitrification. The stagnation of activity at values between 27 and 32 mmol day$^{-1}$ starting around day 230 may have been caused by the removal of about 2.3 liters of culture liquid with biomass (corresponding to ca. 1.1 g protein) for experiments over a 2-month period. In this period, the culture contained 4.75 ± 0.8 g protein, and the specific activity was 3.4 to 5.6 nmol NO$\text{$_2$}^-\text{min}^{-1}$ mg protein$^{-1}$.

Methane oxidation activity and its coupling to denitrification was further demonstrated in different batch experiments (Fig. 3). Initially, all attempts to detect activity in serum bottles failed, which was also observed in a previous study (7). This was apparently due to the use of black butyl rubber stoppers, which caused total inhibition of the activity (Fig. 3A). Anoxic handling of the biomass, in contrast, was not crucial; exposure to oxygen during transfer to the bottles did not lead to lower activity. Repeated boiling of black stoppers in water and diluted HCl did not eliminate the inhibition. It is generally
known that some aerobic methanotrophs can be inhibited by such stoppers, but for anaerobic methanotrophs this was completely unexpected. This observation makes it clear that in future studies of denitrification coupled to methane oxidation it is essential to choose a suitable stopper material. Using thick (0.8 mm) red butyl rubber stoppers manufactured for blood collection tubes or gray butyl rubber stoppers, we obtained specific activities of 1.6 to 2.2 nmol CH$_4$ min$^{-1}$ mg protein$^{-1}$ and 4.7 to 5.1 nmol NO$_2^-$ min$^{-1}$ mg protein$^{-1}$ in small-batch incubations, which were indistinguishable from the values for the continuous culture (3.4 to 5.6 nmol NO$_2^-$ min$^{-1}$ mg protein$^{-1}$). The specific activities observed here also compare well with previously described activities of similar enrichment cultures (3.7 nmol NO$_2^-$ min$^{-1}$ mg protein$^{-1}$ [7, 27]) and cultures of anaerobic, archaeal methanotrophs (1.7 nmol CH$_4$ min$^{-1}$ mg protein$^{-1}$ [24]). The observed stoichiometry of nitrite consumption versus methane consumption (8:3.5) was similar to the theoretical value, 8:3 (7, 27). No ammonium formation was detected (detection limit, 20 µM).

After 5 months of enrichment, FISH was successful using the previously described probes targeting denitrifying methanotrophic bacteria of the NC10 phylum. The amount of bacterial biomass relative to the amount of sediment particles had strongly increased, decreasing the autofluorescence. Individual NC10 cells were visible in a matrix of other bacteria. One month later, the NC10 bacteria had become the dominant bacteria, and the level of enrichment was about 70% after 7 months. In the small rods (ca. 0.8 to 1 by 0.3 to 0.5 µm) the 4',6'-diamidino-2-phenylindole (DAPI) signal was concentrated in the center of each cell, and the cells occurred both as aggregates and as single cells (Fig. 4). Archaea were not de-
ectected at any time, confirming that they are dispensable for the nitrite-reducing, anaerobic oxidation of methane (7).

Even though NC10 phylum bacteria already accounted for more than 50% of the population in the enrichment culture, they were not detected in a clone library (31 clones) obtained after 6 months with general 16S rRNA gene primers (primers 8F and 1545R [12]). Instead, this library was dominated by uncultured Acidobacteria (11 clones) and Chloroflexi (10 clones) (data not shown). In order to explore the diversity of NC10 bacteria, we used combinations of general bacterial 16S rRNA gene primers and specific primers (Table 1) with DNA extracted from the inoculum and the enrichment culture. With this approach, most sequences obtained were affiliated with the NC10 phylum. As expected, their diversity in the inoculum was much greater than that in the enrichment culture after 6 months. The sequences amplified from the inoculum represented two groups, a and b (Fig. 1), but after 6 months only group a sequences were retrieved. This group also includes the strain previously enriched from the Twentekanaal (27) and several sequences from other freshwater environments (e.g., denitrifying zones of Lake Biwa sediments [17] and the Doñana aquifer [23] and methane-bearing sediment from Lake Washington [13]) and seems to be associated with anaerobic methane oxidation. Whether this is also the case for group b, many members of which were also found in the inoculum used, remains to be determined. Still, all sequences of the NC10 phylum known to date (Fig. 1) come from aquatic, potentially anoxic, methane-bearing environments. Very likely, these bacteria are underrepresented in biodiversity surveys performed with general primers, since they were not detected with 16S rRNA gene clone libraries even when they made up the majority of the microbial community. The cause of this strong negative bias is unclear. Our results indicate that the general primers used did not have mismatches with the targeted sequences. Also, there was no overrepresentation of the nucleotides A and T at the priming sites binding to the wobble bases of the degenerate forward primer, another factor shown to decrease amplification efficiency (26).

For the enriched group a, two primer pairs for qPCR were developed and used with samples collected throughout the enrichment procedure (Fig. 2). In negative controls, the cycle threshold value was more than 40 cycles, whereas the cycle threshold value of all samples was less than 29. The melting curve for the PCR products from the first 2 months had several peaks, indicating that there was formation of multiple products. This can be attributed to the high concentration of non-target DNA in these samples. The first two measurements, therefore, are upper estimates and are less reliable than quantifications after day 71, when only one peak was observed. Nevertheless, the reproducible, twofold difference between the two primer sets remains difficult to explain. Both primer sets had no mismatches with the template 16S rRNA gene sequence, and the PCR efficiencies of the dilution curves were identical (100%). Other authors have found differences of up to 26% even with the same primer set (31), illustrating the limits of the qPCR approach. Multiple primer sets, like those used in the present study, do not necessarily generate more reliable results, but they can provide a more realistic view of the uncertainties of this technique and underline the need to confirm the findings with other non-PCR-based methods.

However, the growth of the target population could be demonstrated by qPCR approximately 1 month before its activity became detectable (Fig. 2, inset).

Assuming one or two copies of the 16S rRNA gene per cell (a realistic estimate for slowly growing bacteria [16]), the specific per-cell activity was approximately 0.09 fmol CH₄ day⁻¹ cell⁻¹ (for one copy) or 0.18 fmol CH₄ day⁻¹ cell⁻¹ (for two copies) assessed with qPCR primer pair qP1. With primer pair qP2, this value was 0.20 fmol CH₄ day⁻¹ cell⁻¹ (for one copy) or 0.40 fmol CH₄ day⁻¹ cell⁻¹ (for two copies). These values are low, but given the tiny cell size (volume of roughly 0.05 to 0.2 µm³), they are still on the same order of magnitude as the values for other slowly growing, anaerobic bacteria (e.g., 2.6 to 6.36 fmol NH₄ day⁻¹ cell⁻¹ for anaerobic ammonium-oxidizing bacteria [20]). We also assessed the agreement between the number of cells and the protein content of the culture using the estimates of cell volume (0.05 to 0.2 µm³) to determine the approximate protein content using the formula of Norland et al. (for the relationship between cell volume and dry weight [25]). If we multiplied the dry weight by the cell number obtained by qPCR (see above) and assumed that protein accounts for 50% of the dry weight, we obtained a theoretical content of 0.3 to 4.5 g for the enrichment culture. This matches the measured protein content, 4.75 ± 0.8 g, well, especially when the presence of other nontargeted bacteria is considered.

The steady increase in copy number from day 71 onward coincides with an increase in nitrite-reducing activity and biomass. Together, these results support the hypotheses that the denitrification observed in the first month of enrichment can be attributed to the oxidation of endogenous electron donors (decaying biomass, also indicated by the decreasing DNA content [Fig. 2]) present in the sediment, whereas the increase in biomass and nitrite-reducing activity observed from month 4 onward was predominantly due to the growth of bacteria belonging to NC10 group a using methane as an electron donor. Together with the results of previous studies (7, 27), these findings strongly support a general role for these organisms in the biochemically enigmatic process of anaerobic methane oxidation coupled to denitrification.

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