A novel marine nitrite-oxidizing *Nitrospira* species from Dutch coastal North Sea water

Suzanne C. M. Haaijer1*, Ke Ji1, Laura van Niftrik1, Alexander Hoischen2, Daan Speth1, Mike S. M. Jetten1, Jaap S. Sinninghe Damstè3 and Huub J. M. Op den Camp1

1 Department of Microbiology, Institute for Water and Wetland Research, Radboud University Nijmegen, Nijmegen, Netherlands
2 Department of Human Genetics, Nijmegen Center for Molecular Life Sciences, Institute for Genetic and Metabolic Disease, Radboud University Nijmegen, Nijmegen, Netherlands
3 Department of Marine Organic Biogeochemistry, Royal Netherlands Institute for Sea Research, Den Burg, Texel, Netherlands

**INTRODUCTION**

The ocean is the largest reservoir of fixed nitrogen on Earth containing about five times more fixed nitrogen than terrestrial systems (Gruber, 2008) which renders marine systems of major importance to global nitrogen cycling. Nitrogen, as the bioavailable forms of ammonium and nitrate, is one of the key nutrients in marine waters and may limit primary production especially in coastal systems (Downing, 1997; Wollast, 1998). Most of the fixed organic nitrogen in the ocean is converted to nitrate by remineralization consisting of ammonification and nitrification (Gruber, 2008).

In the two-step process of nitrification, ammonia is oxidized first to nitrite by aerobic ammonia-oxidizing microorganisms and then to nitrate by aerobic nitrite-oxidizing microorganisms. The microbial mediators of nitrification have intrigued scientists ever since the hallmark publication by Winogradsky (1890) in which not only the ability of nitrifying organisms to withdraw energy from mineral substances was reported but it was also concluded that these microorganisms assimilate carbon from carbon dioxide. At present, after 120 years of research efforts, many nitrifying microorganisms are available in culture, and therefore amenable to physiological characterization, but marine species are underrepresented. For instance, when evaluating the phylogeny of *β*-proteobacterial ammonia-oxidizing bacteria (AOB) Aakra et al. (2001) examined no less than 38 isolates of which only five had a marine origin. In the review by Koops and Pomerening-Röser (2001) on the distribution and ecophysiology of nitrifying bacteria the phylogenetic relationship of 19 cultured AOB species is shown and for only five of those species a preference for a marine habitat is indicated. In marine ecosystems ammonia-oxidizing archaebacteria (AOA) species have been shown to outnumber their bacterial counterparts based on direct cell counts and gene (16S rRNA and amoA) copy numbers (Francis et al., 2005; Wuchter et al., 2006; Mincer et al., 2007). Currently, however, the only two cultured AOA species with a marine or estuarine origin are *Nitrosopumilus marina* and *Nitrospina marina* as the next taxonomically described relative (94% 16S rRNA sequence identity). Transmission electron microscopy analysis revealed a cell plan typical for *Nitrosopumilus* species. The cytoplasm contained electron light particles that might represent glycogen storage. *Nitrosopumilus*-targeted polymerase chain reaction analyses demonstrated the presence of the enriched *Nitrosopumilus* species in a time series of North Sea genomic DNA samples. The availability of this new *Nitrosopumilus* species enrichment culture facilitates further in-depth studies such as determination of physiological constraints, and comparison to other NOB species.

**Keywords:** marine nitrification, enrichment, *Nitrosopumilus*, *Nitrosira*, fluorescence in situ hybridization, transmission electron microscopy, 16S rRNA

---

Marine microorganisms are important for the global nitrogen cycle, but marine nitrifiers, especially aerobic nitrite oxidizers, remain largely unexplored. To increase the number of cultured representatives of marine nitrite-oxidizing bacteria (NOB), a bioreactor cultivation approach was adopted to first enrich nitrifiers and ultimately nitrite oxidizers from Dutch coastal North Sea water. With solely ammonia as the substrate an active nitrifying community consisting of novel marine *Nitrosomonas* aerobic ammonia oxidizers (ammonia-oxidizing bacteria) and *Nitrospira* and *Nitrospina* NOB was obtained which converted a maximum of 2 mmol of ammonia per liter per day. Switching the feed of the culture to nitrite as a sole substrate resulted in a *Nitrospira* NOB dominated community (approximately 80% of the total microbial community based on fluorescence in situ hybridization and metagenomic data) converting a maximum of 3 mmol of nitrite per liter per day. Phylogenetic analyses based on the 16S rRNA gene indicated that the *Nitrospira* enriched from the North Sea is a novel *Nitrospira* species with *Nitrospira marina* as the next taxonomically described relative (94% 16S rRNA sequence identity). Transmission electron microscopy analysis revealed a cell plan typical for *Nitrosopumilus* species. The cytoplasm contained electron light particles that might represent glycogen storage. A large periplasmic space was present which was filled with electron dense particles. Transmission electron microscopy analysis revealed a cell plan typical for *Nitrosopumilus* species. The cytoplasm contained electron light particles that might represent glycogen storage. A large periplasmic space was present which was filled with electron dense particles. *Nitrosopumilus*-targeted polymerase chain reaction analyses demonstrated the presence of the enriched *Nitrospira* species in a time series of North Sea genomic DNA samples. The availability of this new *Nitrospira* species enrichment culture facilitates further in-depth studies such as determination of physiological constraints, and comparison to other NOB species.
ENRICHMENT WITH AMMONIA AS THE SUBSTRATE

The culture was amended with 300 μM NH₄Cl and incubated for 19 days as a batch and then for another 2 days after addition of 400 μM NH₄Cl. To avoid nitrite toxicity, the reactor system was thereafter switched to a continuous mode of operation using medium containing 750 μM NH₄Cl at a dilution rate of 0.25 day⁻¹. When nitrite disappeared from the culture, indicating activity of nitrite oxidizers, the ammonium concentration was subsequently increased to 1.5 mM after 3 months, and further to 2, 3, and finally 10 mM after 4, 4.5, and 5.5 months, respectively. The reactor was switched to nitrite as the sole substrate after 7 months.

ENRICHMENT WITH NITRITE AS THE SUBSTRATE

To stimulate growth of the nitrite oxidizers, a batch mode of operation was adopted and 750 μM NaNO₂ provided as the substrate. Whenever nitrite was depleted, it was restored to 750 μM. In this manner, a total of 43 mmol of nitrite were supplied in the first 43 days as a batch and then for another 2 days after addition of 60 mmol of nitrite. After 1 month, a fed-batch mode of operation was adopted by adding medium containing 30 mM NaN₂O₃ at a flow rate starting at 40 ml per day. The pump rate...
of the influent was increased manually in small (~10 ml day$^{-1}$) steps whenever $\text{NO}_2^-$ levels remained below 2 mg/L to a final rate of 100 mg per day. To retain biomass, the reactor content was allowed to settle once for a week after which clarified liquid was removed to maintain a maximum reactor volume of 2 L. Removal of wall growth and fourfold dilution of the biomass were performed as described above after 2 and 4 months. The influent nitrite concentration was raised from 10 to 20, 40, 60, 80 mM and finally 100 mM after 6, 9, 10, 10.5, and 11 months, respectively, by increasing the flow rate from 40 to 100 ml per day in 10 ml steps keeping $\text{NO}_2^-$ levels below 2 mg/L. In order to prevent suboptimal nitrite oxidizer growth rates due to carbon limitation, the gas flow of 80 ml/min of air was supplemented with 10 ml/min Argon/CO$_2$ (95%/5%) from 7.5 months onward. It has furthermore been reported that iron as well as phosphate may become limiting compounds for growth (van de Vossenberg et al., 2008) when a medium containing only natural sea salts is used to enrich marine microorganisms. Therefore, the influent was supplemented with 0.261 ml/L 1 M KH$_2$PO$_4$ and 0.45 ml/L of a 5 g/L FeSO$_4$·7H$_2$O (95%/5%) from 7.5 months onward. During the last month the biomass was no longer allowed to settle prior to medium replenishment resulting in an actual dilution rate of 0.05 day$^{-1}$.  

**CHEMICAL ANALYSES**

To estimate nitrate concentrations liquid samples were measured directly using Merckquot$^\text{a}$ teststrips (range for nitrate 10–500 mg/L; nitrite 2–80 mg/L; Merck BV, Schiphol-Rijk, the Netherlands). At least once a week, 0.5 ml aliquots were centrifuged (3 min 10,000 × g) and the resulting supernatants used for more elaborate colorimetric analyses to monitor residual ammonium and nitrate concentrations. To measure nitrite, a colorimetric method adapted from Griess-Roijen-van Eijk (1966) was used. A mixture of 50 μl with 0.5 ml of reagent A (10 g of sulfanilic acid in 1 L 1 M HCl) and 0.5 ml reagent B (1 g 1-2-N-naphthylethenediamine dihydrochloride in 1 L distilled water) was incubated for 10 min at room temperature, and measurements performed at 540 nm. Ammonium concentrations were determined using ortho-phenaldialdehyde (OPA) reagent (Both, 1971; Taylor et al., 1974). The OPA reagent consisted of 8.54 g of OPA dissolved in 10 ml of absolute ethanol, with 50 μl of β-mercaptoethanol, and filled to 100 ml with sodium phosphate buffer (0.3 M pH 7.3). To measure ammonium concentrations between 0.25 and 5 mM 50 μl sample was mixed with 800 μl OPA reagent, incubated (20 min, room temperature, in the dark), and the extinction measured (420 nm). To measure in the range of 0.25–300 μM, 100 μl of sample was mixed with 2 ml OPA reagent containing only 0.054 g/100 ml OPA, incubated (20 min, room temperature, in the dark) and measured with a fluorescence spectrophotometer (excitation 411 nm, emission 482 nm, slit size 5 nm, 600 V).

**FLUORESCENCE IN SITU HYBRIDIZATION**

Biomass was harvested from 20 ml reactor material by centrifugation (10 min 10,000 × g) and fixed for FISH analyses by addition of 4% w/v paraformaldehyde, incubating on ice (2 h), centrifuging (15 min 10,000 × g) and washing the resulting pellet with phosphate buffered saline (PBS, pH 7.2) and finally adding PBS and 100% EtOH (1:1) to reach a volume of 10% of the original sample. Fixed material was stored at −20°C until analysis. FISH analyses on fixed biomass from the start, after 1 and 6 months of the nitrite-fed period were performed as described by Amann et al. (1990), using 10 μl fixed material per hybridization. Vectashield (Vector Laboratories, Inc., Burlingame, CA, USA) mounting medium with DAPI (4,6-diamino-2-phenylindole) was used to enhance the fluorescent signal and stain all DNA. Specifications and details of probes used in this study are presented in Table 1. Probes were purchased as Cy3-3, Cy-5, and 3(6)-carboxyfluorescein-N-hydroxyuccinimide-ester (FLUOS) labeled derivatives from Thermohybird (Ulm, Germany). To visualize Nitrosomas sp AOB and Nitrosipora NOB simultaneously, probes NEU 653 (FLUOS) and NTSPA 712 (Cy5) were used together with their respective competitors (competitor probes consisted of unlabeled oligonucleotides) in single hybridizations at a formamide concentration of 35%. To detect Nitrospina sp NOB, hybridizations were performed at 29% formamide concentration with probe NTSPN693. To stain all bacteria, a mixture of probes EUB338, EUB338 II, and EUB338 III was used for all hybridizations. Microscopic inspections were performed at a 1000-fold magnification. For image acquisition a Zeiss Axioplan 2 epifluorescence microscope (Zeiss, Jena, Germany) was used with the standard software package (version 3.1). Abundance estimates of cells hybridizing with a particular probe were based on visual inspection of three randomly taken FISH microscopy pictures per hybridization.

**EXTRACTION HIGH MOLECULAR WEIGHT DNA**

Biomass was harvested from 20 ml reactor content by centrifugation (20 min, 2400 × g) after 3.5 months with ammonia, and after 6 months with nitrite as the sole substrate, respectively. Biomass was also harvested from 50 ml reactor content after 12 months with nitrite as the substrate. High molecular weight DNA was extracted using a cetyltrimethyl-ammoniumbromide (CTAB) and sodium dodecyl sulfate (SDS)-lysis-based method adapted from Zhou et al. (1996). Biomass was suspended in 1 ml CTAB extraction buffer (1g/100 ml CTAB, 100 mM Tris, 100 mM EDTA, 100 mM sodium phosphate, 1.5 M NaCl, pH 8), 50 μl lysozyme (10 mg/ml, 66200 U/mg) and 30 μl Rnase A (10 mg/ml, ≥5000 U/mg). After addition of 50 μl of proteinase K (10 mg/ml, 20 U/mg) and incubation for 30 min at 37°C, the mixture was supplemented with 150 μl 10% SDS and incubated at 65°C for 2 h. DNA was recovered by phenol/chloroform extraction and isopropanol precipitation after which it was suspended in 40 μl ultrapure water (MilliQ, Millipore SA, Molsheim, France) and stored at 4°C until use.

**PCR REACTIONS, CLONING, SEQUENCING, AND SEQUENCE ANALYSES**

Polymerase chain reaction analyses (30 cycles, followed by a final extension for 10 min at 72°C) were performed in a T gradient PCR apparatus (Whatman Biometra, Göttingen, Germany) using...
**Haaijer et al. A novel North Sea Nitrospira species**

### Table 1 | Oligonucleotide specifications.

<table>
<thead>
<tr>
<th>Name</th>
<th>Used for</th>
<th>Sequence (5′–3′)</th>
<th>Position</th>
<th>Target</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUB338</td>
<td>FISH</td>
<td>GCTGCCCTCCCGTAGGAGT</td>
<td>338</td>
<td>Most Bacteria</td>
<td>Amann et al. (1990)</td>
</tr>
<tr>
<td>EUB338 II</td>
<td>FISH</td>
<td>GCAACCCACCGTAGGAGT</td>
<td>338</td>
<td>Most Planctomycetes</td>
<td>Daims et al. (1999)</td>
</tr>
<tr>
<td>EUB338 III</td>
<td>FISH</td>
<td>GCTGCCACCGTAGGAGT</td>
<td>338</td>
<td>Most Verrucomicrobiales</td>
<td>Daims et al. (1999)</td>
</tr>
<tr>
<td>NEU653</td>
<td>FISH</td>
<td>CCCCCTCCTCGCAGTCTCA</td>
<td>653</td>
<td>Most Nitrospira</td>
<td>Wagner et al. (1995)</td>
</tr>
<tr>
<td>Competitor NEU653 FISH</td>
<td>TTTCCCACCCCTCTCGCG</td>
<td>Nitrosomonas spp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTS PA712</td>
<td>FISH</td>
<td>CGCCCTCAGCCCGAGCTCC</td>
<td>712</td>
<td>Most members of the phylum</td>
<td>Daims et al. (2001)</td>
</tr>
<tr>
<td>Competitor NTS PA712 FISH</td>
<td>CGCCCTCAGCCCGAGCTCC</td>
<td>Nitrospira</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTS PA863</td>
<td>FISH</td>
<td>TCTCAATTATACGGTTGATT</td>
<td>683</td>
<td>Nitrospira gracilis</td>
<td>Jurutskh (2000)</td>
</tr>
<tr>
<td>610F PCR</td>
<td>AGGTTTTAGYMTGGCTCAG</td>
<td>8</td>
<td>Bacteria</td>
<td>Jurutskh (1999)</td>
<td></td>
</tr>
<tr>
<td>610I IF</td>
<td>GTGCCAGCAGCCGCGGT</td>
<td>679</td>
<td>Most bacteria</td>
<td>Ustinova et al. (2001)</td>
<td></td>
</tr>
<tr>
<td>M13F</td>
<td>GAGACACAGGGGCTACGAG</td>
<td>158</td>
<td>Most Nitrospira</td>
<td>Maixner et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>NTS PA1158R PCR</td>
<td>AGTGGCGAACGGGTGAGGAATA</td>
<td>87</td>
<td>Most Nitrospira</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>NTS PA1124R PCR</td>
<td>GTGCCAGCAGCCGCGGT</td>
<td>1529</td>
<td>Most Nitrospira</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>610F IF</td>
<td>GTGCCAGCAGCCGCGGT</td>
<td>479</td>
<td>Most bacteria</td>
<td>Pochop et al. (2001)</td>
<td></td>
</tr>
<tr>
<td>NTSPN 693</td>
<td>FISH</td>
<td>TCTCCAGAGCTGGCTGCCATTA</td>
<td>1158</td>
<td>Nitrospira gracilis</td>
<td>Maixner et al. (2006)</td>
</tr>
<tr>
<td>NTSPN 693</td>
<td>FISH</td>
<td>TCTGCTCAGCTGAGCTGCCATTA</td>
<td>1158</td>
<td>Nitrospira gracilis</td>
<td>Maixner et al. (2006)</td>
</tr>
</tbody>
</table>

*E. coli numbering.

GoTaq® Green Master Mix (Promega Benelux BV, Leiden, the Netherlands). A PCR cycle consisted of, 1 min at 93°C, 1 min at annealing temperature (Ta) and 1.5 min at 72°C. For each 25 μl volume PCR reaction, 1 μl of 10-fold diluted high molecular weight DNA was used as the template. Resultant products were cloned using the pEASY-T easy vector cloning kit (Promega Benelux BV, Leiden, the Netherlands). Plasmid DNA was extracted using the GeneJet Plasmid Miniprep Kit (Fermentas GMBH, St. Leon-Rot, Germany). Clones were checked by restriction analysis of plasmid DNA (EcoRI, Fermentas GMBH, St. Leon-Rot, Germany). Sequencing (Sanger method) was performed at the division DNA diagnostics of the Human Genetics department of the University Medical Centre Nijmegen St Radboud. The ContigExpress program of the Vector NTI Suite 7.0 software package (Informax) was used to assemble full-length clone sequences. Cloned 16S rRNA gene sequences were compared with their closest relatives in the GenBank database by BLASTN searches. Phylogenetic and molecular evolutionary analyses were conducted using MEGA version 4 (Tamura et al., 2007). The Ribosomal Database Project (RDP) Classifier tool (RDP Naïve Bayesian rRNA classifier version 2.5, May 2012, RDP 16S rRNA training set 9) was used to evaluate the taxonomic position of sequences (Wang et al., 2007). Pairwise analyses to determine sequence identities were performed using the internet tool from the Georgetown University Medical Center.

### 16S rRNA gene sequence analyses of the enrichment with ammonia as the substrate

General bacterial primers 616F and 630R (Ta 56°C, all primer details are listed in Table 1) were used to amplify bacterial 16S rRNA gene sequences from DNA extracted after 3.5 months of operation with ammonia as the sole substrate. The resultant product was cloned, plasmids isolated and sequencing performed on 20 clones using sequencing primer 610IIF. For six clones the entire insert sequence was derived by additional sequencing reactions with primers M13F and M13R.

### 16S rRNA gene sequence analyses of the enrichment with nitrite as the substrate

After 6 months of operation with nitrite as the substrate, Nitrospira-targeted PCR (primer pair 616F and NTS PA1158R, Ta: 56°C) was performed on extracted DNA and the resulting product cloned. Eight clones (clones AC1-8) were randomly picked and sequenced with primer M13F. Additional sequencing was performed with primer M13R to obtain the full insert sequence of clone AC6.

### Accession numbers

16S rRNA gene sequences are available from GenBank under the following accession numbers: KC706457-706479. For sequences sharing at least 99% sequence identity (see “Results”) a representative sequence has been submitted. For the North Sea nitrifier enrichment cultures clone Cb9 (KC706457) represents the Nitrosomonas sp., Cb12 (KC706458) the Nitrospira sp. and Cb 18 (KC706459) “Candidatus Nitrospira saufa.” For the North Sea time...
Table 2 | North Sea time series high molecular weight DNA samples.

<table>
<thead>
<tr>
<th>Sample pool</th>
<th>Time series samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>Jan–Feb–Mar 2004: 02-Jan, 14-Jan, 30-Jan, 09-Feb, 16-Feb, 23-Feb, 01-Mar, 08-Mar, 15-Mar, 22-Mar, 29-Mar</td>
</tr>
<tr>
<td>P6</td>
<td>Jan 2005: 14-Jan, 25-Jan, 31-Jan</td>
</tr>
</tbody>
</table>

*Pools consisted of a mixture of 3 μl of each time series sample.

www.frontline.org March 2013 | Volume 4 | Article 60 | 5
converting 0.75 mmol of nitrogen per liter per day. The raise to
10 mM NH₄Cl (after 5.5 months of operation) resulted in an
ammonium and nitrite accumulation to final concentrations (at
6 months of operation) of 1.8 mM and 100 μM, respectively.
During the last half month of operation therefore approximately
2 mmol of nitrogen were consumed per liter per day.

The PCR performed with general bacterial primers on DNA
extracted from biomass after 5.5 months of operation with ammo-
nia as the substrate yielded correct-sized inserts (1500 nt). The 20
clones picked for plasmid isolation yielded 20 partial (695–845 nt)
16S rRNA gene sequences of which six contained recognizable
nitrifier 16S rRNA sequences based on BlastN searches of the
National Center for Biotechnology Information (NCBI) database
taxonomic assignment using the Classifier tool of the RDP.
Taxonomic assignment of the remaining sequences resulted in
five sequences assigned to uncultured bacteria, two to unclas-
sified Planctomycetes, three to the genus Physicibacteria within
the Planctomycetes, two to unclassified α-proteobacteria, one
to the genus Phaeobacter within the α-proteobacteria, and one
to unclassified Anaerolineae within the Chloroflexi. Nearly full-
length 16S rRNA gene sequences generated from the clones
containing a recognizable nitrifier sequence resulted in three
Nitrosomonas (AOB) sequences (clones Cb9, 10, and 15; >99% shared sequence identity), two Nitrospina (NOB) sequences
(clones Cb12 and 16; 99.5% shared sequence identity), and one
Nitrospira (NOB) sequence (clone Cb18). The phylogenetic posi-
tion of the putative Nitrosomonas-like AOB is shown in Figure 1
which illustrates that the sequence from the enrichment culture is
related to Nitrosomonas marina but does not cluster closely to any
cultivated Nitrosomonas species. The closest match in the NCBI
database (96% sequence identity) with a cultivated species was the
16S rRNA gene sequence of Nitrosomonas sp. NM51 (Parkholder
et al., 2000). This implies that the enriched AOB may represent
a previously uncultured Nitrosomonas species. The closest match
in the NCBI database (99% sequence identity) was to an unpub-
lished marine clone sequence (FP14271, clone LXE3). For another
sequence (FL28823, clone NitA08631, Schmidtova et al., 2009)
sharing 99% sequence identity to the sequence of the enriched
North Sea AOB it was known that this sequence was retrieved
from brackish water from the anoxic fjord Notinat Lake, which
is an environment with an ammonium concentration between
20 and 200 μM. The Nitrospina (NOB) sequences shared only
92% sequence identity to the 16S rRNA gene sequence of the cul-
tivated species Nitrospina gracilis strain 3/211 (FR865038). The

---

**FIGURE 1** | 16S rRNA gene sequence based phylogenetic
tree showing the position of the enriched North Sea AOB
(bold) within the betaproteobacterial AOB. This unrooted
bootstrap/1000 replicated consensus tree was inferred using the
neighbor-joining algorithm. Total of 1365 nucleotides were considered
in the alignment. Bootstrap values are shown at the internal nodes.
The scale bar is in the unit of the number of base substitutions
per site.
Within the first month of the nitrite-fed period (manual supply of Nitrospira marina of Nitrospina ant/halophilic ing with probe NEU 653. This indicates dominance of halotolerant/halophilic Nitrosonomas-like AOB. In addition, around 10% of the bacterial population hybridized with probe NTSP A712 indicating the presence of Nitrosospira-like NOB. No hybridisation with probe NTSP N693 was observed which suggests that Nitrospira NOB were a minority within the nitrifier community.

**NORTH SEA NOB ENRICHMENT WITH NITRITE AS THE SUBSTRATE**

Within the first month of the nitrite-fed period (manual supply nitrite to 0.5−1 mM final concentrations) an average nitrite consumption rate of 1 mmol per liter per day was observed. Fourfold dilutions of the biomass, after 1 week and after 1 month, respectively, did not result in any observed change in nitrite consumption rate. During the operation in a fed-batch mode (between 1 and 11 months of operation) with stepwise increasing influent nitrite concentration (from 10 to 80 mM) followed by continuous operation (D = 0.05 per day; last month of operation) the nitrite consumption rate increased to a final value of 3 mmol per liter per day. The fourfold dilutions after 2 and 4 months of operation, again did not affect the observed nitrite consumption rate.

The FISH analyses (Figure 2) of biomass after 1 and 6 months of operation with nitrite as the substrate revealed an increase in Nitrospira NOB (to a final ∼80% of the total bacterial population) and decline in Nitrosomonas AOB (∼1%), indicating that the population became dominated by Nitrospira NOB.

The eight sequenced clones (AC1-8) obtained through PCR with primers 616F0 and NTSP A1158R using DNA extracted after 6 months of operation, contained 99% identical inserts based on pairwise alignment. Therefore the fully sequenced insert of clone AC6 was used as a representative for phylogenetic analysis (Figure 3). When looking at 16S rRNA gene sequences of taxonomically described species, the enriched North Sea Nitrospira is phylogenetically most related (94% identity) to *Nitrospira marina* strain Nb-295 (X82359, Schmid et al., 1995). The 16S rRNA gene sequence of clone AC6 is 99.9% identical to that of clone Cb18 based on pairwise analysis indicating that the Nitrospira NOB species represented by this clone was already present in the reactor prior to the switch to nitrite as a substrate.

The 454 sequencing run on DNA extracted from biomass at the end of the incubation with nitrite as the sole substrate (after 12 months) generated, after quality trimming, 1,216,565 single reads with an average length of 405 nt. The mapping of all reads to the custom 16S rRNA gene sequence database resulted in 198 mapped reads, of which 147 mapped to *Nitrospira* sp. 16S rRNA gene sequences. This implies an abundance of *Nitrospira* sp. 16S rRNA genes within the total population of 74% which is in agreement with the 80% abundance estimated from the FISH analysis after 6 months of operation with nitrite as the substrate.

**METAGENOME SEQUENCING AND RECONSTRUCTION OF THE 16S rRNA GENE SEQUENCE OF THE DOMINANT NOB**

The 454 sequencing run on DNA extracted from biomass at the end of the incubation with nitrite as the sole substrate (after 12 months) generated, after quality trimming, 1,216,565 single reads with an average length of 405 nt. The mapping of all reads to the custom 16S rRNA gene sequence database resulted in 198 mapped reads, of which 147 mapped to *Nitrospira* sp. 16S rRNA gene sequences. This implies an abundance of *Nitrospira* sp. 16S rRNA genes within the total population of 74% which is in agreement with the 80% abundance estimated from the FISH analysis after 6 months of operation with nitrite as the substrate.

**TEM ANALYSIS OF THE ENRICHED NORTH SEA Nitrospira sp.**

The biomass was mainly situated in small aggregates in the culture. This was reflected in the electron microscopy pictures generated with the TEM analysis of the biomass, harvested from the enrichment after 8 months. These showed dense clumps of cells seemingly embedded in extracellular material (Figure 4A).

Some typical morphological features of a representative cell are pointed out in Figure 4B. Most striking is the large periplasmic space containing many electron dense particles. In addition, large electron light particles are visible in the cytoplasm.

**FIGURE 2 | Fluorescence microscopy pictures of the abundance of Nitrosomonas AOB and Nitrospira NOB during the NOB enrichment.** In green: cell hybridizing with probe NEU653 (targeting most halophilic and halotolerant Nitrosonomas spp.). In red: cells hybridizing with probe NTSP A712 (targeting most members of the phylum Nitrospira). (A) Biomass after 1 month; (B) after 3 months; (C) after 6 months of operation with nitrite as the only substrate.

The biomass was mainly situated in small aggregates in the culture. This was reflected in the electron microscopy pictures generated with the TEM analysis of the biomass, harvested from the enrichment after 8 months. These showed dense clumps of cells seemingly embedded in extracellular material (Figure 4A).
DETECTION OF THE ENRICHED Nitrospira NOB IN COASTAL NORTH SEA WATER

Nitrospira-targeted primer pair 616F/NTSP A1158R did not yield significant amplicons (data not shown) for DNA samples from the North Sea time series, and therefore primers NSE87F and NSE1124R were developed. This primer pair, designed to specifically target the enriched “Candidatus Nitrospira salina”, yielded correct-sized (1037 nt) amplicons with all tested templates (high molecular weight DNA from the North Sea enrichment, Nitrospira defluvii and N. moscoviensis as well as plasmid DNA from respectively sublineage I (Nitrospira defluvii-like), II (N. moscoviensis-like), and IV (N. marina-like). This demonstrates that this primer pair functions well for all tested Nitrospira species and does not specifically target the enriched North Sea species.

Screening of the six separate pools (see Table 2) from the North Sea time series of high molecular weight DNA samples with this primer pair resulted in 25 16S rRNA gene clone sequences of which 22 contained a Nitrospira sequence. Three (clones P3_4, P3_5 and P4_29) clones exhibited a sequence identity of...
99% to the 16S rRNA gene sequences of “Candidatus Nitrospira salina” (Figure 3). The majority (17) of the Nitrospira 16S rRNA gene clone sequences retrieved from the North Sea time series, however, were most closely related (97–99% sequence identity) to a clone sequence (DQ531808, clone Belgica2005/10_ZG-15) retrieved from marine sediment (Gillan and Pernet, 2007) and shared only 91–92% sequence identity with the 16S rRNA gene sequence of “Candidatus Nitrospira salina”.

Surprisingly, North Sea time series clone P3_7 contained an insert most resembling the 16S rRNA gene sequence of Nitrospira defluvii (99.5% sequence identity to sequence NC_014355, Lücke et al., 2010) and clone P1_15 an insert resembling the 16S rRNA gene sequence of Nitrospira moscoviensis (97% sequence identity to NR_029287, Ehrich et al., 1995), which are Nitrospira species associated with freshwater environments.

**DISCUSSION**

**BIOREACTOR CULTIVATION OF MARINE NORTH SEA NITRIFIERS**

The bioreactor approach adopted to enrich North Sea nitrifiers proved successful. Within 6 months a marine assemblage of AOB and NOB was obtained by means of cultivation with ammonia as the substrate. The results from 16S rRNA gene-fiers proved successful. Within 6 months a marine assemblage of AOB and NOB was obtained by means of cultivation with ammonia as the substrate. The results from 16S rRNA gene-fiers proved successful. Within 6 months a marine assemblage of AOB and NOB was obtained by means of cultivation with ammonia as the substrate. The results from 16S rRNA gene-provided for the observed conversion of 2 mmol of ammonium per liter per day. Switching to nitrite as the sole substrate resulted in a high enrichment (80% of the total bacterial population) and the presence of many electron dense particles. In addition, the cytoplasm contained putative storage material, such as glycogen, visible as large electron light particles. Most likely, storage of carbon was triggered by a phosphate limitation during the cultivation. This because TEM analysis was performed on biomass after 8 months of operation and to prevent carbon limitation the reactor had been supplemented with additional CO2 from month 7.5 onward. Additional phosphate to prevent phosphate limitation was provided only after 8 months which may have led to an imbalanced situation in which carbon was plentiful but phosphate was limiting.

**RELEVANCE OF THE ENRICHED NITRIFIERS IN DUTCH COASTAL NORTH SEA WATER**

It has been reported by Pommerning-Röser et al. (1996) that affinity for ammonia varies among members of different lineages within the AOB genus Nitrosomonas but tends to be relatively similar within a specific lineage. The clustering of the enriched North Sea Nitrosomonas AOB 16S rRNA gene sequence with Nitrosomonas species commonly associated with low substrate environments (Figure 1) therefore suggests this species is likewise adapted to relatively low substrate conditions. This thought is strengthened by the origin of clone sequence FJ628323 (clone NitA40631) which shares 99% sequence identity to the sequence of “Candidatus Nitrospira salsa” (97% sequence identity to NC_014355, Lücke et al., 2010). The majority (17) of the clone sequences nearly identical to the 16S rRNA gene sequences obtained from the AOB/NOB co-culture indicating the species originally present in the marine assemblage was successfully stimulated. Phylogenetic analysis showed the enriched North Sea Nitrospira represents a novel species (“Candidatus Nitrospira salina”) only distantly related (94% 16S rRNA gene sequence identity) to the next taxonomically described species Nitrospira marina. In the study by Keuter et al. (2011) the Nitrospira in marine enrichment M1, derived from a marine recirculation aquaculture system, is hypothesized to originate from North Sea water because the system was started and refreshed with North Sea water. The high (within species-range) 16S rRNA gene sequence identity (98.7%) of “Candidatus Nitrospira salina” to the 16S rRNA gene sequence retrieved from enrichment M1 corroborates this. The 16S rRNA gene reads mapping approach and subsequent 16S rRNA gene reconstruction based on metagenomic data corroborated (74% of all 16S rRNA gene reads were affiliated with Nitrospira) the FISH abundance data and showed that the enriched North Sea Nitrospira sp. persisted in the culture converting 3 mmol of nitrite per liter per day after 12 months of operation suggesting a quite stable microbial community. The TEM analysis data fits well with the known cell morphology of Nitrosia species. Watson et al. (1986) reported the presence of a large periplasmic space for Nitrospira marina and the presence of glycogen and polyphosphate deposits in cultures and Spieck et al. (1998) identified electron dense particles from the periplasmic space of Nitrospira moscovien-sis as the nitrite-oxidizing enzyme system. In accordance with the aforementioned, the most striking attribute of the enriched North Sea Nitrospira sp. was a large periplasmic space containing putative proteins of the nitrite-oxidizing enzyme system as suggested by the presence of many electron dense particles. In addition, the cytoplasm contained putative storage material, such as glycogen, visible as large electron light particles. Most likely, storage of carbon was triggered by a phosphate limitation during the cultivation. This because TEM analysis was performed on biomass after 8 months of operation and to prevent carbon limitation the reactor had been supplemented with additional CO2 from month 7.5 onward. Additional phosphate to prevent phosphate limitation was provided only after 8 months which may have led to an imbalanced situation in which carbon was plentiful but phosphate was limiting.

**BIOREACTOR CULTIVATION OF MARINE NORTH SEA NITRIFIERS**

The bioreactor approach adopted to enrich North Sea nitrifiers proved successful. Within 6 months a marine assemblage of AOB and NOB was obtained by means of cultivation with ammonia as the substrate. The results from 16S rRNA gene-targeted PCR followed by cloning and sequencing indicated the presence of putative Nitrosomonas-like AOB (5/20 clones), Nitrospira-like NOB (1/20 clones), and Nitropini-like NOB (2/20 clones), representing novel species. The FISH analysis demonstrated the abundance of the Nitrosomonas-like AOB (80% of the total bacterial population) and Nitrospira-like NOB (30%) of the total bacterial population, but failed to detect Nitrospira cells. Based on these results Nitrosomonas AOB and Nitrospira NOB are assumed responsible for the observed conversion of 2 mmol of ammonium per liter per day. Switching to nitrite as the sole substrate resulted in a high enrichment (80% of the total population based on FISH analysis) of Nitrospira NOB and Nitrospira species (10% of all phyla) which shares 99% sequence identity to the sequence of “Candidatus Nitrospira salsa” (97% sequence identity to NC_014355, Lücke et al., 2010). The majority (17) of the clone sequences nearly identical to the 16S rRNA gene sequences obtained from the AOB/NOB co-culture indicating the species originally present in the marine assemblage was successfully stimulated. Phylogenetic analysis showed the enriched North Sea Nitrospira represents a novel species (“Candidatus Nitrospira salina”) only distantly related (94% 16S rRNA gene sequence identity) to the next taxonomically described species Nitrospira marina. In the study by Keuter et al. (2011) the Nitrospira in marine enrichment M1, derived from a marine recirculation aquaculture system, is hypothesized to originate from North Sea water because the system was started and refreshed with North Sea water. The high (within species-range) 16S rRNA gene sequence identity (98.7%) of “Candidatus Nitrospira salina” to the 16S rRNA gene sequence retrieved from enrichment M1 corroborates this. The 16S rRNA gene reads mapping approach and subsequent 16S rRNA gene reconstruction based on metagenomic data corroborated (74% of all 16S rRNA gene reads were affiliated with Nitrospira) the FISH abundance data and showed that the enriched North Sea Nitrospira sp. persisted in the culture converting 3 mmol of nitrite per liter per day after 12 months of operation suggesting a quite stable microbial community. The TEM analysis data fits well with the known cell morphology of Nitrosia species. Watson et al. (1986) reported the presence of a large periplasmic space for Nitrospira marina and the presence of glycogen and polyphosphate deposits in cultures and Spieck et al. (1998) identified electron dense particles from the periplasmic space of Nitrospira moscovien-sis as the nitrite-oxidizing enzyme system. In accordance with the aforementioned, the most striking attribute of the enriched North Sea Nitrospira sp. was a large periplasmic space containing putative proteins of the nitrite-oxidizing enzyme system as suggested by the presence of many electron dense particles. In addition, the cytoplasm contained putative storage material, such as glycogen, visible as large electron light particles. Most likely, storage of carbon was triggered by a phosphate limitation during the cultivation. This because TEM analysis was performed on biomass after 8 months of operation and to prevent carbon limitation the reactor had been supplemented with additional CO2 from month 7.5 onward. Additional phosphate to prevent phosphate limitation was provided only after 8 months which may have led to an imbalanced situation in which carbon was plentiful but phosphate was limiting.

**RELEVANCE OF THE ENRICHED NITRIFIERS IN DUTCH COASTAL NORTH SEA WATER**

It has been reported by Pommerning-Röser et al. (1996) that affinity for ammonia varies among members of different lineages within the AOB genus Nitrosomonas but tends to be relatively similar within a specific lineage. The clustering of the enriched North Sea Nitrosomonas AOB 16S rRNA gene sequence with Nitrosomonas species commonly associated with low substrate environments (Figure 1) therefore suggests this species is likewise adapted to relatively low substrate conditions. This thought is strengthened by the origin of clone sequence FJ628323 (clone NitA40631) which shares 99% sequence identity to the sequence of the enriched North Sea Nitrosomonas AOB. This clone sequence was retrieved from brackish water from an anoxic foed Nitmat Lake (Schmidtova et al., 2009), for which an ammonium concentration between 20 and 200 μM was reported. Maximum ammonium concentrations in the coastal North Sea water from which the enrichment is derived have, however, been reported to range from 10 to 13 μM during the winter months (Pitcher et al., 2011) which implies aerobic ammonia oxidation will likely be catalyzed by microorganisms with even higher affinities for ammonia. Moreover, AOB have been shown to be outnumbered by AOA (based on 16S rRNA and amoA gene copy numbers) in time series of Dutch coastal North Sea water (Wachtler et al., 2006; Pitcher et al., 2011). The enriched North Sea Nitrosomonas AOB therefore might exhibit a low abundance in coastal North Sea water and its contribution to in situ nitrification may be minor. The retrieval of clone sequences (3/20) from the North Sea time series nearly identical to the 16S rRNA gene sequence of “Candidatus Nitrospira salina” proves that this species does occur in the North Sea. The higher abundance of clone sequences (17/22) forming a separate distinct cluster suggests that another Nitrospira species may actually be more abundant and potentially contribute more to in situ nitrification. Moreover, our data suggested that a minor portion of the nitrifier community may have consisted of Nitrospira NOB after 5.5 months of enrichment with ammonium.
Nitrospira species have often been detected in marine environments (e.g., Mincer et al., 2007; Reman et al., 2010; Santoro et al., 2010; Füssel et al., 2011). Based on our present study, we cannot exclude thatNitrospira NOB may be present in greater abundance or contributing to a greater extent to in situ nitrite oxidation. Cultivation in a biofilter set-up offers a higher degree of control over environmental parameters (pH, T, substrate concentration, product concentration) than more traditional batch cultivation. Selection for a particular species due to the cultivation conditions, however, cannot be excluded completely. Our enrichment was performed with a maximum nitrite concentration of 750 μM (during the first month of operation). Off et al. (2010) reported nitrite tolerances for different species of Nitrospira NOB ranging from a low 1.5 mM for enrichment culture Aa01 derived from a marine sponge to intermediate (6 mM) for Nitrospira marina to high (15–25 mM) for freshwater Nitrospira species. Based on this, the present biofilter cultivation would be expected to yield a Nitrospira NOB associated with low levels of nitrite. Indeed the closest relatives (based on 16S rRNA gene sequence analysis) of the enriched North Sea Nitrospira originated from recirculation aquaculture systems which were described as relatively low nitrite environments (10–40 μM nitrite reported by Keuter et al., 2011; nitrite below detection reported by Brown et al., 2013). Substrate concentration may have contributed to the dominance of “Candidatus Nitrospira salina” in the final enrichment instead of Nitrospira marina-like or Nitrospira-like NOB.

Strikingly, the only pools (P3 and F4) from which “Candidatus Nitrospira salina” sequences were derived were also the only pools consisting of samples from outside the winter months (spring and summer, Table 2). Nitrospira defluvii (enriched from wastewater treatment sludge) Speck et al., 2006; Maixner et al., 2008; Lücker et al., 2010) and Nitrospira moscoviensis (isolated from a partially corroded area of an iron pipe of a heating system, Ehrich et al., 1995) are commonly associated with freshwater environments. The detection of clone sequences most related (99.5% to Nitrospira defluvii, 97% identity to Nitrospira moscoviensis, respectively) to 16S rRNA gene sequences from these Nitrospira species may be caused by terrestrial input (e.g., riverine influx) at the sampling site.

OUTLOOK

Further research, e.g., selective inhibition experiments of AOA versus AOB activity (Yan et al., 2012), may clarify the role of the enriched Nitrosomonas AOB species in Dutch coastal North Sea water nitrification. Biofilter enrichments adopting more stringent substrate levels may result in marine microbial assemblages with a totally different species composition, which would be useful to compare and contrast to the one presently described. Collection of in situ abundance data (e.g., by quantitative PCR analyses) for different species of NOB (e.g., “Candidatus Nitrospira salina” versus other Nitrospira sp. and Nitrospira sp.) may help identify which NOB are of relevance to in situ nitrification. Seasonality in the abundance of this species may be corroborated by future reactor or laboratory enrichment experiments performed at different temperatures. Screening of a high resolution time series may aid in elucidating temporal changes in NOB community composition. The availability of the new Nitrospira species enrichment culture facilitates further in-depth studies such as determination of physiological constraints and comparison to other NOB species. Such characterisations will increase our understanding of microbial nitrogen cycling.

ACKNOWLEDGMENTS

The authors would like to thank Holger Duangs, Frank Maixner, Christiane Dorminger, and Hanna Koch from the University of Vienna for valuable discussion as well as their provision of biomass from C. Nitrospira defluvii, N. moscoviensis and the plasmids containing partial 16S rRNA genes from sublineage I, II, and IV Nitrospira used in this study. Jorin A. Veltman and Christian Gilissen from the UMC Nijmegen are acknowledged for financing/support and primary data analysis/mapping of the 454 sequencer data set. The 454 sequencer was financed through ZonMWgrant 917.66.36. Angela Pitcher and Elda Pansto from the Royal Netherlands Institute for Sea Research are thanked for providing the North Sea time series of high molecular weight DNA samples and Elly van Donnelaar (Utrecht University) for high pressure freezing for the TEM analysis. Joep Reifen and Krishna Nathoene are acknowledged for their work on the PCR analyses of the enriched North Sea Nitrospira species during their respective BSc internships at the Department of Microbiology of the Radboud University Nijmegen. SCMH was supported by the Darwin Center of Biogeosciences (project numbers, 1051 and 3011), Daan Speth and Ke Ji by BE-Basic (FP7-2), Laura van Niftrik by NWO (VENI grant 863.09.009) and Mike S. M. Jetten by ERC (Advanced grant 232937).

REFERENCES


March 2013 | Volume 4 | Article 60 | 1

Griess-Romijn-van Eck. (1966). Phys-

Haaijer et al. A novel North Sea

Juretschko, S. (2000). Hana, F., Radax, R., W oebken, D.,


evin, T. J., and Jencks, P. S. (1971). Molecular and con- 
duction of nitrite-oxidizing bacteria – 
archaea from marine sediments in 
cocyst with sulfur-oxidizing bac-


Downing, J. A. (1997). Marine nitro-

DeLong, E. F., Preston, C. M., Mincer, T ., 

Suzuki, M. T., Preston, C. M., Beja, O., 

T echnical University Munich, 

Fu, B., Kudryavtsev, A., Suzuki, M. T., DeLong, E. F., 

De Riek, W., and Van Niftrik, L. (2012). Polymerase chain reaction analysis: implications for molecu-

Daims, H., Ramsing, N. B., Schleifer, K.-H., 


T echnical University Munich, 

Daims, H., Ramsing, N. B., Schleifer, K.-H., 


T echnical University Munich, 

Daims, H., Ramsing, N. B., Schleifer, K.-H., 


T echnical University Munich, 

Daims, H., Ramsing, N. B., Schleifer, K.-H., 


Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 30 January 2013; paper pending published: 12 February 2013; accepted: 01 March 2013; published online 18 March 2013.

Copyright © 2013 Haaijer, Ji, van Niftrik, Hoischen, Speth, Jetten, Sinninghe Damsté and Op den Camp. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in other forums, provided the original authors and source are credited and subject to any copyright notices concerning any third-party graphics etc.