Expanding DEMON Sidestream Deammonification Technology Towards Mainstream Application

B. Wett[1,§], S.M. Podmirseg[2,3,*,§], M Gómez-Brandón[2,3], M. Hell[4], G. Nyhuis[5], C. Bott[6] and S. Murthy[7]

ABSTRACT: A cross-Atlantic R&D-cooperation involving three large utilities investigated the feasibility of mainstream deammonification—the application of partial nitritation/anammox for full-plant treatment of municipal wastewater at ambient temperatures. Two major process components have been implemented, 1) bioaugmentation of aerobic- and anaerobic ammonia oxidizers (AOB and AMX) from the DEMON-sidestream sludge liquor treatment to the mainstream and 2) implementation of hydrocyclones to select for anammox granules and retain them in the system. Different operation modes have been tested at laboratory- and pilot-scale in order to promote the short-cut (more direct anammox route) in nitrogen removal metabolism. At the full-scale installation at Strass WWTP, stable repression of nitrite oxidizing biomass (NOB) has been achieved for several months. Significant anammox enrichment in the mainstream has been monitored while high efficiency in the sidestream-process has been maintained (96% annual average ammonia removal). *Water Environ. Res.*, **87,** 2084 (2015).

KEYWORDS: anammox, deammonification, DEMON, nitrogen removal, energy efficiency, mainstream.

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Introduction

Since the identification of organisms capable of oxidizing ammonia anaerobically by Strous et al. (1999) and the deciphering of the corresponding stoichiometric equation Strous et al. (1998), huge research efforts have been undertaken to develop a technical application of this process.. High-strength ammonia wastewater, like sludge liquors, so far represented the prime treatment target and since the first full-scale implementation of suspended growth deammonification Wett (2007) almost 30 DEMON®-plants are in operation or under construction or design, respectively. Just recently the research scope has been expanded to the treatment of low-strength ammonia wastewater and wastewater at moderate and low temperatures (e.g. De Clippeleir et al.,2011; Hendrickx et al., 2012). This paper presents results from the development and demonstration of deammonification in a mainstream wastewater treatment scheme.

The investigated scheme considers two main process components:

- Bioaugmentation of AOB and AMX from the DEMON-sidestream reactor to the main liquid process train.
- Anammox enrichment by selective waste activated sludge wasting via hydrocyclones

The following basic process mechanisms have been applied in order to control competition between involved microbial players:

- Competition for oxygen between AOB and NOB (controlled by DO-level, aeration-time and -regimen)
- Competition for nitrite between NOB and Anammox (different nitrite half-saturation and temperature sensitivity)

Materials and Methods

Strass Waste Water Treatment Plant (WWTP). The Strass plant is known as a net energy positive plant providing mainstream treatment by an A/B process and sidestream treatment by the DEMON deammonification process (Figure 1). Anammox granules produced from sludge liquor treatment are seeded to the mainstream and retained and enriched by a hydrocyclone classifier selecting for the high-density waste activated sludge fraction from the waste stream. Two different bioaugmentation procedures are applied, namely:

1) semi-continuous seeding from sidestream cyclone overflow (usually one hour of cyclone operation per SBR-cycle, four SBR cycles/day), the flocculant sludge fraction containing mainly the functional microbial group of AOB but no NOB.
2) periodic transfer of mixed liquor from the sidestream to the B-stage ensuring a defined flux of anammox granules without size selection as well as AOB (average mixed liquor flow-rate of 40 m^3/week out of a reactor volume of 500 m^3).

Anammox Granules Quantification. To quantify the abundance of anammox granules in the biological stage an image analysis with the open source software Fiji (www.fiji.sc) was performed. This method requires no further laboratory processing of the samples, besides an optimized dilution of each sample

[1] ARAconsult, A-6020 Innsbruck, Austria.

[2] University of Innsbruck, Institute of Microbiology, Technikerstrasse 25d, A-6020 Innsbruck, Austria.

[3] alpS GmbH, A-6020 Innsbruck, Austria

[4] Waterboard AIZ, HNr.150, A-6261 Strass i.Z., Austria

[5] Cyklar-Stulz GmbH, CH-8737 Gommiswald, Switzerland

[6] Hampton Roads Sanitation District (HRSD), Virginia Beach, VA 23455, USA

[7] District of Columbia Water and Sewer Authority, SW Washington, DC 20032, USA

[*] University of Innsbruck, Institute of Microbiology, Technikerstrasse 25d, A-6020 Innsbruck, Austria; e-mail: sabine.podmirseg@uibk.ac.at; phone: +43512/507–51321

[§] These authors contributed equally to this work

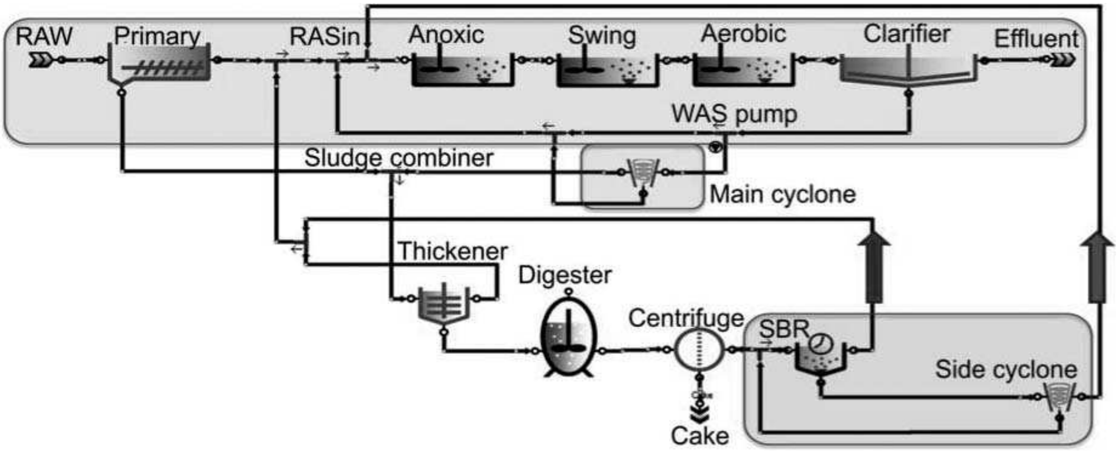

Figure 1—Full-plant deammonification design (B-stage and sludge-line) including the two hydrocyclones (mainstream and sidestream)

type and scanning of the sample. It is perfectly suited to quantify and further classify the granules into size categories. An approximate estimation of granule volume is also possible. For an introduction to this novel technique and more detailed information on the performed analysis protocol with the Fiji-software see also Podmirseg et al. (2015).

Anammox- and AOB&NOB-Activity Quantification. The mass of active anammox organisms is quantified indirectly by *ex situ* tests determining inorganic nitrogen conversion rates. Anaerobic activity tests are applied to mixed 5 L activated sludge samples with covered surface and spiked with $NaNO_2$ (initial concentration of NO_2-N > 50 mg/L) and NH_4Cl (initial concentration of NH_4-N > 40 mg/L), respectively. During 60 min for sidestream samples (incubated at 30 °C, corresponding to the standard process temperature of the sidestream) and 120 min for mainstream samples (incubated at 20 °C, corresponding to Tmax for the mainstream) at least four data points of concentration profiles for NH_4-N, NO_2-N and NO_3-N are measured (Wett et al., 2007). The sidestream system generally exhibits much faster conversion rates that allow for a shorter experimental duration of anaerobic activity tests. Aerobic activity tests are applied to aerated activated sludge samples (resulting in 3 mg/L < DO < 5 mg/L). Then measured inorganic nitrogen conversion is related to measured TSS-concentration.

Results and Discussion

Sidestream Deammonification. Stable sidestream treatment of sludge liquors in the DEMON-system at Strass WWTP has been demonstrated since 2004. Implementation of the hydrocyclone enabled additional enrichment of anammox granules by almost doubling the available active anammox mass (Wett et al., 2009). From the beginning of the demonstration period of the mainstream deammonification scheme the operators were specifically concerned not to sacrifice the robustness of the sidestream process. Despite the high seeding load, which is transferred regularly from the sidestream to the mainstream in this experimental set-up, a deterioration of the ammonium-elimination capacity in the SBR was not observed. The yearly mean ammonium-elimination of the SBR was as high as 96% for 2011, even exceeding the yearly mean of 95% for 2010 (Figure 2). Short downward spikes in Figure 2 around March 2010 and March 2011 could be attributed to single measurement errors

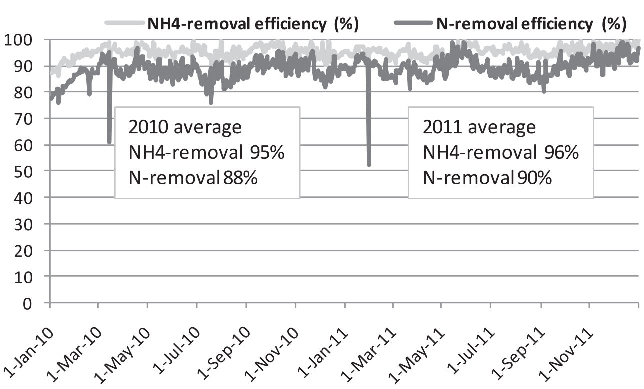

Figure 2—Profiles for ammonium- and total nitrogen removal efficiencies during the years 2010/11 in the sidestream DEMON process

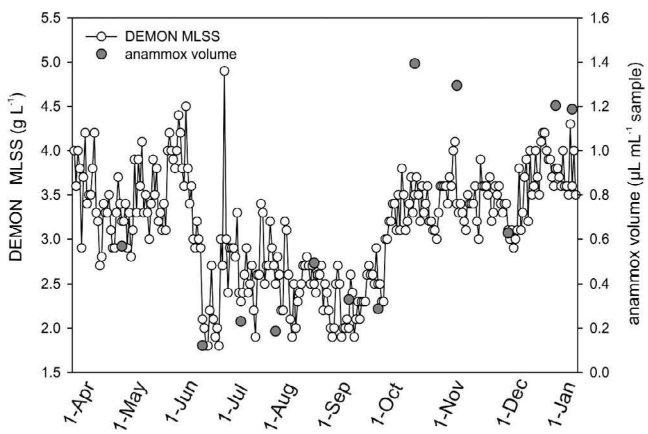

Figure 3—Development of MLSS and overall granule volume in the sidestream-Demon tank in 2011

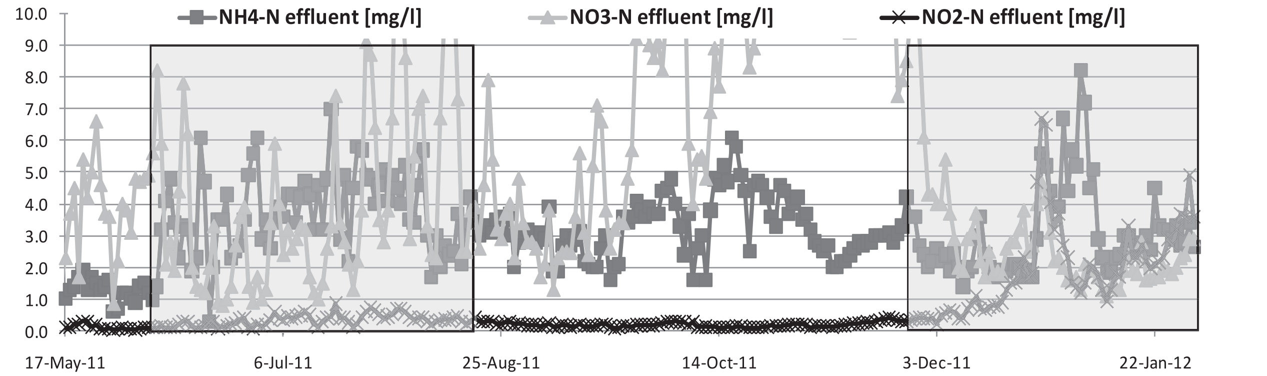

Figure 4—Daily inorganic nitrogen effluent concentrations with nitrite level indicating the two most successful operation modes for NOB-repression, SND-type low-DO (left square) and MLE-type high-DO (right square).

that were not corroborated by results of previous or subsequent measurement days.

The surprising fact that despite high seeding rates the final anammox abundance (in terms of granule volume) in the sidestream system was about twice as high as before the start of the experiment (Figure 3) can be explained by the following effects: Excessive wasting and bioaugmentation from June to October led to a significant drop in mixed liquor concentration (TSS decreased from ca. 4 g/L down to almost 2 g/L). As a consequence of a much lower mass of flocculent biomass the selection efficiency between flocs and granules improved and less granules embedded in the floc-fraction were lost. Additionally high wastage rates of the floc fraction may lead to the washout of protozoa preventing AMX-loss from grazing by predators. After a recovery period of reduced seeding rates the TSS level returned to almost the same level as before but at a much higher portion of granules.

Mainstream Deammonification. Traditionally, the low-loaded biological stage (B-stage) at Strass was operated in an Modified Ludzak-Ettinger (MLE) mode. Under normal operating conditions, the second tank in series would be intermittently aerated and controlled using an on-line ammonia signal at the effluent of the tank. At peak loading conditions, aeration in the first tank in series would be turned on (at a higher range of ammonia set-points). At the beginning of June 2011 along with the start-up of seeding and cyclone operation, the treatment strategy was switched to simultaneous nitrification-denitrification (SND)-mode with all four tanks in parallel operated at low DO setpoints. Then the B-stage was operated with tanks in series with higher DO in the second tank (pre-denitrification), then higher DO in the first tank (post-denitrification), and finally back to MLE high DO-operation. Obviously, highest nitrite accumulation (Figure 4) was achieved at operation modes accommodating transient anoxic conditions along the flow-path.

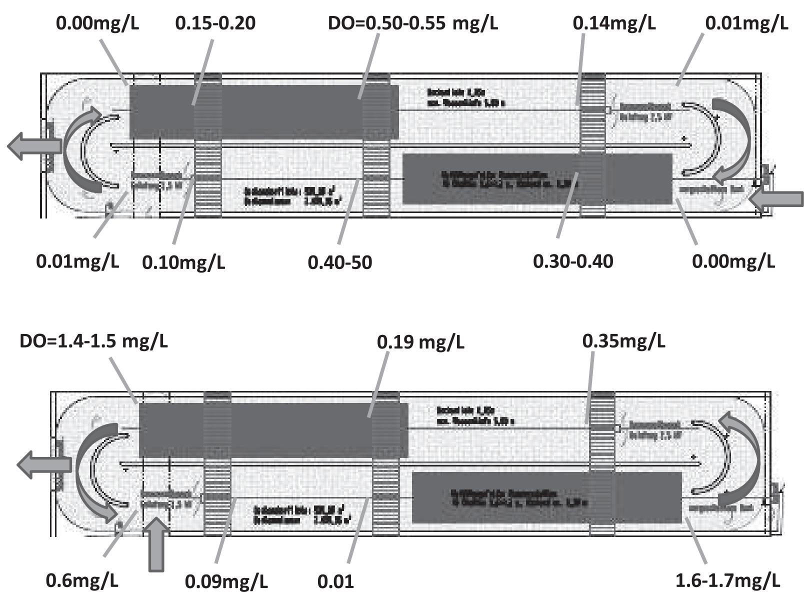

Figure 5—Carousel type aeration tank at Strass WWTP providing a DO-range of 0.00 to 0.55 mg/L

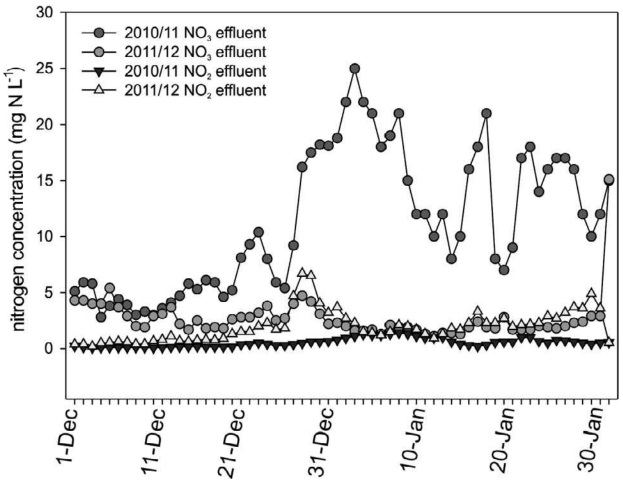

Figure 6—Comparison of 2010/11 and 2011/12 operational data of the full-scale pilot Strass indicating advanced NOB-repression (typically high nitrate level at Christmas peak-load)

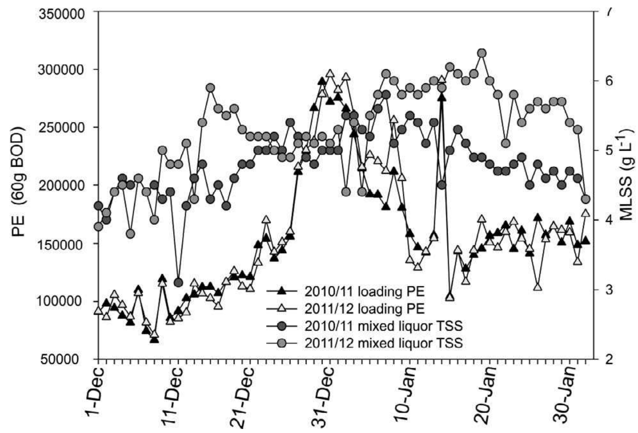

Figure 7—Seasonal load increase up to almost 300000 PE (design-load at 167000 PE) and correspondingly elevated MLSS-concentration.

The location of two diffuser-fields per carousel-tank inducing DO-concentration gradients between aerated zones is further depicted in Figure 5. Additionally to this spatial DO-distribution, applied ammonia-controlled intermittent aeration induced switches between aerobic and anoxic conditions.

The direct comparison of nitrogen removal during the high-loaded Christmas season 2011 against 2010 (Figure 6) shows the enormous benefit from the nitrite route in N-removal. Usually overload conditions (Figure 7) cause intensive aeration of all available diffuser fields driving the nitrate level up beyond 20 mg N/L. This year all operational modifications for mainstream deammonification resulted in lower nitrate than nitrite levels. As confirmed by activity measurements during this period, approximately 25% of ammonia oxidation produced nitrate while the major portion, 75%, was converted via the nitrite shunt (see also Figure 10). Higher reduction rates for nitrite compared to nitrate resulted in a much higher overall nitrogen removal efficiency and less carbon was required.

During the experimental period substantial enrichment in both quantity and granule-size has been achieved (Figure 8). Image analyses clearly indicated higher abundance of granules of larger diameter categories in the underflow of the mainstream cyclones. In the end of the first operational year, granules with a diameter 0.2 to 0.3 mm accounted for 22% of all granules, and granules with a diameter 0.3 to 0.4 mm accounted for 4%, compared to 0% at the beginning of the sampling campaign. The number of granules also showed a substantial increase towards 62 particles m/L at the end of the year.

Higher particle abundance at larger -size represents a significant enrichment of the overall granule mass in the system. Anaerobic activity measurements at 20 °C showed a net-removal of ammonia in the last sample only (time point 12). However, net-ammonia removal includes both ammonia oxidation by AMX as well as ammonia release from the organic solids (Figure 9). The same activity test yielded relatively high nitrite reduction rates compared to the tests in earlier phases of AMX-enrichment (data not shown).

The aerobic activity test showed again a sharp increase of ammonia removal at the very end of the measurement period (Figure 10). Overall ammonia removal of 3.57 mg N/g/h at sampling time point 12 matched the total NOx production of 3.53 mg N/g/h towards a closed mass balance. Nitrite production during this aerobic test (time point 12) amounted to the ca. 3-fold value compared to nitrate production revealing that ca. 75% of the nitrogen is channelled via the nitrite route.

Conclusions

Although significant quantities of anammox biomass granules were transferred from the sidestream SBR reactor to seed the mainstream reactors, the NH_4-removal capacity of the sidestream SBR was maintained and even improved (95% in 2010 versus 96% average NH_4-removal efficiency in 2011). It would appear that anammox bioaugmentation to the mainstream does not present a risk to the stability of sidestream treatment.

Successful NOB-repression has been demonstrated in the full-scale mainstream system, as indicated by measurements of higher concentrations of nitrite rather than nitrate in the effluent and as quantified by aerobic activity tests (ca. 75% repression). During the full-scale testing, the intermittent aeration creating transient anoxic conditions was found most effective for repressing NOBs.

One hypothesis to explain the successful NOB-repression observed in the mainstream deammonification reactors is that the enrichment or bioaugmentation strategy of both the AOBs and anammox organisms from the sidestream supports AOB activity over NOB activity and also enhances the opportunity for the AMX to outcompete the NOBs for nitrite.

Future work will focus on the quantification of the nitrogen flux diverted to the deammonification route and on the temperature dependency of this process.

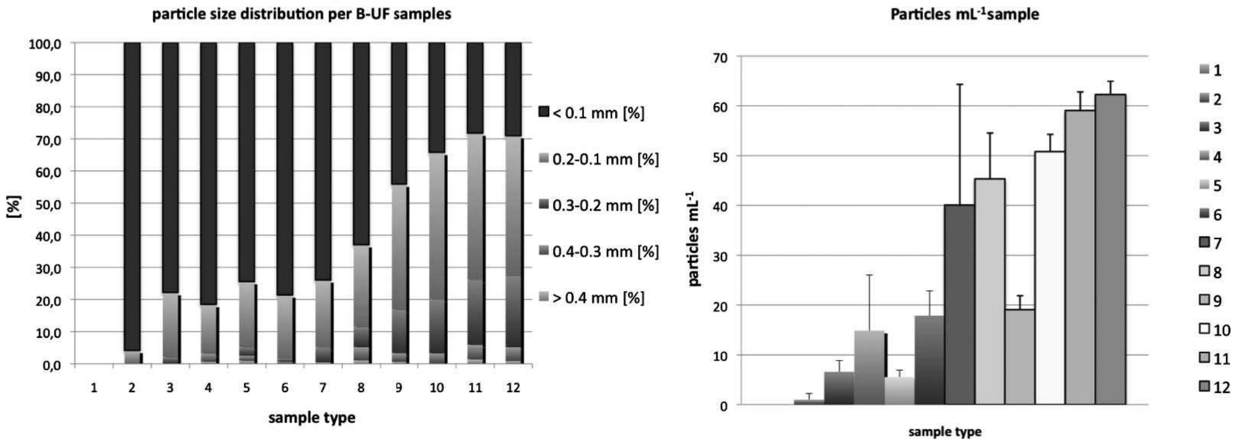

Figure 8—Evolution of the anammox biomass in the mainstream cyclone-underflow fraction (B-UF) from sampling one to twelve (April-December 2011); distribution of granule size fraction (left) and abundance of granules m/L (right)

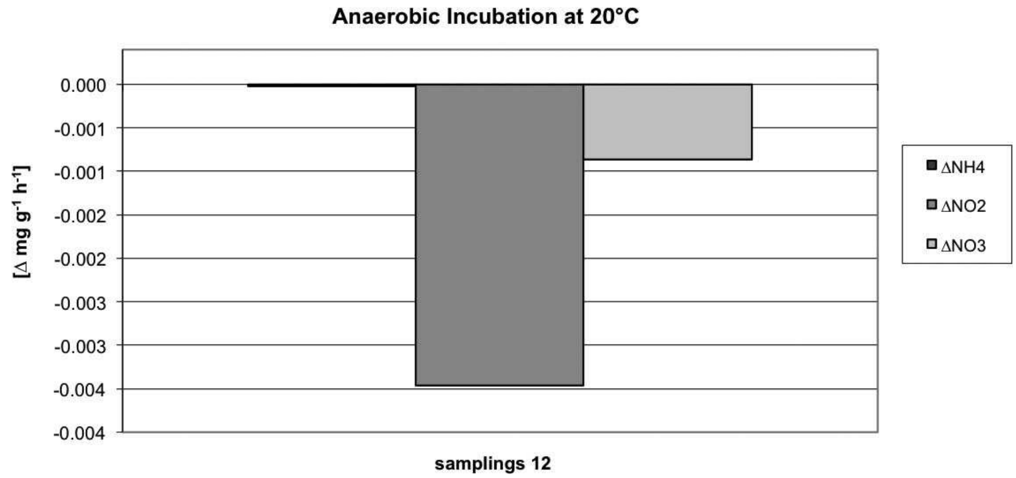

Figure 9—Results of activity tests for anaerobic ammonium oxidisers towards the end of the first year of the pilot period (net ammonium removal at sampling 12 in December 2011)

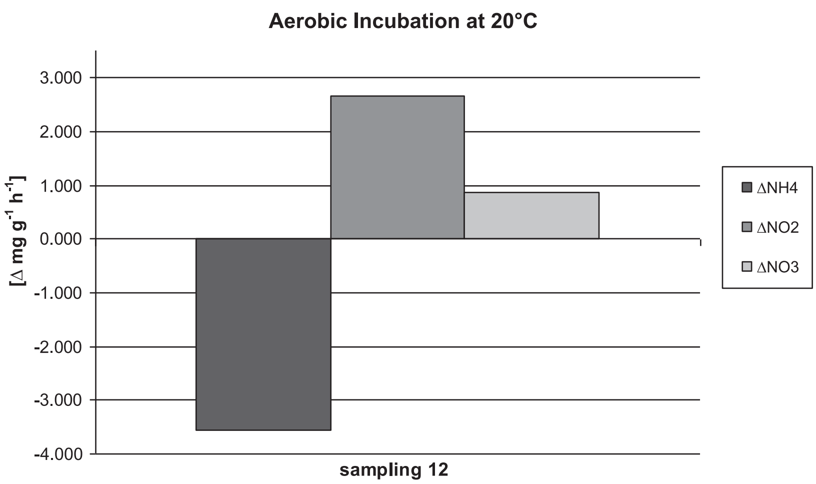

Figure 10—Results of activity tests for aerobic ammonium oxidisers towards the end of the first year of the pilot period (only ca. 25% of produced nitrite gets converted to nitrate at sampling 12 in December 2011)

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