Benthic nitrogen cycling in the North Sea

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Abstract

We present new data on the rates of sedimentary denitrification and its component processes (canonical denitrification, anammox and dissimilatory nitrate reduction to ammonium) for intertidal and subtidal sites in the North Sea using nitrogen isotope addition methods. We find overall average denitrification rates of 6.3 (range 0.4-10.6) µmol m\textsuperscript{-2}h\textsuperscript{-1}, similar to those previously reported for this region and other temperate shelf environments. We find canonical denitrification to be the dominant (>90%) process of the three. At the subtidal sites, most of the denitrification is supported by nitrate generated within the sediments, while at the intertidal site the main source is from the water column. We go on to consider the impact of these rates on nitrogen cycling within the North Sea region and compare the sediment core incubation rate results to estimates derived from modelling approaches. Model rates are somewhat higher than those directly measured and we consider possible reasons for this.

Key words

Denitrification, Anammox, DNRA, sediments, North Sea

Highlights

New measurements of denitrification, anammox and DNRA rates in North Sea sediments.

Denitrification is the dominant process and rates measured compare well to other direct measurements.

Model estimates suggest rather higher rates of nitrogen loss compared to direct measurements and some reasons for this difference are considered.
1. Introduction

Fixed nitrogen (i.e. nitrogen present in the marine environment in forms other than N₂O and the relatively inert gas N₂) is a key limiting nutrient in large areas of the oceans and one whose inputs to the ocean due to human activity have increased markedly (Moore et al., 2013, Sharples et al., 2017, Voss et al., 2013). These inputs potentially contribute to a range of environmental problems in coastal waters including increased phytoplankton biomass (Howarth and Marino, 2006), hypoxia (Diaz and Rosenberg, 2008) and possibly harmful algal blooms (Davidson et al., 2014). However, such linkages between nutrient loadings and ecosystem responses are not at all straightforward (Cloern, 2001, Howarth and Marino, 2006, Paerl et al., 2014) and depend on a wide variety of other physical, chemical and biological factors, as illustrated in the responses of phytoplankton abundance to nutrient inputs seen in the North Sea (McQuatters-Gollop et al., 2007).

The main loss mechanism for nitrogen from the ocean is via a suite of microbial processes sometimes collectively referred to as denitrification, including canonical denitrification and anammox which convert fixed nitrogen to N₂ gas (Seitzinger et al., 2006, Dalsgaard et al., 2005, Devol, 2015, Ward, 2013, Trimmer and Engström, 2011, Thamdrup, 2012). These processes occur under low oxygen conditions, and shelf sea sediments are a globally important environment for these processes within the context of the marine nitrogen cycle, and also in terms of mitigating the effects of fluvial inputs to the oceans (e.g. Voss et al., 2013, Seitzinger et al., 2006, Trimmer and Nicholls, 2009, Devol, 2015, Sharples et al., 2017). Canonical denitrification is a heterotrophic process involving nitrate acting as an alternative electron acceptor for the bacterial oxidation of organic matter, ferrous iron and hydrogen sulphide in the near absence of oxygen, yielding N₂ gas and N₂O as a by-products. In sediments, the source of the nitrate may be from the water column or from nitrification of ammonium released during the degradation of organic matter within the sediments; the latter is sometimes called coupled nitrification-denitrification. Anammox was only identified as a biochemical process about 20 years ago (Thamdrup, 2012, Mulder et al., 1995) and involves chemoautotrophic bacteria oxidising ammonium with nitrite as an energy source. Additionally the reduction of nitrate and nitrite may proceed through the process of DNRA, dissimilatory nitrate reduction in which bacteria reduce nitrate to ammonium, a process by which fixed nitrogen is retained within the sediments. The relative importance of anammox, canonical denitrification and DNRA and the controls on this balance are uncertain, and given the central importance of the marine nitrogen cycle for life in the sea, resolving this uncertainty is clearly important (Voss et al., 2013, Devol, 2015, Trimmer et al., 2013). In subsequent discussion we will refer to the general process of denitrification and where appropriate the three different biochemical pathways of canonical denitrification, anammox and DNRA.
Rates of denitrification have been estimated in several different ways ranging from biogeochemical models (Seitzinger and Giblin, 1996, Fennel et al., 2006) and shelf sea budgeting (Hydes et al., 1999) to direct measurements of rates using a variety of techniques of core incubations (Trimmer and Nicholls, 2009, Devol, 2015, Rysgaard et al., 1993, Kitidis et al., 2017). Recently direct sediment core incubation studies using $^{15}$N additions have allowed accurate estimation of rates with fewer uncertainties than previous approaches. This approach allows the relative importance of canonical denitrification, anammox and DNRA to be determined as well as providing some information on the source of the nitrogen species being converted to $\text{N}_2$. However, these measurements are time consuming and labour intensive, meaning there is rather limited data available from coastal seas. Given the natural heterogeneity of shelf seas, it is important to build the data set of direct measurements and compare it to model and budget approaches to build confidence in shelf sea nitrogen budgets and better understand the process controlling these budgets and hence improve models.

The North Sea is a large semi-enclosed coastal sea with water residence time of a few years and subject to large inputs of terrigenous nutrients, particularly nitrate. (Patsch et al., 2017, Queste et al., 2013). Previous budget and model studies (Hydes et al., 1999, Seitzinger and Giblin, 1996) have suggested that there are relatively high denitrification rates in this region, and these ameliorate the potential harmful ecological effects of terrestrial nutrient inputs.

In the work reported here we have conducted measurements of denitrification rates within the North Sea using the $^{15}$N tracer method. The sampling was targeted to representatively sample widely occurring sediment types within the North Sea in terms of sediment grain size and organic carbon content (Diesing et al., 2017). We also report measurements of denitrification rates from the Wash region, a large shallow and intertidal area where denitrification has been suggested to be acting to substantially reduce nitrate inputs to the open North Sea (Jickells et al., 2014, Trimmer et al., 1998). We compare the results obtained to other data from the North Sea and other temperate shelf systems and also to model and budget estimates of denitrification, with the goal of trying to improve overall estimates of the significance of shelf sea denitrification and the biogeochemical controls on the process.
2. Methods

Full details of all methods are presented in Villa 2016 (Rosales Villa, Alida (2016) *Insight into the nitrogen cycling in the North Sea*. Doctoral thesis, University of East Anglia. Available at [https://ueaeprints.uea.ac.uk/61021/](https://ueaeprints.uea.ac.uk/61021/).

The sampling sites for this survey are in The Wash (Fig 1a), a large area of intertidal sand and mud banks and the North Sea (Fig 1b).

![Figure 1. Sampling sites: The Wash (a), The North Sea (b), showing the sampling sites in blue circles and the station numbers refer to sites in Table 1.](http://upload.wikimedia.org/wikipedia/commons/c/c8/Ordnance_Survey_1-250000_-_TF.jpg)

Table 1. Latitude and Longitude of the sampling stations are listed below

<table>
<thead>
<tr>
<th>Stn</th>
<th>Lat</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>52° 58.277</td>
<td>000° 19.141 E</td>
</tr>
<tr>
<td>68</td>
<td>54° 08.475</td>
<td>000° 12.757 E</td>
</tr>
<tr>
<td>101</td>
<td>56° 51.522</td>
<td>000° 18.290 E</td>
</tr>
<tr>
<td>127</td>
<td>57° 49.977</td>
<td>000° 25.639 W</td>
</tr>
<tr>
<td>141</td>
<td>56° 57.047</td>
<td>000° 23.928 E</td>
</tr>
<tr>
<td>The Wash, May</td>
<td>52° 54.730</td>
<td>00° 08.800 E</td>
</tr>
<tr>
<td>The Wash, June</td>
<td>52° 53.560'</td>
<td>00° 11.180' E</td>
</tr>
<tr>
<td>The Wash, Sept</td>
<td>52° 55.129 N</td>
<td>00° 12.121E</td>
</tr>
<tr>
<td>The Wash, Oct</td>
<td>52° 55.968 N</td>
<td>00° 11.981E</td>
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</tbody>
</table>
In the Wash the sampling was limited to one station called Mare Tail with a total of four sampling visits carried out during May, June, September and October 2013. The site was accessed on board of the RV Three Counties from EIFCA (Eastern Inshore Fisheries Conservation Authority) and then by foot around low tide with samples collected by hand. After their collection, the samples were placed in buckets filled with site water to keep them at the ambient temperature, and then transported promptly (within about 3 hours) by boat and road to UEA laboratories for subsequent analysis.

Samples were also collected during August 2013 at 5 sites in the North Sea (Figure 1b) in the water depth range 28-116 m. Sediment samples were collected using a NIOZ cylindrical box corer deployed from the RV Cefas Endeavour. The depth of sediment in the box corer ranged between 40 and 50 cm and was collected with 15 to 25 L of the original bottom water still in place. Subsamples for the sediment incubations were taken by hand from the box corer along with overlying water. Samples collected on board the Cefas Endeavour were processed on board.

A total of 30 intact sediment core samples were collected at each site in 300 mm plexiglass tubes (6 cm i.d). The sediment column in the core were about 15 cm length with about 420 ml overlying volume of water filling the remainder of the tube. After sampling, the cores were placed in 200 L water containers in a room at in situ temperature and were left in the dark overnight with gentle aeration of the overlying water of the core tubes.

**Experimental design and calculations**

Two types of experiments were conducted in the dark, so far as practical, firstly (a) time-series experiment using intact sediment cores (based on Trimmer et al., 2006, Nielsen, 1992) and secondly (b) end-point anaerobic sediment slurry (Thamdrup and Dalsgaard, 2002). The time-series experiment was designed to determined rates of denitrification, anammox and DNRA, while the aim of the anaerobic sediment slurry experiment was to confirm the presence of anammox.

*(a) Time series experiments.* After being left overnight, the overlying water in the core tube was enriched with $^{15}$NO$_3^-$ (by adding Na$_{^{15}}$NO$_3$ [99% $^{15}$N atom%] Sigma-Aldrich) to a give a final concentration of about 50 µM, approximately twice the ambient concentration. Six of the cores were not enriched to allow measurements to be made for correction for natural abundance. After leaving for 30-60 minutes to allow exchange between sediment and overlying water, three cores were sacrificed as time zeroes, and the remaining cores sealed with rubber bungs and incubated in the dark with gentle magnetic stirring (60 rpm) to ensure
water mixing and minimal disturbance of the sediments. Three cores were subsequently sacrificed every hour for 5 hours. When sampling sacrificed cores, samples of overlying water were first taken for nutrient measurements and the water and sediment were gently slurried. One slurry sub-sample for DNRA rate determination by $^{15}$NH$_4^+$ analysis was collected and frozen. Other slurry sub-samples collected for isotopic analysis of N$_2$ and N$_2$O production were taken in a gas tight vial, poisoned with formaldehyde (100 µL, 38%) and stored sealed at room temperature.

(b) Confirmation of anammox. Sediment samples for the end-point slurry experiment to confirm the presence of anammox were subsampled from cores by extruding a 3-cm thick slice (both oxic and anoxic layers were included). The sediment was homogenised and subdivided into 18 subsamples of 2 mL that were placed in gas-tight vials (Exetainer, Labco), filled with helium degassed seawater and incubated in the dark to eliminate all nitrate, nitrite and oxygen. After 24 hours, 15 vials were spiked with $^{15}$NO$_3^-$ and $^{15}$NH$_4^+$ to achieve a final concentration of 500 nmol cm$^{-3}$ of $^{15}$NH$_4^+$ and 100 nmol cm$^{-3}$ for $^{14}$NO$_3^-$ (by injecting 50 µL of $^{15}$NH$_4$Cl 120 mM; [98 $^{15}$N atom%] Sigma-Aldrich) and 50 µL of Na$^{14}$NO$_3$ (25 mM). The remaining three samples were left un-spiked for natural N abundance measurements. At time zero, three of these vials and the three vials with no isotope addition were sacrificed by adding ZnCl$_2$. Samples were stored upside down at ambient temperature with the remaining samples incubated with gentle rotation for 24 hours at in situ temperatures, before also being sacrificed as above.

Isotopic Measurements. A helium headspace was created in the stored gas-tight vials to allow extraction of gas samples for isotopic measurements of N$_2$ (Dalsgaard et al., 2003) at University of Southern Denmark and N$_2$O (Trimmer and Nicholls, 2009, Trimmer et al., 2006) at Queen Mary University, London. In order to measure DNRA, ammonium was first converted to N$_2$ by the hypobromite method and then its isotopic abundance measured (Risgaard-Petersen et al., 1995). Calibration was carried out with oxygen free nitrogen (99.998% $^{14}$N$_2$) with correction for instrument drift and mass effects using repeat standard analyses throughout the analytical run. The measurements of nitrogen isotopes of N$_2$ were carried out according to Dalsgaard et al (2012). Isotopes of N$_2$O were measured using a Cryo-Focusing; Precon, Thermo-Finnigan. These measurements of N$_2$O can provide a means to separate the contributions of denitrification and anammox based on the assumption that N$_2$O is only produced by denitrification and not be anammox (Trimmer et al., 2006).

Anammox rates in the slurries were calculated as in Thamsdrup and Daalgaard (2002). Denitrification rates and the source of NO$_3^-$ for denitrification were calculated using the equations of Nielsen (Nielsen, 1992) when anammox were not present and Risgaard-Petersen et al. (2003) and Trimmer et al. (2006) when anammox was present:
\[ p_{14} = 2r_{14} \times (p^{29}N_2 + p^{30}N_2 \times (1 - r_{14})) \]

\[ r_{14} = p^{45}N_2O / 2p^{46}N_2O \]

Where, \( p_{14} \) is the total \( N_2 \) production, i.e. total denitrification, \( r_{14} \) \( ^{14}\text{NO}_3^- \) and \( ^{15}\text{NO}_3^- \) in the \( \text{NO}_3^- \) reduction zone and \( p^{39}N_2 \) and \( p^{30}N_2 \) are the measured production rates of the \( ^{15}\text{N} \)-labelled \( N_2 \). The production of \( N_2 \) due to anammox \( (p_{14anammox}) \) was calculated as:

\[ p_{14anammox} = 2r_{14} \times (p^{29}N_2 + 2r_{14} \times 2p^{30}N_2) \]

Denitrification rates supported either by the unlabelled \( \text{NO}_3^- \) diffusing from the overlying water \( (p_{14w}) \) or rates of coupled nitrification-denitrification \( (p_{14n}) \) within the sediments were calculated as follows:

\[ p_{14w} = p_{14} \times r_{14w} / r_{14} \]

\[ p_{14n} = p_{14} - p_{14w} \]

\( r_{14w} \) is the ratio of \( ^{14}\text{NO}_3^- \) and \( ^{15}\text{NO}_3^- \) in the overlying water. Concentrations of unlabelled \( \text{NO}_3^- \) were measured in water samples before adding the \( ^{15}\text{NO}_3^- \). As co-occurrence of anammox and DNRA was not observed (see results), there was no need for corrections taking a coupling of these processes into account (Song et al., 2016).

The nutrients analysis were carried out in the Analytical Instrument Laboratory facilities of the University of East Anglia. Analysis for \( \text{NO}_3^- \) and \( \text{NH}_4^+ \) were determined by colorimetric methods. The protocols and standards preparation were based on the methods described by Grasshoff et al. (1983).

Standard deviation on the rate estimates for denitrification ranged between 0.5 and 3.7 \( \mu \text{mol m}^{-2} \text{ h}^{-1} \).
3. Results

Results are presented in summary form in Table 1. The characteristics of the sediments sampled in this study are included in a wider compilation of sediment characteristics in this region (Diesing et al., 2017 and Parker et al this volume) and only briefly summarised here. The sediments sampled, ranged from sand (>90%) to muddy sand (~80% sand) with average grain sizes ranging from 76-165 µm and the organic carbon content ranged from 0.05-0.48%. The Wash site characteristics were similar on each sampling occasion and intermediate between the North Sea sites in which the deeper sites tended to be finer grained and more organic carbon rich. The sediment oxygen penetration depth measured by electrode ranged from 2-8 mm. Hence, the oxygen penetration depth was small at all sites, but in the Wash sediments (2-4 mm) tended to be shallower than at the North Sea stations (6-8 mm). Ambient water column nitrate concentrations ranged from 0.7-6 µM.

In terms of the sedimentary nitrogen cycling measurements, there were no obvious difference between the measurements made on the Wash sediments and those made in the North Sea, so initially we consider the results from the whole data set, while noting difference where they are evident. Based on anoxic slurry measurements, anammox was detectable at all sited at rates ranging from 0.004-0.73 nmol cm⁻³h⁻¹ which confirms the potential for this process in these sediments. Measured denitrification rates in intact sediment cores range from 0.4-10.6 µmol m⁻²h⁻¹. These rates are comparable to other results from this region and from other marine sediments including (Trimmer et al., 2003, Bale et al., 2014, Trimmer and Engström, 2011, Bonaglia et al., 2017). In the intact sediment cores, which may better reflect the ambient environmental conditions than the slurry measurements (Trimmer and Engström, 2011), our measurements found at all times and all sites that canonical denitrification was the dominant process, compared to anammox. Anammox was only detected at two North Sea locations, and even there contributed less than 10% to the total nitrogen loss. At the Wash site the denitrification appeared to be sustained predominantly by nitrate from the overlying water, while at the North Sea sites, nitrification was consistently the dominant (80-90%) source of nitrate for denitrification. DNRA rates were rather variable and the process was only detected when anammox was absent. The DNRA rates measured at the North Sea sites were zero at 4 of the 5 sites, but at one site the rate was equivalent to 17% of the denitrification rate. At the Wash site DNRA rates were equivalent to ~40% of the denitrification rate in June and September, 6% in October and 0% in May.

4. Discussion

The rates measured, and dominance of canonical denitrification, are very consistent with other data from coastal seas, while much higher rates have been measured in estuarine systems and lower rates
beyond the continental shelf (Trimmer and Engström, 2011 and references therein, Neubacher et al., 2011, Devol, 2015, Na et al., 2017, Deek et al., 2013). Indeed, these published studies demonstrate that there is quite a strong inverse global relationship between denitrification rates and depth and also that the proportion of anammox to denitrification increases with depth, over depth ranges from 0-5000 m. A number of potential controlling variables for denitrification vary systematically with water depth. Several of these authors note these relationships parallel the decreasing oxygen consumption with depth and therefore it is argued that the supply of organic matter to the sediments, rather than the nitrate availability, controls the denitrification rate. Such a depth relationship is not directly obvious within the data set presented here, but this data set is small and spans a rather small depth range. The inverse relationship described by Trimmer and Engström (2011) includes very high denitrification rates within shallow estuarine systems, based on studies in several UK estuaries enriched in organic matter and nitrate (Trimmer et al., 2003, Trimmer et al., 2006, Dong et al., 2009). Similar high rates of denitrification have been reported from the Elbe estuary (Deek et al., 2013) and from permeable sediments in the German Bight (Marchant et al., 2016). Our data from the Wash suggests that in shallow intertidal areas in exposed bays, with lower nitrate and organic matter inputs, denitrification rates are lower than in confined estuaries, although canonical denitrification does still appear to dominate denitrification. The very low rates of denitrification seen in September in the Wash are associated with low water column nitrate and this may suggest that nitrate supply may play a role in regulating the rates of denitrification, although several factors change seasonally in such systems including the temperature and the supply and quality of organic matter as noted by other authors (Deek et al., 2013, Asmala et al., 2017, Brin et al., 2017, Deutsch et al., 2010).

A recent study (Kitidis et al. (2017) reported a detailed description of benthic nitrogen cycling in the Celtic Sea (water depths 100-150m) where they found anammox to dominate over canonical denitrification, although the overall denitrification rate was similar to our results for the North Sea. This observation together with another recent studies where anammox was not measurable at a site where it had previously been recorded (Trimmer et al., 2013), emphasises that we are still a long way from fully understanding the benthic nitrogen cycle in the shelf seas.

Recently Sharples et al. (2017) emphasised the global significance of denitrification for trapping fluvial nitrate within coastal waters and preventing its escape to the open ocean as previously discussed by Seitzinger et al. (2006). Sharples et al. (2017) also noted a systematic effect of the Coriolis force in increasing water residence time with increasing latitude which results in higher latitude shelves such as the North Sea being more effective at retaining nitrate because there is more time for denitrification to consume the fluvial nitrate, compared to low latitude tropical shelf systems. However, they also note that the impact of temperature on denitrification rate could offset this
gradient with shorter residence times in tropical regions with weaker Coriolis force compensated by higher denitrification rates due higher temperatures. The effects of temperature on denitrification rates have been investigated systematically recently (Canion et al., 2014) and it is clear that rates of denitrification do vary with temperature and that communities from different regions have different optimum temperatures demonstrating adaption to the *in situ* temperatures in the different regions. Similarly Brin et al (2017) have shown that denitrification rates increase from 4-25°C and then decline, with similar trends seen for both canonical denitrification and anammox. Within the data set presented here there is no obvious effect of temperature on rates even at the Wash site where seasonal cycling took place. By contrast, in offshore North Sea waters Trimmer et al (2009) did find a difference in rates in spring and autumn and Neubacher et al (2011) also found higher rates in summer and autumn than in winter and spring, although the temperature differences between the seasons was modest. Denitrification rates also depend on the supply and quality of organic matter and on the supply of nitrate (e.g. Deek et al., 2013, Deutsch et al., 2010, Asmala et al., 2017), and hence the overall significance of temperature on the retention of fluvial nitrate as discussed by Sharples et al. (2017) still requires resolution.

**Implications of denitrification for coastal nutrient cycling**

The synthesis and scaling up of denitrification can provide useful insights into the role of denitrification in coastal nutrient cycling (e.g. Asmala et al., 2017, Deutsch et al., 2010, Devol, 2015). We therefore now consider the significance of the observed denitrification rates on fluvial nitrate transport and nitrogen cycling more generally in the North Sea. As noted earlier, the direct measurement of denitrification rates in sediments is a complex and time consuming task meaning that data available for scaling up are necessarily limited. Hence a comparison with alternative approaches based on models and budgets can serve to improve confidence in our estimates.

The Wash System. Jickells et al. (2014) estimated nutrient transport through the Wash system and the extent of nitrate trapping in the context of the loss of intertidal habitat to reclamation in the Wash system, and indeed more widely across the world. That analysis was based on earlier estimates of denitrification rates in the Wash and the associated Great Ouse estuary (Trimmer et al., 1998) using the acetylene block technique which yielded results that are substantially higher than the values reported here for the Mare Tail site. However, the Mare Tail site was selected to be representative of the large intertidal sand and mud banks in the Wash itself, and away from the immediate effects of the riverine nitrogen inputs from the Great Ouse where Trimmer et al sampled. Higher values of denitrification comparable to those reported by Trimmer et al. (1998) have been measured with the isotope technique in estuarine systems (Trimmer et al., 2003, Trimmer et al., 2006, Dong et al., 2009,
This may suggest that estuarine systems are particularly hot spots of denitrification, and hence the loss of intertidal area to reclamation in estuaries may have far reaching implications for coastal biogeochemistry (Jickells et al., 2016, Deek et al., 2013). If the Mare Tail results are representative of the Wash generally, the nitrate retention within this system will, however, be lower than suggested by Jickells et al. (2014).

The North Sea. The importance of denitrification on North Atlantic shelf systems and North Sea in particular has been emphasised in several studies (Seitzinger and Giblin, 1996, Hydes et al., 1999, Fennel et al., 2006). The overall average rate of denitrification from the data in Table 1 is 6.3 (median 7.7) µmol m$^{-2}$h$^{-1}$. The average rates reported for the North Sea by Lohse et al. (Lohse et al., 1996) was 9.8 µmol m$^{-2}$h$^{-1}$ and by Neubacher et al. (Neubacher et al., 2011) was 10 µmol m$^{-2}$h$^{-1}$. Measurements on the Irish Sea shelf (4.8 µmol m$^{-2}$h$^{-1}$) were also similar (Trimmer and Nicholls, 2009) as were the results of Kitidis et al. (2017), although as noted earlier the latter authors found anammox to be dominant. These rates on the N W European shelf are similar to those reported for the Baltic (Deutsch et al., 2010, Asmala et al., 2017) and other shelf seas in the compilation by Trimmer and Engström (2011) and in more recent studies with Na et al. (2017) who report values of 9.2 µmol m$^{-2}$h$^{-1}$ in the east China Sea. Thus there is a general consensus for denitrification rates measured using the isotope pairing approach on temperate shelf seas fall in the range of 5-10 µmol m$^{-2}$h$^{-1}$. These values can be compared to estimates derived by fundamentally different approaches. Seitzinger and Giblin (1996) estimated a denitrification rate for temperate shelves equivalent to 19 µmol m$^{-2}$h$^{-1}$, and for the North Sea specifically of 25 µmol m$^{-2}$h$^{-1}$, using a coupled nitrification/denitrification, sediment oxygen consumption and primary production model. Fennel (2006) developed a high resolution physical-biological model for the mid Atlantic bight region along with a similar approach to Seitzinger and Giblin, and from this estimated a denitrification rate equivalent to 46 µmol m$^{-2}$h$^{-1}$. Hydes et al. (1999) used a completely different approach based on synthesis of nutrient and salinity data within the southern North Sea to estimate denitrification rate equivalent to 29 µmol m$^{-2}$h$^{-1}$, although this estimate is quite sensitive to an estimated water residence time in the North Sea. Hydes et al. used a residence time of 1 year (Blaas et al., 2001, Prandle, 1984), and a longer residence time would result in a lower estimate of denitrification. Brion (2004) synthesised some of these estimates and suggested a North Sea denitrification rate equivalent to 23 µmol m$^{-2}$h$^{-1}$. Thus estimates of denitrification derived from models and integration over large spatial scales (19-46 µmol m$^{-2}$h$^{-1}$) are similar, although higher, than the experimentally derived values based on incubations on sediment cores of 5-10 µmol m$^{-2}$h$^{-1}$. This difference is relatively small and may simply reflect uncertainties in both approaches. However, assuming the budget/model calculations are correct, this may reflect a real difference and we would highlight three possible explanations. Firstly, as noted earlier the denitrification rates in estuaries may
be of the order of ten times higher than those for the more open shelf waters (see compilations of rates in Trimmer and Engström, 2011, Asmala et al., 2017). The area of estuaries is small (~2%), compared to the wider North Sea shelf system (McLusky, 2001) but the high rates of denitrification in estuaries could lead to an underestimate of North Sea shelf wide denitrification, when based on shelf sediment measurements alone. However, even denitrification rates in such estuaries that are 20 times higher than in shelf sediments cannot quantitatively explain the whole difference between the sediment core measured and modelled rates. The second issue is that there may be some issues related to the assumptions behind the isotope pairing technique as discussed by Thamdrup (2012). A third possibility is that direct core water isotope techniques may underestimate total sedimentary denitrification. This could be because such measurements are based primarily on diffusive exchanges between sediments and the water column, and in sandy sediments advective exchanges may be important (Canion et al., 2014, Devol, 2015, Marchant et al., 2016, Asmala et al., 2017). Advection may serve to increase denitrification as has been shown in some simulations (Canion et al., 2014), but others argue that the effect may be small (Devol, 2015), possibly because the increased rate of supply of nitrate from the overlying waters may be offset by the increased oxygenation of the sediments. Diffusive measurements may also be lead to underestimations of rates if bioturbation is an important process increasing the effective denitrification rate (Laverock et al., 2011, Eyre et al., 2011). Further work to understand the extent and significance of advective and bioturbation process on denitrification in sediments is clearly needed.

5. Conclusions

The measured rates of denitrification in the sampled North Sea sediments are in the range 5-10 µmol m⁻² h⁻¹ and are dominated by canonical denitrification, consistent with other data from temperate shelf sea systems. These rates are rather lower than model and budget based estimates suggesting limitations in either the models/budgets approaches and/or in the directly measured rates, or their scaling up. Issues with the direct measurements could arise from assumptions inherent on the methods, the need to include a contribution of much higher denitrification rates in estuaries in overall budgets and/or issues associated with advective and bioturbation rather just diffusional exchanges between sediments and the overlying water column.
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anonymous reviewers of this paper.
Table 1: Measured total denitrification rates and component canonical denitrification, anammox and DNRA rates, plus anammox potential along with sediment organic carbon, grain size and oxygen penetration depth (OPD) and water depth, bottom water temperature and nitrate concentrations. For sampling stations see Figure 1. Dw% is the percentage of total denitrification associated with diffusion of nitrate from the overlying water.

<table>
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<tr>
<th>Site</th>
<th>Denitrification</th>
<th>Canonical</th>
<th>Anammox</th>
<th>DNRA</th>
<th>Dw%</th>
<th>Water Depth</th>
<th>Temperature</th>
<th>NO₃⁻</th>
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and Nitrate and Nitrite Reductase Gene Abundances along an Estuarine Nutrient Gradient (the Colne Estuary, United Kingdom). *Applied and Environmental Microbiology*, 75, 3171-3179.


