Contribution by the Methanogenic Endosymbionts of Anaerobic Ciliates to Methane Production in Dutch Freshwater Sediments

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Summary. Biogenic methane contributes substantially to the atmospheric methane concentration and thus to global warming. This trace gas is predominantly produced by strictly anaerobic methanogenic archaea, which thrive in the most divergent ecological niches, e.g. paddy fields, sediments, landfills, and the digestive tract of various animals. Methanogenic archaea also live as endosymbionts in the cytoplasm of anaerobic protozoa. In marine sediments these endosymbionts can contribute up to 90% to the overall rate of methanogenesis, whereas their role in freshwater sediments is largely unknown. Here we describe the results of a one year’s survey of the methanogenesis by endosymbiotic methanogens in four different Dutch freshwater sediments. The abundance of anaerobic protozoa, in particular ciliates, the methane production rates by the ecosystem and by the protists, and a number of abiotic parameters were measured. A novel method (heat-shock for 5 min) for estimating the contribution by endosymbiotic methanogens was established. Our results reveal large fluctuations of ciliate abundance throughout the year, but on average, only minor contributions by methanogenic endosymbionts to the total methanogenesis in these environments.

Key words: anaerobic ciliates, endosymbionts, freshwater sediments, methanogenesis, single cell PCR, SSU rRNA.

INTRODUCTION

Methanogenic archaea account for an annual global production of some 400 million metric tons of methane (Ferry 1997). This has a profound impact on the global change, because the atmospheric methane, which originates from these biological sources, can contribute for about 20% to global warming (Lindau et al. 1993). Since atmospheric methane concentrations have increased steadily by about 1-2% per year through the last decades, (Ferry 1997), detailed information about the biological - but also the unconventional, i.e. plant-dependent - sources of methane production is required for an assessment of the possibilities for a global management of greenhouse gases (Chynoweth 1996, Waßmann and Rennenberg 1996, Hansen et al. 2000, Frankenberg et al. 2005, Keppler et al. 2006).

Methane formation by methanogenic archaea occurs in nearly all anaerobic environments such as, for example, marine- and freshwater sediments, marshes, wetlands, and tundra's (Williams and Crawford 1984,

In marine sediments, the methanogenic endosymbionts of anaerobic protozoa can contribute substantially to biogenic methane production (Fenchel 1993). Also, rumen protozoa with their epysymbionts can play an important role in the methanogenesis in the gastro-intestinal tract of large herbivorous animals: elimination of these protozoa from the ruminal ecosystem can result in a decrease of methane production by some 9-45% (Newbold et al. 1995, Tokura et al. 1999). Lastly, the methanogenic endosymbionts of anaerobic ciliates in cockroaches are believed to be the major source of methane in the hindgut of these insects (Gijzen et al. 1991, Gijzen and Barughare 1992).

In certain freshwater sediments and rice field soils anaerobic protozoa (with methanogenic endosymbionts) can be rather abundant (Finlay and Fenchel 1991; Khalil and Shearer 1993; Finlay et al. 1998, 1999; Schwarz and Frenzel 2005). However, only a few studies have attempted unravelling the contribution of their endosymbionts to the production of methane in these environments so far, although anoxic freshwater environments are believed to account for more than 20% to the total methane flux to the atmosphere globally. Also, seasonal changes in methane production and the abundance of ciliates did not find the necessary attention in the past. Therefore, we have monitored the abundance of anaerobic ciliates, methane production by ciliates and free-living archaea and several biotic and abiotic parameters in four Dutch freshwater sediments over a period of one year. We established a novel technique (heat-shocking) for assaying the contributions of anaerobic ciliates to the methane emissions in strictly anaerobic microcosms. With the aid of this technique, we were able to demonstrate that the contribution of the endosymbionts of anaerobic ciliates to methanogenesis in these ecosystems differs locally by at least one order of magnitude, and is subject to substantial annual fluctuations. However, on average, the contribution of anaerobic ciliates is marginal with respect to the total emissions of methane in Dutch freshwater ecosystems.

MATERIALS AND METHODS

Freshwater sediments

The samples were collected from October 1994 to September 1995 in one-month-intervals at four different locations in the vicinity of Nijmegen, The Netherlands (51°45’ North 5°55’ East (QRA-locator: J021XS)), i.e. in a ditch of a minerotrophic peat-land (“de Bruuk”), a sludge backing pond of a wastewater treatment (“Dekkerswald”), an oligotrophic pond (“Plasmoelen”) and a low-land brook (“Tieleheek”). Sampling in 11 bottles was performed under strictly anaerobic conditions as described by Lomans et al. (1997). The in situ temperature of the sediment was measured prior to sampling. At larger intervals the alkalinity, the conductivity, the pH, and the velocity of the streaming water at the different sampling sites was measured with the aid of a YSI model 33 SCT meter.

Ciliate count

The number of the anaerobic ciliates was determined under a dissecting microscope at 50x magnification after diluting 100 µl sediment slurry with an equal amount of filter-sterilised (0.2 µm) sediment (pore)-water. The average ciliate number was determined by five independent counts using a Sedgewich rafter (Graticules LTD, Tonbridge, Kent, UK). The anaerobic ciliates were determined to the genus level with the aid of Hausmann (1985) and Patterson and Hedley (1992), which are useful for a rapid determination in vivo. Light- and epifluorescence microscopy of selected (living) specimen at 400x magnification was used to confirm the identity of the anaerobic ciliates and the presence endosymbiotic methanogenic archaea by their characteristic autofluorescence in vivo (Doddema and Vogels 1978).

Molecular identification

Single ciliates were isolated from the sample with the aid of a micropipette made from a drawn out Pasteur pipette, washed three times with sterile, anaerobic electromigration buffer (van Hoek et al. 1999), transferred to a Eppendorf tube and centrifuged. After addition of 50 µl of a 5% Chelex-100 suspension (Walsh et al. 1991) the samples were frozen and stored at -20°C. DNA extraction was performed by adding proteinase K (10 mg/ml), incubation for 3-4 h at 56°C, and subsequent heating at 95°C for 10 min. After centrifuga-
tion, the supernatant was used for PCR with primers directed against the 16S and 18S rRNA genes of the endosymbionts and the ciliate, respectively, as described earlier (van Hoek et al. 1998, 2000).

**Phylogenetic analysis**

Small ribosomal DNA sequences from the anaerobic ciliates and their methanogenic endosymbionts were aligned using the PileUp program of the Wisconsin package, version 8.1 (Wisconsin package Version 8.1, Genetics Computer Group (GCG), Madison, Wisconsin). EDNADIST (Rice et al. 1995) was used to calculate the sequence similarity and evolutionary distances using the Jukes and Cantor (1969) nucleotide substitution model. Phylogenetic trees were constructed using the neighbour-joining method (Saitou and Nei 1987). The 18S rRNA gene sequences of the following ciliates were used for the construction of the phylogenetic trees: Brachonella sp. from “de Bruuk” (AJ009665), Brachonella sp. from “Plasmolen” (AJ009664), Caenomorpha-like sp. 1 from “Dekkerswald” (AJ009658), Caenomorpha sp. 2 from “Dekkerswald” (AJ009660), Caenomorpha-like sp. 4 from “Dekkerswald” (AJ009661), Caenomorpha-like sp. 8 from “Dekkerswald” (AJ009662), Caenomorpha sp. 10 from “Dekkerswald” (AJ009659), Caenomorpha sp. from “Plasmolen” (AJ009663), Caenomorpha uniserialis (U97108), Metopus contortus (Z29516), Metopus palaeformis (M86385), Plagiopyla nasuta (Z29442), Plagiopyla frontata (Z29440), Trinymea compressum (Z29438), Blepaharisma americanum (M97909). The 16S rRNA gene sequences of the corresponding methanogenic endosymbionts have the following accession numbers: Caenomorpha-like sp. 1 from “Dekkerswald” (AJ132648), Caenomorpha-like sp. 4 from “Dekkerswald” (AJ132649), Caenomorpha-like sp. 8 from “Dekkerswald” (AJ132650), Caenomorpha sp. 10 from “Dekkerswald” (AJ132651), Caenomorpha sp. 2 from “Dekkerswald” (AJ132652), Caenomorpha sp from “Plasmolen” (AJ132653), Brachonella sp from “de Bruuk” (AJ132655), Brachonella sp. from “Plasmolen” (AJ132654), Metopus contortus (Z13957), Metopus palaeformis (M86386), Plagiopyla frontata (Z29439), Plagiopyla nasuta (Z29437), Trinymea compressum (M96976), Methanococcus voltae (M59290).

**Contribution by methanogenic endosymbionts**

The dry weight of the sediment was determined after the incubation period by drying to a constant weight at 80°C. To determine the organic weight of the sediments, the dried sediment was reduced to ashes by heating to 550°C for 4 h.

**Measuring the contribution to methane production by anaerobic ciliates**

To estimate the contribution of anaerobic protozoa to the methane production several separation/removal methods, such as filtration over a 100 µm nylron gze, the ice-elution method of Uhlig (Uhlig 1964), electromigration (Wagener et al. 1986, van Hoek et al. 1999), and micropipetting were tested for feasibility and reproducibility. Since all these methods were very time consuming and, in addition, led to irreproducible results, a novel method, a heat treatment of the sediment was developed. A heat-shock of 45°C for 5 min was applied to the incubation flasks in a waterbath. This treatment effectively killed all anaerobic ciliates present in the sediment.

For the determination of the contribution of the methanogenic endosymbionts, well mixed 20 ml of sediment slurries were adjusted to a sediment/water ratio of 1:1 (v/v) and dispensed into 60 ml bottles in an anaerobic glove box. Half of the bottles prepared this way were heat-shocked for 5 min at 45°C to allow determination of the methane production by free-living methanogens, the other half was not heat-shocked for a measurement of the methane production by the undisturbed sediment. The contribution of the endosymbionts was calculated from the difference between both measurements.

**RESULTS**

**Abiotic parameters of the sampling sites**

The four different sampling places near Nijmegen, The Netherlands, [51°45′N 5°55′E (QRA-locator: JO21XS)], are substantially different, but characteristic for many freshwater sediments in the Netherlands (Table 1). “de Bruuk” is a ditch in a minerotrophic peatland, “Dekkerswald” a sludge backing pond of a wastewater treatment, “Plasmolen” an oligotrophic pond in a deciduous forest, and “Tielebeek” a low-land brook. Three of the sampling places contained more or less complex communities of anaerobic ciliates; one site (“Tielebeek”), however, did not contain any anaerobic ciliates throughout the year. The yearly temperature course in the sediments followed largely the average ambient and ground temperatures as documented by the National Centre for Meteorology, the KNMI in de Bilt, The Netherlands (Fig. 1).

**Seasonal variations in the abundance of anaerobic (ciliated) protozoa**

The four different freshwater sediments were screened once a month for the presence of anaerobic protists as
described in Materials and Methods by direct observation \textit{in vivo}. Ciliates were the most abundant anaerobic protists in 3 out of the 4 sediments. Only a few anaerobic flagellates and amoebae were observed. Anaerobic ciliates were completely absent in the “Tielebeek” sediments over the whole one-year’s survey. At the other three sampling places, the number of anaerobic ciliates exhibited a substantial variation over the year with remarkable differences between the different locations (Fig. 2). For example, the number of anaerobic ciliates exceeded 100/ml in the “de Bruuk” sediment only in the first two months of our survey (October, November), but declined to less than 50 ciliates per ml sediment for the rest of the year (Fig. 2A). The number of ciliates in “Plasmolen” sediment revealed no clear trends during some months ciliate numbers were as low as 25 ciliates/ml sediment, whereas in other months up to 90 ciliates/ml sediment were counted (Fig. 2C). On the other hand, the number of ciliates in the “Dekkerswald” sediment exhibited a distinct peak in March with more
than 150 ciliates/ml, which remained at a rather high level of more than 100 ciliates /ml in the following months, with a short dip in April followed by a constant decline of ciliate numbers (Fig. 2B).

Methane production in freshwater sediments

The methane concentration in the headspace was measured in regular time intervals up to 48 h, when the ciliates were still alive. Figure 3 shows that the methane production rates in the four sampling places were different. All exhibited pronounced seasonal variations. “Dekkerswald” sediment had the highest methane production rate of all sites, up to a maximum of 17 µmol CH$_4$/g organic weight/h. The maximal rates of the other three sediments were 5-10 times lower; they did not exceed some 2-3 µmol CH$_4$/g organic weight/h. Also the seasonal pattern was different for the “Dekkerswald” sediment: the methane production rate showed an unimodal distribution from November until September of the next year with a peak in May while the other three sediments exhibited a bimodal distribution of methane production with a minimum production in May (Figs 3A, C, D).

Contribution to methane production by anaerobic ciliates

Figure 3 clearly shows that in all three ciliate containing sediments the peaks of methane production did not coincide with the maxima of the ciliate abundance. Accordingly, the removal of the ciliates in the microcosms by heat-shocking had no significant effect on the methane production in the ciliate-free slurries. Only in samples with ciliate counts above 70-80 ciliates/ml the methane production was slightly, but significantly, lowered after the removal of the ciliates (grey bars in Fig. 3). This was the case only the months February, March, and April in the “Dekkerswald” samples (Fig. 3B), and the month July in the “Plasmolen” samples. Unexpectedly, the heat-shock treatment of “Dekkerswald” samples in the months May, June, and July led to a slightly increased methane production (Fig. 3B). In all other months, the removal of ciliates by the heat-shock treatment did not cause significant changes in the methane production, confirming a minor role of the methanogenic endosymbionts in methane formation. Notably, the validity of the heat-shock technique for the removal of the ciliates was confirmed by the absence of any significant changes in methane production by the samples in 11 out of the 12 months studied from the “Tielebeek” location where ciliates were absent through-

Figs 2A-C. The total number of anaerobic ciliates and the distribution of the species in the four different sediments; A - “de Bruuk” sediment; B - “Dekkerswald” sediment; C - “Plasmolen” sediment. At regular time intervals gas samples were taken from the headspace after shaking. The “Tielebeek” sediment did not contain any anaerobic ciliates throughout the screening. The circles, the triangles, and the diamonds indicate the total number of anaerobic ciliates in the three different sediments, respectively. Open bars indicate the percentage of Brachionella spp. of the total number of anaerobic ciliates; light-grey bars Caenomorpha spp.; dark-grey bars Metopus spp.; black bars Plagiopyla spp.
out the year (Fig. 3D). In 8 of such samples, heat-shock treatment caused an insignificant decrease of the methane production, whereas in 3 samples a slight, but insignificant increase could be observed.

Diversity of the anaerobic ciliates

Sediments lacking anaerobic ciliates completely, (and significant numbers of anaerobic flagellates as well), can produce up to 2 µmol CH$_4$/g organic weight/h (Fig. 3D, “Tielebeek”). These methane emissions, on average, are higher than those from “Plasmolen” samples that can host up to some 90 ciliates/ml, and only slightly lower than those from “de Bruuk”, where up to 150 ciliates/ml were observed. The “Dekkerswald” sediments on the other hand, have methane production rates, which are up to four times higher. In the latter sediment, the highest numbers of ciliates and the highest ciliate diversity were observed (Figs 2, 3). To rule out whether these differences correlate with ciliate diversity or not, single cell PCR was used to discriminate between identical and different ciliate species in the various sampling places and to get a preliminary overview about complexity of
Contribution by methanogenic endosymbionts

The isolation of DNA from single cells allows the retrieval of SSU rDNA sequences from both the ciliate and the endosymbiont, which permits an unequivocal identification of identical species (van Hoek et al. 2000). Therefore, the 18S rDNA of individual ciliates and the 16S rDNA of their methanogenic endosymbionts were amplified by PCR: and subjected to DNA sequence analysis. Phylogenetic analysis revealed that a distinct ciliate 18S rDNA always correlated with a specific 16S rDNA from the methanogenic endosymbiont, regardless of the sampling place. On this basis, it was possible to identify even closely related ciliates unequivocally. Figure 4 shows, that ciliates with nearly identical “ribotypes” could be discriminated by their different methanogenic endosymbionts. On this basis, in the “Dekkerswald” sediment the most diverse population of anaerobic ciliates could be identified - exceeding the expectations based on the in vivo identification by far (Figs 2, 4).

Especially, it revealed the existence of ciliates, which look very similar to Caenomorpha uniserialis, but are phylogenetically rather unrelated, i.e. the various Caenomorpha-likes. On the other hand, the combination of ciliate and endosymbiont SSU rRNA data also
demonstrated unequivocally that only the *Brachonella* sp. found in both “de Bruuk”- and “Plasmolen” sediments were identical (i.e. *Brachonella* sp., Fig. 4). All other anaerobic ciliates studied here were unique for their particular sampling places.

**DISCUSSION**

Analysis of four different sampling sites near Nijmegen, The Netherlands, at monthly intervals over a period of one year, clearly showed that a correlation between the methane emissions and the number of anaerobic ciliates in the particular sample did not exist. Ciliate counts of about 100 ciliates/ml can correlate with methane emissions and the number of anaerobic ciliates in the sediments after the removal of ciliates did not allow testing the validity of the extrapolations so far. Here, we have shown here, that the contribution of anaerobic ciliates to the methane production in Dutch freshwater sediments - in general - is marginal throughout the year (Fig. 3) - in clear contrast to the situation in marine sediments (Fenchel 1993), where the contribution of anaerobic ciliates to the methane production is significant. These observations principally confirm earlier speculations about a minor impact of freshwater ciliates on methane emissions (Finlay and Fenchel 1991; Khalil and Shearer 1993; Finlay *et al.* 1998, 1999) which were based on measurements of isolated ciliates under highly artificial conditions. However, the lack of suitable methods to measure the methane production of freshwater sediments after the removal of ciliates did not allow testing the validity of the extrapolations so far. Here, we...
have established that heat-shocking for 5 min at 45°C allows a quantitative and efficient killing of the anaerobic ciliates in the sample without interfering significantly with the methane production by the free-living methanogens in the sample. This method requires only a short temperature pulse and avoids the difficult interpretation of results obtained after the treatment of freshwater sediments with high doses of antibiotics. All ciliates in the sample burst and become completely disintegrated within 5 min. Endosymbiotic methanogens from Caenomorpha/Caenomorpha-like ciliates might survive outside their hosts for some 48 h, but it is very unlikely that significant numbers of the endosymbions of the other ciliates can survive in pore water of such a low osmotic pressure. Microscopical observations suggest that the methanogens burst easily after release from their ciliate hosts due to osmotic shock both in freshwater sediments and cockroach guts (unpublished).

Studies on several Nyctotherus strains from the hindgut of cockroaches have revealed substantial differences in the number of methanogenic endosymbions between ciliates from different lines of cockroaches (van Hoek et al. 2000). A similar situation can be anticipated for the various anaerobic ciliates from the freshwater sediments on the basis of differences in the intensity of the autofluorescence of the ciliates (not shown). However, because of the sensitivity of the anaerobic ciliates for manipulations, and a rapid fading of the autofluorescence of the endosymbios of the endosymbionts it is rather difficult to count the endosymbionts of the various species with the necessary accuracy. Interestingly, a simple correlation between the number of methanogenic endosymbionts and the methane production rates of the various ribotypes of cockroach-dwelling ciliates does not exist (van Hoek et al. 2000). Rumen ciliates produce approximately a hundred times more methane (83-250 pmol/h) - potentially due to the high numbers of methanogens, which can attach to the surface of the rumen ciliates (Kisidayova et al. 2000, Ushida and Jouany 1996). Nevertheless, it is possible to make some rough estimation about the methane production by the endosymbions. Assuming that a single methanogenic bacterium can produce about 1 fmol CH₄/h (Fenchel and Finlay 1992), then a single ciliate with some 1000-5000 endosymbiotic methanogens would be able to produce 1-5 pmol methane per hour. Comparable values have been measured after incubation of anaerobic freshwater ciliates in vitro (Fenchel and Finlay 1992) and for Nyctotherus ovalis isolated from the cockroach hindgut (2.6-7.1 pmol CH₄/ciliate/h; van Hoek et al. 2000), but measurements in situ, which can take into account the real diversity of ciliates in the samples and the availability of nutrients and methanogenic substrates will allow to obtain more detailed results in the future.

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