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Virus-driven nitrogen cycling enhances phytoplankton growth

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ABSTRACT: Viruses have been implicated as major players in aquatic nutrient cycling, yet few data exist to quantify their significance. To determine the effect of viruses on ammonium regeneration by bacteria, experiments were carried out in the oligotrophic Indian Ocean and productive False Creek, Vancouver, Canada. Bacteria were concentrated and then diluted with virus-free water to reduce virus abundance, or with virus-replete water to restore natural virus abundances. Virus-replete treatments showed increased ammonium concentrations compared to treatments with viruses removed (differences of 0.287 ± 0.14 and 1.44 ± 0.73 µmol l⁻¹, mean ± SD, in the Indian Ocean and False Creek, respectively). Bacterial abundances were lower, while phytoplankton abundances and chlorophyll a (chl a) concentrations were greater in the virus-replete treatments, consistent with the increased availability of ammonium in the presence of viruses. These data demonstrate that viral lysis leads to ammonium production, likely through the liberation of dissolved organic N that is remineralised by uninfected bacteria. In turn, the released ammonium fuels primary production. These results show that viruses play a critical role in the marine N cycle, and suggest that viral lysis likely supplies a significant portion of the global N requirements of phytoplankton.

KEY WORDS: Ammonium · Virus · Bacteria · Remineralisation · Nitrogen

INTRODUCTION

Viruses are the most abundant biological entities in the ocean, of which the majority are thought to infect bacteria (Suttle 2007). Every day, viruses lyse an estimated 20 to 40% of the bacterial production in the ocean (Suttle 1994), releasing bacterial cell contents to the surrounding environment. This process has been termed the ‘viral shunt’, to describe the viral-mediated transfer of nutrients from particulate to dissolved material (Wilhelm & Suttle 1999, Suttle 2005). The lysis products are used by uninfected bacteria (Middelboe et al. 1996, 2003); therefore, viruses play an important role in recycling carbon and nutrients within the bacterial community. Viral loop models (e.g. Fuhrman 1992, Bratbak et al. 1994) incorporate virus-induced cycling of carbon within the bacterial size fraction into the pelagic food web model, and suggest that viral activity primarily acts as a sink of organic carbon by removing whole cells from grazing and increasing bacterial respiration. This was verified experimentally by Middelboe & Lyck (2002), in a study in which viral activity stimulated carbon recycling and respiration by uninfected bacteria, and reduced the accumulation of microbial biomass. Further studies have confirmed efficient bacterial recycling of carbon from bacterial (Middelboe et al. 2003) or algal lysates (Haaber & Middelboe 2009).
There is also persuasive evidence that viruses are important agents of N cycling in aquatic environments. Viral lysates are rich in free and combined amino acids (Middelboe & Jørgensen 2006), and are therefore a potentially important source of labile organic N. Moreover, bacteria assimilate dissolved organic nitrogen (DON) resulting from the lysis of infected microorganisms, especially when nutrient-limited (Gobler et al. 1997). During carbon-limited conditions, bacteria hydrolyse amino acids and other nitrogenous products to access the carbon, producing ammonium as a by-product (Goldman et al. 1987). Assuming that the C:N ratio of viral lysates is similar to that of bacteria (i.e. between 4:1 and 5:1; Goldman et al. 1987) and that carbon growth efficiencies of uninfected bacteria are in the range of 0.2 to 0.3 (Middelboe et al. 1996), viral lysates contain N in excess of bacterial requirements. Consequently, bacterial metabolism of viral lysates should produce inorganic N that is available to phytoplankton (Haaber & Middelboe 2009). In addition to fuelling bacterial metabolism, viral lysis therefore may represent a significant pathway for the regeneration of ammonium, a major N source that fuels primary production in the ocean.

We hypothesise that viral lysis of bacteria releases cellular debris to the dissolved organic matter (DOM) pool, accessible to uninfected bacteria. The subsequent turnover is potentially an important source of N for phytoplankton growth (e.g. Haaber & Middelboe 2009). Therefore, viral activity would not only be a carbon sink, but would also indirectly stimulate primary productivity, and thus carbon production. The strongest evidence that viral lysis supports the growth of phytoplankton was seen in several experiments conducted in the Gulf of Mexico and Mediterranean in which the growth rates and the proportion of dividing *Synechococcus* cells were higher in treatments with viruses than in treatments in which viral concentration was either reduced by dilution with ultra-filtered seawater or was heat-inactivated (Weinbauer et al. 2011).

To determine whether ammonium regeneration associated with viral lysis influences phytoplankton growth, an initial experiment was conducted in the Gulf of Mexico and Mediterranean in which the growth rates and the proportion of dividing *Synechococcus* cells were higher in treatments with viruses than in treatments in which viral concentration was either reduced by dilution with ultra-filtered seawater or was heat-inactivated (Weinbauer et al. 2011). Viruses are not simply parasites that disrupt food web flow (Azam & Worden 2004), but play a significant role in nutrient recycling (Fuhrman 1999, Wilhelm & Suttle 1999) and ultimately provide N that supports primary production.

**MATERIALS AND METHODS**

**Description of sampling sites**

Samples were collected from the surface waters of False Creek (FC), Vancouver, Canada (49°16′N, 123°7′W) on 3 November 2008, and from 10 m depth in the Indian Ocean (IO) (19°46′S, 114°52′E) on 12 November 2006. The 2 study sites represented very different environments. The IO station is oceanic and oligotrophic with a high degree of DOM recycling (A. W. Visser et al. unpubl. data), and was characterized by very low concentrations of chlorophyll *a* (chl *a*: 0.2 µg l⁻¹), inorganic nutrients (nitrate, 0.12 µmol l⁻¹; phosphate, 0.08 µmol l⁻¹; ammonium, 0.16 µmol l⁻¹), a sea surface temperature of 28°C, and a salinity of 35.0. In contrast, FC is a small productive inlet which is heavily influenced by neighbouring English Bay, the Fraser River, and freshwater runoff from the City of Vancouver. Tidal mixing results in a vigorous exchange of water between the sampling site at the mouth of FC and English Bay. Surface salinities in English Bay typically remain at ~25 to 26 during November and December (Short & Suttle 2003), and temperatures range from ~7 to 10°C. These data are consistent with sea-surface temperatures for November 2008 of 10°C estimated from satellite data (http://las.pfeg.noaa.gov/oceanWatch/oceanwatch.php). In November, chl *a* was low (0.47 µg l⁻¹), and nutrient concentrations high (nitrate, 14.8 µmol l⁻¹; phosphate, 1.43 µmol l⁻¹; ammonium, 3.50 µmol l⁻¹).

**Experimental design**

The IO and FC experiments were designed to examine the impact of viruses on ammonium production and subsequent effects on phytoplankton growth. In both experiments, triplicate +V and −V treatments were set up with the objectives of keeping bacterial abundances at near *in situ* levels in both treatments, while reducing (−V) or maintaining (+V) near *in situ* viral abundances.

In the FC experiment, water was filtered in series through 2.0 and 0.2 µm pore-size, 47 mm diameter
polycarbonate filters (AMD Manufacturing), with the first filter removing larger phytoplankton and zoo-
plankton, and the second concentrating bacteria (Wilhelm et al. 2002). A transfer pipette was used to
keep the bacteria in suspension above the 0.2 µm fil-
ter. Viruses were removed using a Prep Scale-TFF
Cartridge (Millipore) with a 30 kDa molecular weight
cut-off. The −V treatment was prepared by adding
50 ml of bacterial concentrate to 450 ml of virus-free
water, and the +V treatment was prepared by adding
50 ml of bacterial concentrate to 450 ml of 0.2 µm fil-
tered water. Incubations ran on a light:dark cycle of
14:10 h at in situ temperature, and subsamples were
collected at time 0, 5.5, 10.25, 19, and 24.5 h.

The IO experiment was performed similarly; how-
ever, water was filtered through a 20 µm pore-size
filter before bacteria were concentrated above a
0.2 µm pore-size Pellicon filter (Millipore), and
viruses were removed using a 47 mm diameter
0.02 µm pore-size Anodisc filter (Whatman). Incuba-
tions were run at in situ light and temperature condi-
tions in flow-through, on-deck incubators, and sub-
samples were collected at 0, 6, 10.5, 17.5, and 23.5 h.

The effect of the concentration step on bacterial pro-
duction in the IO experiment was measured using tri-
titated thymidine (TdR) incorporation (Fuhrman &
Azam 1980). TdR incorporation rate, normalised per
cell, was 12 ± 5% higher in untreated water than
after the concentration step, indicating a minor effect
of the procedure.

**Cell and virus counts**

Volumes of 1 ml (viruses and bacteria) and 5 ml
(phytoplankton) were fixed with gluteraldehyde at a
final concentration of 0.5%, frozen in liquid N, and
stored at −80°C. Samples were counted using a Bec-
ton Dickinson FACSCalibur flow cytometer, using
SYBR Green I (Sigma-Aldrich) to stain the viruses
and bacteria (Brussaard 2004). Phytoplankton were
enumerated unstained (Olsen et al. 1993).

**Chlorophyll and nutrient determinations**

Samples were filtered through acid-washed syr-
inges fitted with Milli-Q-soaked 0.45 µm pore-size
cellulose-nitrate membrane filters (Whatman Schlei-
cher & Schnell). The first 5 ml were discarded, and
the rest was collected into acid-washed 15 ml
polypropylene screw cap tubes and frozen at −20°C.
The filters were folded and placed in similar screw
cap tubes, kept in the dark, and frozen at −20°C.
Chl a and ammonium were determined fluorometric-
ically following the respective protocols of Parsons et
al. (1984) and Holmes et al. (1999).

**Statistical methods**

Differences of means were tested using 2-tailed
Student’s t-tests. Equality of variance was tested
using an F-test.

**RESULTS**

**Bacterial and viral abundances**

Bacterial and viral abundances (mean ± SD) in the
initial water samples at IO and FC were 8.61 ± 0.45 ×
10^5 and 19.1 ± 1.58 × 10^5 cells ml⁻¹ and 15.3 ± 5.4 ×
10^6 and 17.3 ± 1.72 × 10^6 viruses ml⁻¹, respectively.
As expected, viral abundances at the start of the IO
and FC experiments were significantly less in the −V
than in the +V treatments (IO: decrease of 70%, t =
36.7, df = 2, p < 0.001; FC: decrease of 39%, t = 3.88,
df = 4, p < 0.05; 2-tailed Student’s t-test). Increase in
viral abundance over the FC experiment was signifi-
cantly greater in +V than in −V (Fig. 1B; t = 4.30, df =
2, p < 0.001; 2-tailed Student’s t-test). Time-course
data for the IO experiment indicates that viral pro-
duction occurred in the +V treatment (Fig. 1A),
although there was a net decrease of viral abundance
from the initial to final time point.

**Phytoplankton growth**

In the FC samples, small cyanobacteria that were
not removed by 2 µm filtration increased significantly
in +V compared to −V treatments (t = 3.88, df = 4,
p < 0.05; 2-tailed Student’s t-test), consistent with the
increase in chl a in +V (Fig. 2). In the IO samples,
chl a increased in the +V treatment and decreased in
the −V treatment, with significant differences
between treatments at the final time point (t = 2.78, df
= 4, p < 0.05; 2-tailed Student’s t-test).

**Ammonium concentrations**

Ammonium concentrations were initially indistin-
guishable in +V and −V for both experiments (IO: +V
= 0.25 ± 0.02 µmol l⁻¹, −V = 0.22 ± 0.02 µmol l⁻¹; FC:
but at the end of both experiments were significantly higher in +V than in −V (Fig. 3; IO: $t = 7.00$, df = 4, $p < 0.005$; FC: $t = 4.55$, df = 4, $p < 0.05$; 2-tailed Student’s t-test).

**Fig. 1.** Time series of viral abundance in seawater samples from (A) the Indian Ocean (IO) and (B) False Creek (FC) experiments in which viruses had been reduced (−V) or maintained at near in situ abundance (+V). Error bars represent the SD of abundance estimates from triplicate incubations.

$+V = 3.38 \pm 0.12 \text{ µmol l}^{-1}$, $−V = 3.13 \pm 0.18 \text{ µmol l}^{-1}$), but at the end of both experiments were significantly higher in +V than in −V (Fig. 3; IO: $t = 7.00$, df = 4, $p < 0.005$; FC: $t = 4.55$, df = 4, $p < 0.05$; 2-tailed Student’s t-test).

**DISCUSSION**

The most important findings of the present study were that ammonium and chlorophyll production decreased in temperate and tropical seawater samples in which viral abundances were reduced.

Increases in chl a and picoalgae

Increases in chl a in the presence of the ambient viral community relative to treatments in which viral abundances were reduced is consistent with ammonium increases in the +V treatments supporting...
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increased phytoplankton growth (Fig. 2). Interestingly, the dilution of the viral size fraction in −V resulted in less phytoplankton biomass and chl a concentrations in both experiments, indicating that phytoplankton production depended on viral lysis of bacteria.

**Impact of grazers**

Contribution to the DOM pool by grazers cannot be excluded from either experiment, although in the FC experiment grazers were undetectable (<10⁴ cells ml⁻¹). Infection of grazers by viruses might have occurred (e.g. Saura et al. 2011), but would not change the results, because infection would simply provide another source of virus-induced DOM to the treatment, intensifying the results. Grazing of viruses may also have occurred; however, removal rates are generally minimal relative to the large standing stock of viruses (Gonzalez & Suttle 1993, Bettarel et al. 2005).

**Ecological implications**

Significant rates of viral mediated ammonium regeneration in both oligotrophic oceanic and productive coastal environments emphasise the importance of viruses in regenerating N and supporting phytoplankton production. Unlike carbon, for which viral lysis of bacteria has been considered a futile loop (Azam & Worden 2004), N remineralisation by viruses appears to be an important process in both low- and high-productivity regions of the oceans. Our results show that the removal of viruses reduces ammonium production and decreases phytoplankton growth, supporting evidence from other studies in which the removal of viruses decreases growth rates of *Synechococcus* (Weinbauer et al. 2011).

The dependence of phytoplankton growth on N regeneration mediated by viral lysis is a feedback mechanism that has not previously been documented, and which is likely significant on a global scale. Instead of acting as a carbon sink, viral activity stimulates N recycling that, in turn, fuels primary production and system productivity. Assuming global bacterial production of 26 to 70 Gt C yr⁻¹ (Ducklow & Carlson 1992), a loss from viral lysis of 20 to 40 % of the production (Suttle 1994, 2005), and a bacterial C:N of 5, the global annual production from viral lysis would be ~1 to 6 Gt N. Compared with an estimated annual global marine primary production of 49.3 Gt C (Ducklow & Carlson 1992), this corresponds to a demand by phytoplankton of approximately 7.4 Gt N (according to the Redfield ratio). Hence, viral lysis is potentially responsible for supplying a large portion of the global N requirements of phytoplankton.

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