Effect of resuspension on mineralisation of organic material

Laboratory studies of water movement intensity and concentration of suspended sediment

Charlotte Stenborg Larsson

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Abstract
The Earth’s surface contains of 71% oceans and a large part of the global carbon cycle takes place in the oceans. In the aquatic environment, the sediment-water interface plays an important role for the mineralisation of organic material. One factor that can affect the mineralisation is resuspension. Resuspension cause mixing of surface sediments and bottom water and result in a redistribution of the sediment when it settles again. Resuspension also increases the transport of oxygen into the sediment, reduces the diffusive boundary layer surrounding particles, and enhance the nutrient uptake. Resuspension can be induced by both wave action and bottom currents and is a common physical process in both shallow coastal areas and in the deep ocean. Human impacts, such as dredging and trawling, can also cause resuspension.

The effect of resuspension on mineralisation of organic material was studied in two experiments during December to April 2004/2005. The aim for Experiment 1 was to investigate how the intensity of the resuspension event affects the degradation rate. The aim for Experiment 2 was to investigate how different concentrations of resuspended sediment affect the degradation rate of organic matter. Sediment samples were collected in December and late March at a marine field station, Askö, Sweden. Sediment and bottom water were transferred to and incubated in sealed bottles. For Experiment 1, resuspension was created in bottles with a specially designed rotary table, creating different intensity of water movements. In Experiment 2, bottles with different concentrations of sediment were put on an ordinary rotary table. The mineralisation rates were in both experiments monitored by daily sampling of sediment-water slurry, and analysed for total inorganic carbon by a gas chromatography with a thermal detector, GC-TCD.

Results from Experiment 1 did not show any clear patterns regarding inorganic carbon formation. Experiment 2 did show clear patterns for two of six replicates of mineralisation of organic material. For these replicates the mineralisation rate were low according to previous studies. However, the sediment concentration seems to not affect the mineralisation rate. For both experiments, valuable information on how to better design experiments to investigate the importance of resuspension and the effect of mineralisation of organic material was yielded. Hence, further studies are needed to continue the investigation of the importance of resuspension for the mineralisation rate of organic material, and its impacts on the nutrient fluxes in the oceans.
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The effect of resuspension on mineralisation of organic material was studied in two experiments ex situ during December to April 2004/2005. The aim for Experiment 1 was to investigate how the intensity of the resuspension event affects the degradation rate. The aim for Experiment 2 was to investigate how different concentrations of resuspended sediment affect the degradation rate of organic matter. Sediment samples were collected in December and late March at a marine field station, Askö, Sweden. Sediment and bottom water were transferred to and incubated in sealed bottles. For Experiment 1, resuspension was created in bottles with a specially designed rotary table, creating different intensity of water movements. In Experiment 2, bottles with different concentrations of sediment were put on an ordinary rotary table. The mineralisation rates were in both experiments monitored by daily sampling of sediment-water slurry, and analysed for total inorganic carbon by a gas chromatography with a thermal detector, GC-TCD.

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In laboratory studies it does not always go as planned and in this work I have had to deal with some unforeseen factors. However, everything comes to an end, so even this thesis. Today, I am glad it took some time to finish my thesis and I would like to thank following persons for help and support:

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My family, who stands behind me all the time, especially my mother.

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1. Introduction

The Earth’s surface contains of 71 % oceans and a large part of the global carbon cycle takes place in the oceans (Smith & Smith, 2001). In the ocean, continents and the open sea connect through continental margins, such as coastal areas. These areas are very important for the biogeochemical carbon cycle, especially regarding the mineralisation of organic matter (Accornero et al., 2002 and references therein; Arnosti & Holmer, 2003). As much as 83% of the global sedimentary mineralisation takes place in these areas (Jorgensen, 1983, in Middelburg et al., 1993).

In the aquatic environment, the sediment-water interface plays an important role for the mineralisation of organic matter (Anderson et al., 1986). The shallower a sea, the more important the sediment is for the mineralisation than relative to the water column (Anderson et al., 1986). The generally large primary production in a shallow sea brings a large load of organic material to the sediment in coastal areas (Middelburg et al., 1993).

There are several factors that can affect mineralisation rates in surface sediments. Many of these, such as temperature, pH, redox potential, and organic matter quality, have been frequently studied in both freshwater and marine environments (e.g. Hulthe et al., 1998, Bastviken et al., 2003, Tranvik et al., 1994). Another such factor rarely addressed is resuspension. Resuspension events cause mixing of surface sediments and bottom water and result in a redistribution of the sediment when it settles again after being resuspended. In addition, resuspension increase the transport of molecular oxygen \((O_2)\) into the sediment, and at the same time the turbulence reduces the diffusive boundary layer surrounding particles including bacterial cells, potentially enhancing the nutrient uptake. In line with this, it has been shown, that the microbial production are stimulated by resuspension events (Wainright & Hopkinson, 1997). Other studies also indicate that resuspension enhance mineralisation rates (Ståhlberg et al. submitted). In other words, since microorganisms are responsible for most of the organic matter mineralisation, resuspension events should be important for mineralisation rates. In this study I therefore address the question how resuspension affect sediment mineralisation rates.

Resuspension can be induced by both wave action (Christiansen et al., 1997) and bottom currents and is a common physical process both in shallow coastal areas and in the deep ocean (Tengberg et al., 2003). Natural events, e.g. strong winds, biological activities and currents, can cause resuspension. In addition, human impacts such as dredging and trawling can also cause resuspension (Tengberg et al., 1993; Wainright & Hopkinson, 1996).

It is the productivity at the ocean surface and at the water depth that controls the torrent of organic matter to the sediment. The time the sediment is available for mineralisation depends on the water depth (Middelburg et al., 1993). One of the main factors, that control both the spatial and temporal distribution of particles in shallow water environments, is wave action (Christiansen et al., 1997). When friction of water moves across the sediment surface, resuspension occurs. Depending on the strength of the water friction, different sizes of sediment particles come in motion upward the water.

Studies on resuspension after a storm have shown that a variation of microorganism’s biomass can be seen upwards the water in the oceans (Ritzrau & Graf, 1992). The effect of resuspension caused by winds, shows that a higher amount of suspended material is
found at the bottom (7 cm over the sediment surface) during a storm event (Ritzrau & Graf, 1992) compared to calm conditions in the autumn. Hence, the microorganisms have a larger amount of the suspended matter to consume closer to the sediment surface. Marine sediment environment contains a 1000 higher bacterial volume than the water above the sediment (Wainright, 1987). When resuspension occurs, it has been shown to increase the standing stock of bacteria directly over the sediment (Wainright, 1987). In these cases, resuspension did affect the bacterial communities compared to calm conditions, causing a higher amount of bacteria attached to suspended sediment. Studies have also shown that the bacterial uptake of organic matter increases through fluid motion (Logan & Kirchman, 1991).

According to Middelburg et al. (1993) future studies on organic matter mineralisation in sediments should focus on sediments in coastal areas rather than deep-sea because of the large mineralisation that occurs in coastal areas. In this study, sediment samples from coastal areas in the Baltic Proper will be examined. The study focuses on how resuspension affects the mineralisation rate of organic matter from top sediment in brackish water. Inorganic carbon (IC, including carbon dioxide and different carbonate species) present in the water/sediment slurry was analysed to estimate the mineralisation. The experiments were performed ex situ (i.e. in the laboratory) during wintertime.

1.2 Aim

In this study two different questions were addressed:

1) Does the intensity of the water movements causing resuspension affect organic matter mineralisation? (Experiment 1) This is relevant since resuspension events may vary in intensity (Logan & Kirchman, 1991).

2) Does the amount of sediment resuspended affect mineralisation rates? (Experiment 2) This relates to the spatial variability of the potential resuspension effect on organic matter mineralisation since the amount of resuspended sediment will vary depending on the distance from the bottom during a resuspension event (Ritzrau & Graf, 1992).

1.2.1 Experiment 1

The aim for Experiment 1 was to investigate how the intensity of the resuspension event affects the degradation rate. The experimental question is: Does the degradation rate change depending on different intensity of the resuspension event? In the experimental set up water-sediment mixtures with the same sediment concentration was agitated with different intensity.

1.2.2 Experiment 2

The aim for Experiment 2 was to investigate how different concentrations of resuspended sediment affect the degradation rate of organic matter. The experimental question is: Does different concentrations of sediment in suspension affect the degradation rate? This was tested experimentally by agitating water-sediment mixtures with different sediment concentrations at the same intensity.

These experiments also tend to evaluate two different methods to study resuspension ex situ.
2. Method

2.1 Sampling site & Sediment sampling

For both experiments, the sediment and water samples were taken in Krabbfjärden near the marine field station at Askö, Trosa archipelago, Sweden (58°49.0921N; E17°34.2580, Experiment 1; 58°48.6714N; E17°36.5731, Experiment 2) with a Ruttner water sampler and kajak sediment sampler. These sampling sites were chosen since the type of sediment found in this area has a high content of organic material and the top layer resuspends easily. Sampling for Experiment 1 occurred November 30th 2004 at a depth of 27 m. The water temperature was 3.1°C and air temperature 2.1°C. A total of 11 sediment samples were taken. (Figure 1)

For Experiment 2 the sampling occurred March 31st 2005 at a depth of 39 m. The water temperature was 3.1°C and air temperature 5.9°C. The salinity was 0.6 psu at a depth of 15 m. A total of 5 sediment samples were taken.

![Picture of the pipe with the sampled sediment from Krabbfjärden (Experiment 1). The sediment sampled for Experiment 2 was similar to this. Photo: C. Stenborg Larsson](image)

On shore, for both experiments, the sediment was pushed up in the pipe with a pusher and the uppermost 2 cm sediment layer in each of the samples was sliced off with a slicer. The sliced off samples were mixed in a plastic box and stored in a cooler during transportation to the laboratory, to minimise temperature changes. 1-2 mm water above the top of the sediment was included when the sediment was sliced to not lose too much of the top layer of the sediment, presumably being most easily resuspended.

2.2 Sediment characteristics

Based on the brown colour and absence of odours from reduced sulphur compounds (Bydén et al., 2003), oxic conditions probably prevailed in the retrieved sediment for both experiments.

Dry substance (DS) and loss on ignition (LOI) was both measured according to Swedish Standard 027116 (105°C to constant weight and 550°C for 2 hours respectively; SIS, 1989). The sediment for both experiments had a high amount of water. Experiment 1 had a water content of about 92% of the wet weigh (WW) (min 90.91% and max...
93.02% WW) and the water content in Experiment 2 was between 84.2 % (min) and 84.5% (max) WW). LOI was approximately 12% of the dry weight for both Experiment 1 (min 11.76% and max 12.18%) and Experiment 2 (min 11.75%, max 13.67%).

2.3 Experimental set up

2.3.1 Experiment 1
Each bottle (120 ml) was weighed before and after 1 ml of the well-mixed sediment sample was put in with a syringe. 90 ml of aerated water was added before the bottles were closed with stoppers. Afterwards, 20 ml air was also added with a syringe before the bottles were placed at the shaking at a temperature of 4°C. Bottles with corresponding volumes of water and air but without sediment were also prepared to enable correction for processes not related to sediment particles (incubated at the same conditions). pH was measured initially when the sediment had been mixed with the water and the air.

The bottles were placed lying down on a specially designed rotary table (Figure 2 & 3). The specially designed rotary table was a steel construction linked to an ordinary rotary table. When the ordinary rotary table was moving (55 rounds/min), the steel construction moved back and forth in a bow formation and created waves with different intensity depending on where the bottles were lying.

![The specially designed rotary table. Photo: C. Stenborg Larsson](image)

The 12 bottles were removed from the incubation every 12th hour during a 4-day period and thereafter 12 bottles were removed every 24th hour during a 4-day period. For preservation of the removed bottles, 1.0 ml 5 M H₂SO₄ was added to the bottles with a syringe. The preserved bottles were storied at 4°C until analysis.

2.3.2 Experiment 2
7 different concentrations of sediment were prepared in Ehrlenmeyer-flasks by using a scale. One litre of water was weighed and thereafter different sediment volumes (0.0 ml; 0.05 ml; 0.1 ml; 0.25 ml; 0.5 ml; 1.0 ml and 5.0 ml)(Puig et al., 2001; Tengberg et al., 2003) were added with a syringe (Figure 4) and mixed with the water. This yielded
water/sediment mixtures with sediment concentrations corresponding to 0 mg; 0.026 mg; 0.053 mg; 0.13 mg; 0.26 mg; 0.53 mg; 2.6 mg dry sediment L⁻¹, respectively (Table 1). 270 g of the each water/sediment mixture was transferred to two 331 ml bottles yielding two replicate bottles per sediment concentration. The bottles were closed with stoppers. The stoppers were pierced with 12 cm Teflon-tubing (5.0 mm outside and 3.5 mm inside diameter) attached to a three-way luer lock valve for water sampling from the bottom of the bottle and with a syringe needle for headspace sampling. In total, 13 bottles (one bottle with water only and duplicate bottles with the six different water/sediment mixtures) were placed at a rotary table (100 rounds/min) in a climate chamber with a temperature of 4°C (Picture 4). The proportion of 270 ml slurry and 60 ml headspace yielded a smooth shaking on the rotary table when the bottles were lying down. pH was only measured initially after the different sediment volumes had been mixed with 1 L of the water.

![Figure 4](image-url) Picture of the bottles with different sediment concentrations. From left to right 0.026 mg; 0.053 mg; 0.13 mg; 0.26 mg; 0.53 mg; 2.6; 0 mg dry sediment L⁻¹.  
*Photo: C. Stenborg Larsson*

![Figure 5](image-url) Picture of the sample bottles with different sediment concentrations on the rotary table in the climate chamber. Start from the top left: 0.0 mg, 2.6mg, 2.6mg, 0.53 mg, 0.53mg & 0.26mg dry sediment L⁻¹and start from the bottom left: 0.026mg, 0.026mg, 0.053mg, 0.053mg, 0.13mg, 0.13mg & 0.26mg dry sediment L⁻¹. *Photo: C. Stenborg Larsson*
Samples for analysis of the production of CO$_2$ were collected from all bottles at 0, 22, 44, 68, 92, 140 and 188 hours. At each sampling occasion, 5 ml gas and 5 ml water samples were sampled. Before gas sampling, the syringe was washed with headspace gas once. Before sampling water, the bottles were shaken to be sure that the sediment was thoroughly mixed with the water. Then the syringe was washed three times with the sediment/water mixture prior to sampling. Notes were taken of temperature and air pressure in the climate chamber and in the laboratory. The sampled amount of headspace gas and water were replaced by adding same amount of air from the climate chamber and aerated water from Askö. Samples of the added air and water were analysed to correct for carbonate and carbon dioxide additions. When replacing water without sediment to the bottles, the concentration of sediment in the bottles decreased. This was considered in subsequent calculations. Altogether, 105 samples were taken during 7 occasions.

The gas samples were collected in 13 ml vials except for the air samples, which were transferred to 30 ml vials. Afterwards, 20 ml of N$_2$ were added to the gas samples in the 13 ml vials to be sure that a high pressure existed facilitating the withdrawal of sub-samples for analysis by gas chromatography. Water samples were taken with 5 ml syringe and added to a 50 ml syringe through a 3-way luer-lock valve. Subsequently, 0.5 ml H$_2$SO$_4$ and 40 ml N$_2$ were added to each 50 ml syringe. The syringes were shaken 30 seconds and kept still 30 min and thereafter shaken for another 30 seconds. The acid converts all inorganic carbon in the sample to CO$_2$ and the shaking procedure was to equilibrate the CO$_2$ between the water and the headspace in the 50 ml syringe (Bastviken et al., 2003). The headspace in the syringe was thereafter transferred to 30 ml vials for analysis of IC and methane (CH$_4$).

### 2.4 Analysis of inorganic carbon and methane

Each gas sample was analysed for CO$_2$ by triplicate 1.0 ml gas injections into the gas chromatograph with a thermal conductivity detector, GC-TCD (Shimadzu Gas Chromatograph GC-8A; He 30 ml/min, injector/detector 100°C, colon temperature 60°C; Fifield & Haines, 1995). The gas samples were taken from the sample vial with a 1.0 ml syringe and before sampling the syringe was washed with air three times. The same procedure before sampling as for carbon dioxide was done also for methane. Methane was primarily used as an indicator of anoxic conditions in both experiments.

Methane was analysed by triplicate 0.5 ml injections into a gas chromatograph with a flame ionisation detector, GC-FID (Chrompack, CP 9001; N$_2$ 30 ml/min, injector/detector 150°C, colon temperature 125°C; Fifield & Haines, 1995). The same procedure before sampling as for carbon dioxide was done also for methane. Methane was primarily used as an indicator of anoxic conditions in both experiments.

The amount of CO$_2$ and CH$_4$ in ppm in vials was calculated according to linear regression, $y = kx + m$, made from analysis of samples with known concentrations (standard curve). Henrys law ($C_{aq} = K_h p$) describing partitioning of gases between water and gas phases (Stumm & Morgan, 1996) was used to correct for the CO$_2$ distribution between water and headspace during extraction in the 50 ml syringe.
2.5 Statistical analysis

For the statistical analysis, non-parametric correlations (Kendalls tau) were first used to detect significant changes in inorganic carbon concentrations over time. Thereafter, if significant formation of inorganic carbon occurred, and since most such relations appeared approximately linear, linear regression was used to estimate rates of formation from the regression slope. SPSS for windows 11.5 was used, and the significance level was chosen to be 5% (Helsel & Hirsch, 1992).

Analysis of covariance (ANCOVA), also in SPSS for windows 11.5, was used to test if the regression slopes were different or not (Sokal & Rohlf, 1995).
3. Results

3.1 Experiment 1

The results of carbon dioxide did not show any clear patterns regarding IC formation or mineralisation, probably because of a combination between problems with the specially designed rotary table, low IC accumulation rates relative to the IC background concentrations, and the experimental set up in which the bottles were sacrificed after sampling. Therefore this only discussed in terms of method evaluation in the following text.

3.2 Experiment 2

The initial concentrations of inorganic carbon (IC) varied between 1.62 mmol/L and 1.91 mmol/L. According to these results, the sediment concentration did not affect the initial amount of IC, indicating that the sediment did not contain precipitated carbonates. The results for sediment amount 5.0 ml for the initial amount of IC are considered as extremes or even erroneous since they are lower (0.89 mmol/L) than the initial concentration for water and will not be discussed in the text below.

Figure 6 shows the concentration of inorganic carbon (IC, mmol/L) over time for bottles with 0.13 mg dry sediment. The first 70 h of the experiment IC concentrations appear to increase. After 70 h the amount of IC decreases or develops almost a steady state during the rest of time. A similar pattern is found for the other bottles with detectable IC formation and therefore the regression analysis to estimate mineralisation rates was done for the first 70 h for all of the bottles.

![Graph showing IC concentration over time for the bottles with 0.13 mg dry sediment/L.](Image)

Figure 6 Graph showing IC concentration over time for the bottles with 0.13 mg dry sediment/L.

Figure 7 shows the concentration of inorganic carbon (IC, mmol/L) over time during the first 70 hours for all treatments. Significant formation of IC over time was detected in treatments with sediment concentrations of 0.053 mg and 0.13 mg dry sediment L⁻¹ (Table 1).
Concentration of inorganic carbon (IC, mmol/L) over time during the first 70 h of the experiment for sediment concentration 0.026 mg dry sediment L\(^{-1}\) (A), 0.053 mg dry sediment L\(^{-1}\) (B), 0.13 mg dry sediment L\(^{-1}\) (C), 0.26 mg dry sediment L\(^{-1}\) (D), 0.53 mg dry sediment L\(^{-1}\) (E), 2.6 mg dry sediment L\(^{-1}\) (F), 0 mg dry sediment L\(^{-1}\) (G). Squares and triangles denote the different replicate bottles in each treatment. Lines represent linear regression lines.

**Figure 7** Concentration of inorganic carbon (IC, mmol/L) over time during the first 70 h of the experiment for sediment concentration 0.026 mg dry sediment L\(^{-1}\) (A), 0.053 mg dry sediment L\(^{-1}\) (B), 0.13 mg dry sediment L\(^{-1}\) (C), 0.26 mg dry sediment L\(^{-1}\) (D), 0.53 mg dry sediment L\(^{-1}\) (E), 2.6 mg dry sediment L\(^{-1}\) (F), 0 mg dry sediment L\(^{-1}\) (G). Squares and triangles denote the different replicate bottles in each treatment. Lines represent linear regression lines.
The mineralisation rate (k) as determined from the regression slopes are shown in Table 1. The analysis of both Kendalls tau and Pearson’s test for correlation shows that only bottles with 0.053 mg dry sediment/L and 0.13 mg dry sediment/L sediment has a significant change of inorganic carbon over time (Table 1). This was confirmed by the linear regressions.

The result from ANCOVA shows that there was no difference between the slopes for the sediment concentrations 0.053 mg dry sediment/L and 0.13 mg dry sediment/L, since the p-value was 0.15.

Altogether, there was no detectable IC formation in four of the six treatments, and significant and clearly detectable formation in the remaining two treatments. These results did not appear to be related to the sediment concentration.

Table 1 p-values for correlations and correlation coefficients (Kendalls tau and Pearson’s); slopes from linear regressions corresponding to mineralisation rates (k), and p-values for regression slope, used when analysing the potential formation of IC over time for the different sediment concentrations. Alpha was chosen to 0.05 and H2O denotes a blank treatment with water only to check mineralisation in water without sediment.

<table>
<thead>
<tr>
<th>Sediment (ml)</th>
<th>Sediment (mg dw/L)</th>
<th>Kendalls tau p-value</th>
<th>Kendall correlation coefficient</th>
<th>Pearson’s correlation coefficient</th>
<th>Pearson correlation coefficient</th>
<th>k (mmol CO2/h/L) slope</th>
<th>p-value regression slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 ml</td>
<td>0.026</td>
<td>0.07</td>
<td>-0.55</td>
<td>0.10</td>
<td>-0.62</td>
<td>-0.0054</td>
<td>0.004</td>
</tr>
<tr>
<td>0.1 ml</td>
<td>0.053</td>
<td>0.04</td>
<td>0.62</td>
<td>0.004</td>
<td>0.88</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>0.25 ml</td>
<td>0.13</td>
<td>0.04</td>
<td>0.63</td>
<td>0.04</td>
<td>0.73</td>
<td>0.0026</td>
<td>0.040</td>
</tr>
<tr>
<td>0.5 ml</td>
<td>0.26</td>
<td>0.90</td>
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<td>0.31</td>
<td>-0.41</td>
<td>-0.005</td>
<td></td>
</tr>
<tr>
<td>1.0 ml</td>
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<td>0.44</td>
<td>0.24</td>
<td>0.51</td>
<td>0.28</td>
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</tr>
<tr>
<td>5.0 ml</td>
<td>2.6</td>
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<td>0.46</td>
<td>0.38</td>
<td>1.4591</td>
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</tr>
<tr>
<td>H2O</td>
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<td>-0.33</td>
<td>0.84</td>
<td>-0.16</td>
<td>-0.0014</td>
<td></td>
</tr>
</tbody>
</table>
4. Discussion

4.1 Experiment 1: Method evaluation

No patterns regarding IC formation could be detected in this experiment. This was probably because of a combination between problems with the specially designed rotary table, low IC accumulation rates relative to the IC background concentrations, and the experimental set up in which the bottles were sacrificed after sampling. In this set up the initial IC concentration in each bottle is unknown and cannot be corrected for, which is problematic if initial concentrations are high compared to the actual concentrations change.

The specially designed rotary table also have to be designed differently if this experiment is to be repeated. In this case, after bottles were taken away for discarding, the specially designed rotary table became unstable due to the weight losses, making resuspension intensity variable and unpredictable at all positions on the table. To overcome this problem, e.g. the link between the ordinary rotary table and the steel construction has to be stronger to have the strength to carry the steel construction, because of the great summed weigh of the all the bottles.

The sampling method as in Experiment 2, with collection of sub-samples from the same bottles throughout the experiment, could be done also in this type of experiment. The weight of the specially designed rotary table would then change less through the whole experiment, possibly reducing the risk for unevenness in the bow motion of the specially designed rotary table.

There is also a problem with no input of new material (sediment) in the bottles. If no material is put in the bottles, the microorganisms do not get any new material to degrade. However, this is a general problem of all experiments with closed systems and therefore the relevance of such experiments under natural conditions should always be interpreted with caution.

In summary, Experiment 1 yielded valuable information about how to better design experiments for studying how the resuspension intensity affects mineralisation rates. In spite of the methodological problems this still appear to be an important issue, especially the storm frequency and intensity is predicted to increase due to climate change, resulting in more frequent resuspension in the future.

The remaining text focuses on Experiment 2. Experiment 2 relies on a different set up where the same bottles are sampled repeatedly throughout the experiment, yielding information about initial concentrations in each bottle and thereby more robust estimates of IC formation.

4.2 Experiment 2

In Experiment 2 an ordinary rotary table was used during the incubation time for the 13 bottles. If this experiment is to be repeated, there are a few things that need to be designed differently. First, more replicates give more reliable results. Secondly, to secure the bottles not moving on the rotary table, the bottles need a steadier frame between them to tie each of them up individually. This would probably also make it easier to release them when sampling. Having something, like plastic, under the bottles to make sure that they lay still on the rotary table, is also important.
Small-scale laboratory experiments, such as this one, are important since they can reveal information of the studying phenomena. This type of information can be hard to gain in situ because it is expensive to measure and difficult to access.

However, in order to properly interpret results from laboratory studies of resuspension it is important to compare sediment concentrations used in the experiments with sediment concentrations in situ during a resuspension event. In Experiment 2, sediment concentrations ranged from 0.026 to 2.6 mg dry sediment L$^{-1}$. In situ concentrations of suspended sediment depend on where and at what time of the year the measurement takes place, but have ranged between 0.5 mg/L up to 4.5 mg/L at 2 m above bottom in an experiment between November 1996 and July 1997 in North-western Mediterranean (Puig et al., 2001). The highest concentrations of suspended sediment were during a Gregal storm (winds from southwest). During a storm in the winter month 2001/2002, Tengberg et al. (2003) measured the sediment concentration to 11 mg/L in the archipelago outside Göteborg, Sweden. This illustrates that the chosen concentrations are well suited when measuring resuspension at different heights and within the range found in nature. The highest concentration could show suspended sediment during a storm.

Oxygen, O$_2$, was most likely available throughout the experiment. There was a large O$_2$ reservoir in the headspace of the bottles. In addition, O$_2$ was added to the bottles during the incubation with the air that was injected to replace sampled volumes. In addition, the absence of methane formation indicates presence of O$_2$, but in marine systems where sulphate reduction often outcompete methane formation this indicator is not as robust as in freshwater systems.

Difficulties in simulating resuspension events ex situ (e.g. in a laboratory) include creating the environment representing the surface of coastal sediment, the seasonal variability and the water content and the strength of water currents. One can also miss some of the biological activities that are on the surface layer of coastal sediments (Baker & Feely, 1978). Obviously, experiments in bottles where one single factor is isolated (in this case the sediment concentration) cannot represent the full complexity under natural conditions. However, small-scale laboratory studies can reveal important knowledge about specific processes that cannot be studied separately taking the full complexity into account.

This study was based on short-term incubations with sediment/water slurries. According to Arnosti & Holmer (2003) short-term incubations can affect reduced products in a way, where the products assemble in the sediments temporarily. This can lead to an underestimation of the mineralisation rate through measurements of the oxygen concentration. However, in this experiment the mineralisation rate were measured through accumulation of IC. Hence, our experiments include all possible mineralisation pathways regardless of how much O$_2$ each pathway consumes. Other studies have shown that the mineralisation of organic matter in the benthic mixing layer zone can cause oxygen depletion (Valeur et al., 1995). If this happened in our experiments, it would have been more likely to happen in the high sediment concentration treatments. These treatments have more organic material, which at least theoretically should leads to a higher total mineralisation and in turn higher oxygen consumption. However, the higher concentrations of sediment did not increase the mineralisation rates, and I see no reason to suspect oxygen depletion in any treatment of this experiment.
The sediment for this experiment was collected in March/April when there is little new production of fresh organic material in the water. This means that most of the organic matter being readily available for degrading microorganisms was probably already mineralised, and that the organic material left in the sediment may have been very resistant to degradation. In correspondence with this, several of the sediment/water slurries did not show an increase of the mineralisation rate. One reason to this could depend on when the slurries are exposed to resuspension, the old organic matter is stirred with the overlying water and is diluted. When the organic matter is diluted, fewer bacteria can contribute to mineralisation per unit of volume in the sediment-water compared to before resuspension (Tengberg et al., 2003). It is difficult to draw any conclusions, more studies are needed to explain why this occurs.

In this experiment, it was among the lowest concentrations (0.053 mg dry sediment/L and 0.13 mg dry sediment/L; 0.1 ml and 0.25 ml, respectively) of sediment that showed an increase of mineralisation (Table 1). The amount and quality of the sediment have vital importance when studying the mineralisation rate. Andersson et al. (1986) showed values of total carbonate production in autumn of 15.4-15.6 mmol m⁻² d⁻¹ and in winter 6.8-7.0 mmol m⁻² d⁻¹. However, these sediments were not prone to resuspension. In a study set out in November comparing mineralisation rates before and after a resuspension event, Tengberg et al. (2003) showed a decrease in the mineralisation, from 12-35 mmol m⁻² d⁻¹ before resuspension to 1-15 mmol m⁻² d⁻¹ after resuspension. These studies indicate that the quality of the organic matter in the sediment is an important factor.

With low IC formation rates, it is difficult to detect formation of IC at all with only two replicates, and as a general rule more replicates per treatment is needed the lower the desired detection limit. In this case time allowed only two replicates, but if mineralisation rates during wintertime is to be studied in these sediments in the future, more replicates are needed. Hence, further experiments require several replicates with the same amount of sediment. Then the result would probably be more confident and give notes on how resuspension can affect the mineralisation rate. In this experiment with different concentrations of sediment, two of the lowest concentrations increased the mineralisation of organic carbon. That nothing happened in the other concentrations could be due to the old organic material. There are not enough studies to be able to draw any certain conclusions why this phenomenon occurs. Several studies independent of the time of the year are needed to be able to explain why the lowest sediment concentrations in this experiment had an increase of mineralisation.

Tengberg et al. (2003) investigated the resuspension effect in the archipelago outside Gothenburg during the winter month 2001/2002. In several cases, the rate of the fluxes of total carbonate decreased upon resuspension. Tengberg et al. (2003) concluded that the organic matter was old and the microorganisms did not have much new matter to degrade and they were less effective. This is similar to this experiment, except that this was done at a laboratory and the sediment was taken in March/April.

A model in STELLA over resuspension events showed that resuspension is very important when determining the rate of mineralisation in organic material (Wainright & Hopkinson, 1997). There was a large increase of organic material mineralisation in the total system. In the same time the major mineralisation site shifted from the top sediment to an almost equal part between the surrounding environment and the sediment.
(Wainright & Hopkinson, 1997). Comparing with this study, it is hard to see any of this in the results except that the sediment concentration does not affect mineralisation. Less carbon burial can be a result if the resuspension event speed up the general mineralisation of organic material according to Wainright and Hopkinson (1997).

In shallow waters the sediment has easier to resuspend depending on more frequent resuspension events (Christiansen et al., 1997). This affects the mineralisation of organic material because the sediment is easier resuspended and the organic matter content decreases with resuspension. Resuspension can also affect the algae growth by increasing turbulence and decrease the light (Christiansen et al., 1997). This could reduce the algae bloom in the summer. The mineralisation rate of organic matter is also affected by the quality of the organic matter (Arnosti & Holmer, 2003). In this study the organic matter was old and had high content of water but still the LOI was high. When the sediment samples were taken, it had only gone one week since the ice break up. This could also affect the organic matter content. The total organic carbon (TOC) has not been measured in this study and future studies should involve measurements of TOC.

It is important to remember that the mineralisation rate can vary depending on the time of the year. Future studies should focus on sediment sampling when the amount of organic matter is high in the water, probably late spring or autumn (Bydén et al., 2003). The studies should also measure every 12th hour because during a resuspension event the first 12th hour is the most important for mineralisation. The organic matter is new blended and the microorganisms are then presumably very active. If it is possible, future studies should be in situ to study resuspension and mineralisation in place.

However, further studies are needed to continue the investigation of the importance of resuspension for the mineralisation of organic matter. It is also important to understand resuspension and its impacts on the fluxes of nutrients in the oceans. These cycling are necessary for the life in the oceans, especially on the continental margins (Fanning et al., 1982).
5. Conclusions

Experiment 1 did not show any clear patterns regarding the mineralisation rate of organic material. This was probably due to the specially designed rotary table, the method with removing the bottles from the experiment after sampling and low inorganic accumulation in the bottles. However, valuable information of how to better design experiments to investigate the importance of resuspension and water movement intensity for the mineralisation of organic material was yielded.

In Experiment 2, according to the statistical tests, only two of the lowest concentration of sediment showed an increase of the mineralisation rate of organic material. These mineralisation rates were low, when comparing with other investigations. This could be due to the lack of new organic material in the sediment samples, since the samples were collected in March/April. The concentration of sediment seems to not affect the mineralisation rate. In future experiments, more replicates per treatment are needed, and it should be preferable to take samples when there is new organic material in the sediment. Future studies should as well include TOC measurements. More studies are needed to investigate resuspension and the effect of mineralisation rate.
6. References


