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Title:
The effect of temperature on the decomposition of urban layers at Bryggen in Bergen

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Summary:
The present report describes the initial investigations of the effect of soil temperatures on the decay of urban archaeological layers at Bryggen in Bergen, Norway. The oxygen consumption was measured at different temperatures and used to quantify the temperature dependency of the decay rates. Measurements were made in soil samples from both unsaturated and waterlogged conditions. The results show that the soil temperature has a significant effect on the decay, and that a 10°C temperature rise could increase the decay rate in all samples by 100-180%. Thus the temperature effect is so significant that it should be included in future evaluations of preservation conditions. The results further show that soil material from waterlogged conditions is 10 times more reactive compared to material that has been under oxic conditions for a prolonged period. In future studies the reactivity data from this study should be used to evaluate in situ decay rates using results from the monitoring of oxygen availability and temperature at Bryggen that was initiated in October 2010; however this is postponed until longer time series are available. It is suggested that further studies are carried out focussing on the effect of increased soil temperatures on the soil water content and oxygen availability and on how heat production from decomposition of organic matter influences soil temperatures.

Signatures

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Introduction

Soil temperatures in built-up areas are often increased due to heat-release from "urban heat sources" such as buildings, long-distance heating pipes and other infrastructural installations. This may accelerate the decay of organic cultural layers, as the rate of decomposition of organic material increases with increasing soil temperature. Moreover, an increase in soil temperature may have a drying effect on the soil and thereby increase the availability of oxygen and the decomposition of organic material.

The buildings at Bryggen in Bergen are currently settling by up to 6-8 mm/year due to the organic cultural layers becoming decomposed (Jensen, 2007). These rather high settling rates are mainly thought to be a consequence of a lowered groundwater-table that increases the availability of oxygen. However, groundwater temperatures at Bryggen are up to 5°C higher than the mean annual air temperature of 7.5°C, which suggests that soil temperatures in the cultural layers are increased by "urban heat sources" (Figure 1). The question is to what extent the increased temperatures affect the decay rate of the cultural layers at Bryggen. In order to answer this question The National Museum of Denmark has been contracted by Riksantikvaren to make a preliminary investigation.

Figure 1: Map of Bryggen, Bergen, showing the mean annual groundwater temperature in various dipwells. The temperature should be compared with a mean annual air temperature in Bergen of 7.5°C (Map: Hans de Beer, NGU).

Background

The microbial decomposition of organic matter is the dominant process causing decay of organic cultural layers. Soil organisms oxidize soil organic matter to inorganic forms primarily to extract energy for growth. Microbial decomposition rates depend strongly on the quality of the organic matter and on different environmental controls, of which water, oxygen availability and temperature are considered the most important (Schuur et al. 2008).The roles of oxygen and water in relation to the decay of the cultural layers at Bryggen are already being investigated and several reports dealing with oxygen and water dynamics at Bryggen have been published (Matthiesen, 2007a; Matthiesen & Hollesen, 2011). The role of temperature on the other hand still remains unknown.

Temperatures within soils are normally a product of the meteorological conditions at the surface: the conditions at the boundary between air and soil (snow, water, vegetation, pavement etc.); the physical properties of the soil; and the geothermal gradient (heat coming from the interior of the earth). However, in more complex soil environments such as urban areas several other factors may influence temperatures. Heat from buildings, long-distance heating pipes and other infrastructural installations may have a significant warming effect on the soil (Figure 2). Measurements by Reed & Edvardsen (2005) have shown that the construction of a building in Tønsberg, Eastern Norway, increased the temperatures in the cultural deposits below the building by more than 10°C and at the same time caused soil water contents to decrease. Moreover, data from Ribe, Denmark, show that even an unheated building may increase soil temperatures by more than 5°C (Ryhl-Svendsen et al., 2011).

Even small increases in soil temperature may have a significant influence on the decomposition of soil organic material. Several studies have shown that under oxic conditions decomposition rates in both natural soils and cultural layers increase exponentially with increasing soil temperatures (Hollesen et al., 2011a; Elberling, 2003; Fang & Moncrieff, 2001). The temperature dependency of decomposition is often expressed using the Q_{10} value – which is the proportional change in decomposition rate given a 10°C change in temperature.

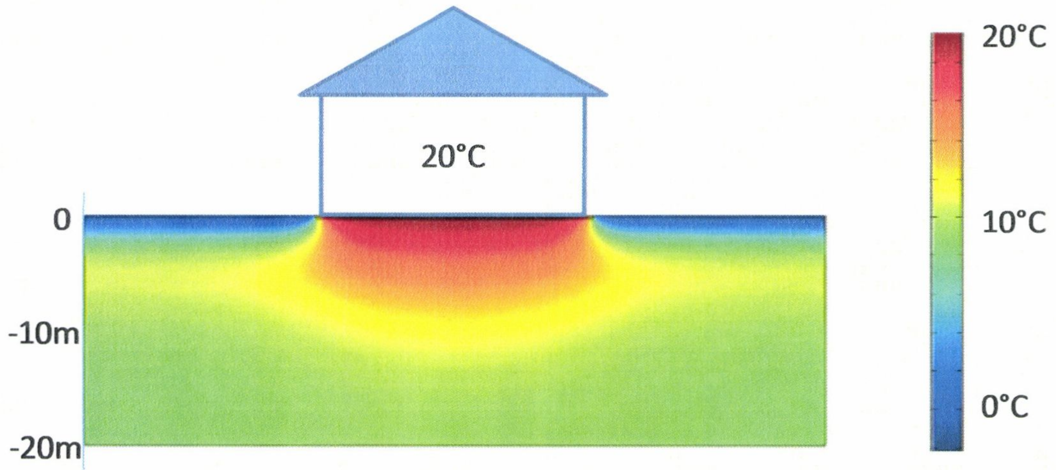

Figure 2: Modelled example of how a heated, unisolated building may influence soil temperatures on a winter's day. (Model: Benny Bøhm, The National Museum of Denmark).

Methodology

The decomposition rate is difficult to measure real-time in the field and therefore it is most often measured under controlled conditions in the laboratory. Several methods are available, each of them with their own advantages and disadvantages. The two most common methods used to study decomposition of organic material under oxic conditions are measurements of the CO_2 production or the oxygen consumption in soil samples based on the assumption that Organic material + $O_2 \rightarrow CO_2$ (Scheirs et al 1995; Elberling, 2003).

To include partial oxidation of organic material, i.e. decay that doesn't produce CO_2, the oxygen consumption method was used in this study. This method has the limitation that it will not show decay of the organic material by other oxidants (such as nitrate, sulphate and others), but these processes are normally slow in oxic environments. Another limitation is that there may be inorganic materials in the soil (for instance pyrite) that also consume oxygen, which means that the oxygen consumption may overestimate the decay of organic material.

The oxygen consumption was measured in soil samples from Bryggen at 5, 10, 15 and 20°C to investigate the temperature dependency of the decomposition of soil organic material. Soil samples from a test-pit at the northern end of the Bredsgården tenement (Matthiesen, 2007a; Dunlop, 2008; Matthiesen & Hollesen, 2011) and from dipwells MB-15 (Dunlop, 2010b; Matthiesen, 2010) and MB-34 (Dunlop, 2010a; Matthiesen, 2011) were used (Table 1). Measurements were made in three replicates of each soil sample according to Matthiesen (2007b). In short: 3–5 g humid soil was transferred to 12.1 ml glass vials, the samples were flushed with atmospheric air and the vials closed with an airtight lid. The oxygen consumption was subsequently measured by monitoring the decrease of headspace O_2 concentrations over time by using oxygen optodes from PreSens (www.presens.de).

Soil sample	**Description**
1:Testpit layer 8 (3.1 m asl)	Organic-rich sandy layer with timber
2:Testpit layer 9 (2.7 m asl)	Alternating layers of lime, charcoal and stone
3:Testpit layer 14 (2.1 m asl)	Organic layer, with timbers
4:Dipwell MB34-4 (-3.3 m asl)	Highly organic refuse stratum
5:Dipwell MB15-1 (-0.3 m asl)	Relatively compact brown humus with a lot of fine sand and some pebbles
6:Dipwell MB15-3 (-2.5 m asl)	Organic-rich with plant/vegetable remains and woodchips
7:Dipwell MB15-5 (-4.5 m asl)	Organic-rich with plant/vegetable remains and woodchips
8:Dipwell MB15-6 (-5.5 m asl)	Organic-rich with plant/vegetable remains and woodchips

Table 1: The soil samples used to measure oxygen consumption. Each individual soil layer has been thoroughly described by archaeologist Rory Dunlop (2008, 2010a, 2010b) using the Norwegian Standard layer recording system. An ultra-short description of the layers is given in the right column.

Results&discussion

Figure 3 shows an example of the oxygen consumption measurements that were made at four different temperatures for all eight soil samples. The oxygen concentration in the vials was almost halved during a week in the example. Overall, the samples showed a good reproducibility and the oxygen concentration decreased (almost) linearly over time, indicating constant oxygen consumption during the experiment.

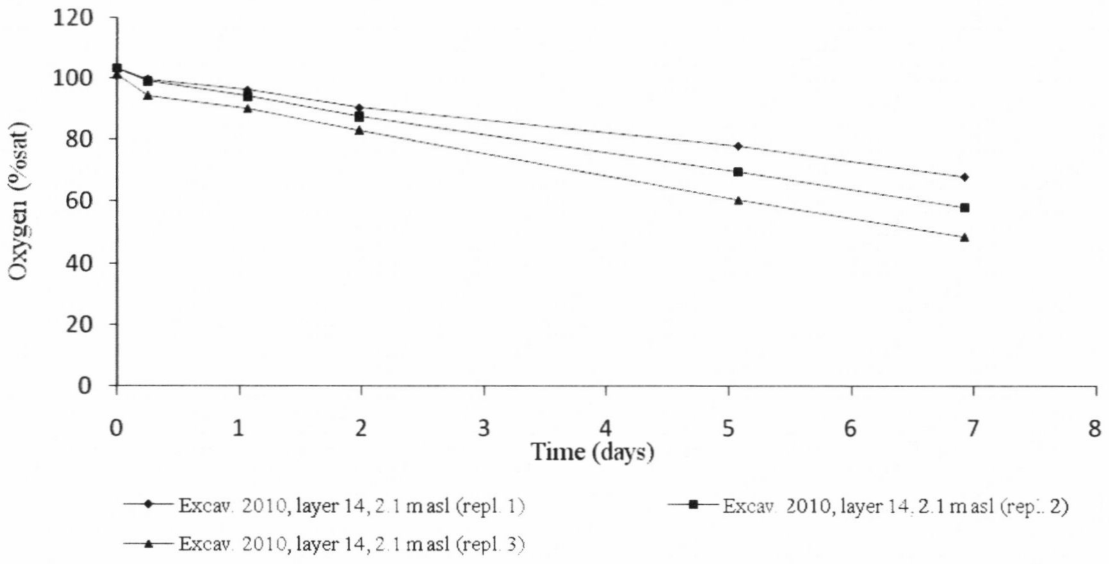

Figure 3: Example of oxygen consumption measured at 10°C in 3 replicates from soil sample 3.

The oxygen consumption measurements were used to calculate the Oxygen consumption rate:

$$\textit{Oxygen consumption} = V \cdot C \cdot (\Delta O_2/\Delta t) \, / \, m \cdot 100$$

where V is the volume of air inside the vial (cm^3), C is the initial concentration of oxygen (mg/cm^3), $\Delta O_2/\Delta t$ is the decrease in oxygen saturation over time (%sat/day – taken as the slope of the curves in Figure 3), m is the mass of the wet sample (g) and 100 (%) is a scale factor.

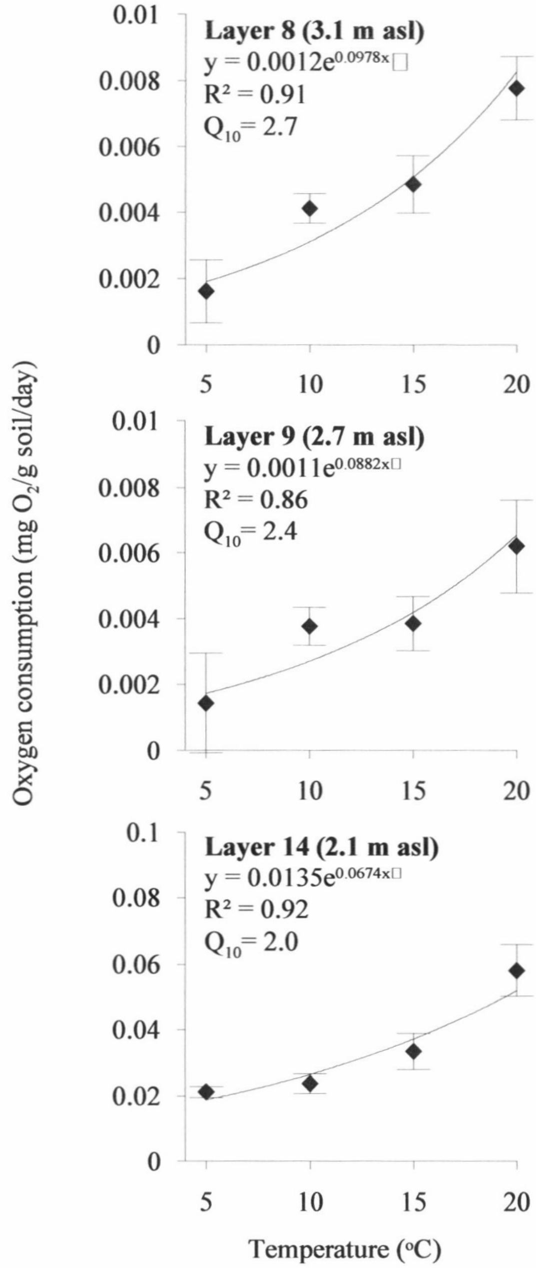

Figure 4: Temperature dependent oxygen consumption rates measured in samples taken from layers 8, 9 and 14 in the reopened test-pit at the northern end of Bredsgården. For each of the samples measurements were made on three replicates and vertical error bars show ± 1 standard deviation.

Figures 4 & 5 show the oxygen consumption rates at different temperatures for all of the investigated soil samples. The measurements were made under oxic conditions. Therefore the results/discussion below reflects what happens if the investigated soil layers are drained and oxygen becomes available.

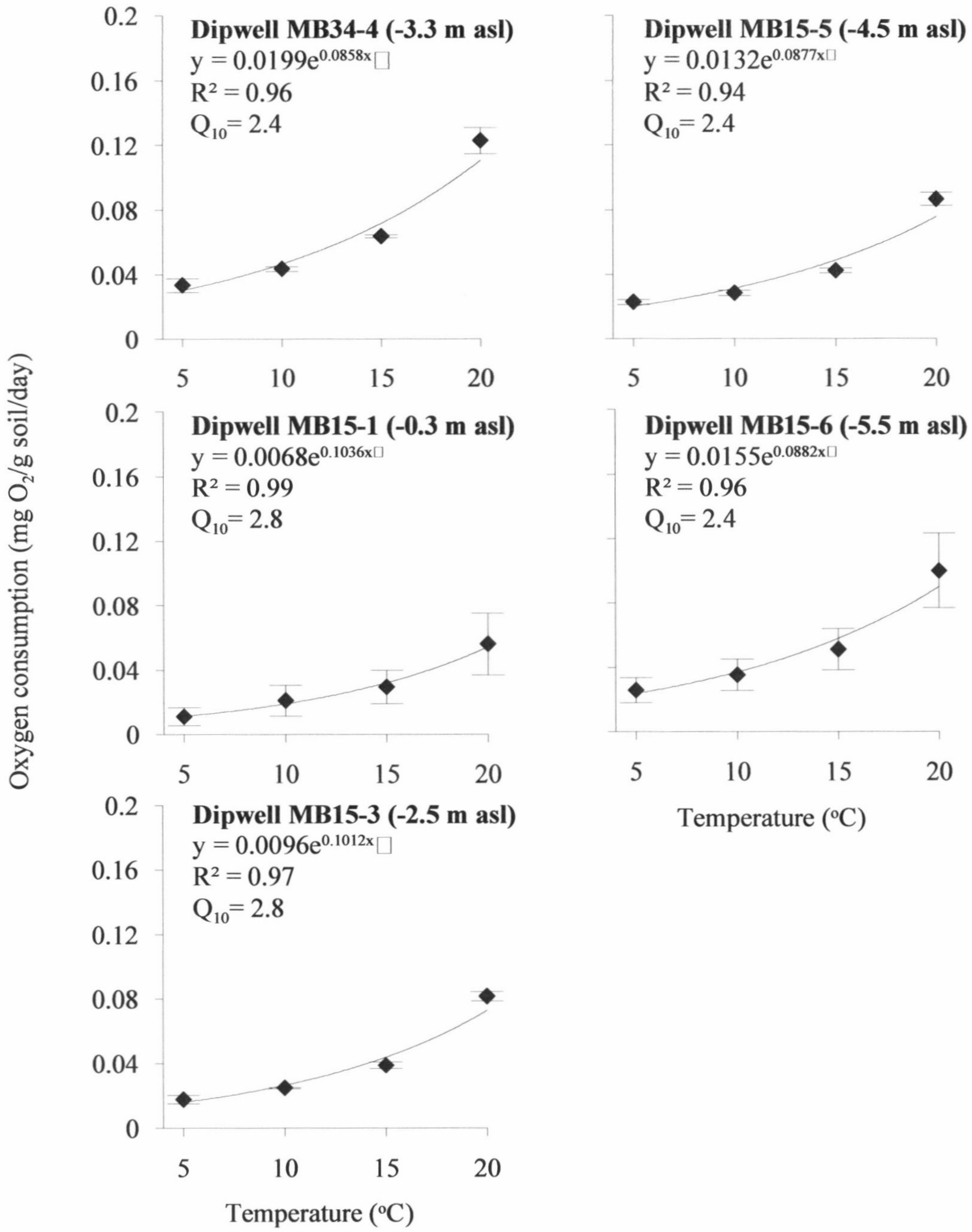

Figure 5: Temperature dependent oxygen consumption rates measured in samples taken from dipwells MB-15 and MB-34. For each of the samples measurements were made on three replicates and vertical error bars show ± 1 standard deviation.

The used method proved to be very accurate with good exponential agreement between oxygen consumption and temperature, and fairly low standard deviations between sample replicates. In seven out of eight samples the Q_{10} value varied between 2.4 and 2.8 with the only exception being sample 3, which had a Q_{10} of 2.0. The results are in good agreement with other studies that have found Q_{10} values between 2 and 3 in soils (Hollesen et al., 2011a; Elberling, 2003; Fang & Moncrieff, 2001).

In Figure 6 the percent increase in oxygen consumption rates is shown for the range of Q_{10} values found in this study (2.0–2.8). When assuming that the soil is not depleted of reactive organic matter, a temperature increase of 1°C could increase oxygen consumption rates by 7–11%, a 5°C increase by 40–70% and a 10°C increase by 100–180%.

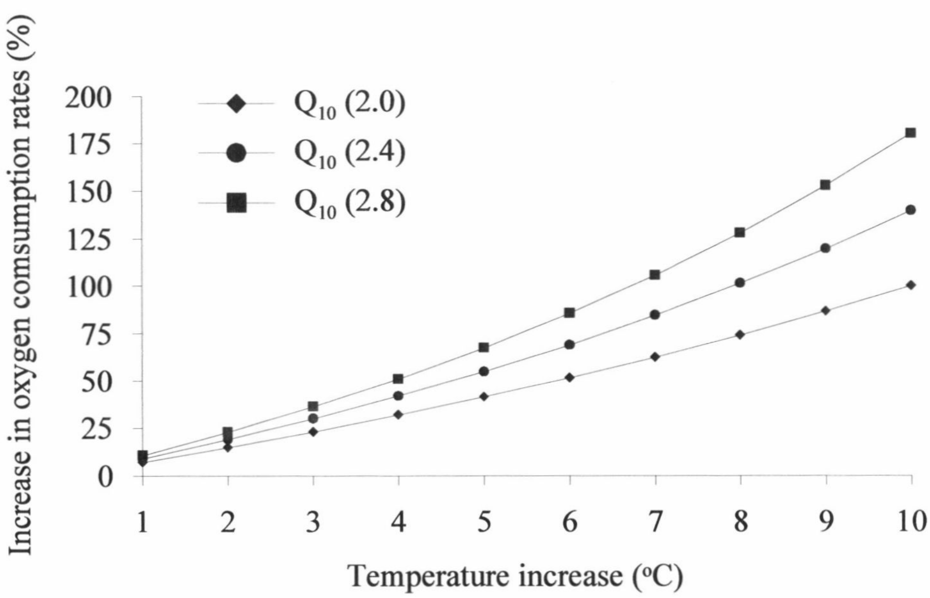

Figure 6: The percent increase in oxygen consumption rates with increase in temperature shown for the range of Q_{10} values found in the samples from Bryggen, Bergen.

There is a great difference in the overall rate of oxygen consumption between the two upper layers of the test-pit (sample 1 and 2) and the deeper laying layers (sample 3-8) with the deeper layers consuming oxygen 10 times faster (Figures 4 & 5). Some of this oxygen may be used to oxidize different reduced inorganic species in the samples, but if we assume (as a worst case) that the main oxygen consumer is the organic material it is possible to put these rates in perspective: at a mean soil temperature of 7.5°C, samples 1 and 2 consume approximately 0.0025 mg O_2/g soil/day, or 1 mg O_2/g soil/year. At present the soil from samples 1 and 2 contains approximately 60-80 mg organic material per g wet soil, and hence 1-2% of this organic material disappears every year (as 1 mg of oxygen may oxidize approximately 1 mg of organic material with the brutto formula CH_2O all the way to CO_2). For comparison, the oxygen consumption rates of samples 3-8 are 10 times higher, and even though the organic content is much higher in these samples 5-10% of the organic material could disappear in only one year if unlimited amounts of oxygen were available. However, samples 3-8 come from layers where the oxygen availability is currently limited and furthermore it is very unlikely that the material in samples 3-8 would continue to decompose at the rates that are currently measured. The most reactive material will decompose first and then with time the remaining material will be less and less reactive. This is emphasized in Figure 7 where the oxygen consumption per g soil organic matter is shown for all of the eight samples. The organic matter in the soil samples from two upper layers of the test-pit (samples 1 & 2), which are partly oxic, is much less reactive than the samples from the deeper well-preserved anoxic layers. If unlimited amounts of oxygen became available in the deeper layers the decomposition rates would initially be very high and then with time decrease to the levels seen in samples 1 and 2, or even lower. How long time this would take is unknown. Even though the high rates measured in samples 3-8 only represent the first period after dewatering, they clearly emphasize that draining of the organic culture layers may have a severe effect on the preservation of organic material, especially if soil temperatures at the time of drainage are increased by heat from urban heat sources.

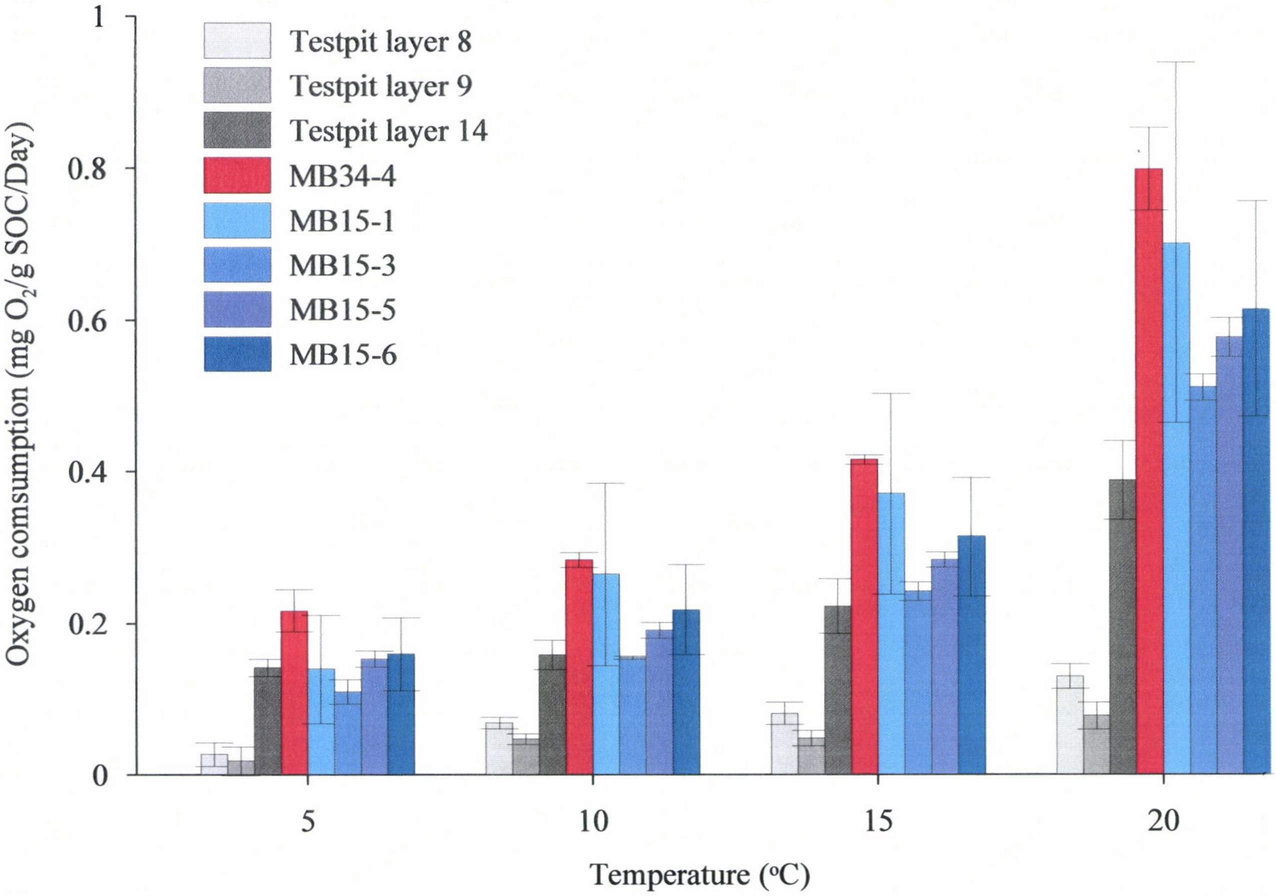

Figure 7: Temperature-dependent oxygen consumption per g soil organic carbon (SOC) measured in the eight samples from Bryggen. The vertical error bars show ± 1 standard deviation.

The current study has focused on the direct effect of a temperature rise on the oxygen consumption when unlimited amounts of oxygen are available – fortunately this is not the case concerning all of the investigated soil layers. However, some indirect effects of a temperature rise could increase the availability of oxygen: if the temperature increases locally, water may evaporate and cause the soil to dry out. This may in turn increase the oxygen availability and thereby increase the decomposition of the organic material. This "drying-out effect" is difficult to quantify, but a starting point might be to measure the oxygen consumption of soil samples with varying water contents.

The decomposition of organic material may be accompanied by a heat production that can increase the soil temperature. Investigations by Hollesen et al. (2011b) show that heat production within a permafrost soil at Zackenberg in Greenland may slightly increase soil temperatures. Considering that cultural layers can produce 25 times more heat than the permafrost soil (Elberling et al., 2011) it is plausible that heat production could have a significant influence on soil temperatures and decomposition rates in the cultural layers at Bryggen. Therefore, heat production rates should be measured to investigate whether this is the case.

In this study all measurements were made under oxic conditions. Microbial decomposition in anoxic environments, where oxygen supply is restricted by slow diffusion rates in water, relies on other elements to serve as electron acceptors (such as nitrate, sulphate, iron, and CO_2) for respiration. Decomposition rates using alternative electron acceptors are normally slower because of lower energy yield but may still have an influence on the preservation of the organic cultural layers, especially if temperatures are increased. Therefore the temperature-dependent decomposition under anoxic conditions should be investigated further.

Conclusions and future work

To sum up the results of this preliminary study:

- The method chosen (oxygen consumption) gives highly reproducible results and seems well suited for studying the effect of temperature on decomposition of organic cultural layers under oxic conditions.
- The soil temperature has a significant effect on the oxygen consumption. With Q_{10} values between 2.0 and 2.8, a 10°C increase in soil temperature could increase the oxidation rates by 100-180%.
- The temperature effect is so distinct that it should not be ignored when evaluating preservation conditions for archaeological sites.
- The degree of reactivity of the investigated samples was highly variable: samples from the unsaturated zone that have been under oxic conditions for a prolonged period were the least reactive, whereas samples from waterlogged zone were 10 times more reactive.

Future work should include:

- A combination of the reactivity data from this study with the on-site monitoring of oxygen concentrations and soil temperatures at Bryggen.
- A study of how much oxygen is used for oxidizing inorganic components.
- Additional measurement of the oxygen consumption in soil samples from other urban deposits to validate the levels measured here.

- A study of the "drying-out effect" whereby increased soil temperatures increase the evaporation of soil water and the oxygen availability.
- A study of the temperature effect on decomposition under anoxic conditions.
- A study of the heat production from decomposition of organic material from urban deposits.

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