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Take a ZOOM into eutrophication of coastal water bodies – The Zingster Outdoor Benthocosms

Abstract

Many coastal waters are still affected by eutrophication. Not always have remediation measures led to an improved ecosystem condition. The resilience of the ecosystem status to all measures raises new research questions. Why does the ecosystem not respond to the reduction of nutrient input, or only very slowly, or in any other way that was expected? Experiments are an approach when such processes are too slow to respond within expected response times or the desire for improvement. However, *in situ* enclosures can be very resource-intensive. This study presents a cost-efficient and stable *ex situ* mesocosm approach to gain insight into a non-tidal, shallow lagoon system at a shorter time scale. A major question regarding such experiments is, if they reproduce the natural conditions well. This question was assessed by comparing temperature and oxygen saturation in the mesocosms and in the ecosystem. Water temperature differed only within ±1.5 K between mesocosm and Zingster Strom, which is comparable to other mesocosm or enclosure approaches. Oxygen saturation during the day was slightly higher, but night time saturation was at the same level as in the adjacent lagoon system. Hypoxia was not observed. Overall, the mesocosm approach appears to be suitable for biomanipulative studies.

Keywords: Mesocosms, eutrophication, lagoon

1 Introduction

Anthropogenically induced eutrophication is one of the greatest impacts on coastal water bodies. Waters worldwide have been affected by elevated nutrient inputs, leading to a change of a macrophyte dominated system to a phytoplankton dominated one in most systems (e.g. CAPON et al. 2015; SCHEFFER & CARPENTER 2003; WEISNER et al. 1997). For decades, one of the main objectives has been to reverse the effect of human impact on aquatic ecosystems. Consequently, the EU-water framework directive aims at the "good ecological state" for each water body (EUROPEAN COMMUNITY 2000). The reduction of nutrient inputs from point sources may not be sufficient to achieve visible improvements of water quality, i.e. mostly expressed as Secchi depth or water transparency.

A well-studied ecosystem is the eutrophic Darß-Zingst Bodden chain (DZBC), a shallow lagoon system at the southern Baltic Sea. It is a typical lagoon system of the Baltic Sea and has been monitored for decades with accompanying experiments (SCHIEWER 2006, SCHIEWER 2007). First descriptions of lost underwater vegetation and phytoplankton dominance were described to be from the 1930s (GESSNER 1957, SCHLUNGBAUM et al. 2000). Interestingly, the total phosphorus concentrations in the inner lagoon parts in the 1930s were as high as they are today (long-term median 4 µmol TP l^{-1}, BERTHOLD et al. 2018, GESSNER 1957). In the meantime, total P loads, mainly due to point sources, increased to more than 80 t P a^{-1} and dropped again to 20 t P a^{-1} (BACHOR et al. 2013).

However, there is still no improvement in turbidity or a lower phytoplankton biomass after all measures in the catchment area and the registered reduced inflows (BACHOR et al. 2013). Recurring hypotheses are that either the sediment loads the water column with nutrients during suboxic events (e.g. NAUSCH & SCHLUNGBAUM 1991) or that the food web remineralization within the water column occurs very quickly (e.g. SCHIEWER 1997). The hypotheses of bottom-up control can be tested in experimental approaches. Perhaps, there is also some influence of food webs on the matter cycling (top-down control).

These questions should be investigated, e.g. in whole lakes, in enclosures, mesocosms or minicosms. However, it is not always possible to carry out holistic ecosystem approaches (e.g. due to their protection status). Therefore, experimental approaches are necessary and well established on a smaller scale, i.e. mesocosms or enclosures. There are several different definitions. Therefore, it is defined here as follows: a whole system experiment is the term for an experiment in which the ecosystem is divided into several parts that are treated differently (e.g. BUCK et al. 2008). Enclosures are set up as an area or volume, which is separated and analysed without the impact of e.g. changing currents affecting it. Different treatments are possible. Actually, most of the Zingster "mesocosms" were enclosures (ARNDT et al. 1990, FORSTER & SCHUBERT 2000, SCHIEWER et al. 1993). Mesocosms are installed completely out of the system, but with a large volume (>100 l water, e.g. Benincá et al. 2008, WOHLERS-ZÖLLNER et al. 2012). They may be easier to be powered and more accessible. Mesocosm approaches can be short- or long-term incubations, manipulating nutrients or other abiotic factors and studying species composition. Minicosms are defined here as very small volume and rather short term incubations, e.g. plankton volume of 10 ml to 3 l (e.g. SCHUMANN et al. 2009) or sediment cores (GEBHARDT & FORSTER 2018), which are incubated for 24 h up to 10 d.

If mesocosms contain benthos, they can also be called benthocosms. The Kiel Outdoor Benthocosms analysed the effect of rising CO_2 levels on the marine environment (WAHL et al. 2015). The Sylter Benthocosms are used for food web experiments and impacts on seagrass development (PANSCH et al. 2016). The Marine Ecosystem Research Laboratory (MERL) is used for experiments with nutrient driven impact, like eutrophication, in the Narragansett Bay (USA) (OCZKOWSKI et al. 2014). The Sylter benthocosms and the MERL are constructed on land and are true mesocosms.

Among the abiotic factors recorded are water temperature, air exchange, light climate, nutrient fluxes and salinity. However, temperature control in mesocosms and enclosures is one of the most important abiotic factors, especially when the compartments are incubated on land or in a laboratory. Temperature can be controlled by water exchange (PANSCH et al. 2016) or artificial cooling systems (WAHL et al. 2015). The Zingster outdoor mesocosms (ZOOM), which share the properties of benthocosms, are buried in the soil and cannot be cooled further. Atmospheric exchange cannot be controlled in all outdoor-installations (enclosures), e.g. by wind-induced mixing, gas exchange and external nutrient supply by precipitation. Salinity, nutrient concentrations and currents depend on the system, but can be artificially manipulated.

The problem is that any *ex situ* mesocosm experiment can be highly artificial, which limits the extrapolation of results and concepts to the real ecosystem (PERCEVAL et al. 2009). The distinction between the conditions in mesocosms compared to the enclosures or more so to the original ecosystem can be quite large compared to enclosures. Therefore, long-term experiments were conducted with mesocosms in a narrower sense, i.e. land based, to assess the stability of the experiment and the plankton community and to minimize possible handling problems for subsequent manipulations. A stable, cost-efficient mesocosm approach is presented here for the simulation of a non-stratified shallow lagoon system. The ZOOM were constructed as an alternative for enclosure experiments, which can be considerably more expensive in construction and maintenance if they should last longer than a few days. The feasibility of this approach was tested by comparing the temperature and oxygen evolution within a mesocosm to the adjacent lagoon system for the growth period of June to August 2015.

2 Material and Methods

2.1 Experimental design

The mesocosms were built on the grounds of the Biological Station Zingst, University of Rostock and contained about 1750 l of water and almost 100 l of sediment (Fig. 1). The basin material was fiberglass reinforced plastic, is chemically and biologically inert, stable against UV, temperature changes and high tear forces by changing groundwater (Cemo). The mesocosms had a surface area of 2 m^2 at the surface, and 1.9 m^2 at the bottom. The control of abiotic parameters i.e. temperature, radiation, had to be cost-efficient and comparable to the observed ecosystem. A partly buried outdoor mesocosm should be cooled by the surrounding soil and be less prone to overheating compared to mesocosms standing above ground. The total area exposed to sunlight would be minimized to the actual water surface. This terrestrial-cooling approach allows a similar light climate as in the real system, because the water surface is at the same level as the lagoon system. The buried mesocosms were free of surrounding structures that would interfere with diurnal cycles of sunrise and sunset.

Internal water pumps (pump capacity: 300 l h^{-1}, Neptun) were used to prevent stratification of the water body and allow a permanent circulation similar to that in shallow coastal water bodies. At least three of those pumps were used per mesocosm to let the whole water column circulate within two hours. The wind fetch area was 2 m^2 and would at least allow minor additional circulation by wind induced mixing.

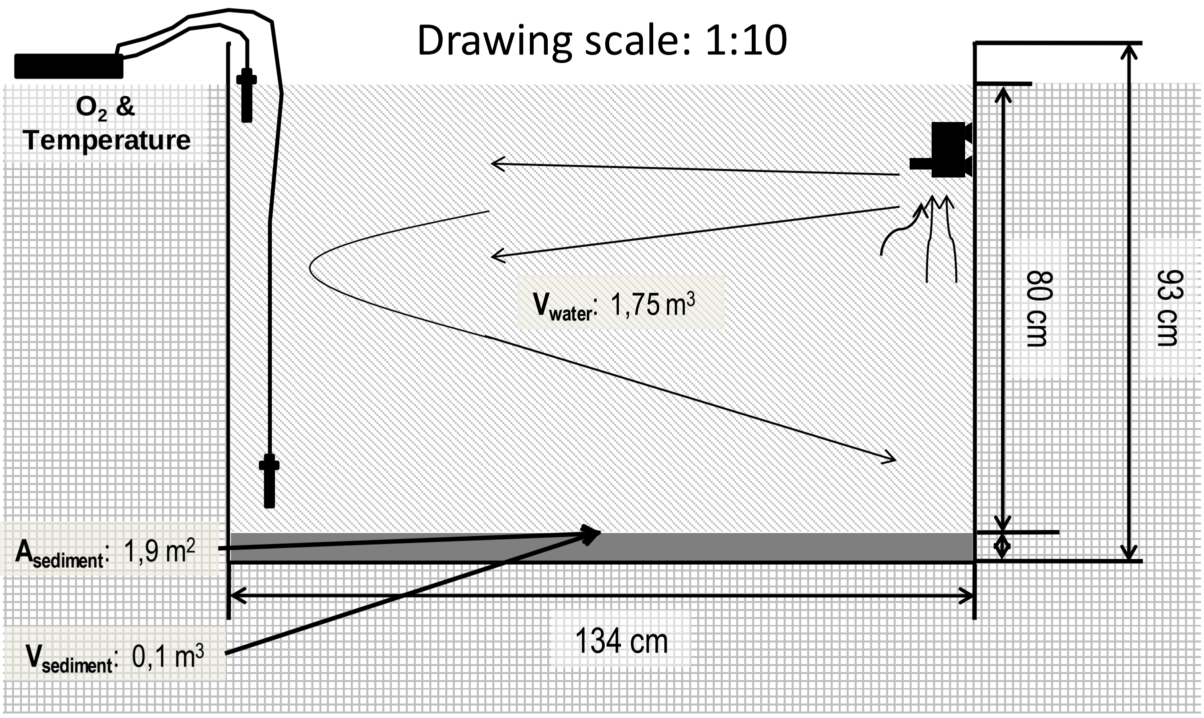


Fig. 1 Scheme of the Zingster Outdoor Mesocosms (ZOOM).

Sediment from the DZBC was filled in the mesocosm with a height of 4 – 5 cm (Fig. 2A). The sediment was sampled in the shallow areas (20 – 50 cm) of the lagoon to include diaspore banks of submerged macrophytes. Sampling locations were Michaelsdorf (Bodstedter Bodden) and Dabitz (Grabow, Tab. 1) with the dominating macrophyte species of *Stuckenia pectinata*, *Ruppia* sp., *Chara* spp.

Water for all mesocosms was taken from the Zingster Strom, the middle part of the adjacent lagoon system 90 m away from the experimental setup. Water was pumped into the mesocosms by an electrical water pump at the beginning of the experiment. Water loss by evaporation was not compensated by addition of Zingster Strom water to prevent increasing salinity and changing water parameters. Rain was the only natural water inflow during the time of the experiment.

Fig. 2 **A:** Filling of the 2000 l mesocosms with sediment. **B:** Zooplankton is sampled in the ZOOM mesocosms.

Tab. 1 Overview of Zingster Outdoor Mesocosms (ZOOM)

Year	Number	Treatments	Starting date	Sediment source	Aim
2015 2016 2017	2 4 4	With and without goby (*Pomatoschistus microps/minutus*) and shrimps (*Palaemon elegans*)	07.05.2015 24.06.2016 16.05.2017	mixture from Bodstedter Bodden (54°22,306'N 12°34,136'E) and Grabow (54°22,017'N 12°48,358'E)	Food web structure & production

The concept of ZOOM was to test the effects of the food web composition on a possible “top-down” control. One set of mesocosms were with fish and shrimp, to include as many trophic levels as possible. In the other set of mesocosms, zooplankton and gammarids were liberated from grazing, by excluding fish and shrimp. Zooplankton was sampled regularly in both sets of mesocosms (Fig. 2B). The later approach was tested to compare the real ecosystem to the mesocosm approach. Therefore, only oxygen increase by primary productivity and temperature were analysed and will be presented here. In total, there were three series of ZOOM mesocosms from 2015 through 2017 (Tab. 1). The water came always directly from the Zingster Strom.

2.2 Measurement of abiotic parameters

The main parameters oxygen and temperature were measured automatically in a 5-min interval to be directly compared with the automatic measuring unit in the Zingster Strom (15-min interval) of the Biological Station Zingst. Temperature and oxygen were measured with a coupled sensor by an LDO (Hq-40d, Hach). Two of those sensors were installed into each mesocosm. One sensor was hung right below the water surface, the second one above the sediment in 80 cm water depth. The sensor in the Zingster Strom measures at a water depth of 100 cm. The sensors were calibrated before the start. It was assumed that the salinity was more or less stable so that the automatic salinity correction of the Hach-device was used to read out device-calculated oxygen concentrations. Additionally, water parameters, like salinity (salinity probe, WTW) and pH (pH probe, Hach), were measured in a biweekly interval and compared to the monitoring of the Biological Station Zingst.

Oxygen concentrations of the mesocosm sensors were averaged, as production in both water depths was most likely different. Furthermore, daily medians of oxygen concentration were calculated to improve visibility of long-term trends instead of diurnal cycles.

2.3 Statistical analysis

All measured oxygen and temperature values of the mesocosms were compared with values of the automatically measuring unit in the Zingster Strom by a frequency distribution analysis (Excel). Only simultaneously measured values were compared, so that the data set of the more frequently measured mesocosms (5 min) was reduced to the 15 min intervals in the Zingster Strom.

3 Results

3.1 Temperature development

In 2015, there were only two compartments of large ZOOM mesocosms. The one without fish and shrimp is compared here to the *in situ* conditions in the Zingster Strom over the summer season. This compartment is called “the mesocosm” further on.

The absolute and strong variations of about 10 K over some days are normal and reflect the meteorological forcing onto a shallow brackish lagoon and more so on the true mesocosm (Fig. 3A). There was no temperature stratification within the mesocosm throughout the observation period. The majority of temperature values (~85 %) were within a ±0.5 K range between surface and bottom sensor (Fig. 3B). Highest differences (> 1.0 K) were measured during the beginning of the experiment in June during the longest and first warming period, but not afterwards. This result indicates a well-mixed water column.

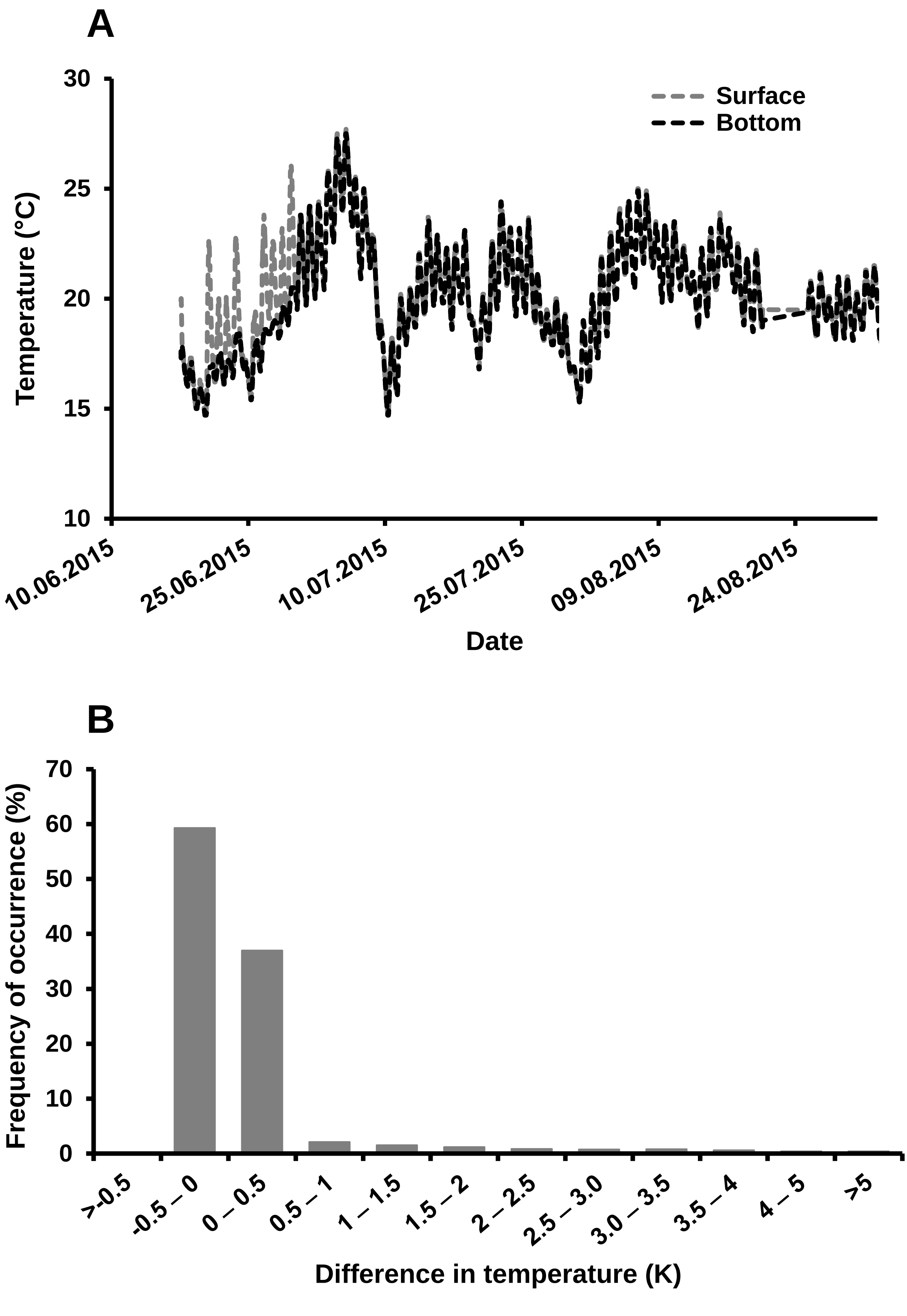


Fig. 3 **A:** Total temperature development inside the mesocosm at the surface (20 cm) and bottom (80 cm). **B:** Temperature difference (K) as percentage frequency of occurrence of surface and bottom water inside the mesocosm between June and August 2015. Temperature was measured every 5 minutes simultaneously at surface and bottom (n = 20588).

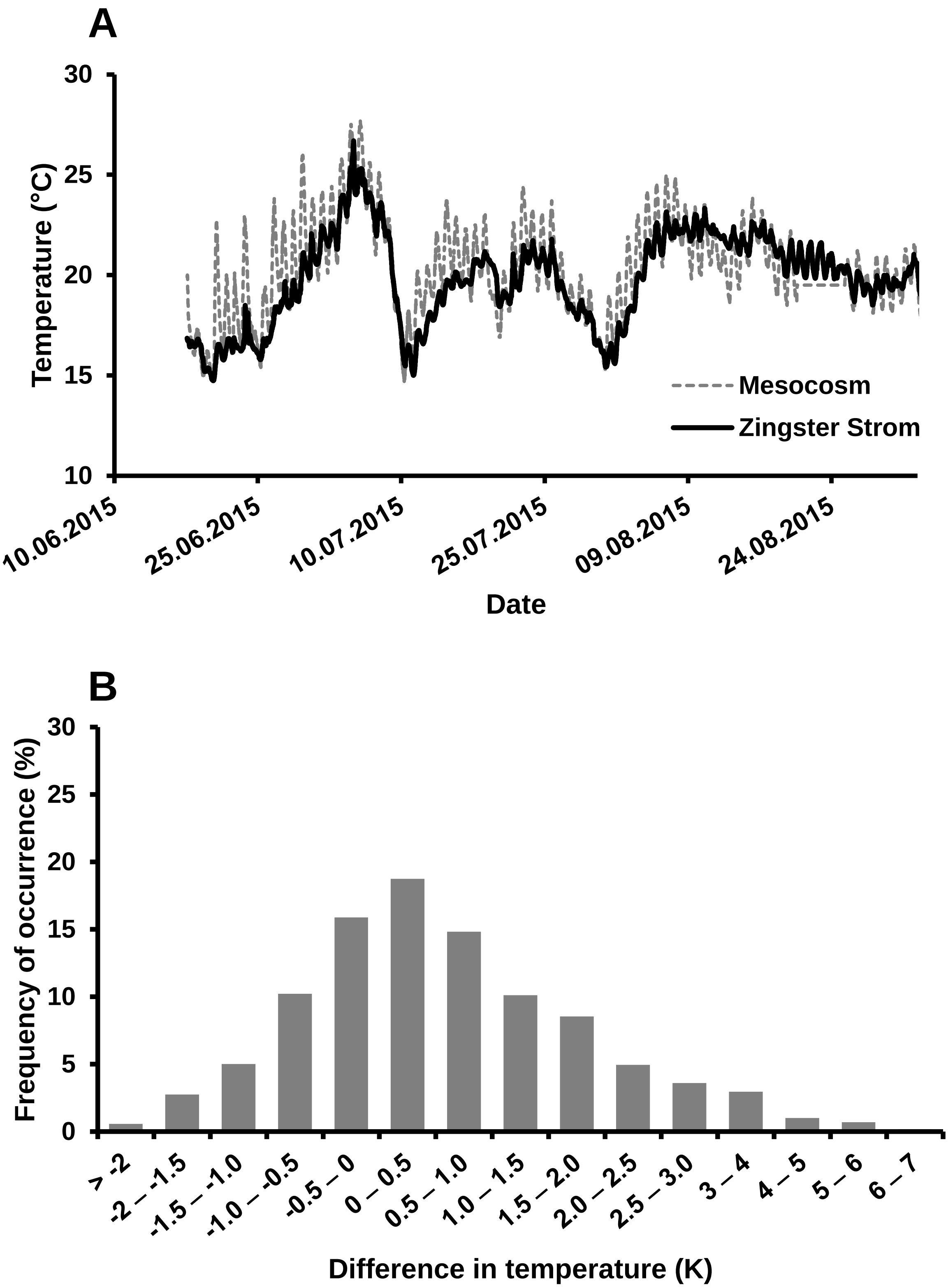


Fig. 4 **A:** Temperature development inside the Zingster Strom (actual ecosystem) and the experimental mesocosm. Temperature was measured every 15 minutes inside the Zingster Strom (n = 9209) and every 5 minutes in the mesocosms (n = 20588). **B:** Temperature difference (K) as percentage frequency of occurrence between surface mesocosm water and the Zingster Strom during June and September 2015. Compared were only simultaneously measured values (n = 6921).

The mesocosm showed the same temperature development like the Zingster Strom (Fig. 4A). However, the daily amplitude, especially the maximum values, reached up to 5 K higher in the mesocosm compared to the Zingster Strom. Only very rare (< 5 %) lower temperatures were measured in the mesocosm. Temperatures got more similar to the ecosystem during night times. Obviously, solar radiation was better absorbed in the mesocosms and less well dissipated. Perhaps, the vessel material absorbed energy itself. Three-quarters of all temperature differences between the Zingster Strom and the mesocosm were within ±1.5 K (Fig. 4B). Additionally, the highest differences were measured only during periods of fair weather, i.e. intense solar radiation, what again hints to different energy uptake behaviour of the mesocosms (material).

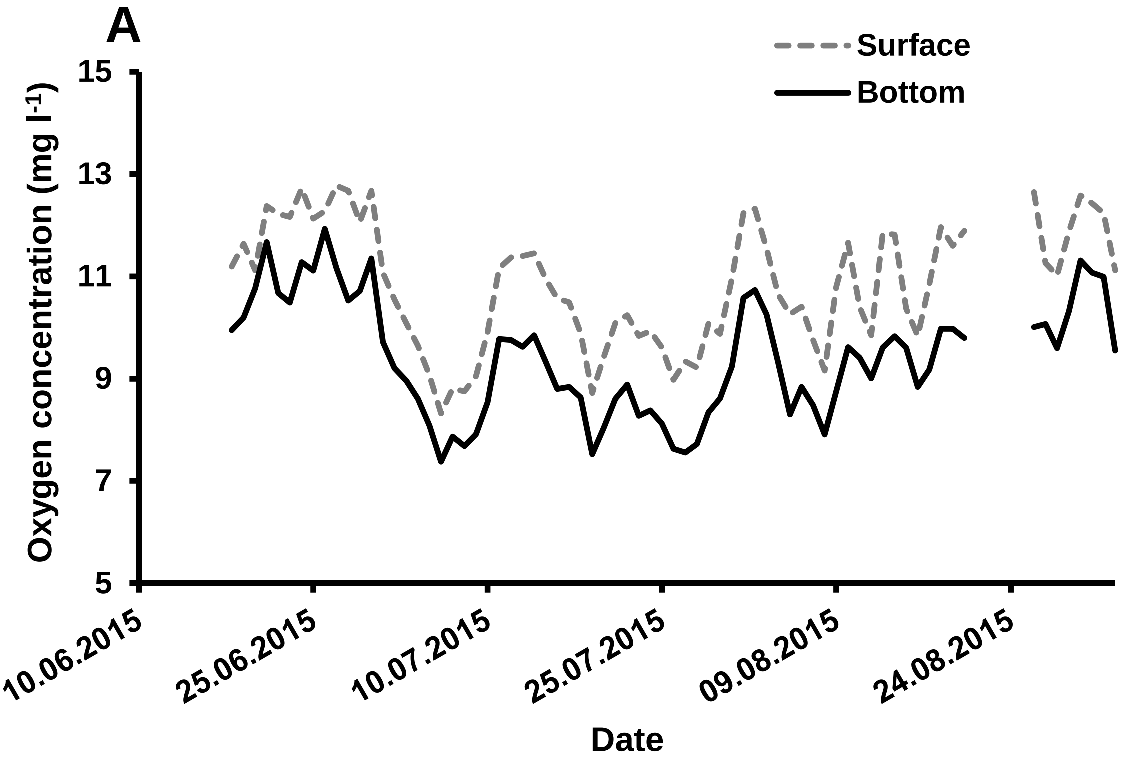
3.2 Oxygen development

The mesocosm was almost never severely undersaturated, i.e. < 50 %. The bottom layer was only rarely < 70 % oxygen saturation and only one third of the time below 100 % saturation. The upper layer was only 20 % of the time < 100 % saturation, but also 20 % of the time > 150 % (n = 20226). The oxygen concentration (daily median) was never below 7 mg l^{-1} in the water column (Fig. 5A).

The oxygen saturation and concentration at the bottom showed a time lag during the day, i.e. it increased as expected later compared to the surface. Phytoplankton at the bottom may have produced less oxygen there, but that would also indicate that the water current in the mesocosm did not completely mix the water column. In contrast to the stable temperature values inside the mesocosm, 65 % of all oxygen saturations were at least 10 % higher at the surface compared to the bottom of the mesocosm. The oxygen concentration at the surface was 70 % of the time at least 1 mg O_2 l^{-1} higher compared to the bottom (Fig. 5B). This observation brings another factor into the mesocosm function: sediment respiration. This respiration is present day and night and may explain the above mentioned time lag of oxygen increase over day at the bottom layer as well as the frequently lower oxygen saturations at any time.

The mesocosm had always much higher oxygen saturations at the surface during the day, but only slightly less saturations during the night (data not shown). However, the sensor at the bottom measured at the same water depth, as the sensor in the Zingster Strom. Therefore, the mean oxygen concentration in the water mesocosm water column was used to compare it to the Zingster Strom.

The oxygen concentration in the mesocosm showed the same reaction to weather forcing (not shown) but at the beginning and in the end of the experiment considerably different amplitude than the Zingster Strom (both daily median, Fig. 6A). These results indicate that both systems are equal stable during night, i.e. that the sediment respiration impact onto the water column was representative for the ecosystem. In contrast, the production of mostly phytoplankton had a much higher impact on the oxygen saturation of the much smaller water column during day. Macrophytes were not very abundant in the mesocosm. Oxygen saturation of both systems were within a range of ±10 % difference at only one third of all sampling points, and oxygen concentration of ±1 mg O_2 l^{-1} almost half of the time (Fig. 6B).



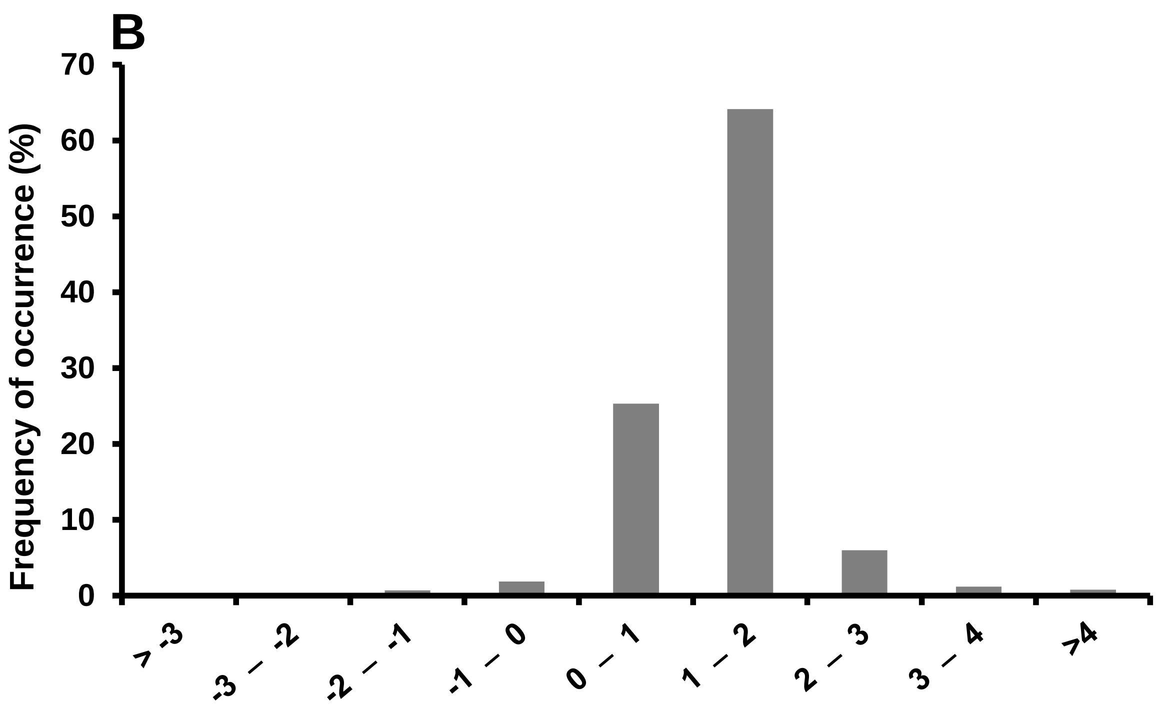


Fig. 5 **A:** Oxygen saturation concentration (daily median) at the surface and the bottom of the mesocosm. **B:** Oxygen concentration difference (mg l^{-1}) as percentage frequency of occurrence of surface (20 cm) and bottom (80 cm) water inside the mesocosm between June and August 2015. Oxygen was measured every 5 minutes at surface and bottom and only simultaneously available values were compared (n = 19597).

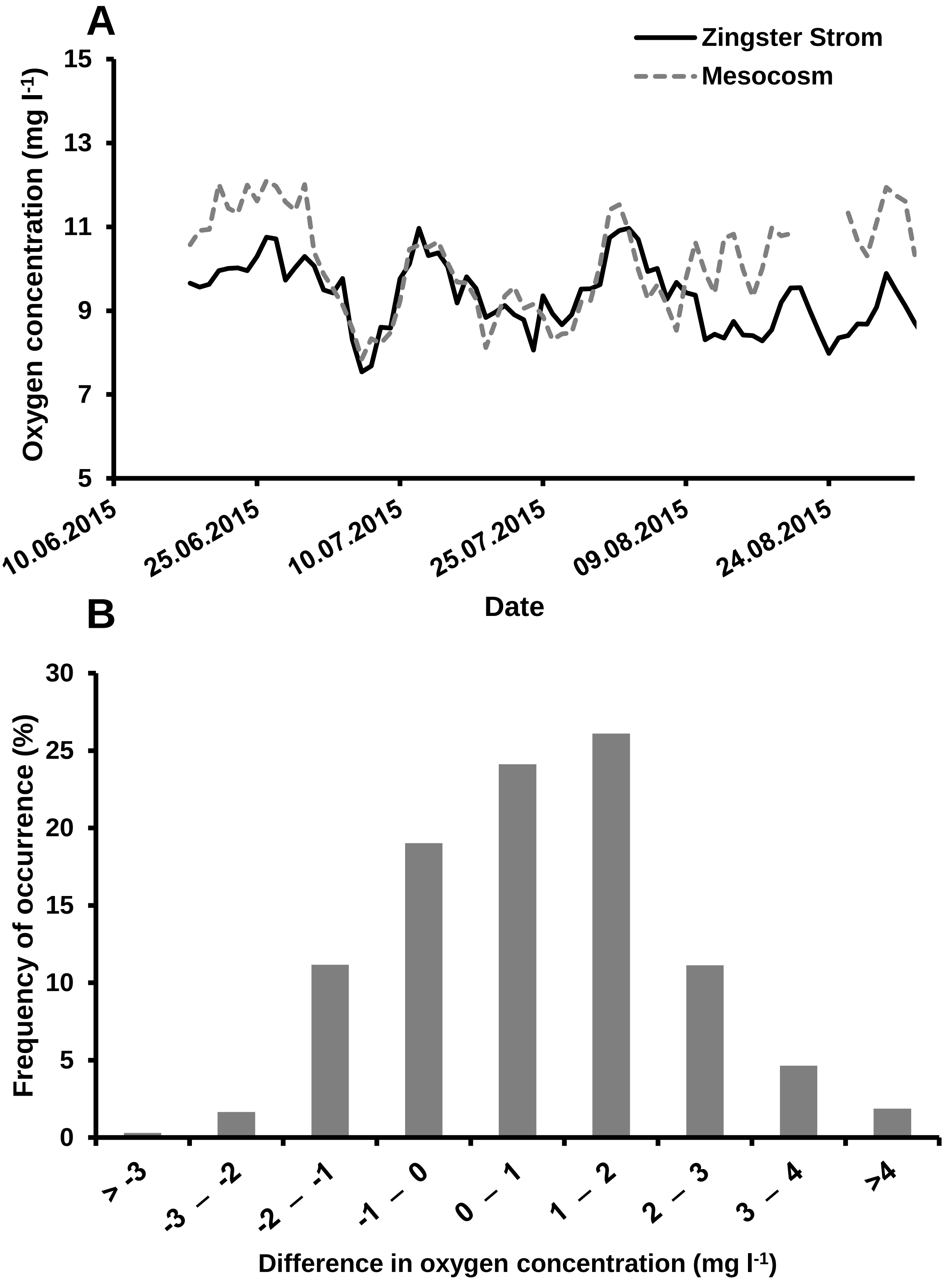


Fig. 6 **A:** Oxygen concentration (daily median) inside the Zingster Strom and the experimental mesocosm. Oxygen was measured every 15 min inside the Zingster Strom (n = 9209) and every 5 min in the mesocosms (n = 19597). **B:** Difference in oxygen concentration (mg l^{-1}) as percentage frequency of occurrence between mesocosm water (mean concentration surface & bottom) and the Zingster Strom during June and September 2015. Compared were only simultaneously measured values (n = 6869).

4 Discussion

4.1 Technical considerations

The construction costs, technical equipment and maintenance of the here presented ZOOM mesocosms are rather low compared to the large mesocosms mentioned in the introduction. The sediment should be either stored cool or taken fresh from the system, depending on the inclusion of macrozoobenthos. All automatic logging devices and the tank walls are prone to biofouling. Therefore, the easy accessibility also several times per day for maintenance and sampling profited from the near vicinity to the lab. Moreover, boats were not needed like for lake-site enclosures and, power supply was easy.

However, terrestrial invertebrates were a problem. The tanks had to be checked for snails, insects and worms very often. HARGRAVE (2006) used a 1.0 mm mesh to prevent invertebrates to enter the mesocosms. However, a mesh negatively affects the light climate by reducing the available light. It is possible to use translucent high-density polyethylene lids, which allows up to 90% of the PAR to pass (PANSCH et al. 2016). This construction would prevent evaporation and contamination by invertebrates, but may increase the temperature if installed on land.

Additionally, atmospheric dry deposition would be partly prevented. However, atmospheric dry and wet deposition can be an important source for nutrients into the water column (TIPPING et al. 2014). In total, 156 mm precipitation or 312 l rain water were transported into the mesocosm (18 % of total volume) during the experiment (data Biological Station Zingst). The very near vicinity to land may have increased dry nutrient deposits on the other hand, what could not be evaluated well enough so far. Salinity was on median 6.6 ± 0.5 (n = 10) and was not diluted much due to precipitation. An addition of brackish water was not necessary.

4.2 Comparability of coastal waters with the Zingster Outdoor Mesocosms

The temperature development between the lagoon system and the mesocosm was comparable. The temperature difference of 75 % at ±1.5 K was at the same range as described in the KOB (WAHL et al. 2015). The KOB benthocosms had 78 % of the time an off-set of ±1.5 K between fjord and benthocosm (WAHL & BUCHHOLZ 2015). The approach burying the ZOOM into the ground showed the same cooling efficiency, as enclosures or systems, which are cooled by adjacent water flow. Another way was to insulate heavily, like the SBC, which were constructed with double walls and filled with Styrofoam (PANSCH et al. 2016). The cooling effect was probably influenced by the high groundwater level in the surrounding area. Therefore, ZOOM was not only cooled by the ground, but also indirectly by water.

4.3 Dimensions of planktonic and benthic oxygen budgets

Although the temperature of the mesocosm was comparable to the Zingster Strom, the diurnal oxygen development differed strongly. This unbalance was observed, even though the water column was mixed permanently. There was also a slight oxygen gradient from top to bottom layer in the ZOOM. Causes for this difference (Zingster Strom *versus* mesocosm) and gradient (within the mesocosm) can be:

1. The gradient resulted from lowered primary production at the bottom due to light limitation. However, the attenuation in the mesocosms were not higher than in the Zingster Strom.
2. The measurable gradient can be attributed to an insufficient water mixing in the mesocosm. Such a gradient was not observed in the Zingster Strom, which is a site of high water current velocities.
3. The sediment oxygen demand was higher in the mesocosms compared to the Zingster Strom. However, oxygen saturation in both systems were more comparable during night, so that this can only be a minor cause for differences and gradients.
4. The production in the mesocosm was much higher than in the Zingster Strom, what caused high oversaturations. Perhaps, there was a higher nutrient influx, a better light climate due to higher phytoplankton sedimentation and a lower gas exchange with the atmosphere by a weaker wind fetch.

MEYERCORDT & MEYER-REIL (1999) described a sediment oxygen demand of 0.7 – 1.1 mmol O_2 m^{-2} h^{-1} (17 – 26 mmol m^{-2} d^{-1}) in an embayment of the DZBC with sediment characteristics comparable to the ones used in this study. The difference of oxygen concentration between surface and bottom is 40 – 47 mmol O_2 m^2 d^{-1}, if the water column is separated into two equal halves. Therefore, it can be assumed half of the difference between surface and bottom can be explained by sediment respiration. The remaining gradient has to be accounted to a high attenuation in these turbid waters (SCHUBERT et al. 2001). SCHUMANN & KARSTEN (2006) described a strong cyano-bacterial dominance for the DZBC. It was described for shallow lakes that cyano-bacteria can lower light climate over-proportionally (SCHEFFER et al. 1997) and the DZBC shows the lowest Secchi depth and highest cyanobacterial biovolume across coastal water bodies of the southern Baltic Sea (BERTHOLD et al. 2018). Hence, the bottom parts of the mesocosms were probably less productive due to light limitation, than the surface even with constant water mixing. The remaining difference between the oxygen balances of the ecosystem and the mesocosm results from the much higher oversaturation during the day and a slightly lower undersaturation at night. However, this difference had no influence on the general similarity of the mesocosm with the Zingster Strom, since the oxygen concentrations were > 6 mg O_2 l^{-1} in 95 % of the cases. Oxygen concentrations above this level were also continuously described by monitoring in the lowest part of the DZBC (BACHOR et al. 2013).

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