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Diurnal stratification of oxygen in shallow aquaculture ponds in central Europe and recommendations for optimal aeration

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ABSTRACT

The common carp (*Cyprinus carpio*) is an important livestock in regions of Central Europe, where it is bred in shallow, turbid ponds (mean depth 1 m). A frequent problem observed in this form of aquaculture is hypoxia, which confines the fish close to the surface, preventing them from optimally feeding at the bottom. According to information propagated in textbooks and good practice guidebooks and internet documents, the best solution to that is aeration in the early morning hours, when oxygen concentration is supposed to be minimal. While we wanted to test the feasibility of photovoltaic power for aeration of ponds, we detected that on days with bright sunshine the lowest oxygen concentration occurs in the afternoon at the bottom layer of a shallow pond, and that oxygen distribution is highly influenced by thermal stratification. This formation of layers of different temperatures within the water body inhibits the diffusion of oxygen. A breaking of the stratification effectively increases the oxygen concentration, elevating the overall amount of oxygen in the pond. Consequently, the drop in oxygen concentration at night is less dramatic, and critically low levels of oxygen in deeper zones of the pond are avoided. A comparison between the oxygen distribution and daytime or nighttime aeration showed that on days with bright sunshine it is more effective to force mixing of the entire water column during the day, making the use of a photovoltaic power system feasible. This offers a simple and elegant solution for ponds which are not connected to the power grid.

1. Introduction

Fish and fishery products are of enormous importance as protein source for a fast growing human population. The total demand of fishery products in 2016 was about 175 million tons, which is 4 million tons more than in 2015 (FAO, 2016). Due to the overexploitation of natural resources over decades, marine and fresh water aquaculture play an increasing role in meeting market demands: almost half of fishery products on the market originate from aquaculture. From the 171 million tons of fishery products consumed in 2015, 93.5 million tons were provided by capture fisheries and 77.5 million tons by aquaculture (FAO, 2016). Various types of marine and fresh water aquaculture exist, for example sea cages for cultivation of Atlantic salmon (*Salmo salar*), seawater ponds for production of prawn (e.g. *Penaeus monodon, P. merguiensis*, and *P. japonicus*), closed loop circulation systems for intensive cultivation of trout (*Salmo truta*), and shallow fresh water ponds. The latter plays an important role in production of fish and other commercially relevant species all over the world, such as the giant river prawn (*Macrobrachium rosenbergii*) or the noble crayfish (*Astacus astacus*). In Bavaria (Germany), four regions are traditionally commercially important for cultivation of the common carp (*Cyprinus carpio*), the “Aischgrund” in the region around Höchstadt (Franconia), and the regions Ansbach/Dinkelsbühl, Tirschenreuth, and Schwandorf (Bätzing, 2013). Typical carp ponds of this area are shallow (average depth about 1–1.2 m) and often lack a natural water influx, which means the only replenishment of lost water comes from rain and the surrounding area, thus making an elaborate water management necessary. While the most important fish in these ponds is the common carp, other species are sometimes co-cultivated, such as catfish (*Silurus glanis*), pike (*Esox lucius*), tench (*Tinca tinca*) or pikeperch (*Sander lucioperca*). Besides the production of fish, these areas play an enormous role as habitats for many rare and threatened plants and animals, and

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have a considerable importance for tourism (Bätzing, 2013). The regions show a typical temperate oceanic climate with pronounced four seasons that present cold winters and hot summer. The very low temperatures inhibit the growth of carps during winter and it can take up to three years to produce fish with optimal size (1–2 kg) for the market.

Successful cultivation of carps is strongly related to environmental factors, especially oxygen concentration and temperature, both of which follow a seasonal pattern: towards the end of the production season in August, hypoxia occurs more frequently. At that time, the photosynthetic organisms do not produce the same amount of oxygen, as the days grow shorter. In addition, fish have a relatively high oxygen demand when the water is warmer. When the phytoplankton starts to die, the available biomass for the bacteria contributes further to a high oxygen demand.

Carps rummaging through the muddy bottom to find their prey (like chironomids and tubifex) or algae blooms give the ponds their usual turbid characteristic. The constant resuspension of sediments leads also to a high biological oxygen demand. Severe lack of oxygen in the water is easy to spot from the shore of a pond: the carps are close to the surface and very obviously breathe with effort, sometimes even reaching out of the water with their mouths.

Oxygen concentration in a pond is dependent on a number of factors: the atmospheric oxygen is in equilibrium with the dissolved oxygen in the water. As diffusion is the main force behind the exchange, the process is slow: even a vertically mixed pond will not reach saturation (as the diffusion into the water body cannot compensate for the consumption) during nighttime, when there is no photosynthetic oxygen production.

Production of oxygen occurs by photosynthetic organisms, mostly phytoplankton, but also higher plants. One problem in a carp pond is that due to the bottom feeding of its inhabitants, the water is usually quite turbid, narrowing the zone for photosynthesis down to a water layer at the surface and limiting photosynthesis. Another problem are the algae themselves, as they can grow to such a density that they contribute substantially to turbidity.

Oxygen is consumed by the heterotrophic organisms in the pond, i.e. the animals, but also to a considerable extend by the microbial community in the mud. Additionally, the phytoplankton consumes oxygen during the night or at very low solar irradiance.

As oxygen depletion is an obvious problem due to the pathetic display of the carps gasping for oxygen rich water, a common strategy to solve this problem is the aeration of ponds. However, many ponds are in remote locations and not connected to the power grid. If a fish farmer identifies a situation that requires aeration in such a remote pond, he might use a modified accessory to his tractor, like a manure mixer or another propeller-like contraption, in order to provide mixing until the behavior of the fish suggests that the hypoxic crisis is over (Fischerzeugerring Mittelfranken e. V., 2006). A disadvantage to this approach is that he will be busy for some time and unable to do other work. If daytime aeration were a solution for the problem, solar energy could be used to generate off-the-grid power. The fish farmer would have to check his ponds only now and then, leaving him free for other work. Current progress in microelectronics (such as internet of things) could provide connectivity for remote control.

In this study, the effect of daytime and nighttime aeration on temperature and oxygen concentration in ponds was analyzed and compared to results from the same ponds without aeration. Probes were placed close to the bottom and at roughly half the depth in the water column. Additionally, solar irradiation and wind speed were recorded. Representative results of the measurements are presented in this manuscript.

2. Material and methods

2.1. Location and experiment period

Experiments were performed in two ponds of the Bavarian State Research Center for Agriculture, Institute for Fisheries, Department for Carp Farming, in Höchstadt, Germany (49°41′55.70″N, 10°48′0.05″E). One pond has a surface area of 200 m^2 and the other a surface area of 1000 m^2. Maximum depth of the ponds is about 1.0 m. The ponds were populated with two-year-old common carps (*Cyprinus carpio*) at a density of about 1500/per hectare. The experiments were perforemed from 08.07.2015 to 11.09.2015. This corresponds to the mid and second half of the usual open-air growing season, which starts in May and ends in October.

2.2. Aeration of the ponds

Pond 3 with a surface area of 200 m^2 was aerated with one 150 W-aerator (*Aqua-Hobby*), and pond 7 with 1000 m^2 surface area with a 500 W-aerator (*Aqua-Wheel*, both Linn Gerätebau GmbH, Lennestadt-Oedingen, Germany). The aerators were operated with time switches either at night or during the day. Aeration time was 7 h, either from 22:00–05:00, or from 10:00–17:00.

2.3. Measurement of physical parameters

Probes for measurement of oxygen and temperature (both WTW, Weilheim, Germany) were placed in a depth of 40 cm and 80 cm, respectively. The distance to shore was 2 m. Oxygen and temperature data were collected with a MIQ/TC 2020 XT-terminal (WTW, Weilheim, Germany) every 10 min. Solar radiation and weather data were taken from an agrometeorological station of the Bavarian State Ministry for Food, Agriculture and Forestry in Hoechstadt, which is situated close to the experimental ponds.

3. Results

3.1. Measurements without aeration

At wind speed below 3.5 m/s, stratification occurred and a distinct pattern of oxygen and temperature distribution between the 40 cm and the 80 cm horizon was recorded (Fig. 1). In the morning, the 40 cm layer responded with a phase shift in oxygen concentration of about 6 h to the intensity of solar radiation, reaching maximal values in the evening. The 80 cm layer got oxygen-depleted during the day and late evening. Oxygen concentrations often reached a minimum below the critical (for carp) threshold of 1 mg/L. At night, oxygen concentration in 40 cm depth decreased while it sharply increased in the 80 cm-horizon. In the course of several hours, the oxygen concentrations between the two layers became equilibrated. After that, both concentrations declined. After sunrise, oxygen in the 40 cm level increased again, while in the 80 cm level oxygen concentration dropped to very low values. Temperatures of the two depths were almost identical in the morning before sunrise. During solar irradiation, water temperature in the 40 cm level rose considerably faster compared to the 80 cm horizon. At night, temperature in the 40 cm level decreased while it simultaneously increased in the 80 cm layer. In the early morning, both temperatures became equilibrated and decreased until sunrise. At this point, the cycle started from the beginning.

3.2. Results of pond aeration

Aeration at night (22:00–05:00, Fig. 2) lead to an increase of oxygen in the 80 cm layer. The kinetic of oxygen and temperature development was very similar to the results obtained without aeration. Aeration during the day (10:00–17:00, Fig. 3) also increased the oxygen

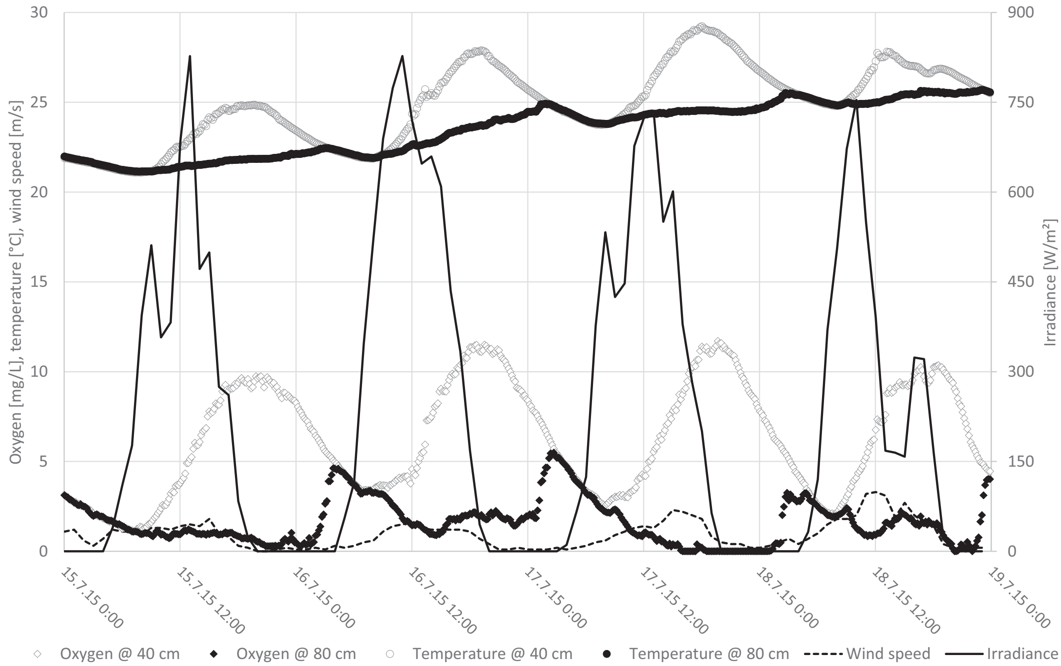

Fig. 1. Data plot of pond 7 from 15.07.15 to 19.07.15 without aeration. Oxygen (diamonds) and temperature (circles) over four days at different depths (full symbols: 80 cm, empty symbols: 40 cm). Additionally, solar irradiance (solid line) and wind speed (dotted line) are plotted.

concentration at 80 cm. Oxygen levels as well as temperatures were almost identical in both depth. Maximum oxygen concentration in the 40 cm-horizon was lower as compared to not-aerated ponds (but still at a high range), but in the lower level oxygen concentration always stayed above 2 mg/L. Only in the morning hours, oxygen drops were more pronounced in 80 cm compared to 40 cm.

4. Discussion

Up to now, it is generally believed that oxygen concentration in ponds is high during the day because of photosynthetic activity of algae and water plants. Oxygen values are expected to decrease (often dramatically) in the night, when the photosynthetic activity of these organisms does not take place and the oxygen consumed by respiration is not replaced (Billard, 1999). Chang and Ouyang investigated effects of temperature, wind and light in lakes at the Pearl River in China and

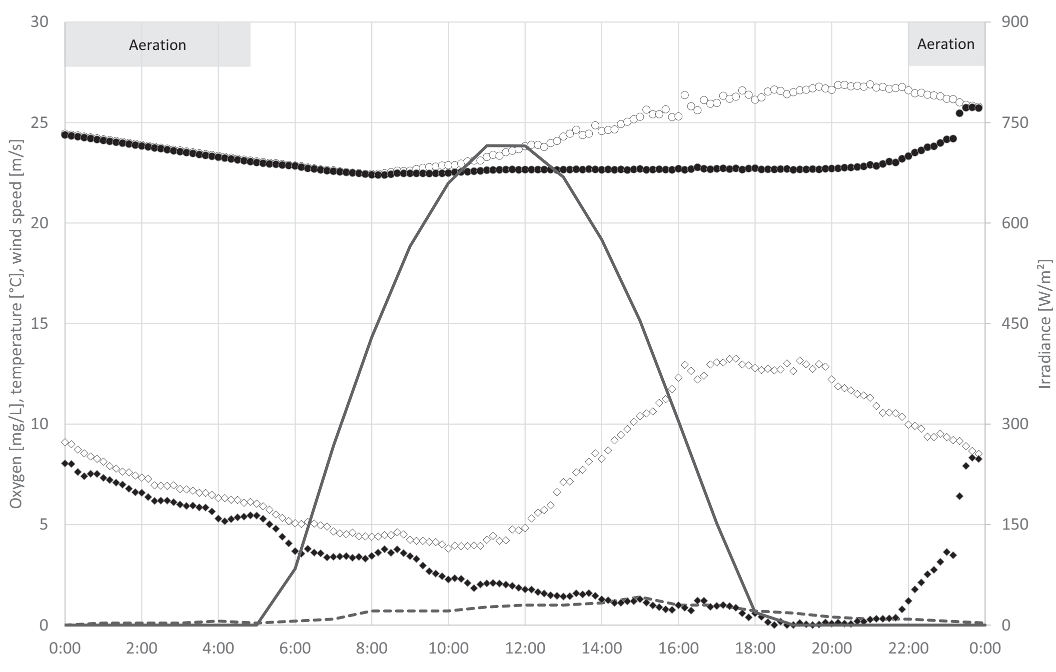

Fig. 2. Data plot of pond 7 with aeration during the night (30.07.15). Oxygen (diamonds) and temperature (circles) at different depths (full symbols: 80 cm, empty symbols: 40 cm). Additionally, solar irradiance (solid line) and wind speed (dotted line) are plotted. Note that aeration commenced the previous day at 22:00 and showed a steep increase in oxygen at 80 cm depths as it does in the data shown at 22:00.

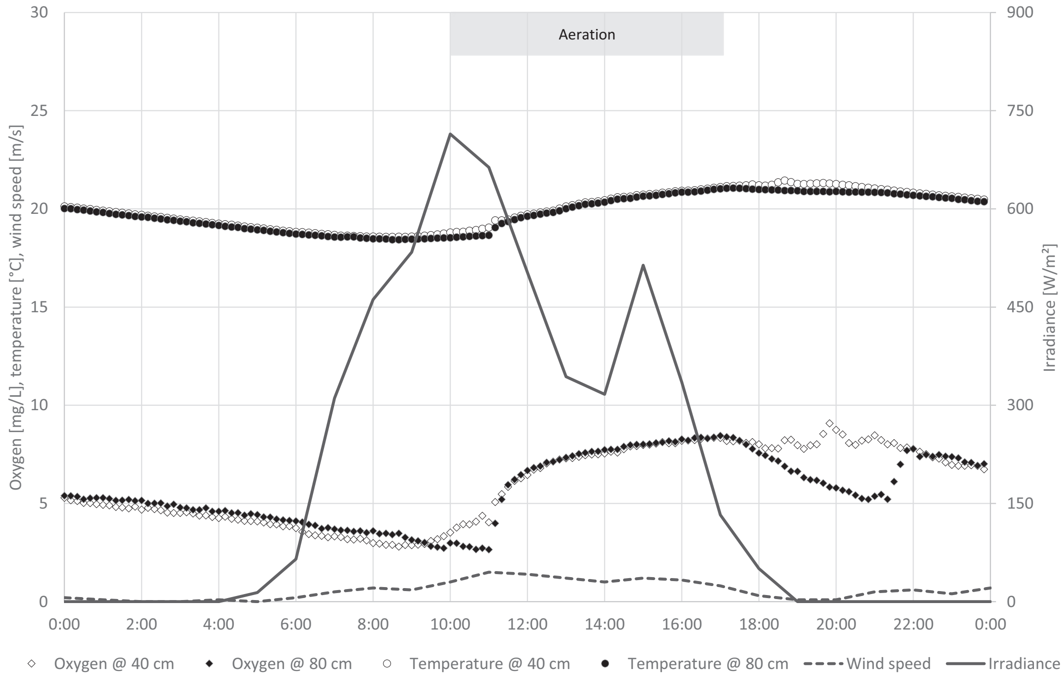

Fig. 3. Data plot of pond 7 with aeration during the day (22.08.15). Oxygen (diamonds) and temperature (circles) at different depths (full symbols: 80 cm, empty symbols: 40 cm). Additionally, solar irradiance (solid line) and wind speed (dotted line) are plotted. Aeration duration was from 10:00 to 17:00.

constructed a model of dissolved oxygen dynamics and vertical circulation based on measurements and mathematical calculations (Chang and Ouyang, 1988). The authors measured oxygen concentrations in ponds in a spatial interval of 10 cm from the surface to 120 cm. They found that thermal stratification only occurs on calm sunny days. Oxygen distribution very much depended on thermal stratification. In the morning of sunny days, low oxygen concentration in all horizons of the water column were detected (overall about 2 mg/L). After sunrise, surface oxygen content increased, while deeper layers were not enriched with oxygen. The concentration difference became even more drastic at noon and in early afternoon. During the night, oxygen equilibrates at first in the water column (decrease at the surface and increase in deeper horizons). After equilibration, oxygen concentration decreases equally in all horizons. This kinetic speaks very much for a temperature driven stratification.

In this study, two probes were installed at 40 cm and 80 cm depths of a pond with an overall depth of about 100 cm. The results show a steep increase in the oxygen concentration in the middle layer of the water body during the day (Fig. 1). The bottom layer is quite unaffected by daylight, probably because of the turbidity of the water, which does not allow enough sunlight to penetrate into the deeper layers and therefore, no photosynthetic oxygen production occurs. Additionally, oxygen is constantly consumed by the microbiota in the mud. This leads to a more or less continuous decrease of oxygen concentration. A closer look into the oxygen data (Fig. 1) seems to indicate that the decline in the oxygen concentration is caused by the lack of daylight, as it sharply decreases after nightfall. However, this is not only due to the lack of photosynthetic oxygen production, while the consumption continues. It is also strongly related to the temperature: after nightfall, temperature decreases at 40 cm depth, until after some hours, the temperature curves at the two depths merge. At that point, no difference in the oxygen content is observed any more, clearly indicating that the formation of thermal layers is responsible for the oxygen distribution. In other words, during the day, a thermal gradient develops within the water body with lower temperature at the bottom and higher temperature at the surface, separating the zones of oxygen consumption at the bottom and oxygen production and atmospheric uptake near the surface. The recorded temperature difference between the 80 cm horizon and the 40 cm horizon was found to be in a range of 4.5–6 K, which corresponds to a density difference of more than 1‰ (density of water: $\delta_{29^\circ C} = 995.64$ g/L, $\delta_{23^\circ C} = 997.54$ g/L). This thermal gradient inhibits the exchange of oxygen between the two layers. The deeper layers of the water column deplete in oxygen, although a lot of oxygen is produced at the surface. At night, air temperature usually drops and a heat transfer from the water surface to the atmosphere occurs, which results in decreasing temperature of the surface water. The temperature-driven density difference disappears, and so does the oxygen difference, as the water masses formerly divided by a thermocline mix and unify. Right now, oxygen is evenly distributed in the entire water column.

It is important that the presence of carps rummaging through the muddy bottom does not destroy the thermal gradient, even though the low spatial resolution of the measurement does not allow for an estimate of the size of the zone of influence of the fish-induced water movement.

As lack of oxygen is commonly observed in the morning hours, it seems a reasonable idea to aerate the water at night. In fact, some fish farmer associations and carp specific literature promote aeration late at night or in the small hours (Fischerzeugerring Mittelfranken e. V., 2006; Horváth, Seagrave, & Tamás, 2002; Kirchmaier, 2015). The result of that, however, is not very much different from no action at all as shown in Fig. 4, which shows the oxygen and temperature data from pond 7 on two different days. The days were selected in due consideration to the irradiance. While the absolute values are different, the overall trend remains very similar, which probably is a consequence of the fact that in the early morning, oxygen concentration increases in the deep layers anyway due to the breakdown of the thermal stratification. Aeration only accelerates the process and does not seem to introduce very much oxygen into the water. On the contrary, even during aeration, oxygen levels drop (Fig. 4, triangles), while they do not do it at all in the bottom layer of the pond without aeration (diamonds). This was observed in two different ponds (3 and 7) during the same night (Table 1).

Daytime aeration on the other hand elevates the oxygen concentration in the bottom layer, sometimes close to saturation levels. This strongly suggests that any increase in oxygen concentration due to aeration is in fact caused by a distribution of the oxygen produced by

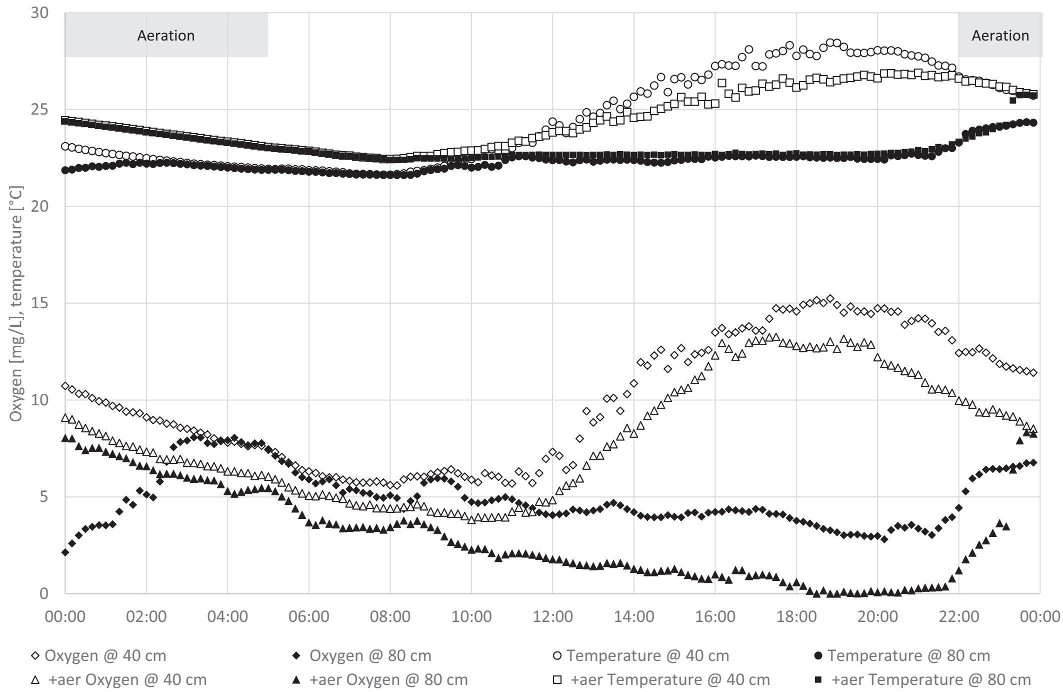

Fig. 4. Superimposition of two days in pond 7 (16.07.15 as in Figs. 1, and 30.07.15 as in Fig. 2). Diamonds and circles without aeration, triangles and boxes with aeration as indicated by the grey bars on top. Full symbols: 80 cm depth, empty symbols: 40 cm depth. The general trend of the corresponding lines is quite similar.

the photosynthetically active plankton. In untreated ponds at high irradiation levels, the levels of oxygen exceed saturation even in 40 cm depth (Fig. 1, saturation between 7.67 and 8.69 mg/L), and can be assumed to be even higher closer to the surface, as the turbidity of the water does not allow for deep penetration of light and hence, photosynthesis is impaired. Consequently, if supersaturation occurs at half-maximum depth, it is to be expected to be even more pronounced higher up. The mixing of this water layer into the water column will drastically increase the overall content of oxygen in the water, forming an enormous buffer, which contains enough oxygen to provide for the nightly demand without reaching critical levels.

The dynamics of photosynthesis in a turbid pond are multifaceted. It might appear counterproductive to move algae down into dimly lit layers, as this will decrease their photosynthetic oxygen production. It is important to keep in mind that an excess of light can inhibit photosynthesis by damaging the pigments involved or (especially the ultraviolet fraction of sunlight) the organism itself (Häder, 2006). As the stratification traps phytoplankton constantly in the top layer, it is not unlikely that in the course of the day, photosynthetic efficiency decreases. At the same time, algae trapped in deeper layers do not get sufficient light. A mixing of the layers might therefore be beneficial, as both constantly excessive and constantly low light conditions are avoided for the phytoplankton community as a whole.

Overall, our results show that in shallow ponds, aeration during the day yields better results than during the night, as it increases oxygen concentration throughout the water column. However, we only measured during sunny days, when photosynthetic oxygen production is substantially higher compared to overcast days. We also want to stress that our findings are valid for shallow ponds. In personal communications, one of the authors (M.O.) was advised by Czech scientists that it might be detrimental to mix a pond with a thick anoxic section within the water column. This would decrease the oxygen concentration in the upper layers to unfavorable levels; however, their ponds are deeper than 1 m. To understand that concern, it is helpful to imagine two ponds of identical surface, but different depths, 1 m and 2 m, and to assume that the oxygen in the pond comes primarily from photosynthesis, not from diffusion from the atmosphere. The turbidity shall be the same, as well as the stocking with fish and plankton. Light penetrates in sufficient intensity down to 0.5 m for the phytoplankton to perform photosynthesis (the so called euphotic zone). Consequently, in the shallow pond, the ratio of the volume of oxygen production compared to the whole volume is 1:2. In the deep pond, the ratio is only 1:4. If a given amount of oxygen is to be distributed equally in the water body, the final concentration will only be half in the deep pond

Table 1
Synopsis of the oxygen and temperature values at 80 cm depth. Mode: day or night aeration, subscript start indicates values at 0:00 for night mode and 10:00 for day mode, subscript end indicates 5:00 for night and 17:00 for day mode. Saturation at standard pressure between 21 °C and 22 °C is 8.68 mg/L and 8.53 mg/L, respectively. Arrows indicate the trend, which is always up for daytime aeration and always down for night aeration.

Pond	Date	Mode	oxy_{start} [mg/L]		oxy_{end} [mg/L]	$temp_{start}$ [°C]		$temp_{end}$ [°C]
7	22.08.2015	Day	1.57	↗	6.99	18.45	↗	21.18
7	23.08.2015	Day	2.55	↗	7.39	18.64	↗	22.29
7	25.08.2015	Day	3.69	↗	8.36	19.76	↗	21.04
3	22.08.2015	Day	2.98	↗	8.46	18.53	↗	21.02
3	23.08.2015	Day	3.66	↗	8.60	18.82	↗	22.19
3	25.08.2015	Day	3.13	↗	8.30	20.02	↗	21.00
3	30.08.2015	Night	6.88	↘	5.37	24.06	↘	22.61
7	30.08.2015	Night	8.05	↘	5.45	24.38	↘	23.01

compared to the shallow one. So, if the euphotic zone of a pond is too small compared to the overall water depth, the effect of mixing might indeed be a negative one. However, there are many additional factors to be considered, such as the fact that in a deeper pond, the rummaging of the carps at the bottom might not influence the upper water layers. Therefore, we cannot simply assume that our observations in shallow ponds can be automatically transferred to deeper ones.

Consequently, the use of photovoltaic power is feasible for the task. A minimal approach just with a solar panel would provide energy for aeration when it is most efficient. A system with a battery could provide power for overcast days, but would need some electronic control. As the ponds are sometimes remote and off the grid, a photovoltaic system can combine an elegant solution with the most efficient method to avoid or at least minimize hypoxia, especially for smaller and shallow ponds.

5. Conclusions and outlook

The oxygen and temperature dynamics of a carp pond are more complex than they might seem at first glance. The strong link between temperature-driven stratification and oxygen distribution calls for more detailed analyses with a better spatial resolution. For that reason, an automatic sampling and measurement system is being constructed, which will be employed in an upcoming campaign. It will allow for autonomous and simultaneous measurement and logging of twelve temperatures (including air temperatures), air pressure and humidity, and oxygen content and turbidity in up to eight different depths.

Additionally, different approaches in breaking the stratification should be explored instead of the commonly used aerators that produce a cloud of droplets, which increases evaporation. As mentioned before, many ponds get their water only from rain, and the region is already prone to dry weather. Hence, a pump system which only circulates the water column might help reducing water loss and break the thermal stratification as effectively as the rotating brush type aerator. Such a system might even be more efficient as it is more suitable to avoid outgassing of dissolved oxygen.

At last, one has to consider the profound effect of a lack of stratification in the pond: the average temperature will be the same throughout the depths, but consequently there will be sectors ending up warmer or colder than before. This, together with the equilibrated oxygen content, will have consequences for the "local" organisms. It can be expected that the decomposition processes in the mud will be accelerated in the presence of oxygen and at elevated temperatures. Bottom-dwelling prey of the carps might grow better, although they probably are adapted to low oxygen levels and even an obverse effect could occur. Over all, only a long term campaign can finally determine the effect of aeration on the complex ecosystem that is a carp pond.

Conflict of interest statement

The authors declare no conflict of interest.

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