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Negligible effect of hypolimnetic oxygenation on the trophic state of Lake Jyväsjärvi, Finland

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Abstract

Hypolimnetic oxygenation by pumping oxygen-rich surface water to the hypolimnion (HLO) is a commonly used tool for the restoration of nutrient-loaded dimictic lakes. However, in recent years its effectiveness has been questioned. In this case study we evaluated monitoring data covering a period of 23-years to show that, although experimental cessation of HLO drastically changed the lake's temperature and dissolved oxygen regimes, it did not significantly affect its trophic status. Thus, we recommend that the limited financial resources available are better directed towards further lowering the lake's external phosphorus load than continuing HLO.

Keywords

Automated monitoring; Chlorophyll *a*; Dissolved oxygen; Nutrients; Year-round oxygenation

1. Introduction

Different methods of hypolimnetic oxygenation (HOx) have been suggested for the restoration of eutrophic lakes to prevent deep water anoxia and the consequent accelerated internal loading of phosphorus during stratification (Beutel and Horne, 1999; Gantzer et al., 2009b; Singleton and Little, 2006). Hypolimnetic oxygenation by pumping oxygen-rich surface water to the hypolimnion (HLO) is a form of HOx often used in restoration of dimictic lakes in Finland (Lappalainen and Lakso, 2005; Salmi et al., 2014). The aims of HLO are to maintain thermal stratification in summer, oxygenate the hypolimnion and sediment, and allow aerobic decomposition in near-bottom layers (Lappalainen, 1994). However, the method causes increased hypolimnetic temperatures in summer and is expected to promote cooling of the water column under ice (Lappalainen, 1994; Salmi et al., 2014).

HLO is considered a cost-effective restoration method to prevent undesirable effects of progressive anoxia, especially when a lake has a high socio-economical value. This has been the case with Lake Jyväsjärvi, an urban humic lake in the city of Jyväskylä, Central Finland. The lake has been transformed from one of the most heavily polluted lakes in Finland in the 1970s to a scenic part of the townscape of the city with high recreational value (Salonen et al., 2005). Much restoration effort has been put into the lake during its history, including legal obligations for the paper industry. Due to a gradual decrease in the external anthropogenic nutrient loading, the role of HLO in restoration of the lake has recently been questioned, although local environmental authorities have been cautious about stopping the HLO. Results from HOx in general and HLO in particular have been variable (Bryant et al., 2011; Horppila et al., 2015; Lappalainen and Lakso, 2005; Liboriussen et al., 2009), and recently even the key role of dissolved oxygen (DO) in regulating internal nutrient load has been questioned (eg. Gächter and Müller, 2003; Müller et al., 2012; Orihel et al., 2015).

In this case study we investigated seasonal and long-term effects of experimental shutdown of HLO on a dimictic lake with the aid of automated water quality monitoring (AWQM). Effects of HLO on the trophic status of Lake Jyväsjärvi were studied with time series analyses of 23 years of data for nutrients, algal biomass measured as chlorophyll *a* (Chl *a*) concentration, DO and water temperature. Our aim was to evaluate whether there is still a need to apply year-round HLO to treat the symptoms of eutrophication in the lake by comparing the last three years without HLO to long-term trends in the lake. We also evaluated seven years of AWQM data to study the seasonal variability in DO and temperature structure of the lake with and without HLO.

2. Material and Methods

2.1. Study site

Lake Jyväsjärvi (3.1 km^2) in Central Finland (62°14.5′N, 25°46.2′E) is surrounded by the city of Jyväskylä and has an urban catchment area of 38 km^2. The lake has a maximum depth of 25 meters and a mean depth of 5.8 meters. The volume of Lake Jyväsjärvi is 1.8×10^{-2} km^3 with a mean water retention time of 2.7 months. The lake is typically ice-covered from late December to the beginning of May.

Lake Jyväsjärvi suffered from massive eutrophication in the past (Salonen et al., 2005). The lake received a heavy load of untreated paper mill and municipal wastewaters until the establishment of a sewage water treatment plant in the mid-1970s. As frequent DO depletion in the deep water of the lake was observed, HLO was initiated in 1979 and improved in the 1990s when a new HLO system (Mixox-1100, Water Eco Ltd., Kuopio, Finland), pumping 1 m^3 s^{-1} surface water (from 3 m) to the hypolimnion (12 m), was installed at the deepest point of the lake. Since then HLO has been operated year-round with one to three devices, apart from some breaks due to instrument malfunction. The local paper mill, which previously was the most important polluter, was legally obliged to continue HLO until 2010. After this obligation ended, the city of Jyväskylä was advised by the local environment authorities to continue HLO of the lake because a continuing tendency for low DO conditions in the hypolimnion during summer was considered a risk for lake biota and trophic status, and hence for the recreational value of the lake. HLO was stopped on April 10th 2012 for this experiment. However, due to frequent instrument malfunctions during 2011 meaning ineffective HLO, that year was considered the first OFF year in statistical analyses.

2.2. Data

2.2.1. Water quality monitoring

Lake Jyväsjärvi was monitored for DO, temperature, total phosphorus (P), total nitrogen (N) and Chl *a* concentrations in summer (June-August 1992-2014) and for DO, temperature, P and N in winter (January-March 1993-2015) at its deepest point (sampling station 510, Finnish Environment Institute database). The sampling occasions represent summer and winter stratification periods after the last substantial change in external loading to the lake. Samples were collected with a Limnos-sampler from depths of 1, 20 and 23 meters. DO was analysed with Winkler titration, P spectrophotometrically (SFS–EN ISO 6878:2004) and N by standard method SFS-EN ISO 11905–1:1998. Epilimnetic samples from the depth of one meter and averages of hypolimnetic samples from depths of 20 and 23 meters were used for the time series analysis. Calculation of annual averages of DO, temperature, P and N was based on 3-4, 1-3, 4-6 and 2-4 samples for summer epilimnion, winter epilimnion, summer hypolimnion and winter epilimnion, respectively. Chl *a* concentration was measured spectrophotometrically after ethanol extraction (SFS 5772:1993) from a 0–2 meter composite sample taken 3 to 8 times between June and August and the seasonal averages were calculated for the time series analysis.

2.2.2. Automated water quality monitoring

Since 2008 an AWQM station, situated 300 meters north from the deepest point of Lake Jyväsjärvi, has measured hourly profiles of temperature and DO (Oxygen Optode 3835, Aanderaa Data Instruments, Bergen, Norway) from 1 to 15 meters at intervals of 0.5 meters (max depth 16 m at AWQM location). Data were supplemented for temperature (Thermochron 1922L, Express Thermo, San Jose, CA, USA, ±0.5°C) and DO (YSI6600-V2, YSI Inc., Yellow Springs, Ohio) in cases of instrument malfunction during the 7-year dataset (www.paijanne.org). Winter 2011 data were not used for analysis of the AWQM data.

2.3. Data analysis

The effects of shutdown of HLO (OFF years) on the trophic status of Lake Jyväsjärvi were studied with time series analysis of the 23-year dataset by first fitting linear regressions for the log-transformed annual averages of P, N and Chl *a* measured from the summer epilimnion in 1992-2010 (ON years), and for P, N, DO and water temperature measured from summer hypolimnion (1992-2010) and winter hypolimnion (1993-2010). The second and third degree polynomials were also fitted but did not explain the data significantly better ($p>0.05$) than the first degree models. Constant functions (y became a constant value) were used for the P and water temperature data from the winter hypolimnion because the higher degree polynomials did not explain the data significantly better than the constant functions. Secondly, deviation of observed annual values from those estimated by linear regression or by subtracting the constant value (see Table 1 for methods used for each variable) was calculated for all variables and for winters and summers for both ON and OFF years. There was no temporal autocorrelation between the deviations of any variable ($p>0.05$). Differences in the deviations of P, N, DO, Chl *a* and water temperature between ON and OFF years were tested with t-test. Winter ON years were 1993-2010 and 2012, and OFF years were 2011, 2013, 2014 and 2015. Summer ON and OFF years were 1992-2010 and 2011-2014, respectively.

Effects of HLO on winter and summer temperature and DO structure were also analyzed with the 7-year AWQM dataset. A summer thermocline was considered to exist when a vertical temperature gradient exceeding 1°C m^{-1} was observed. Water heat content (H, Joules; Wetzel and Likens, 2000) and stability (S, kJ cm^{-2}; Idso, 1973; Schmidt, 1928) were calculated from the temperature data (between May and November for S). Annual maxima for H and S were determined for both ON and OFF years. AWQM data were also used to determine average daily rate of temperature change in the hypolimnion (°C d^{-1}) during both summer and winter (from 15 m). Average daily hypolimnetic DO net-consumption rates (ΔDO, mg l^{-1} d^{-1}) during winter and summer were calculated from the AWQM DO data (observed at 15 m) for the periods between freeze-over and the beginning of stratification and the following DO concentration minimum, respectively.

3. Results

3.1. Effect of HLO on trophic status

The shutdown of the HLO did not significantly delay the rate of recovery of the lake’s trophic status (Fig. 1). During summer in the productive epilimnetic layer of the lake, both annual Chl *a* and P concentrations followed the observed decreasing trend and their deviations from this linear trend did not differ significantly between ON and OFF years (Fig. 1a&b, Table 1). In the epilimnion, the observed annual N concentrations deviated from the linear trend significantly more strongly in ON years than in OFF years (Fig. 1b, Table 1). Deviations from the trend of hypolimnetic P and N concentrations did not differ between ON and OFF years in summer (Fig. 1c), and neither did P in winter (Fig. 1d). However, deviations of N in the winter hypolimnion differed significantly between ON and OFF years (Fig. 1d, Table 1). In the hypolimnion, deviations from the trends of water temperature and DO differed significantly between ON and OFF years in summer and winter (Fig. 2, Table 1); DO concentrations were lower in OFF years in both seasons while the hypolimnetic water temperature in OFF years was lower in winter and higher in summer than in ON years.

3.2. Seasonal changes in thermal structure and DO

During summer, HLO shortened the duration of stratification by an average of 1.8 months (Fig. 3a&b). The summer maximum H varied between 420-450 J regardless of the HLO conditions, but an average drop in maximum S of 55 kJ cm^{-2} was observed when HLO was in operation. Temperature increased in the hypolimnion by 0.092 °C d^{-1} and 0.011°C d^{-1} during ON and OFF summers, respectively. Average ∆DO was 0.093 mg l^{-1} d^{-1} during ON summers and 0.082 mg l^{-1} d^{-1} in OFF summers (Fig. 3c&d).

In winter, HLO mixed the under-ice water column completely, leading to colder near-bottom temperatures (Fig. 4a) and a homogenous DO distribution (Fig. 4c). A gradual increase in both H and hypolimnetic temperature was observed in OFF winters (Fig. 3b). The maximum H under the ice (40-67 J) varied depending on temperature conditions before ice formation. Hypolimnetic DO saturation varied between 46-83% in ON winters and between 26-93% in OFF winters (Fig. 4c&d). ∆DO was slightly higher (average 0.024 mg l^{-1} d^{-1} higher) in OFF winters than in ON winters.

4. Discussion

Our results show that after the shutdown of HLO the trophic status of Lake Jyväsjärvi did not deviate from the long-term trend of oligotrophication observed in the lake, and therefore we conclude that at the current level of external nutrient loading HLO is no longer necessary for the restoration of the lake. Furthermore, hypolimnetic temperatures in the lake were strongly altered due to use of this method. Oxygenation methods based on mechanical agitation are known to have a major impact on hypolimnetic temperature (Grochowska and Gawrońska, 2004; Salmi et al., 2014). In summers without HLO, cold hypolimnetic water remained relatively well-oxygenated, but as stratification continued DO concentrations eventually fell below 2 mg l^{-1}. In winter, HLO slowed down the development of low DO conditions in deep water layers due to the oxygen supply and induced complete mixing of the water column. Specifically, DO demand under ice is known to be controlled by the amount of organic matter in the water column (Golosov et al., 2007) and no new DO is added to the system by HLO (Lappalainen, 1994). Changes in summer and winter DO conditions due to HLO had no effect on the trophic status of the lake.

Based on the classical study of Mortimer (1941, 1942) lake managers assumed for decades that maintaining aerobic conditions in sediment overlaying water generally minimized benthic phosphorus release and hence contributed to lake water quality restoration. This concept has been repeatedly questioned because the sediment processes are actually more complex, with phosphorus release determined by its amount, quality and transformation in sediment, and varying between lakes (Bryant et al., 2010; Gächter, 1987; Gächter and Müller, 2003; Gächter and Wehrli, 1998; Gantzer et al., 2009a, Hupfer and Lewandowski, 2008; Orihel et al., 2015; Schaller et al., 1997). Some studies on the effects of HOx on lake nutrient status have reported that the observed changes in P concentrations have been mainly caused by the decrease in external loading rather than by the oxygenation itself (Horppila et al., 2015; Liboriussen et al., 2009; Matzinger et al., 2010; Schindler, 2006) and that DO consumption in the hypolimnion is caused by current lake productivity (Matzinger et al., 2010) rather than sediment uptake. However, HOx has been observed to suppress metal concentrations (e.g. mercury and manganese) by controlling their release from the sediment (Beutel et al., 2014; Gantzer et al., 2009a).

It has been proposed that HOx may have positive effects on benthic invertebrates by improving hypolimnetic DO conditions (Doke et al., 1995) but this has not always been the case (Dinsmore and Prepas, 1997). The HLO used in this study may alter the benthic community by favouring eurythermic and warm-water species and reducing habitat for the cold-water species often used as indicator species for oligotrophic conditions (Jyväsjärvi et al., 2013). Despite the HLO, the recent ecological status of the benthic community in Lake Jyväsjärvi has been categorized as poor or moderate (Jyväsjärvi et al., 2013). Thus, HLO does not seem to be an effective restoration method for benthic communities in order to achieve good ecological status of the lake (Jyväsjärvi et al., 2013). HLO may also reduce suitable habitat for cold-water fish such as vendace (*Coregonus albula*, Hamrin, 1986) and smelt (*Osmerus eperlanus*, Keskinen et al., 2012; Nellbring, 1989) which prefer water temperatures < 15 ˚C.

In conclusion, continuous HLO does not currently seem to be a necessary restoration action for reducing the P load in Lake Jyväsjärvi. Considering the gradual decrease in external nutrient loading due to enhanced land and wastewater management policies, Lake Jyväsjärvi and other lakes may no longer benefit from this type of HLO, and rehabilitation of these lakes may actually be impeded because limited management resources are being directed ineffectually towards controlling internal nutrient loading. The focus should instead be shifted towards management of catchment areas to further lower the external P load.

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Figure 1. Annual average concentrations of Chlorophyll *a*, total phosphorus (P, circles) and total nitrogen (N, squares) in Lake Jyväsjärvi. a) Epilimnetic (depth of 1 m) Chlorophyll *a* concentration in summer (June- August 1992-2014); b) epilimnetic P and N concentrations in summer; c) hypolimnetic (average from depths of 20 and 23 m) P and N concentrations in summer; and d) hypolimnetic P and N concentrations in winter (January-March 1993-2015). Solid black symbols represent years when hypolimnetic oxygenation was not in operation (since 2012 and individual winter 2011).

Figure 2. Annual averages of water temperature and dissolved oxygen (DO) concentration in Lake Jyväsjärvi. a) Hypolimnetic (average from depths of 20 and 23 m) water temperature in summer (June- August 1992-2014); b) hypolimnetic water temperature in winter (January-March 1993-2015); c) hypolimnetic DO in summer; and d) DO in winter. Solid black symbols represent years when hypolimnetic oxygenation was not in operation (since 2012 and individual winter 2011).

Figure 3. Examples of development, fluctuation and decay of thermal stratification (a&b) and dissolved oxygen (DO) concentration (c&d) with and without hypolimnetic oxygenation (HLO) as registered by the automated water quality monitoring (AWQM) station near the main basin of Lake Jyväsjärvi during the first AWQM summers with (in 2008) and without (in 2012) HLO (ON = with HLO and OFF = without HLO).

Figure 4. Examples of development, fluctuation and decay of winter stratification (a&b) with dissolved oxygen (DO) concentration (c&d) with and without hypolimnetic oxygenation (HLO) as registered by the automated water quality monitoring (AWQM)

station near the main basin of Lake Jyväsjärvi during the first AWQM winters with (2009-2010) and without (2012-2013) HLO (ON = with HLO and OFF = without HLO).

Table 1. Statistical test results (t-test) for Chlorophyll *a* (Chl *a*), total phosphorus (P), total nitrogen (N) concentrations, water temperature and dissolved oxygen (DO) concentration in winter and summer at different depths between ON and OFF years. The deviations of observed values of each variable from the trend line were compared by t-test between ON and OFF years. The t-value, degree of freedom (df) and p-value of t-tests are given separately. The detailed implementation of the t-tests is explained in section 2.3.

Season	Depth	Variable	Type of time series model	t-test between ON and OFF years		
				t	df	p
Summer	Epilimnion (1 m)	Chl *a*	linear regression	0.337	20	0.739
		P	linear regression	0.184	20	0.856
		N	constant function	1.990	21	**0.047**
	Hypolimnion (20 and 23 m)	P	linear regression	0.655	21	0.519
		N	constant function	1.847	20	0.080
		Temperature	linear regression	13.599	21	**p<0.001**
		DO	linear regression	2.609	20	**0.017**
Winter	Hypolimnion (20 and 23 m)	P	constant function	0.080	19	0.937
		N	linear regression	3.280	18	**0.011**
		Temperature	constant function	3.341	21	**0.003**
		DO	linear regression	10.645	21	**p<0.001**

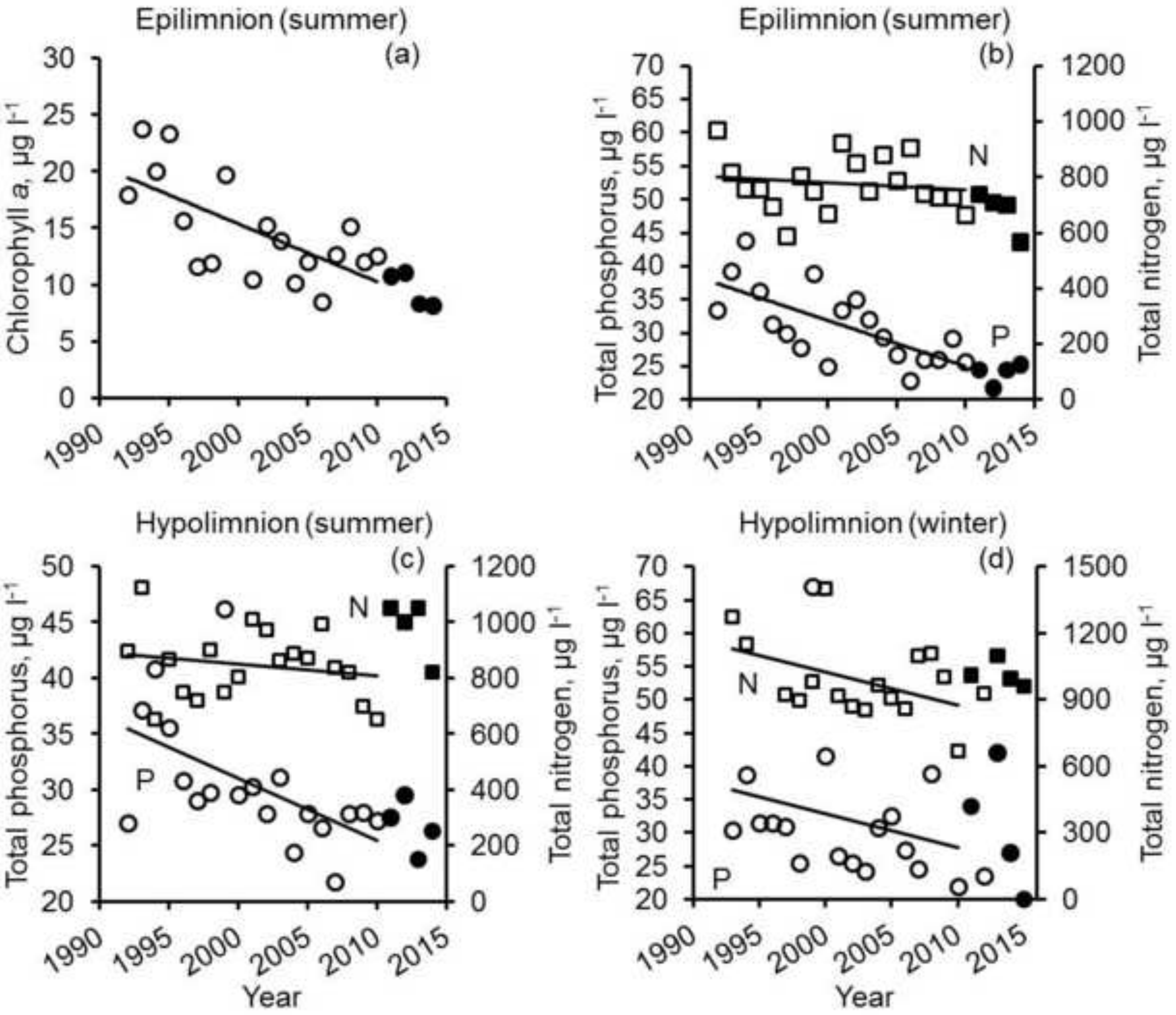

Epilimnion (summer)
(a)
Chlorophyll a, μg l-1
30
25
20
15
10
5
0
1990
1995
2000
2005
2010
2015
Epilimnion (summer)
(b)
Total phosphorus, μg l-1
70
65
60
55
50
45
40
35
30
25
20
N
P
1200
1000
800
600
400
200
0
Total nitrogen, μg l-1
1990
1995
2000
2005
2010
2015
Hypolimnion (summer)
(c)
Total phosphorus, μg l-1
50
45
40
35
30
25
20
N
P
1200
1000
800
600
400
200
0
Total nitrogen, μg l-1
1990
1995
2000
2005
2010
2015
Year
Hypolimnion (winter)
(d)
Total phosphorus, μg l-1
70
65
60
55
50
45
40
35
30
25
20
N
P
1500
1200
900
600
300
0
Total nitrogen, μg l-1
1990
1995
2000
2005
2010
2015
Year

Figure2

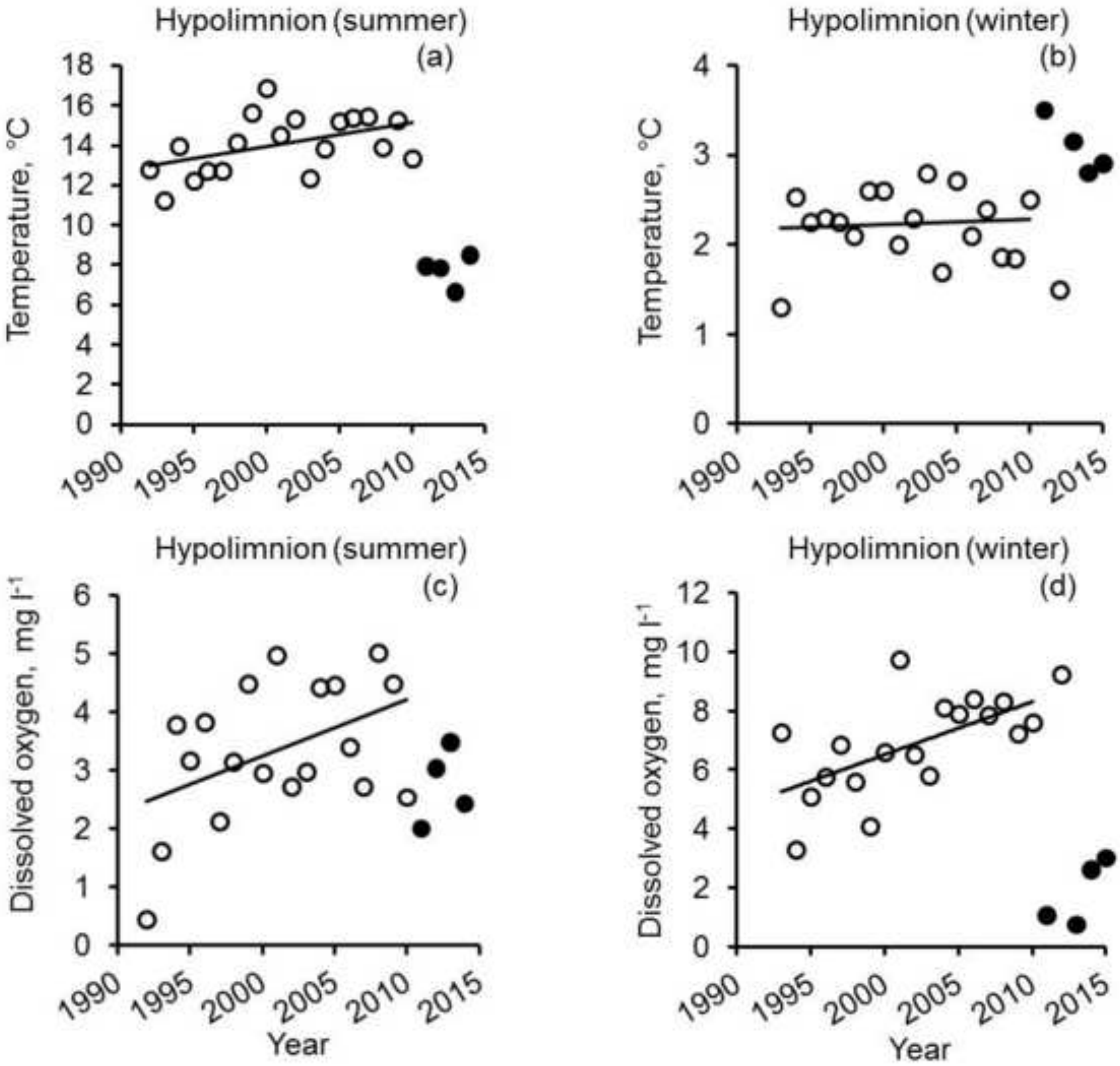

Hypolimnion (summer)
(a)
Temperature, °C
18
16
14
12
10
8
6
4
2
0
1990
1995
2000
2005
2010
2015
Hypolimnion (winter)
(b)
Temperature, °C
4
3
2
1
0
1990
1995
2000
2005
2010
2015
Hypolimnion (summer)
(c)
Dissolved oxygen, mg l-1
6
5
4
3
2
1
0
1990
1995
2000
2005
2010
2015
Year
Hypolimnion (winter)
(d)
Dissolved oxygen, mg l-1
12
10
8
6
4
2
0
1990
1995
2000
2005
2010
2015
Year

Figure3

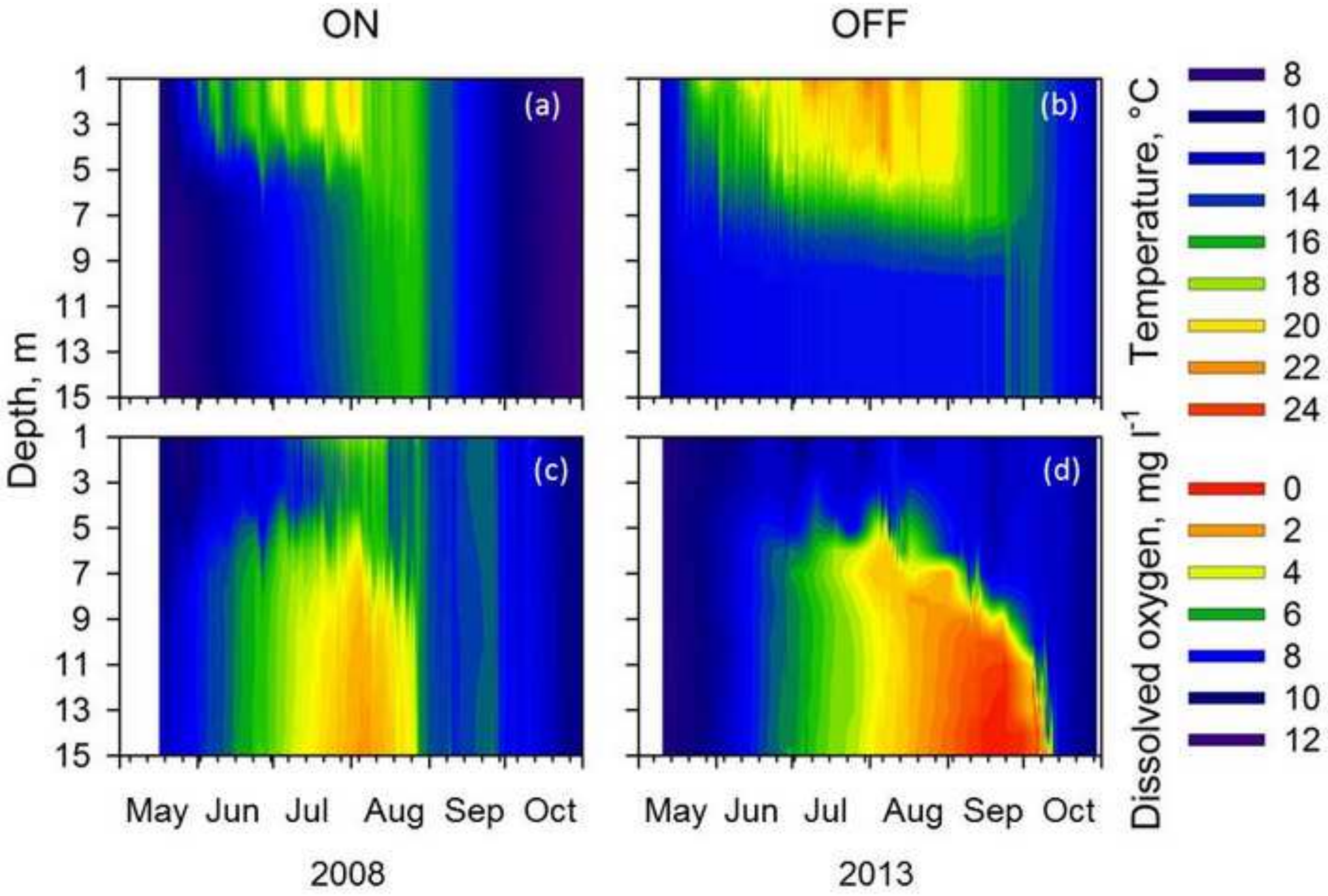
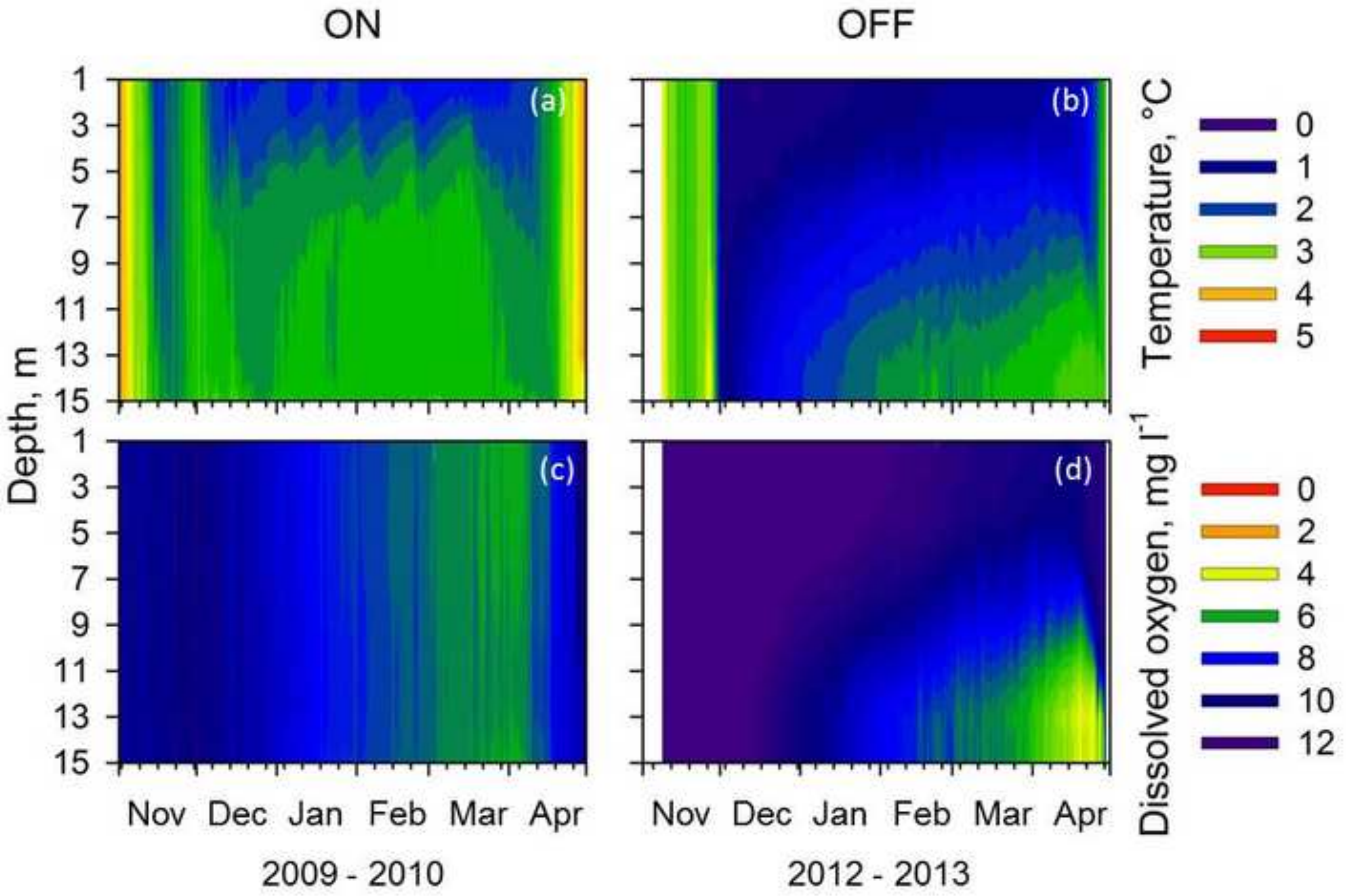

ON
OFF
(a)
(b)
(c)
(d)
Depth, m
1
3
5
7
9
11
13
15
May
Jun
Jul
Aug
Sep
Oct
2008
2013
Temperature, °C
8
10
12
14
16
18
20
22
24
Dissolved oxygen, mg l-1
0
2
4
6
8
10
12

Figure4


ON
OFF
(a)
(b)
(c)
(d)
Depth, m
1
3
5
7
9
11
13
15
Nov
Dec
Jan
Feb
Mar
Apr
2009 - 2010
2012 - 2013
Temperature, °C
0
1
2
3
4
5
Dissolved oxygen, mg l-1
0
2
4
6
8
10
12