Climate change and eutrophication - global problems of lakes worldwide

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Interreg
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A few words about me

I am associate professor in Ecology at the Department of Chemistry, Life Sciences and Environmental Sustainability of the University of Parma, where I coordinate the Laboratory of Benthic Functioning (BeFun).

To say that I am affiliated at Klaipeda University is reductive. I was feeling home from the very first time I came to Lithuania, back in 2009, and during these 14 years I received a lot from my colleagues, and from the human and natural environment.

I am a biogeochemist and ecosystem ecologist broadly interested in aquatic ecosystems and in how humans alter their functioning. I am focused on answering questions about energy flow and biogeochemical cycling of elements as C, O, S, N, P, Si across the land-water continuum.

Research themes include: -eutrophication; - primary production in aquatic environments; - bioturbation and benthic heterotrophic processes; - greenhouse gas dynamics in shallow water bodies; - interactions between microbial communities and macrophyte roots; - nutrient mass balance at different spatial scales; - the impact of agriculture, animal farming and aquaculture on aquatic environments.

That was one of the early test that Mindaugas and Tomas did to me. «If you are able to collect sediment cores from Plateliai Lake in winter you can join the group». That is still far from being a true samogitian but I passed the exam.

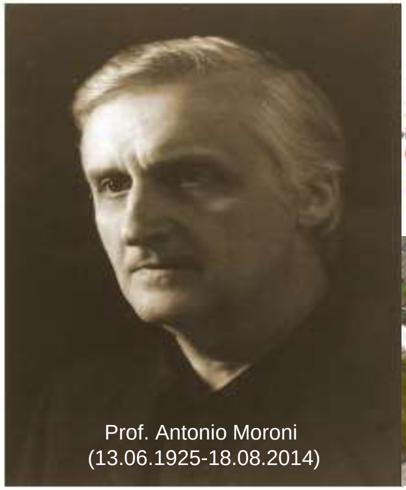
Ecology & Limnology in Parma

They were introduced as scientific disciplines by the end of 1960 by Prof. Antonio Moroni.

He founded the Laboratory of Ecology (1973), the Institue of Ecology (1976), and the Italian Society of Ecology (1976).

He was a limnologist and he started his research monitoring the Appenine Lakes and in particular the risk of their acidification.

He strongly believed in long term series of data, in the necessity of **frequent monitoring** to catch changes. He was also thinking of **remote lakes as environmental sentinels** (he was right…)



Prof. Antonio Moroni
(13.06.1925-18.08.2014)

Acid rain, lakes as atmosphere sentinels

The SENTINEL issue

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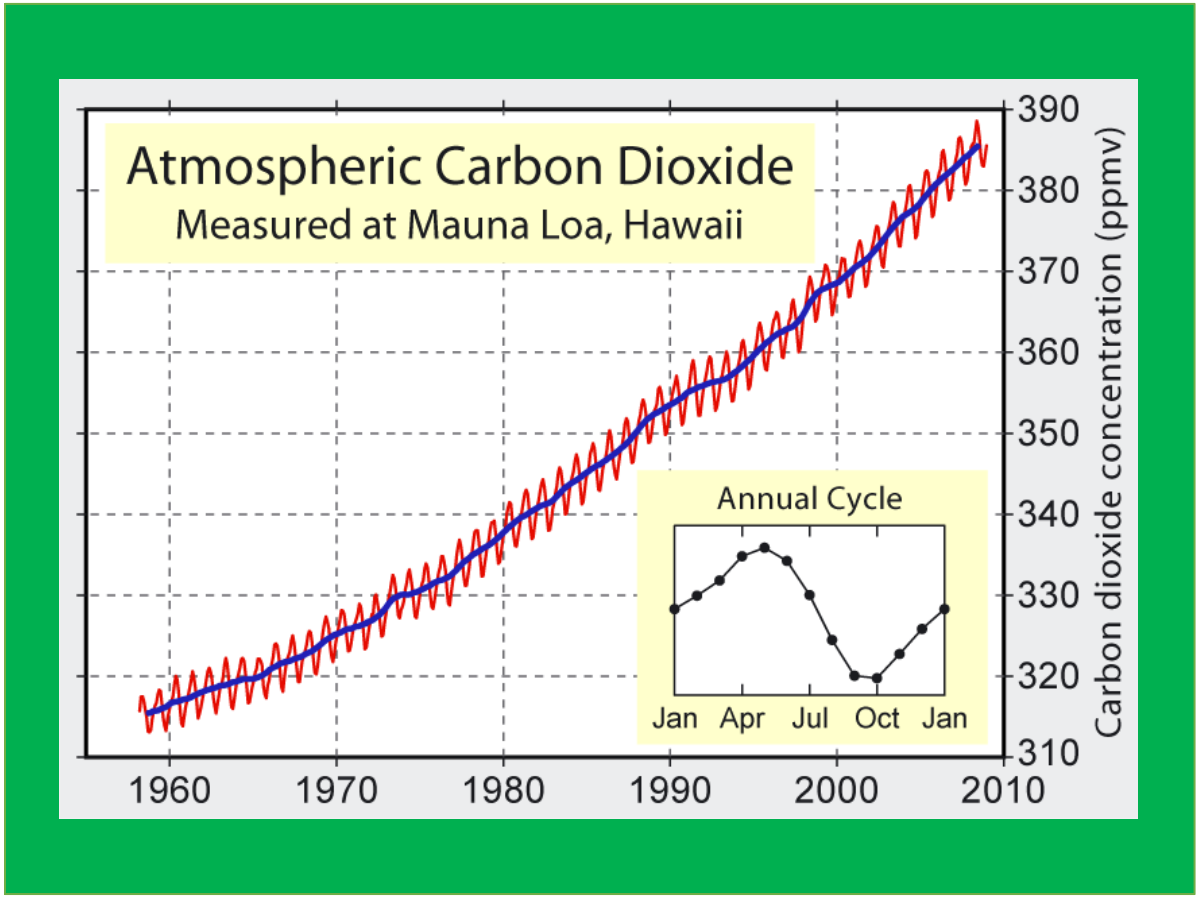
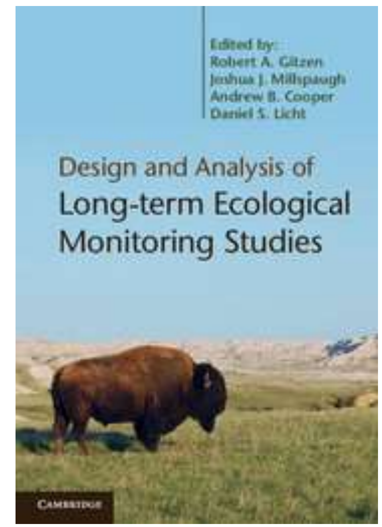
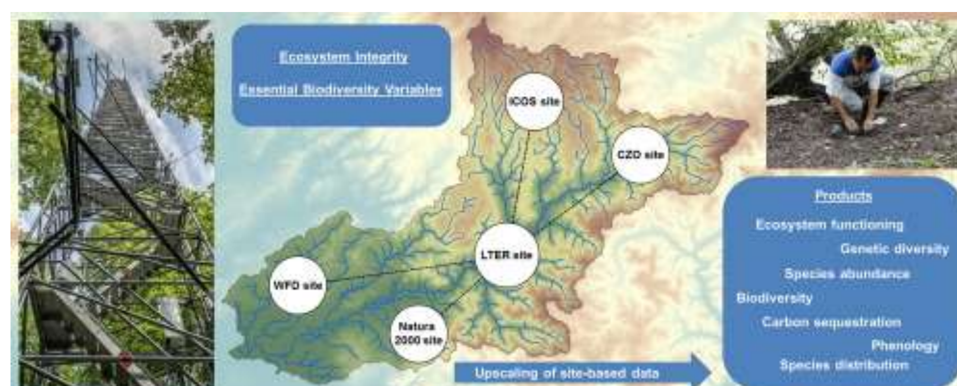
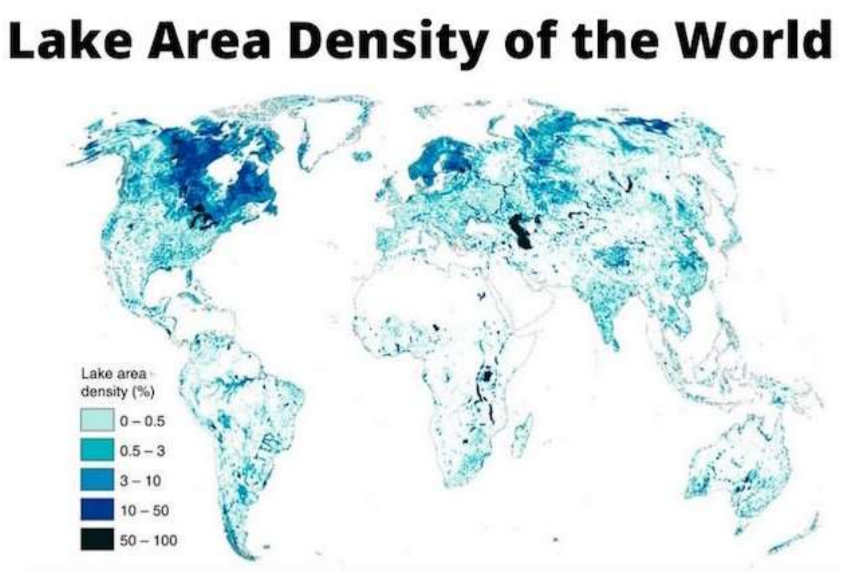




LONG TERM
ECOLOGICAL
MONITORING PROGRAM



The vast majority of lakes in the world are small. A few are huge



Messager, Mathis Loic, et al. "Estimating the Volume and Age of Water Stored in Global Lakes Using a Geo-Statistical Approach." Nature Communications, vol. 7, no. 1, Dec. 2016.

Lakes represent small sufaces of the planet, however they are important elements of the landscape and offer a large number of ecosystem services

In order to fully understandhow climate change and eutrophication affect their functioning, we need to speak about gas solubility, water density, watersheds to lake surface ratios, differences with terrestrial ecosystems and regime shifts

Terrestrial and aquatic access to O_2

-The earth atmosphere contains an incredible amount of oxygen (21%). At sea level such amount corresponds to nearly **300 mg O_2 per litre of air**.

-Atmospheric oxygen concentration does not vary among seasons or between night and day hours and it does not undergo long-term changes

-Terrestrial organisms are never oxygen-limited. In unsaturated soil air (and oxygen!) can penetrate by meters and meters

-What about dissolved oxygen in lakes?

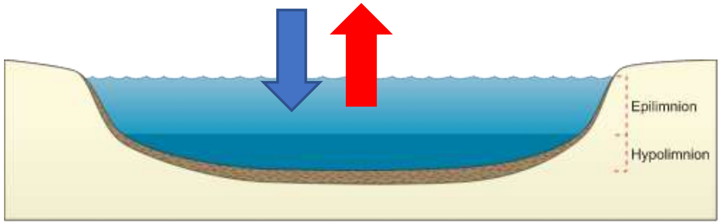
Gas solubility

Henry law

$$K_{eq} = \frac{[A(aq)]}{[A(g)]}$$

equation:	$k_{H,pc} = \frac{p}{c}$	$k_{H,cp} = \frac{c}{p}$	$k_{H,px} = \frac{p}{x}$	$k_{H,cc} = \frac{c_{aq}}{c_{gas}}$
units:	$\frac{L \cdot atm}{mol}$	$\frac{mol}{L \cdot atm}$	atm	*dimensionless*
O_2	769.23	1.3×10^{-3}	4.259×10^{4}	3.181×10^{-2}
H_2	1282.05	7.8×10^{-4}	7.099×10^{4}	1.907×10^{-2}
CO_2	29.41	3.4×10^{-2}	0.163×10^{4}	0.8317
N_2	1639.34	6.1×10^{-4}	9.077×10^{4}	1.492×10^{-2}
He	2702.7	3.7×10^{-4}	14.97×10^{4}	9.051×10^{-3}
Ne	2222.22	4.5×10^{-4}	12.30×10^{4}	1.101×10^{-2}
Ar	714.28	1.4×10^{-3}	3.955×10^{4}	3.425×10^{-2}

N_2, O_2, Ar, CO_2, CH_2…



- P = kC
- P= Pressure of a gas
- k= Henry's Law Constant
- C=concentration of the gas

Oxygen solubility in freshwater

Prof. C. Boswell, Dr. G. E. Francis, Miss M. Blundell and Miss M. Jeremy for help in various ways.

DENNIS LACY
Department of Zoology and Comparative Anatomy,
St. Bartholomew's Medical College,
London, E.C.1. March 16.

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Solubility of Oxygen in Water

THE rate at which self-purification can occur in waters polluted by oxidizable organic matter may depend largely on the rate at which oxygen from the air is dissolved by the water. In natural water the rate of solution is influenced by many variable factors; but Adeney and Becker[1] have stated that for constant conditions, and for a uniformly mixed body of water, it is proportional to the difference between the concentration of oxygen in solution and the saturation or equilibrium concentration. Unfortunately, the absolute saturation values are not known with great precision; indeed, some of the values published by several independent investigators differ by as much as 0·4 part of oxygen per million at temperatures in

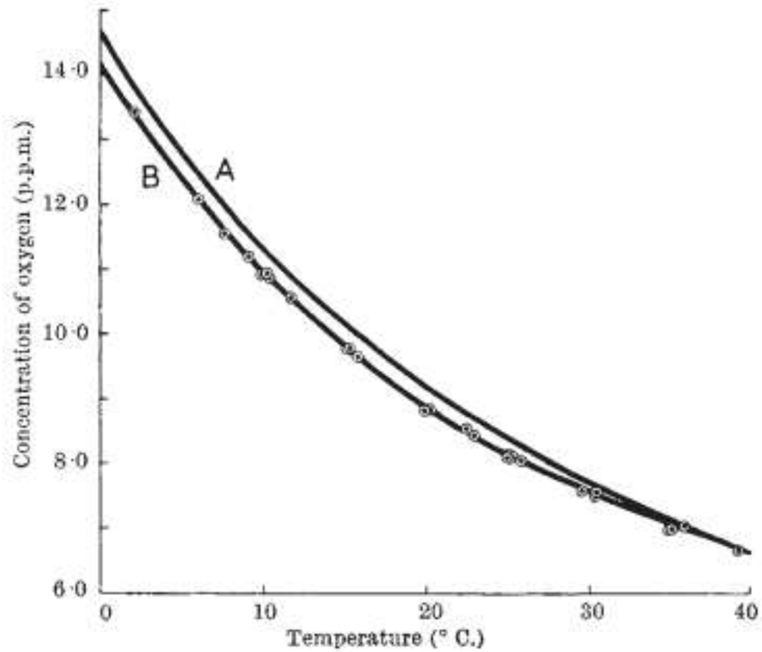


Fig. 1. Curve *A*, saturation values taken from "Standard Methods" calculated by Whipple and Whipple on measurements made by C. J. J. Fox (atmosphere assumed to contain 20·9 per cent oxygen); curve *B*, saturation values determined by the Winkler method

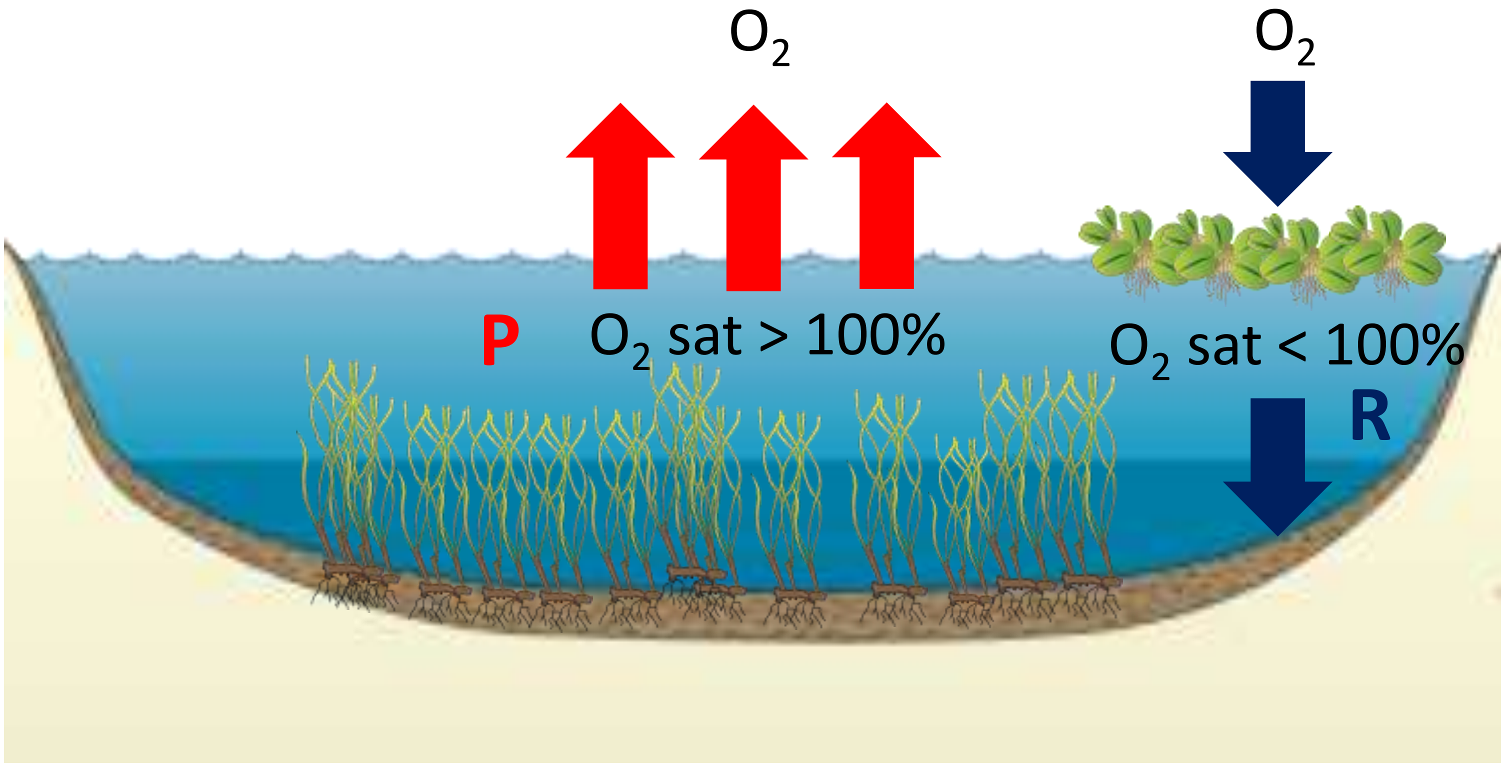
pressure. This value was assumed to be the saturation concentration at the temperature of the experiment. The results obtained by this procedure are related by the empirical equation $C_s = 14{\cdot}16 - 0{\cdot}3943T + 0{\cdot}007714T^2 - 0{\cdot}0000646T^3$, where C_s equals saturation concentration in parts of oxygen per million and T equals temperature in degrees C.

Oxygen availability in lakes

- The law of Henry allows to calculate the theoretical concentration (the **saturation**) of a given gas in the water, knowing its concentration in the atmosphere and its solubility
- At 20°C, theoretical oxygen concentration in a freshwater lake is nearly 9 mg per litre, around **30 times less** than the atmospheric concentration (!)
- Solubility increase at lower temperatures but decrease at higher temperatures, coinciding with hight metabolic activity

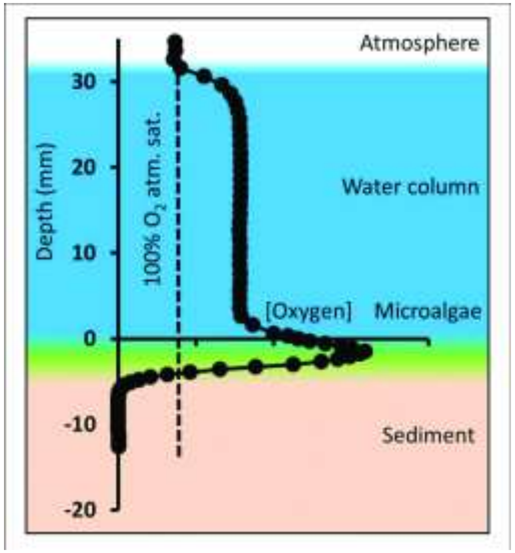
Lakes have much lower oxygen than terrestrial ecosystems!

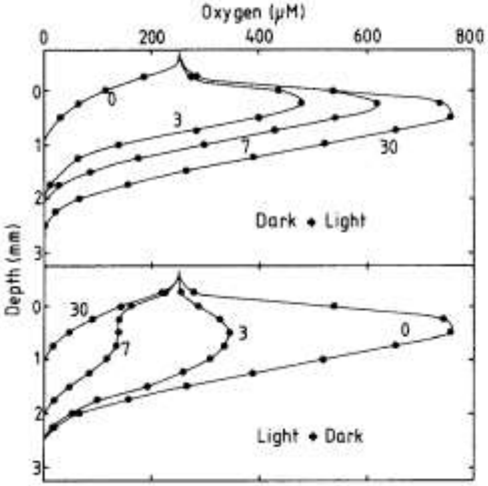
Supersaturation, undersaturation and the paradox of production



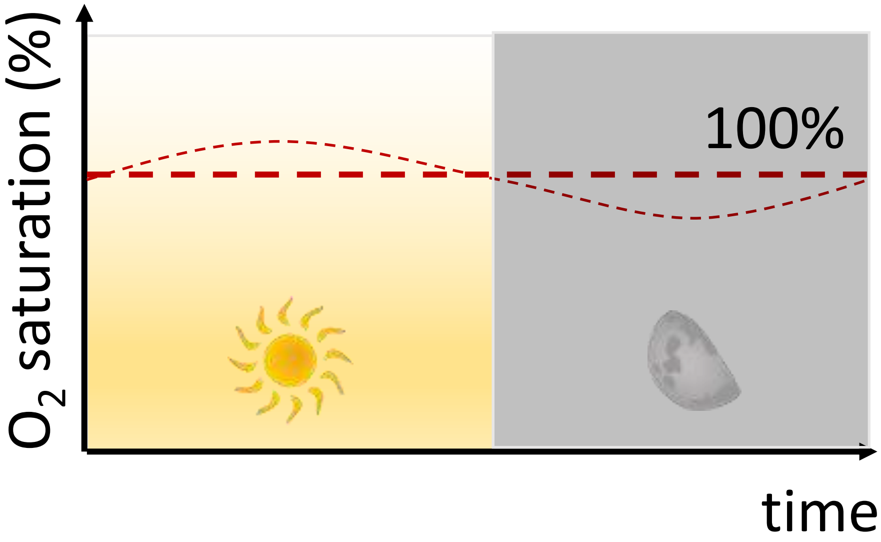
Macrophytes production can lead to transient oxygen supersaturation, that results in excess oxygen evasion to the atmosphere to restablish Henry equilibrium. Benthic or pelagic respiration can result in oxygen undersaturation, stimulating atmospheric oxygen diffusion into the water column.

Microprofiling revealed that lakes sediments are mostly anoxic

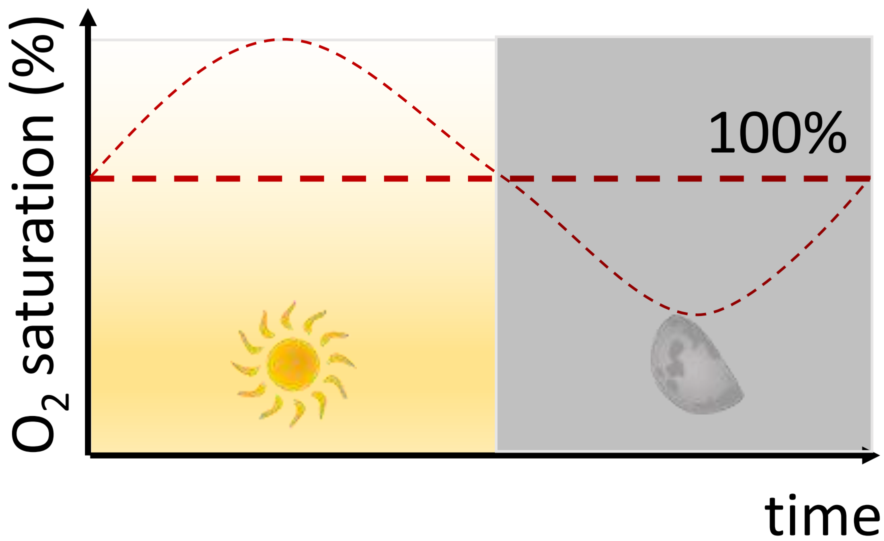




Is it better to be a very productive lake?

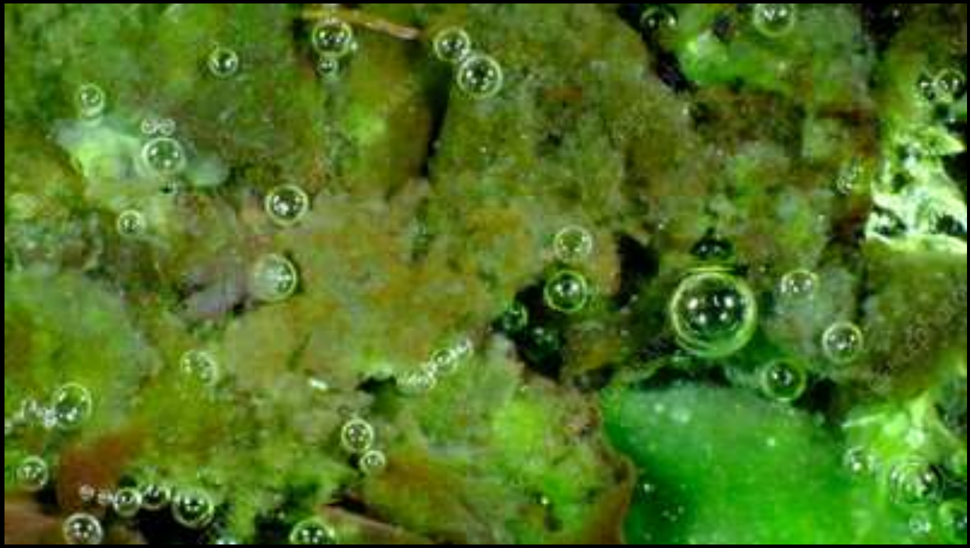


Oligotrophic/Mesotrophic
(low production, slight over or undersaturation)



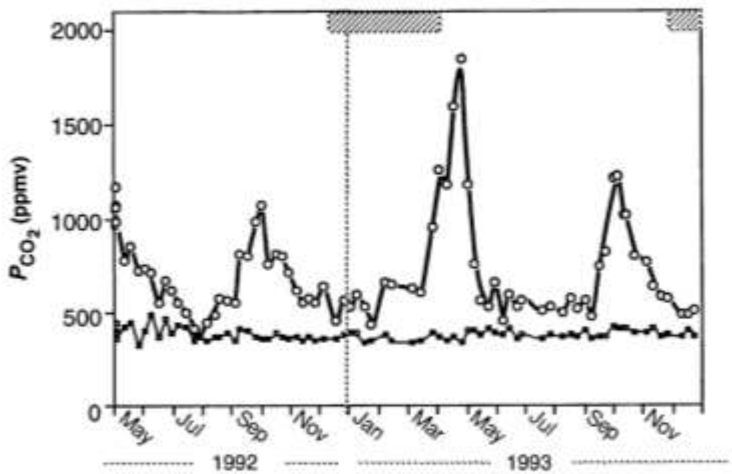
Eutrophic
(high production, high over or undersaturation)

The biomass remains, the oxygen goes



What about CO_2?

- Very low atmospheric concentration (0.04%)
- Very high solubility



Lakes are always CO_2 supersaturated
As such they are CO_2 (and CH_4!) sources to the atmosphere, due to large OC inputs from watersheds!

Carbon Dioxide Supersaturation in the Surface Waters of Lakes

Jonathan J. Cole, Nina F. Caraco, George W. Kling, Timothy K. Kratz

Data on the partial pressure of carbon dioxide (CO_2) in the surface waters from a large number of lakes (1835) with a worldwide distribution show that only a small proportion of the 4665 samples analyzed (less than 10 percent) were within ±20 percent of equilibrium with the atmosphere and that most samples (87 percent) were supersaturated. The mean partial pressure of CO_2 averaged 1036 microatmospheres, about three times the value in the overlying atmosphere, indicating that lakes are sources rather than sinks of atmospheric CO_2. On a global scale, the potential efflux of CO_2 from lakes (about 0.14 × 10^{15} grams of carbon per year) is about half as large as riverine transport of organic plus inorganic carbon to the ocean. Lakes are a small but potentially important conduit for carbon from terrestrial sources to the atmospheric sink.

Fig. 1. Seasonal cycle of direct measurements of the P_{CO_2} in the surface water of Mirror Lake (circles) and in the overlying air (squares), showing persistent supersaturation. Mirror Lake is a soft water lake in New Hampshire (*15*); ppmv, parts per million by volume. The hatched areas represent ice cover.

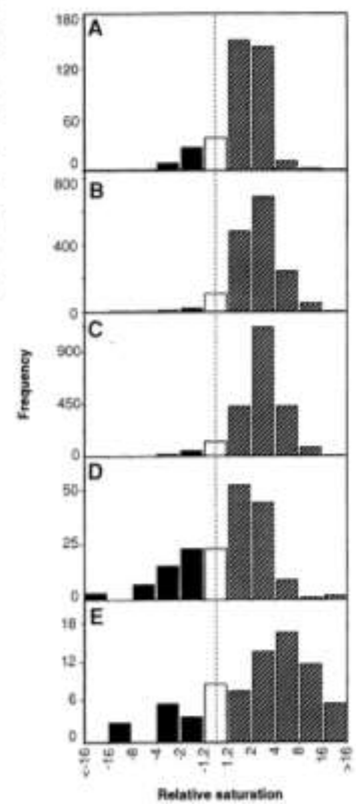


Fig. 2. Frequency diagram (by numbers of samples) for calculated P_{CO_2} in the surface waters of lakes from five different, nonoverlapping data sets: (**A**) direct measurements, (**B**) autumn survey, (**C**) full seasonal data, (**D**) summer survey, and (**E**) tropical Africa. Only values from the ice-free season are shown. Relative saturation (RS) is the degree of supersaturation (hatched bars) or undersaturation (solid bars) relative to atmospheric equilibrium. For supersaturation,

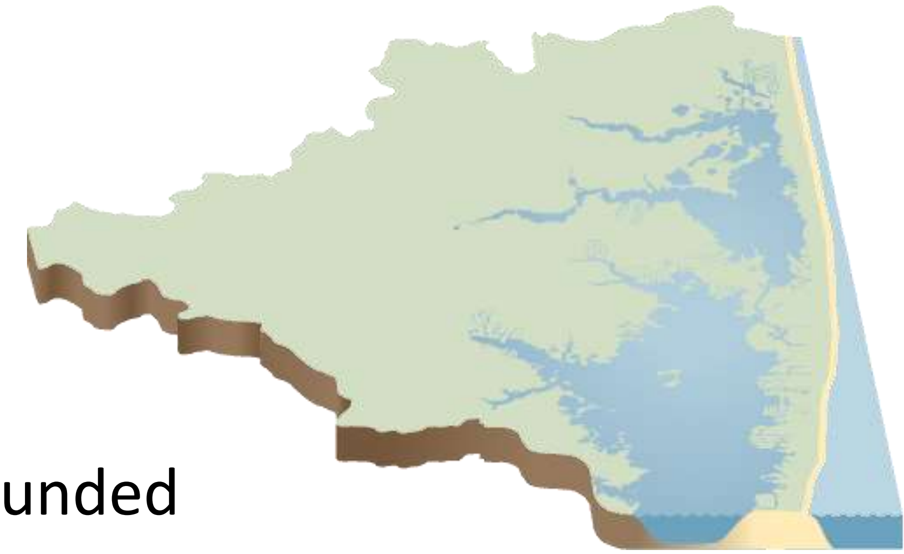
$$RS = P_{CO_2}(\text{water})/P_{CO_2}(\text{air})$$

For undersaturation,

$$RS = -P_{CO_2}(\text{air})/P_{CO_2}(\text{water})$$

On this scale, water with twice the P_{CO_2} of the atmosphere has a value of 2; water with half the value of the atmosphere has a value of −2. The vertical dotted line represents equilibrium with the atmosphere (RS = 1.0), and the open bars represent the samples in near equilibrium with the atmosphere (±20% of equilibrium). See Table 1 for characteristics of the data sets.

Lakes as Watershed sentinels

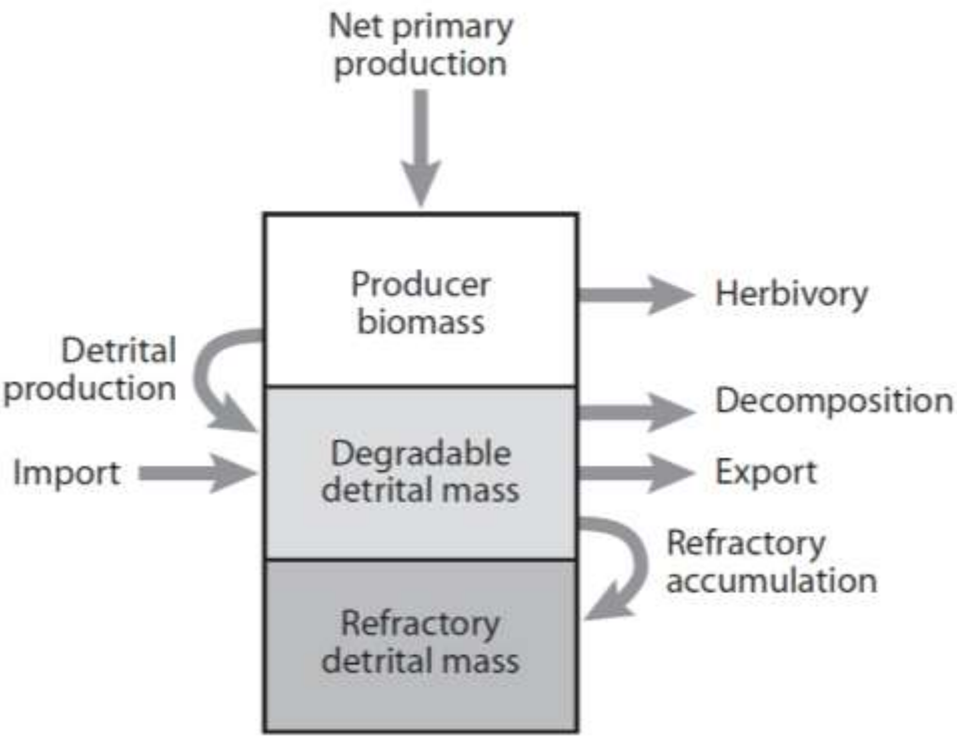


- Lakes are island of waters surrounded
  by large amounts of forested or cultivated land.
- Land use changes produce measurable effects in lakes
- Such changes can be due to agriculture, fires or to climate change, affecting primary production by forests
- The watershed to lake surface ratio is so high that no primary producer can contrast OC input, its mineralization and CO_2 production, resulting in constant supersaturation and evasion

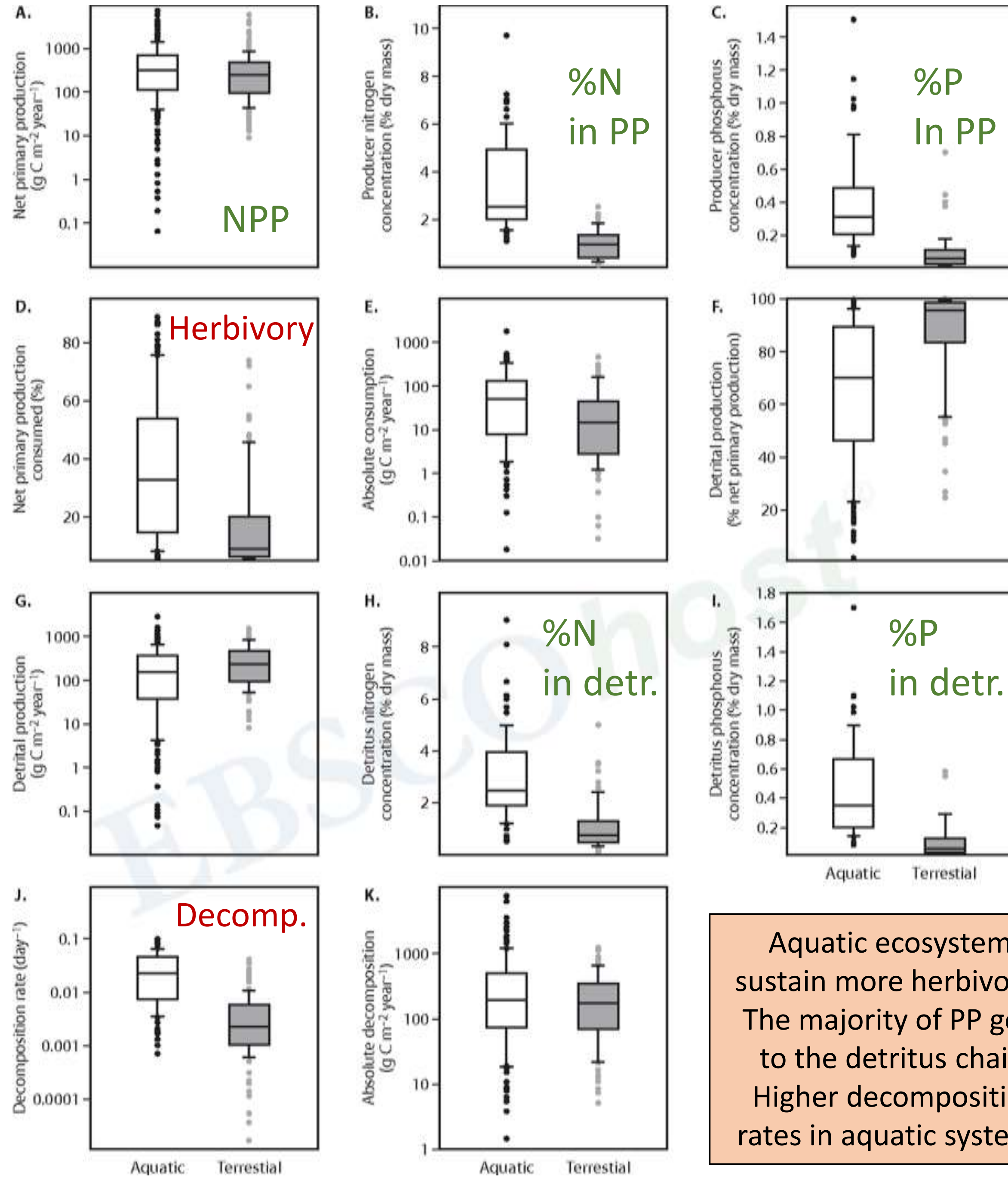
Net autotrophy, net heterotrophy, C sink, C source, burial, CO_2 evasion

Another important issue…

- …making the functioning of terrestrial and lake ecosystem overall similar but as a result of different pathways: *herbivory and decomposition* pathways



Terrestrial and aquatic ecosystem productivity and carbon flow



Aquatic ecosystems sustain more herbivores. The majority of PP goes to the detritus chain. Higher decomposition rates in aquatic systems.

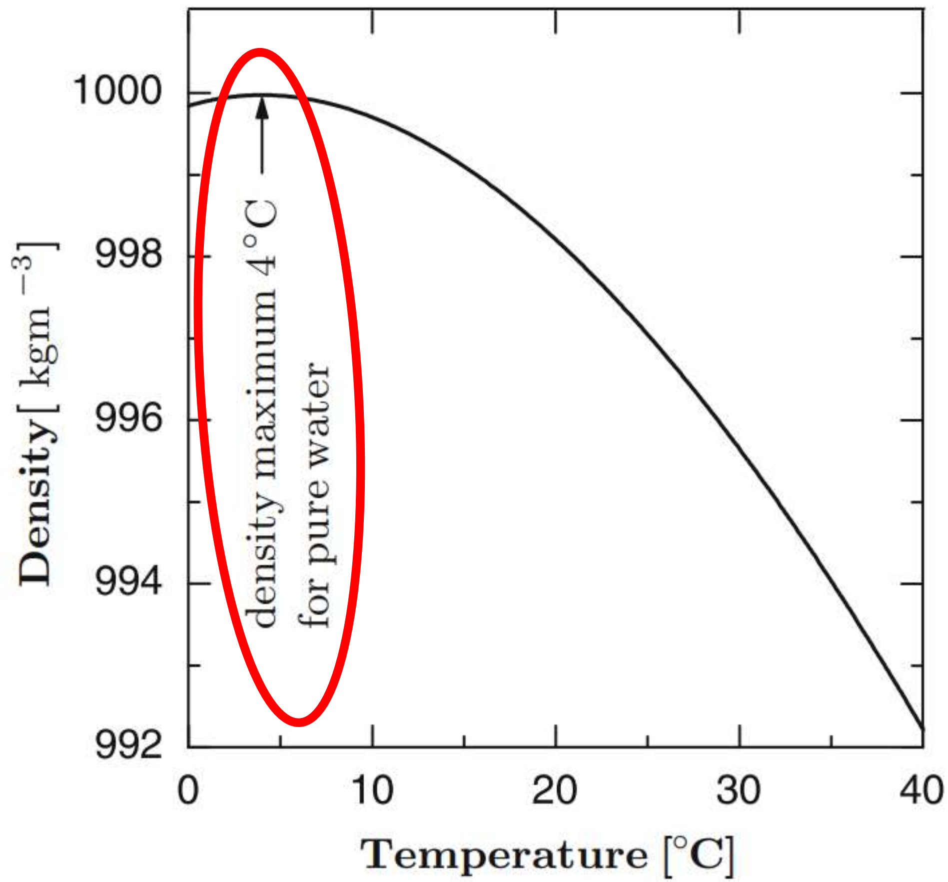
Take home message

- Oxygen availability is much lower in lakes than in terrestrial ecosystems and lakes cannot trap or retain oxygen
- Lakes retain organic carbon that they produce or that they receive from surrounding terrestrial ecosystem
- Better to produce less, to avoid oxygen problems
- Lakes are seldom included in globas C budgets
- Any increase of temperature or change in land use can decrease gas solubility, increase heterotrophic activity and nutrient inputs (climate change is similar to eutrophication…)

Density-temperature relationships, stratification, mixing and climate change

Water density varies together with temperature. It peaks at 4°C.

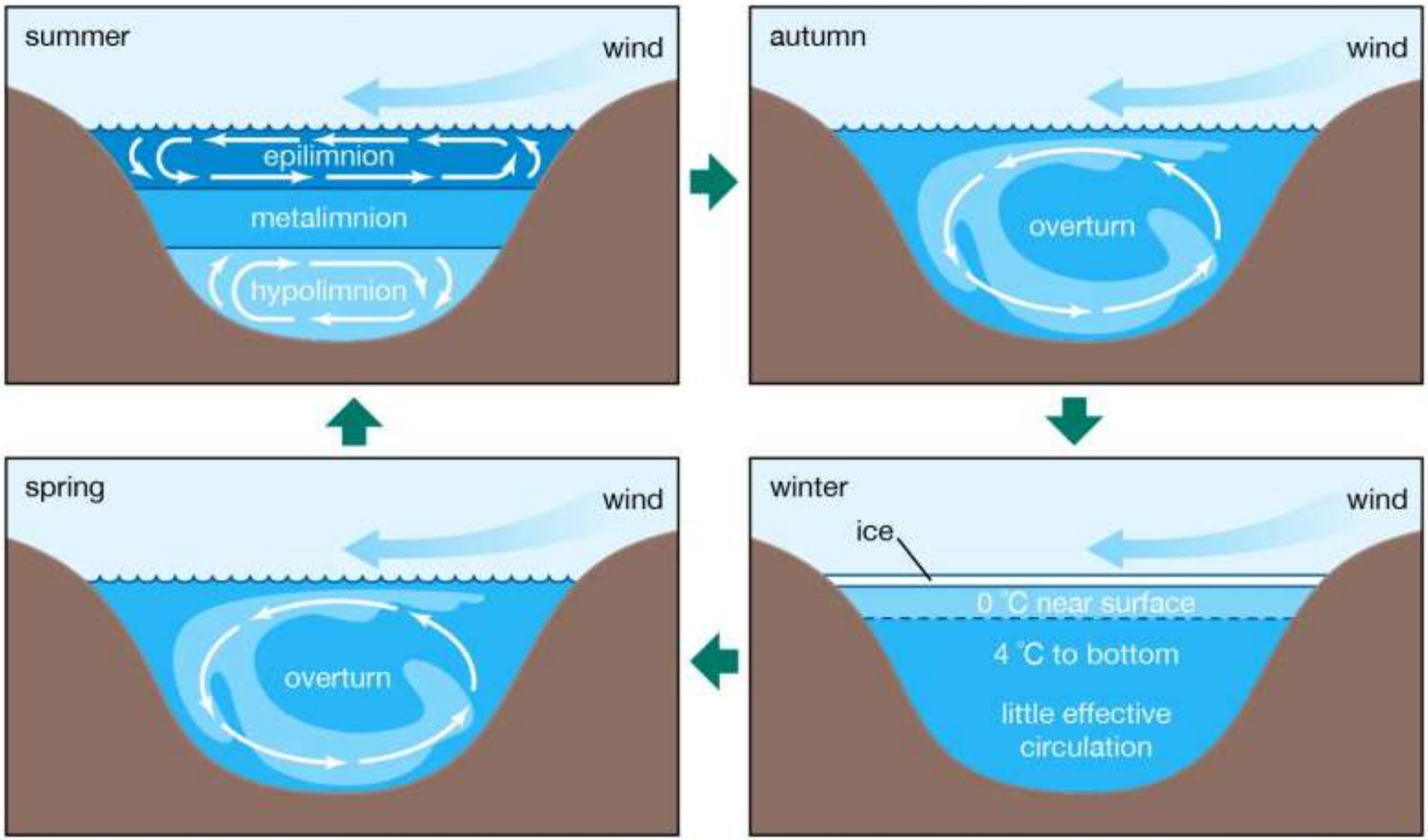
Water with temperatures below or above 4°C are therefore lighter.



Empirically we test this relationship during summer, when we swim in a lake and feel the cohexistance of stratified water masses (warmer in the surface, colder and heavier deeper).

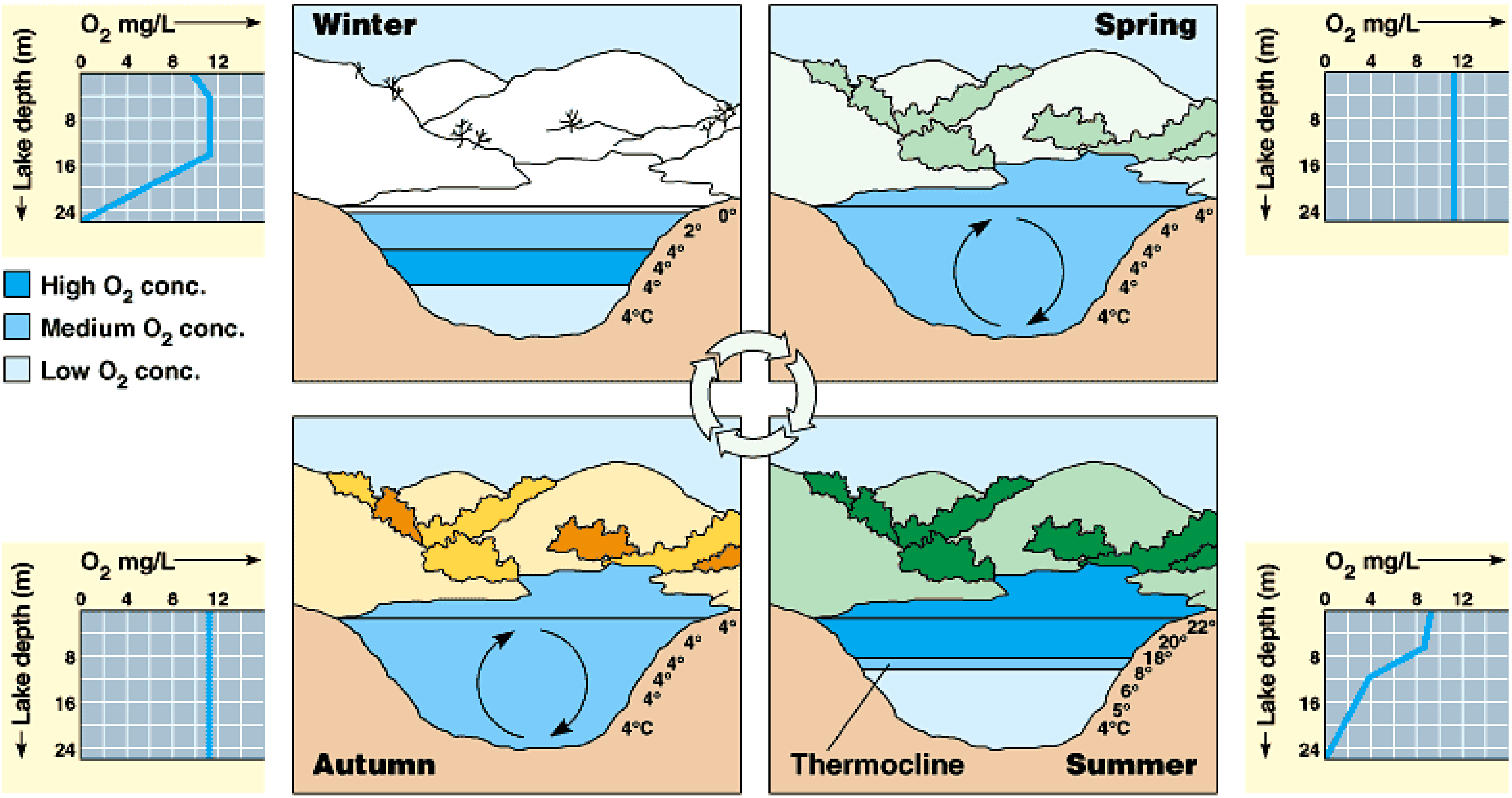
The same phenomenon occurs during witner, with water close to 0 °C that float over warmer waters at 4°C. **But you need to be samogitian to validate this with your body.**

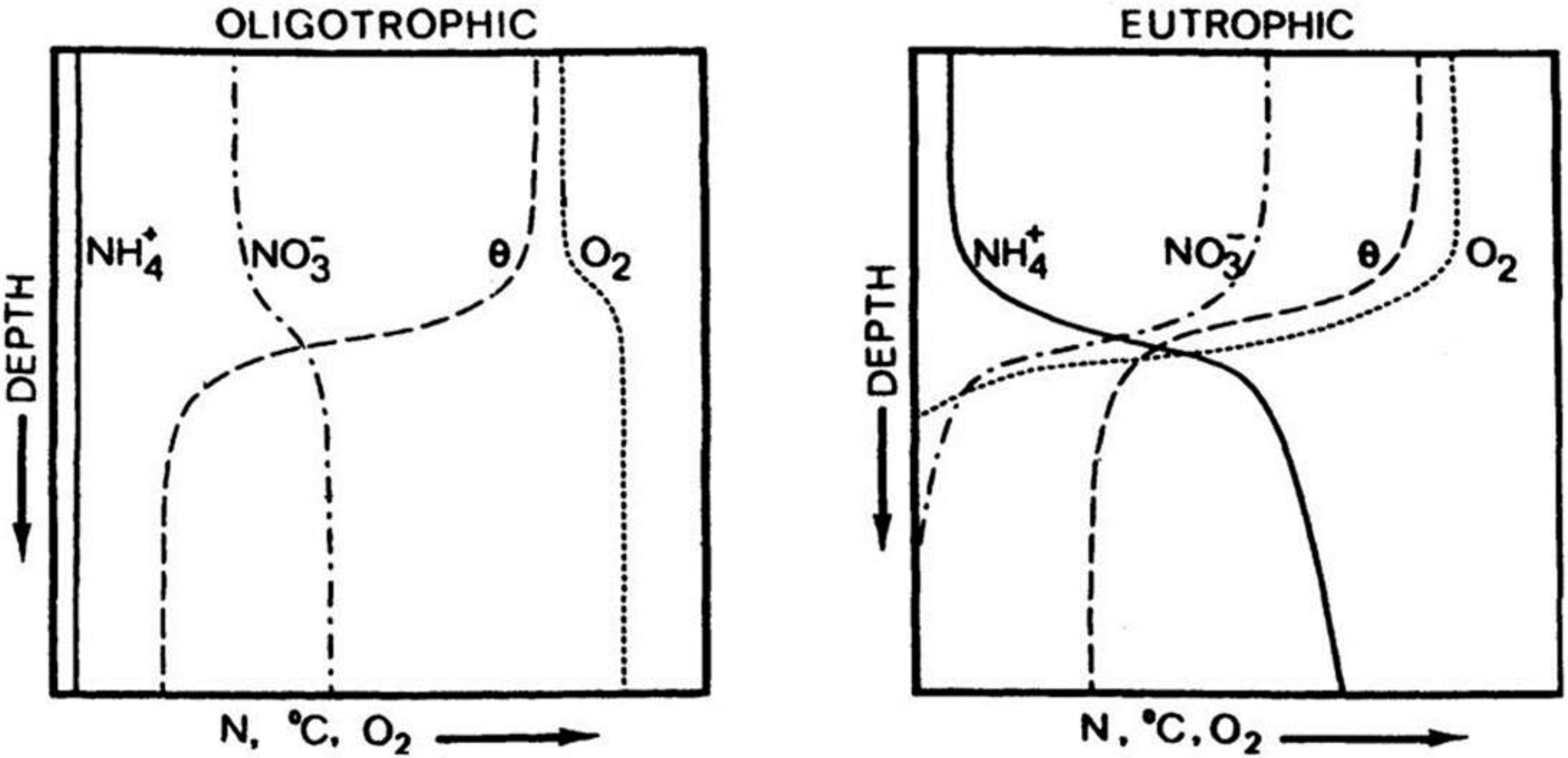
Temperature-dependent density and seasonal lake stratification



Critial periods for a lake are those of stratification. The full overturn represents instead a short, vital phase for lakes, during which oxygen and nutrients are redistributed along the whole water column.

What happens to lake water chemistry (oxygen) during stratification?

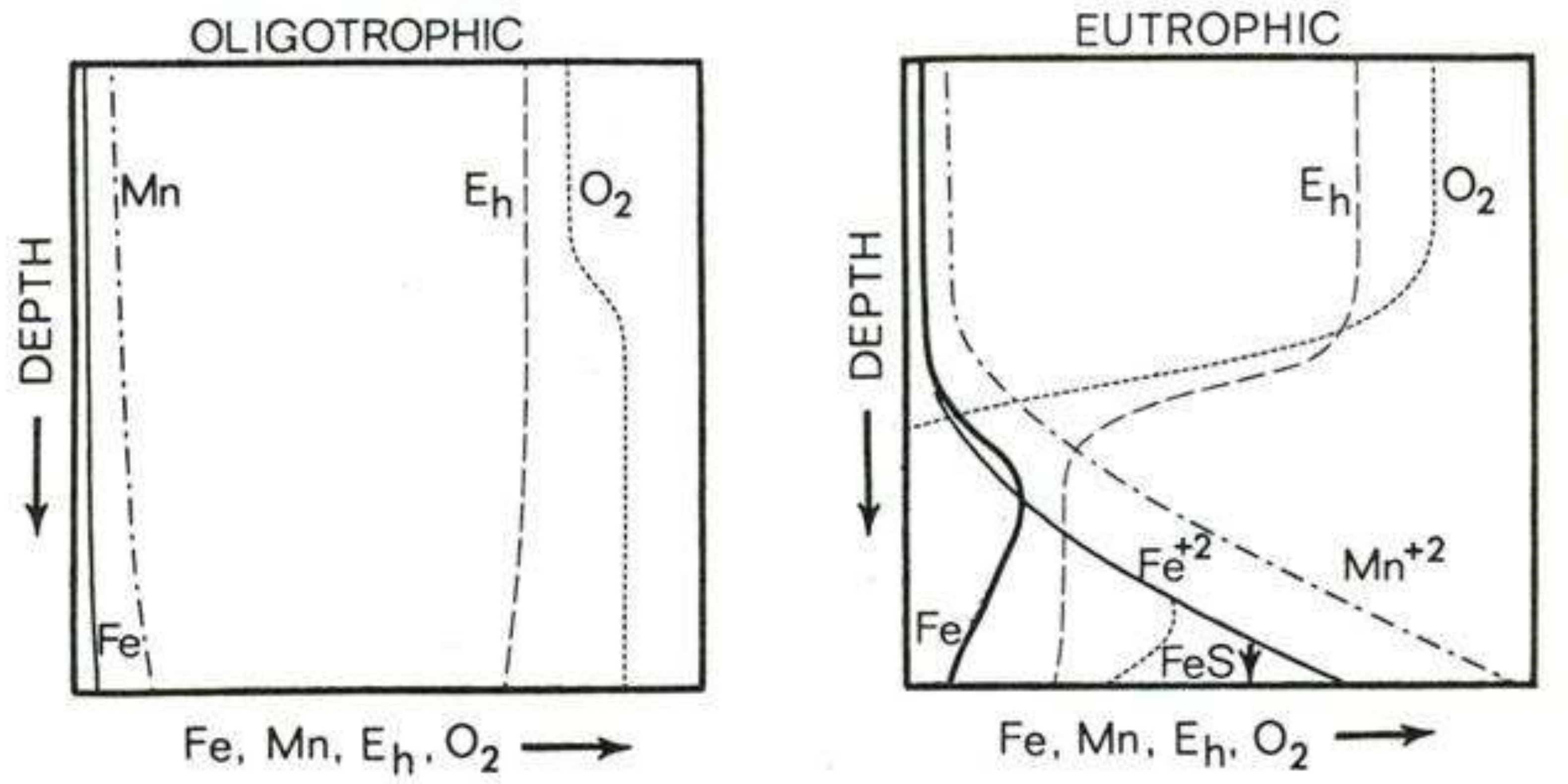




What happens to lake water chemistry (nitrogen) during stratification?

The effects of stratification depend on the trophic status

What happens to lake water chemistry (metals) during stratification?

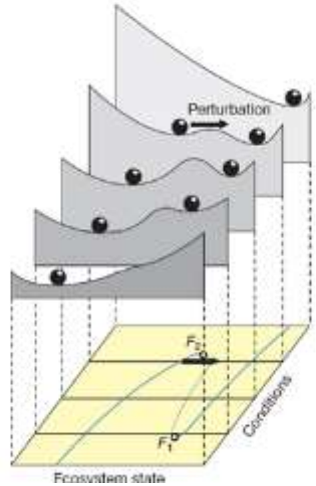


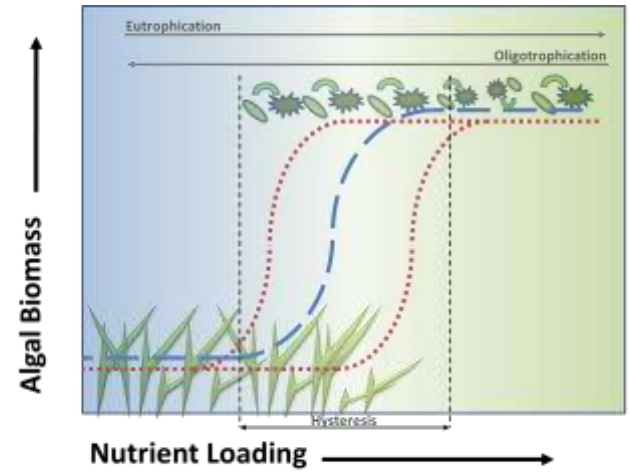
Profiles of redox potential and of reduced metals are steeper under eutrophic conditions

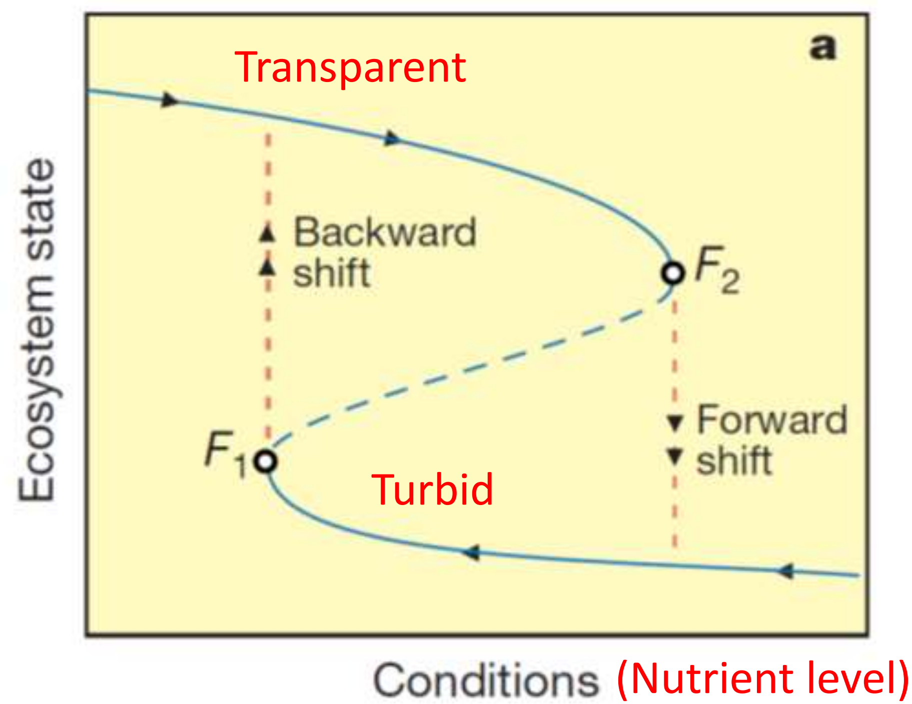
Take home message

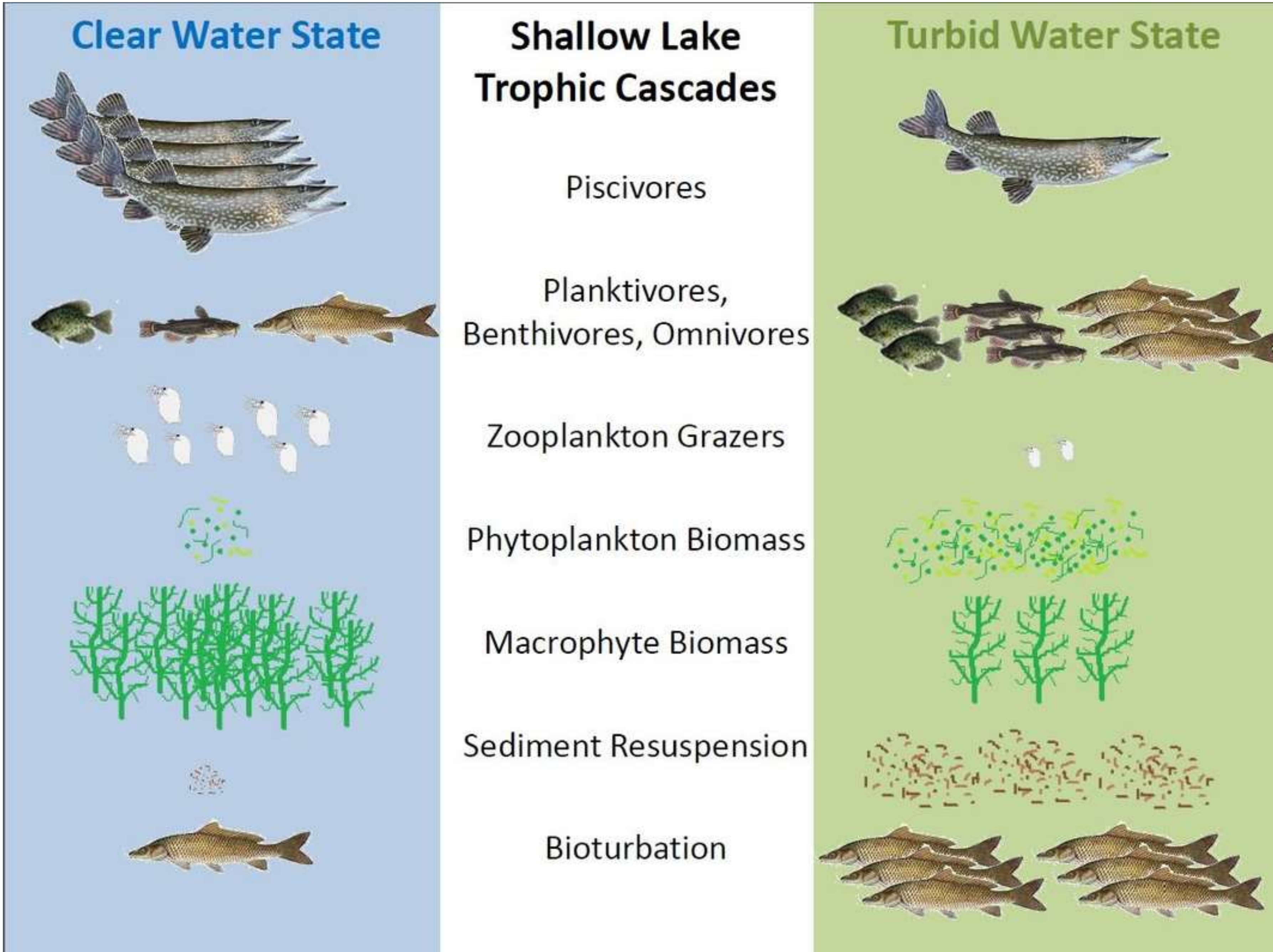
- Due to density-temperature relationship lakes can stratify
- Lakes can be polimictic, dimictic, monomictic, oligomictic and meromictic
- The effect of prolonged stratification on lakes biology and chemistry depends on the trophic status
- Climate change surely affects stratification, acting upon water temperature, ice-cover period, lakes heating and cooling, wind, precipitation

Regime shift theory








Clear Water State
Shallow Lake
Trophic Cascades
Turbid Water State
Piscivores
Planktivores,
Benthivores, Omnivores
Zooplankton Grazers
Phytoplankton Biomass
Macrophyte Biomass
Sediment Resuspension
Bioturbation

Carp Exclusion

Climate change should decrease fish mortality (e.g. vial less ice cover), and increase nutrient levels in lakes (due to transport, regeneration, hypoxia). It should facilitate the transition between stable transparent and stable turbid states

With all this in mind what are the expected effects of climate change on lakes?

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL066235

Rapid and highly variable warming of lake surface waters around the globe

Catherine M. O'Reilly, Sapna Sharma, Derek K. Gray, and Stephanie E. Hampton joint first authors

Catherine M. O'Reilly[1], Sapna Sharma[2], Derek K. Gray[3], Stephanie E. Hampton[4], Jordan S. Read[5], Rex J. Rowley[1], Philipp Schneider[6], John D. Lenters[7], Peter B. McIntyre[8], Benjamin M. Kraemer[8], Gesa A. Weyhenmeyer[9], Dietmar Straile[10], Bo Dong[11], Rita Adrian[12], Mathew G. Allan[13], Orlane Anneville[14], Lauri Arvola[15], Jay Austin[16], John L. Bailey[17], Jill S. Baron[18], Justin D. Brookes[19], Elvira de Eyto[20], Martin T. Dokulil[21], David P. Hamilton[22], Karl Havens[23], Amy L. Hetherington[24], Scott N. Higgins[25], Simon Hook[26], Lyubov R. Izmest'eva[27], Klaus D. Joehnk[28], Kulli Kangur[29], Peter Kasprzak[30], Michio Kumagai[31], Esko Kuusisto[32], George Leshkevich[33], David M. Livingstone[34], Sally MacIntyre[35], Linda May[36], John M. Melack[37], Doerthe C. Mueller-Navarra[38], Mikhail Naumenko[39], Peeter Noges[40], Tiina Noges[40], Ryan P. North[41], Pierre-Denis Plisnier[42], Anna Rigosi[19], Alon Rimmer[43], Michela Rogora[44], Lars G. Rudstam[24], James A. Rusak[45], Nico Salmaso[46], Nihar R. Samal[47], Daniel E. Schindler[48], S. Geoffrey Schladow[49], Martin Schmid[50], Silke R. Schmidt[12], Eugene Silow[27], M. Evren Soylu[51], Katrin Teubner[52], Piet Verburg[53], Ari Voutilainen[54], Andrew Watkinson[55], Craig E. Williamson[56], and Guoqing Zhang[57]

Key Points:
- Lake surface waters are warming rapidly but are spatially heterogeneous
- Ice-covered lakes are typically warming at rates greater than air temperatures
- Both geomorphic and climate factors influence lake warming rates

Supporting Information:
- Figures S1–S4 and Tables S1–S4

O'Reilly, C. M., et al. (2015), Rapid and highly variable warming of lake surface waters around the globe, Geophys. Res.Lett.,42, 10,773–10,781, doi:10.1002/2015GL066235.

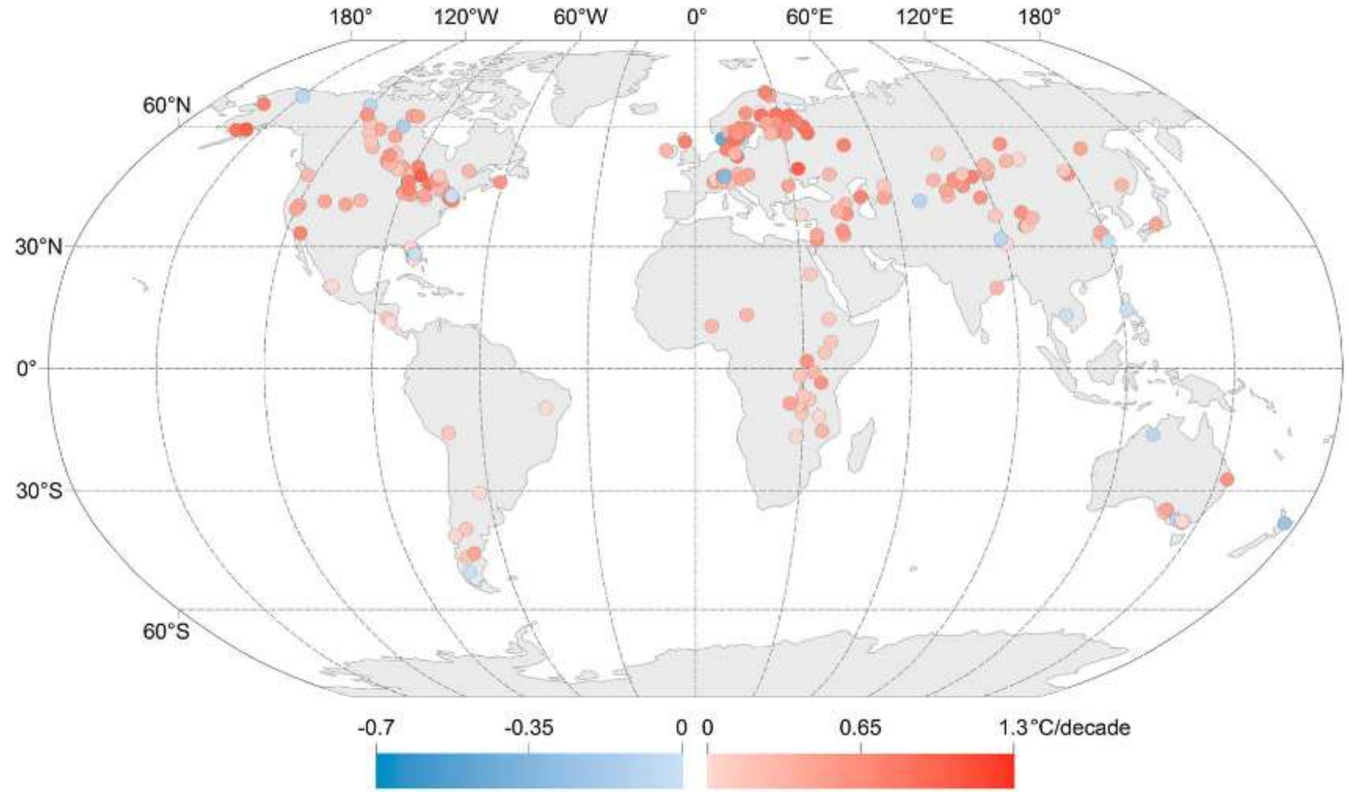


Figure 1. Map of trends in lake summer surface temperatures from 1985 to 2009. Most lakes are warming, and there is large spatial heterogeneity in lake trends. Note that the magnitudes of cooling and warming are not the same.

Lake summer surface water temperatures (LSSWT) are **warming significantly**, with a mean trend of **0.34°C decade^{-1}** (95% CI: 0.16–0.52), across **235** globally distributed lakes between 1985 and 2009 (Figure 1). This warming rate is consistent with the rapid annual average increase in air temperatures (**0.25°C decade^{-1}**) and ocean surface temperatures (**0.12°C decade^{-1}**) over a similar time period (1979–2012).

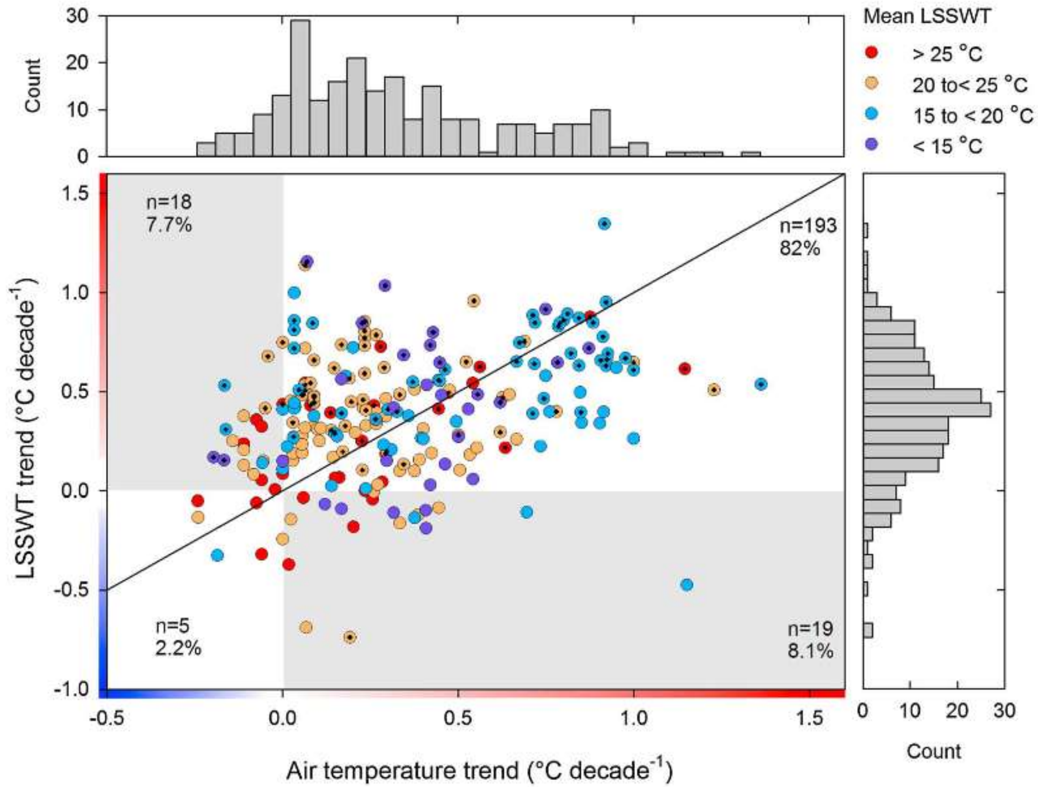


Figure 2. Lake summer surface water temperature (LSSWT) trends varied widely. Although the slope of the linear regression line between LSSWT trends and air temperature trends was not significantly different from 1, there was wide variation in both air and lake temperature trends. LSSWT trends significant at $p < 0.1$ are indicated by a black central dot within a data point. Included are the 1:1 line and counts (*n*) and % in each quadrant. Histograms show distribution of data along that axis.

For individual lakes, air and lake temperature trends often diverged (Figure 2), emphasizing the importance of understanding the various factors that control lake heat budgets rather than assuming lake temperatures will respond similarly to air temperatures. Although warming is widespread, LSSWT trends range from 0.7 to 1.3°C decade^{-1} and show clear regional variation. Previous studies that have used only satellite data, necessarily constrained by the technology to focus on larger lakes, also reported a range of warming rates, in step with or exceeding that of air temperature.

Article

Widespread deoxygenation of temperate lakes

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Check for updates

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Jane, S.F., Hansen, G.J.A., Kraemer, B.M. et al. Widespread deoxygenation of temperate lakes. Nature 594, 66–70 (2021). https://doi.org/10.1038/s41586-021-03550-y

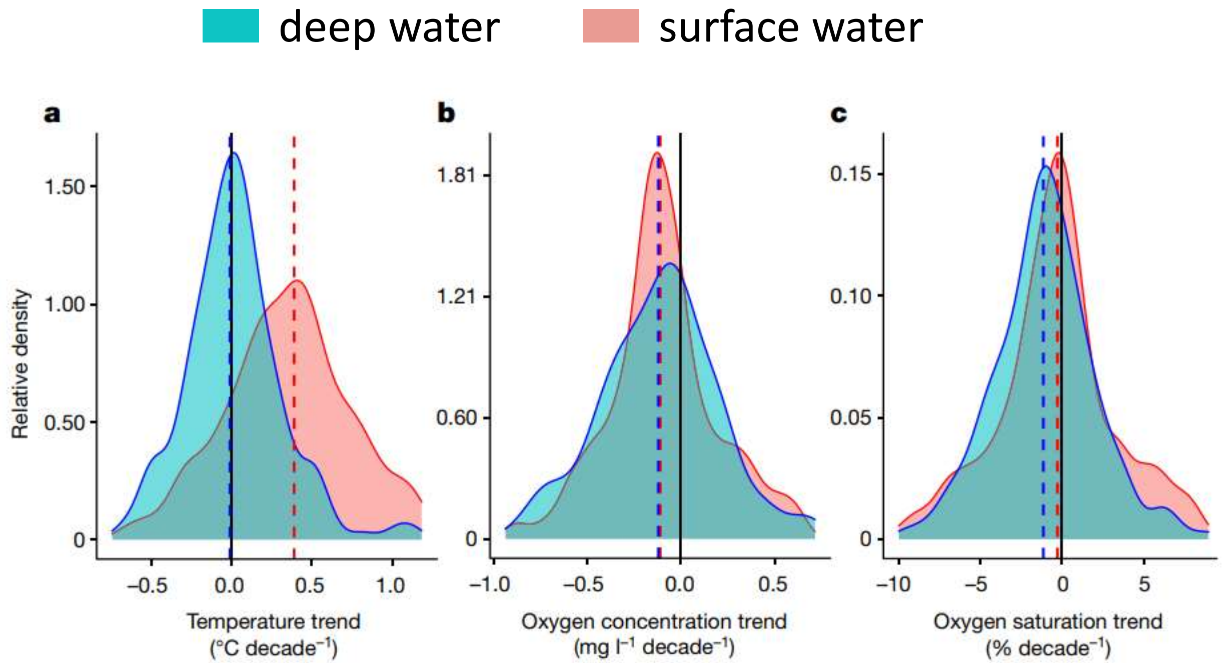


Fig. 1 | Trends in dissolved oxygen and temperature. a–c, Density plots of trend magnitudes for temperature (°C decade^{-1}) (**a**), DO concentration (mg l^{-1} decade^{-1}) (**b**) and DO percentage saturation (% decade^{-1}) (**c**). The red distribution indicates surface-water trends ($n = 393$), and blue indicates deep-water trends ($n = 191$). The x-axis range for each plot covers two standard deviations from the median, or approximately 95% of data. The vertical dashed lines indicate median trends, and the zero trend is highlighted by a black vertical line.

Although deep-water temperatures have been almost stable since observations began (−0.01 °C decade^{-1}) (Fig. 1a), both deep-water DO concentration and the percentage saturation declined over time (−0.12 mg l^{-1} decade^{-1} and −1.2% decade^{-1}, respectively) (Fig. 1b, c). **Declines were unrelated to solubility as predicted changes based on solubility (slight increase of 0.01 mg l^{-1}) were negligible compared with observed losses (median of −0.23 mg l^{-1}) based on the last five years relative to the first five years of each time series.**

Deoxygenation is a widespread phenomenom in all aquatic ecosystems

Oceans suffocating as huge dead zones quadruple since 1950, scientists warn

Areas starved of oxygen in open ocean and by coasts have soared in recent decades, risking dire consequences for marine life and humanity

A fisherman on a beach in Temuco, Chile that is blanketed with dead sardines, a result of algal blooms that suck oxygen out of the water. Photograph: Felix Marquez/AP

"Ocean deoxygenation is taking place all over the world as a result of the human footprint, therefore we also need to address it globally."

"Dead zones will continue to expand unless the major meat companies that dominate our global agricultural system start cleaning up their supply chains to keep pollution out of our waters."

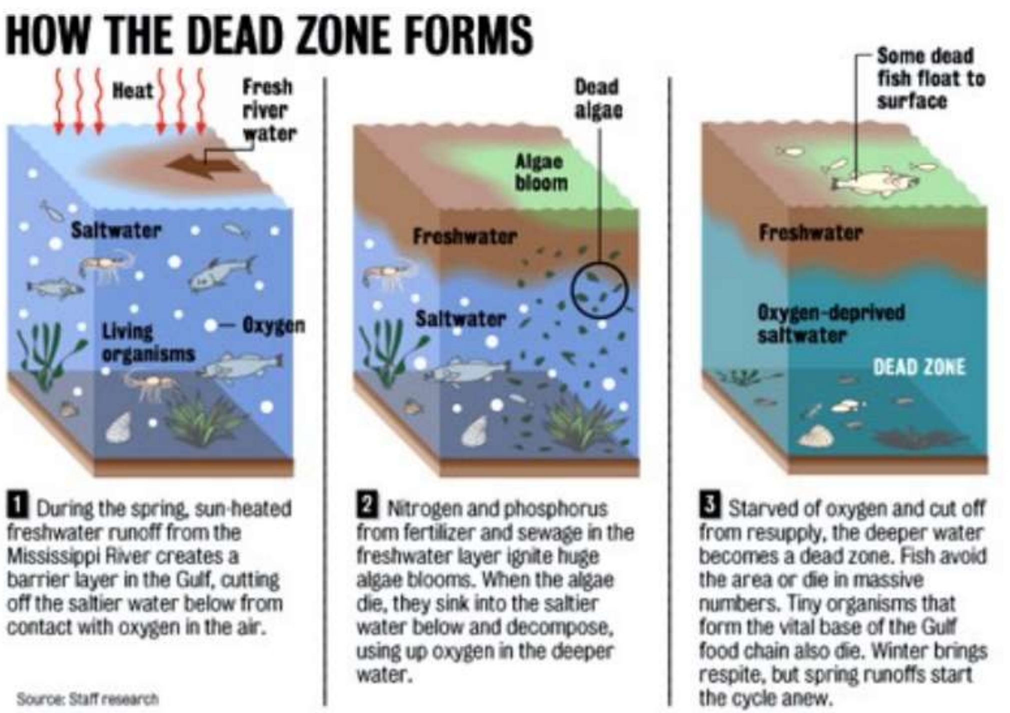
The Guardian

Waters where oxygen is lower than 2 milligrams per litre

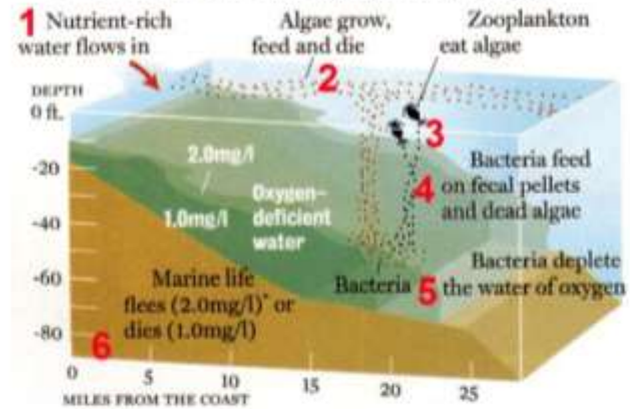
Guardian graphic | Source: Global Ocean Oxygen Network, Science

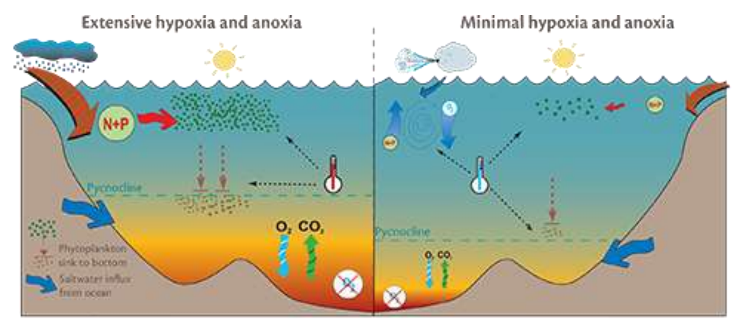
Furthermore, the level of oxygen in all ocean waters is falling, with 2% - 77bn tonnes - being lost since 1950. This can reduce growth, impair reproduction and increase disease, the scientists warn. One irony is that warmer waters not only hold less oxygen but also mean marine organisms have to breathe faster, using up oxygen more quickly.

Eutrophication, hypoxia (and climate!)



- **Formation of Hypoxic Zones**
  1. Nutrient-rich water flows in
  2. Algae grow, feed, & die
  3. Zooplankton eat the algae
  4. Bacteria feed on the fecal pellets & dead algae
  5. Bacteria deplete the water of oxygen
  6. Marine life leaves (2.0 mg/l) or dies (1.0 mg/l)





	Loads	Phytoplankton	Decomposition	Temperature	Wind event
Large amount of low dissolved oxygen	Large nitrogen and phosphorus loads	Elevated nutrients cause large phytoplankton blooms	High oxygen consumption by decaying phytoplankton	Warm water a) Stimulates decomposition b) Stratifies water column c) Stimulates phytoplankton	No wind event: water column remains stratified
Little amount of low dissolved oxygen	Small nitrogen and phosphorus loads	Less nutrients lead to small phytoplankton blooms	Low oxygen consumption by decaying phytoplankton	Cool water: a) Slow decomposition b) Mixed water column c) Slow phytoplankton growth	Wind events destratifies water column: a) Bottom water aerated b) Nutrients move to surface

Remember, the biomass remains and the oxygen goes

What about the Italian Alpine Lakes?

Alpine lakes are warming and the risk associated is permanent stratification (mild winter to not allow them to loose heath) Permanent stratification leads to hypoxia and anoxia (Lugano, Iseo, Idro).

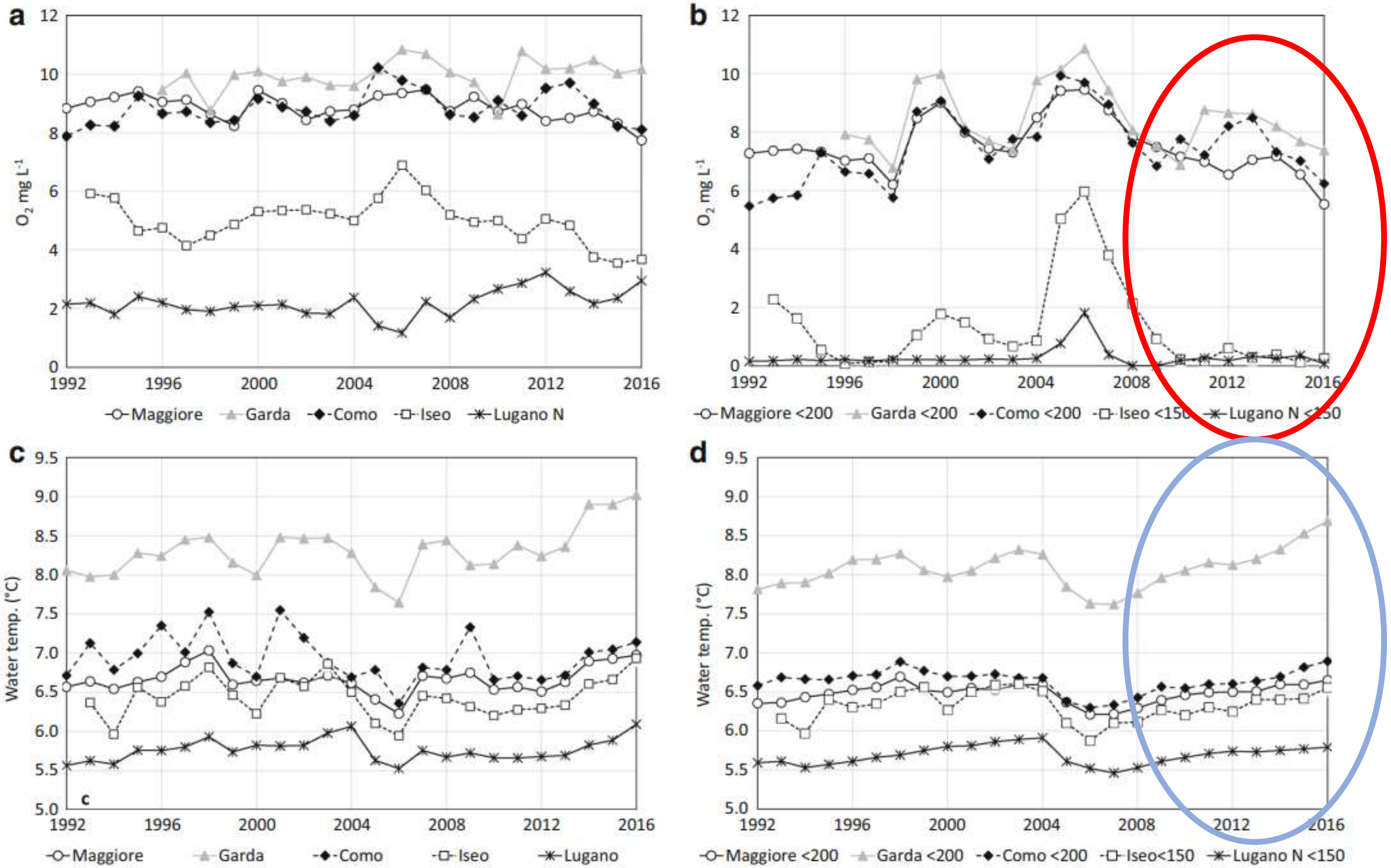
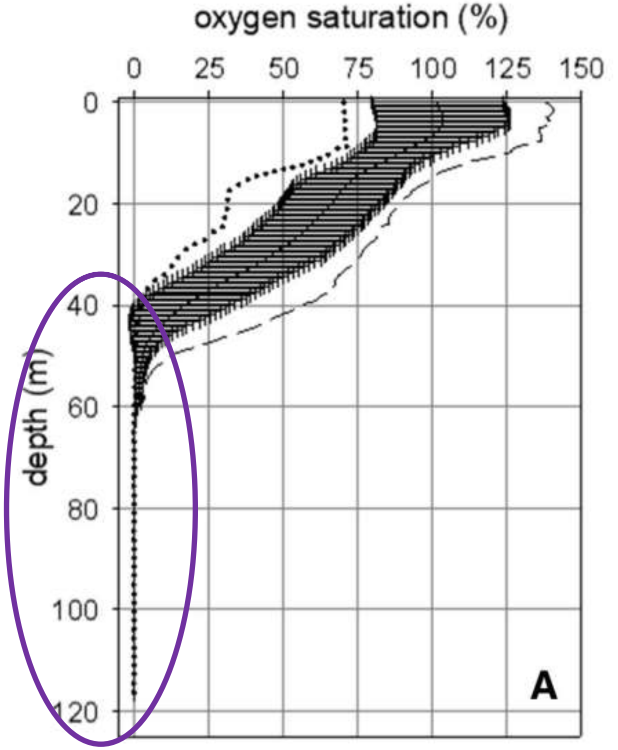
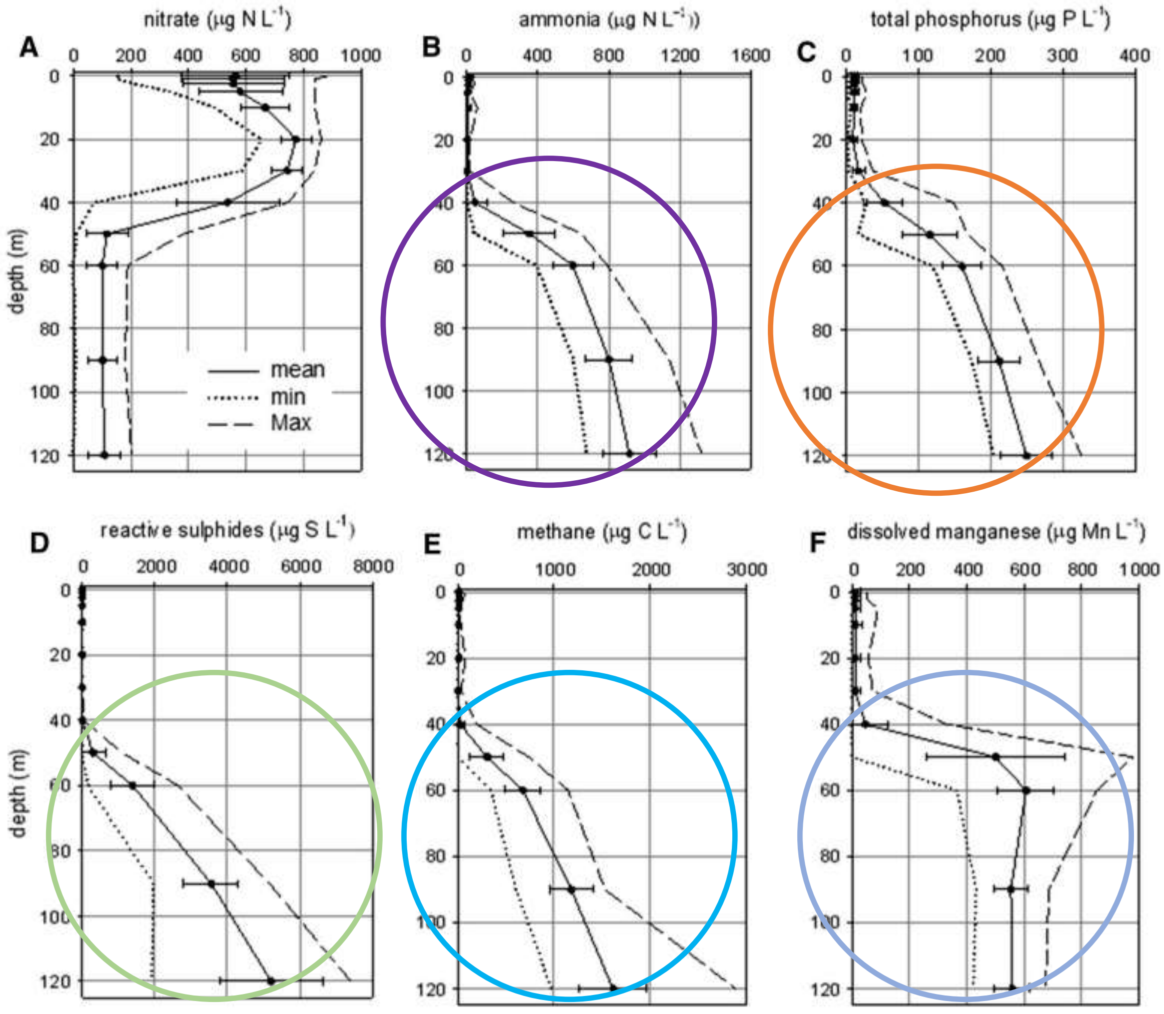


Fig. 2 Trends of oxygen concentrations and water temperature in the DSL in the period 1992–2016. Average values of DO and temperature in the water column (**a**, **c**) and in the deep layer (**b**, **d**) measured during winter–spring turnover (usually in March)

Climatic effects on vertical mixing and deep-water oxygen content in the subalpine lakes in Italy. Rogora et al. Hydrobiologia, 2017

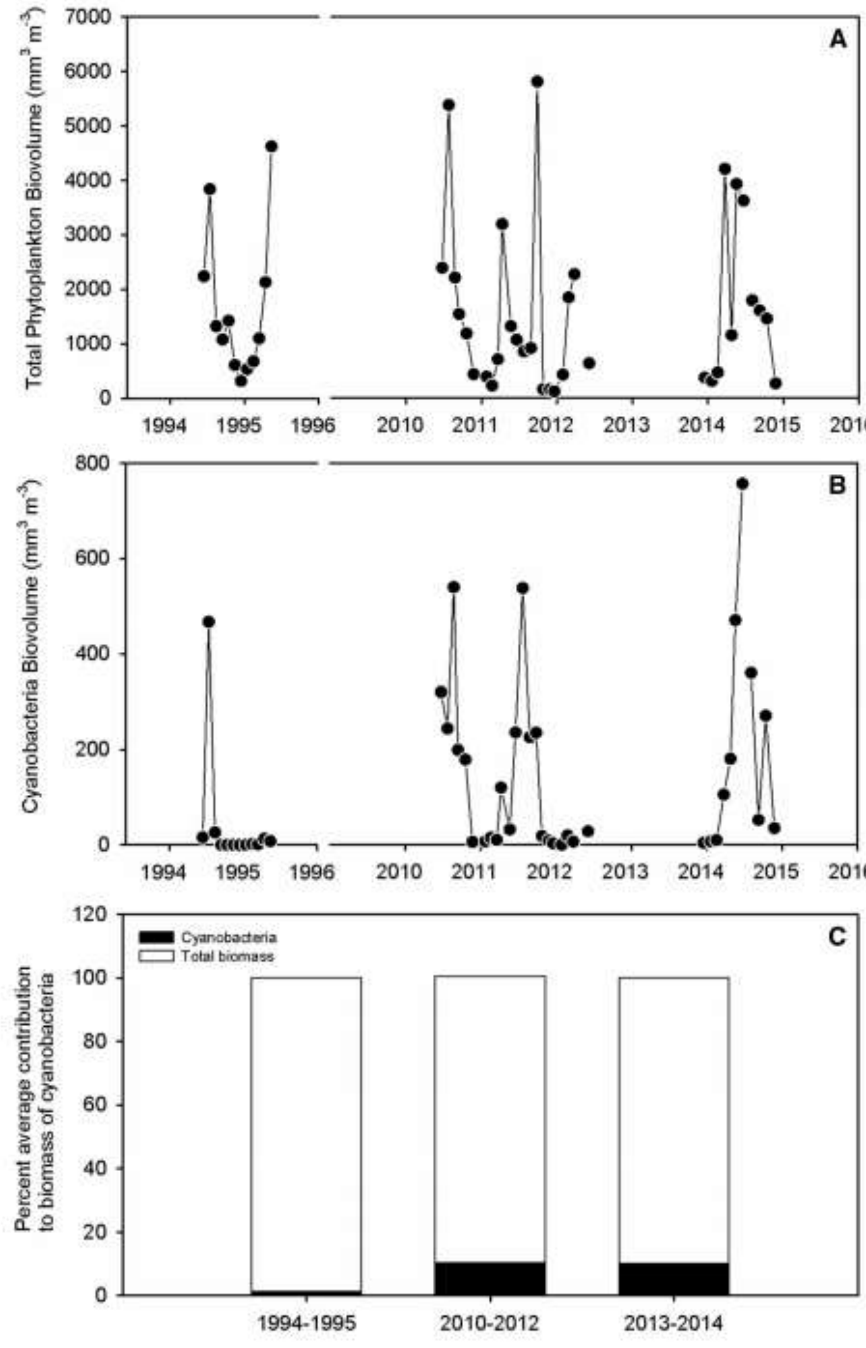
Idro Lake, a meromictic lake



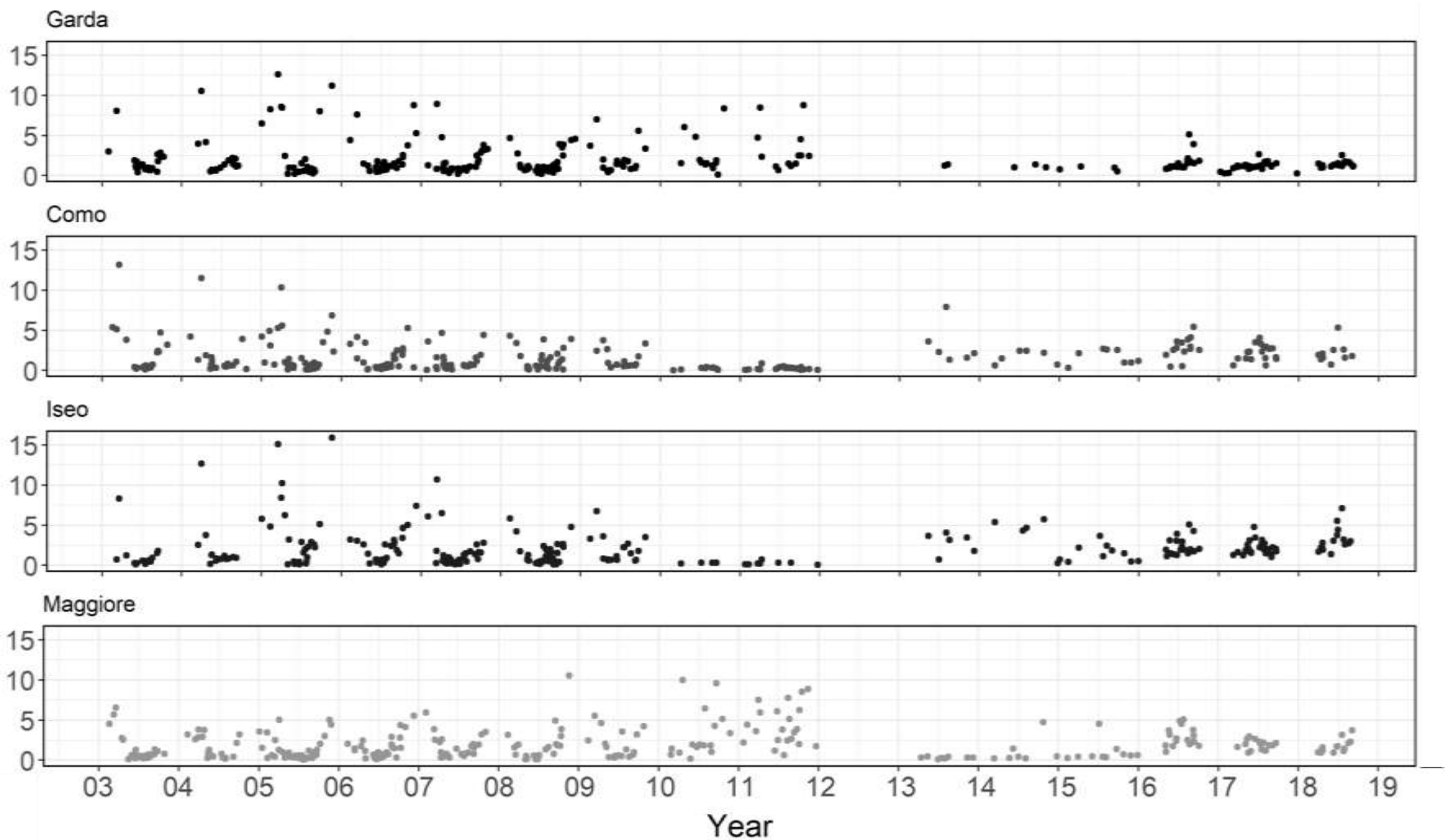


80 m thick water layer without oxygen, but with a lot of undersired solutes

A decreasing phytoplankton productivicty but an increasing proportion of cyanobacteria



Chlorophyll a trends (2003-2019)



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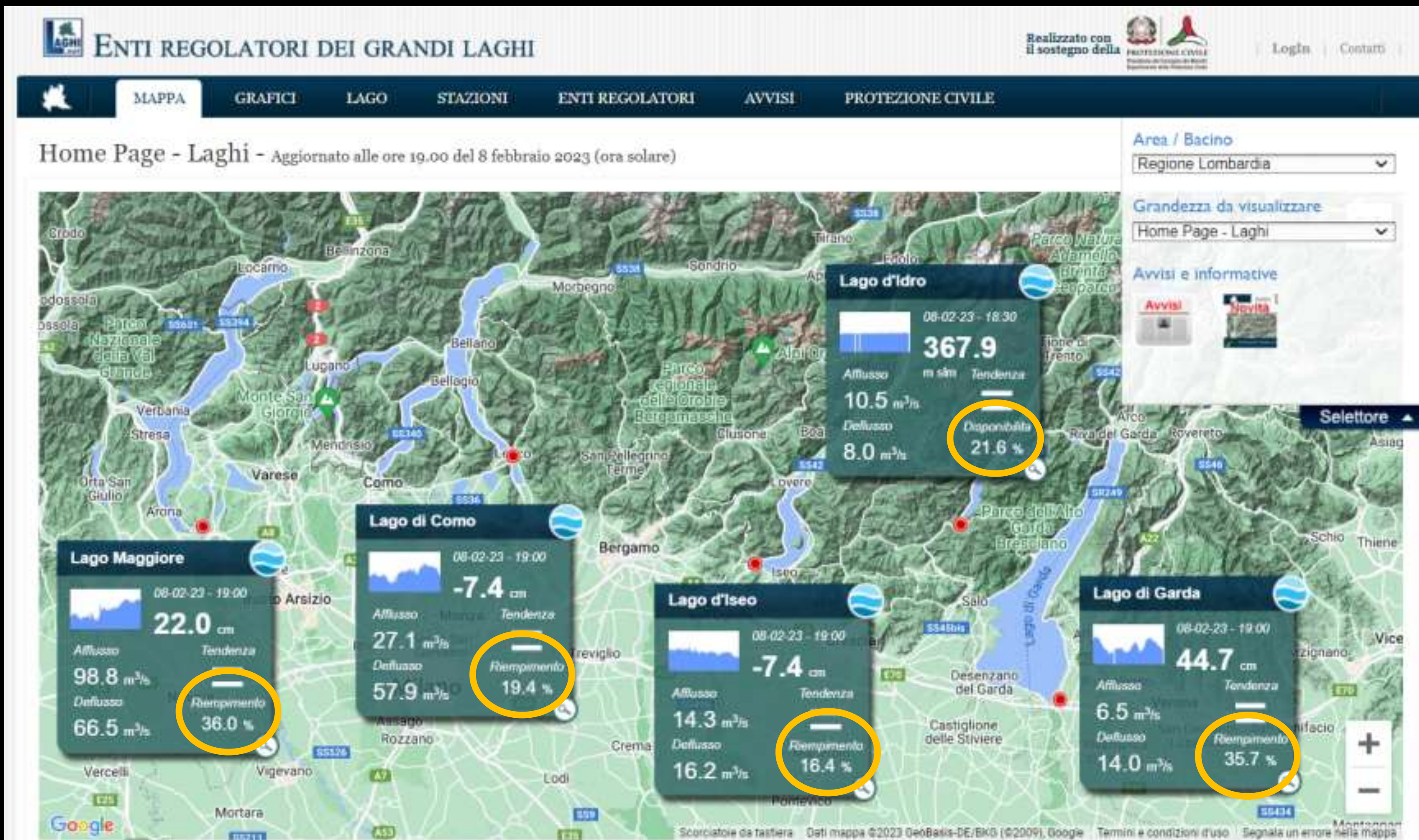
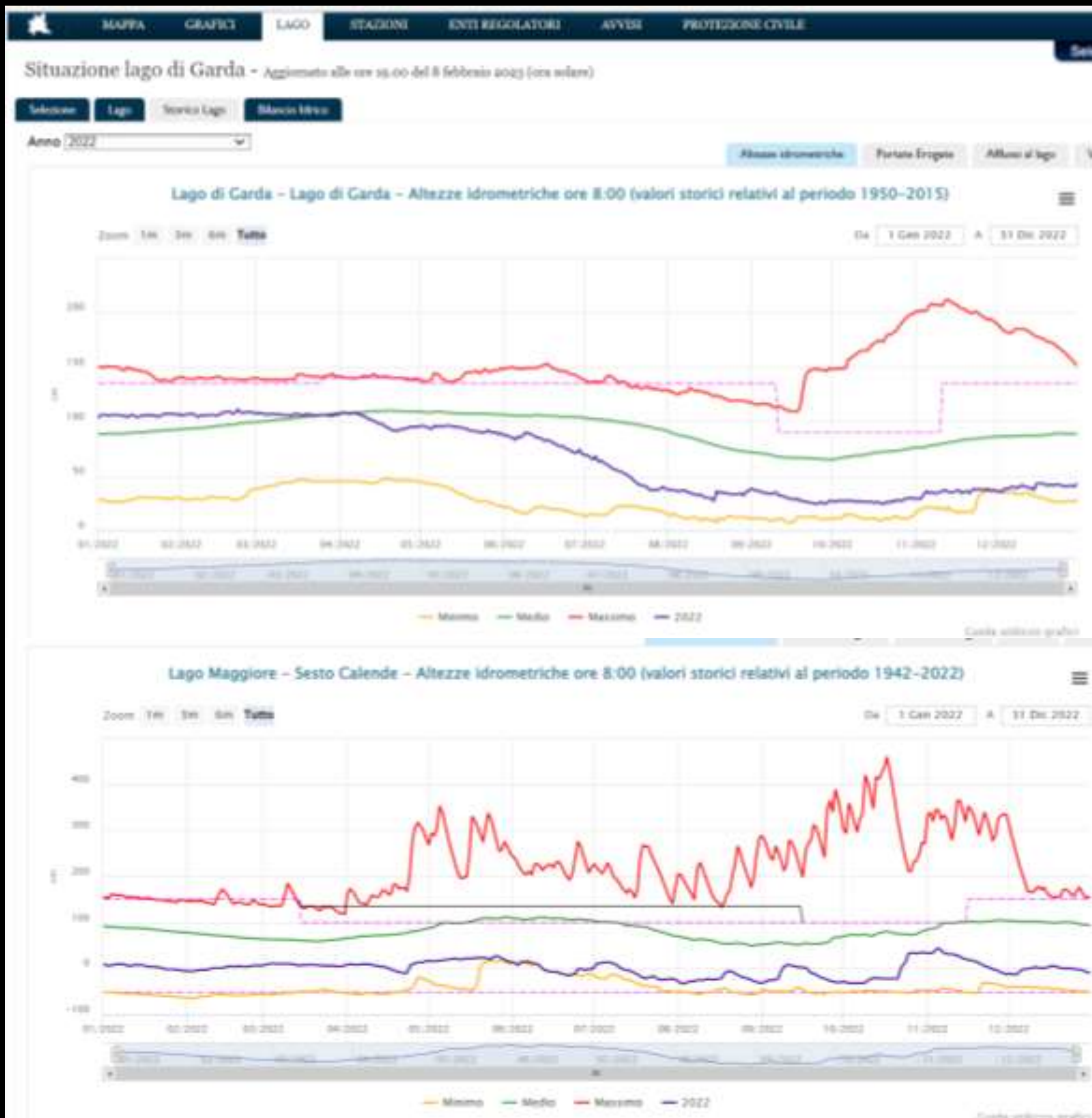


Lake levels: easy to observe proxies of climate change



- Garda Lake

Red line: historical maximum
Green line: historical average
Yellow line: historial minimum
Blue line: 2022

- Maggiore Lake

Concluding remarks

Climate change affets temperature, watershed features, precipitation patterns, ice cover, food webs, whole system lake metabolism.

Overall it will produce similar effects of eutrophication or it will make the effects of eutrophication more extreme

In small lakes, to contrast these effects it’s mandatory to reduce nutrient input at the watershed scale and to preserve the littoral zone.