SCOPE Newsletter special issue: Climate Change, Nutrients and Catchment Management

This is the second SCOPE Newsletter special issue addressing the **links between phosphorus, nutrients and climate change**, in cooperation between the *Sustainable Phosphorus Alliance*, North America, and the *European Sustainable Phosphorus Platform*.

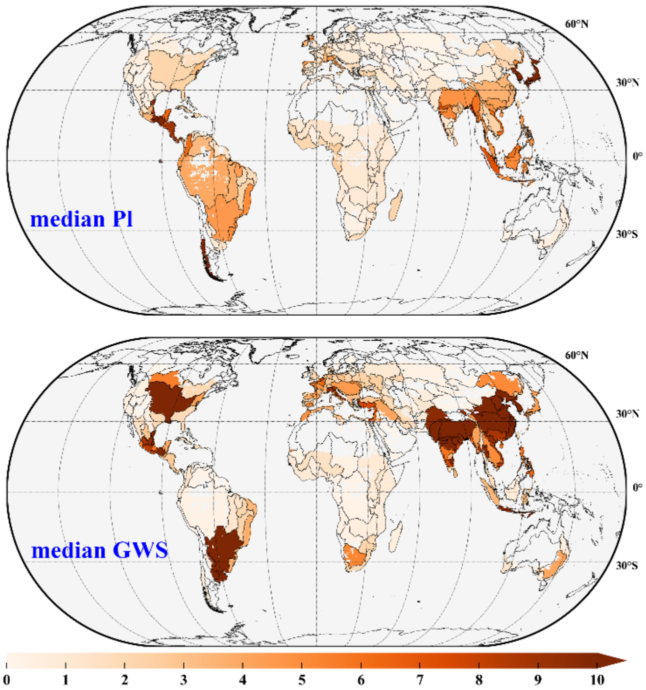
The first issue covered aquatic **methane emissions** (*SCOPE Newsletter n°135*, July 2020).

As is usual for the SCOPE Newsletter, this issue is based on targeted 'layman's' summaries of relevant information from selected recent scientific papers, from which we have tried to draw overall conclusions.

Currently in preparation are further special issues on:

- **interactions between climate change, nutrients and soil carbon**
- **climate change impacts of nutrient recycling and stewardship technologies**

*ESPP wishes to thank for their support and input: **Amin Soltangheisi** (Lancaster University), **Matt Scholz** (Sustainable Phosphorus Alliance) and **Sara Johansson**, all the authors of papers summarised who sent their corrections and comments, and ESPP's members whose support makes this possible.*



Impacts of high precipitation on phosphorus losses (PI) and on Gray Water Stress (GWS). Showing data from 1991-2010, which can be used to predict impacts of expected increased precipitation with climate change. Reprinted with permission from W. Liu et al. Environ. Sci. Technlol. https://doi.org/10.1021/acs.est.0c03978 copyright 2020 American Chemical Society (see summary below, page 4).

Executive summary

Recent published science, as summarised in this SCOPE Newsletter, confirms that interactions between nutrients and climate change will vary considerably between different regions (*Wade.*), depending on anthropogenic impacts, regional climate, type of water body and catchment characteristics, including specific factors such as soil iron levels (*Q. Tan.*). Publications include a considerable number of modelling studies, for rivers, lakes and coastal waters in different regions of the world, but also a few laboratory tests with water samples (*Lee, M. Liu*).

Phosphorus losses to surface waters are expected to increase with climate change, with overall increased precipitation, and especially with soil erosion in extreme rainfall or snow-melt events, but also with increased mineralisation in soil. Phosphorus losses are expected to increase significantly more than nitrogen losses *(W. Liu, Ockenden, L. Wang, El Khoury*).

In many cases, **climate change is expected to significantly accentuate eutrophication, algal blooms and dead zones** (*Glibert, UKEA, M. Wang, Raimonet, Laurent, Liu, Kalcic, Bartisiva, Visser*), in particular with changes in precipitation, but also with temperature changes, sunlight, wind changes, increased atmospheric carbon dioxide (eCO_2) … Impacts may be accentuated by increased stratification of lakes (*Radbourne*), and by reduced sinking of nutrients to sediments, or their release from sediments, which may be accentuated by microplastics (*Y. Zhang*). Nutrients and eutrophication will in turn have feed-back impacts on climate change, by increasing aquatic methane emissions (*SCOPE Newsletter n°135*) and, conversely, by increasing carbon sinking to sediments (*Anderson, Z. Chen, C. Cheng*).

With increasing temperatures, atmospheric carbon dioxide (eCO_2), precipitation changes and N deposition, **climate change is expected to reduce plant-available phosphorus in soil**, but increase crop PUE Phosphorus Use Efficiency (*Bhattacharya, K. Yue, D. Gao, Q. Deng*). This may result in more 'phosphorus stress days' and lower crop yields (*Mehan*). Increases in crop productivity resulting from eCO_2 are likely to be limited by nutrient availability of N and/or P (*Terrer*).

The interactions of climate change with nutrients and eutrophication have **important implications for nutrient policies, for catchment management and for agriculture**. Reductions in nutrient standards for surface waters may be necessary (*Huo*). For some point sources, e.g. sewage works, significant discharge reductions will be required, e.g. as lower water flow means reduced dilution (*UKEA, Raimonet*). Considerable changes in agricultural practice will be necessary, including conversion to other types of land use (*Ockenden, Forber, Weber, Sinha, Motelica-Wagenaar*), as well as changes in diet and nutrition (*Macdiarmid*). These actions will be very demanding, but offer important synergies with soil and biodiversity conservation.

A challenge will be to combine agricultural nutrient loss reductions with ensuring crop productivity, as soil available P becomes lower but crop P requirements increase with climate change.

__Note__: names indicated above refer to papers summarised in this Newsletter. Full references are found below each summary. For reasons of space, papers cited above do not cover all papers relevant to a given point included in this SCOPE Newsletter.

How climate change impacts eutrophication

Increased temperature

- Accelerated algal development, longer bloom seasons
- Warmer winter/spring facilitates spring algal blooms
- Increased stratification
  - lower surface water nutrient levels favour blue-greens
  - anoxic sediments release P
- Increased metabolism of organics releases legacy P
- Warmer water has lower oxygen concentration
  - anoxic areas release legacy P
  - reduced self-cleaning capacity
- Increased evaporation means lower summer flows
  - algae not flushed
- Lower water viscosity
  - green algae sink faster, favouring buoyant blue-greens
- eCO_2 may stimulate harmful algae

Increased solar radiation (generally linked to temperature)

- Increased primary production (algal growth)

Changes in precipitation

- Increased precipitation results in increased nutrient runoff
- More storm events
  - increased soil erosion increases P losses to water
  - increased remobilisation of river sediment nutrients
- More drought / low flow periods
  - low flow and increased nutrient concentration

Increasing winds or variable winds

- High winds
  - resuspension of legacy P from sediments
  - mixing (upwelling) bringing nutrients to surface
- Low winds enable increased stratification

A scientist's vision - UK

Philip M. Haygarth, Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom, p.haygarth@lancaster.ac.uk

Photograph showing accelerated soil erosion (and so accompanying phosphorus transfer) the morning after Storm Desmond, taken by PM Haygarth 16th December 2015.

The devastating storms and flooding that have occurred over recent years in the UK, my home, and elsewhere worldwide, remind us of the great dynamics and power in our weather and climate. As well as the immediate flood and human hazards, such events also have great influence on the phosphorus cycle, as the increased energy leads to physical detachment and delivery of particularly particulate phosphorus.

In the UK, a team of many contributors has been studying the extent to which phosphorus losses from land to water are being impacted by climate change and land management, with detrimental impacts on aquatic ecosystems and food production. The basis of the work was published in Nature Communications (*Ockenden et al.* 2017, *summarised below*). There was a great challenge in determining this, with all the complexities, controversies and uncertainties that surround it. The team used a combination of methods to evaluate the impact of projected climate change on future phosphorus transfers, and to assess what scale of agricultural change might be needed to mitigate these transfers in the UK. The team combined high-frequency phosphorus flux data from three representative catchments across the UK, a new high-spatial resolution climate model, uncertainty estimates from an ensemble of future climate simulations, two phosphorus transfer models of contrasting complexity and a simplified representation of the potential intensification of agriculture based on expert elicitation from land managers. We showed that with climate change, average winter phosphorus loads are predicted to increase by up to 30% by the 2050s. **Such increases can be offset only by large-scale agricultural changes, in the range of 20–80% reduction in phosphorus inputs**. Are we ready for this? I am not convinced that we are really on top of how the phosphorus cycle will react to climate change, and I hope that this specially focused issue of SCOPE will help cast light on this.

A scientist's vision - USA

Laura Johnson, National Center for Water Quality Research, Heidelberg University, Ohio ljohnson@heidelberg.edu

In the midwestern United States, we have been experiencing years with extremely high precipitation leading to flooding, and other years with warm winters and summer drought. These extremes challenge understanding the potential effects of climate change on algal blooms and dead zones, but also on how to manage agricultural areas to prevent phosphorus losses to waterways.

In Lake Erie, the reductions needed to reduce harmful algal blooms to acceptable levels are substantial: targets call for a 40% reduction in March – July total (TP) and dissolved reactive phosphorus (DRP) loads from the Maumee River in 9 out of 10 years. However, the frequency of intense storm events (> 1 inch) has increased in the past 15 years, leading to increased flow in rivers feeding Lake Erie, and contributing ~35% of the increased tributary DRP loads, so feeding harmful algal blooms.

The comprehensive summary in this issue of the SCOPE Newsletter highlights that the effects of climate change are not always straight forward. We have recently seen this in the Maumee River watershed. In 2019, spring discharge was the third highest ever measured, after high precipitation. This prevented farmers from planting crops in 41% of the watershed, so reducing the application of P fertiliser (46% of typical amounts sold), and delaying manure application until late in the summer. The resulting DRP loads were 29% lower than expected (based on the flow) but were still high enough to cause a significant algal bloom (rated 7.3/10). This showed that a large part of DRP load (up to 70%) is a holdover from past years. This accentuates the difficulty in predicting the effect of climate change on nutrient loads.

Overall, our findings for Lake Erie corroborate the findings in the UK: **massive agricultural P reductions may be needed to protect our freshwater ecosystems**. But how do we achieve this? And how can we be certain that these reductions will serve our future needs regarding water sustainability?

Image of the Microcystis *cyanobacteria bloom in western Lake Erie on August 5, 2019, produced using data derived from Copernicus Sentinel-3 data provided by EUMETSAT. Credit: NOAA and EUMETSAT.*

Climate change and P losses

Global P-losses from croplands

Modelling suggests that increased precipitation will lead to a 17% - 31% increase in global annual P-losses from croplands (in wet years, by the end of this century).

Phosphorus losses by surface runoff, leaching and soils erosion (particulates) were estimated using the PEPIC (Python-based Environmental Policy Integrated Climate) model, for four principal crops (maize, rice, soybean, wheat), with a global gridded crop map (0.5 arc degrees). The model covered 188 river basins worldwide, and was based on modelled runoff, related to precipitation and evapotranspiration.

94% of the river basins showed a **statistically significant precipitation : P-loss correlation** for >50% of (100) model simulations.

The impacts of P-losses on freshwater P levels were modelled, taking into account dilution by increased precipitation.

Global phosphorus losses are estimated to increase from c. 3.6 kgP/ha/year at baseline (1991-2010) in wet years (2.7 kgP/ha/year in median year) to 4.2 to 4.7 kgP/ha/year (climate scenarios RCP2.6 and RCP8.5) by the end of this century, as a consequence of increased precipitation only (not considering e.g. land use, management).

That is, for wet years, an increase in total global cropland phosphorus loss from 2.1 MtP/y to 2.7 MtP/y (million tonnes phosphorus per year).

Impacts of increasing precipitation on P-losses are largest in dry regions, in particular the Middle east, Central Asia, North Africa and the Western United States. Freshwater P dilution capacity would be exceeded in ¾ of the world's river basins (40% of global total annual runoff volumes) and **populations exposed to severe phosphorus pollution would increase from 5 to 7 billion**.

The authors note that this study can help identify regions where actions are needed to mitigate the impacts of climate change on phosphorus pollution.

"Global Phosphorus Losses from Croplands under Future Precipitation Scenarios", W. Liu et al., Environ. Sci. Technol. 2020
https://dx.doi.org/10.1021/acs.est.0c03978

UK

Modelling suggests that climate change will increase phosphorus concentrations in many English rivers, by reducing summer flows and so dilution, although results are very variable.

It is concluded that reducing all sewage works P emissions to 0.5 mgP/l will not suffice to achieve water quality objectives at all sites, and that diffuse P sources must be addressed.

Data from the Future Flows and Groundwater Levels project for 282 river catchments and 24 water tables was combined with the Hadley Centre Regional Climate Model and with paired data sets to establish relationships between river flow and phosphorus concentration. The Land Apportionment Model (LAM), based only on routinely collected monthly concentration and flow data, was used to identify whether P inputs were from sewage works or from diffuse sources.

Results suggest that **climate change, in different scenarios, will generally result in reduced river flows, leading to increased annual and summer phosphorus concentrations in around 80% of rivers**, with the median summer P concentration change varying from -8% to +36%.

The models estimate that if discharge from all sewage works was reduced below 0.5 mgP/l, then 2/3 of sites would be largely dominated by diffuse P releases (> 90% of remaining would be diffuse). Even under this sewage treatment investment scenario, Good Quality Status (EU Water Framework Directive) would not be achieved at around 40 sites in England, showing that **diffuse P sources must be addressed** at these sites.

It is not discussed whether investment in P-removal at sewage works would be cost-effective, compared to actions to address diffuse P sources, at other sites. However, as climate change reduces summer flows, **the importance of addressing sewage works discharges will increase even in rivers where most phosphorus comes from diffuse sources**.

"Mapping eutrophication risk from climate change: Future phosphorus concentrations in English rivers", M. Charlton et al., Science of the Total Environment 613–614 (2018) 1510–1526
http://dx.doi.org/10.1016/j.scitotenv.2017.07.218

Italy

Modelling of a river basin near Venice, Italy, indicates **high probability of significantly increased water flow and nutrient loadings in Autumn for phosphorus, nitrate and ammonium**.

The nutrient loads in the **Zero river basin, near Venice** (140 km^2) are modelled under different climate scenarios, using Bayesian Networks.

Nutrient losses could be slightly lower in summer with reduced precipitation and increased phosphate immobilisation at higher temperatures. On the other hand, increased temperatures, increased evaporation and reduced flow are liable to accentuate summer eutrophication.

"A Bayesian Networks approach for the assessment of climate change impacts on nutrients loading", A. Sperotto et al., Environmental Science and Policy 100 (2019) 21–36 https://doi.org/10.1016/j.envsci.2019.06.004

Baltic

Climate change is estimated to result in +14% phosphorus input to the Baltic by 2050 and +8% for nitrogen (averages of four scenarios). These changes can be significantly affected by socioeconomic drivers, resulting in -6% to +9% change for phosphorus and -13% to +11% for nitrogen when three socioeconomic scenarios were combined with climate change.

Modelling of temperature and precipitation changes for the Baltic Sea catchment using different climate change projections (*CORDEX*) and of 'shared socioeconomic pathways' (as used in the global climate research community) were combined with the hydrological and nutrient transport model E-HYPE. This was calibrated using data from 1981 to 2010.

Under four climate scenarios representing different projections for the RCP8.5 scenario, **stream/river water discharge into the Baltic could increase by +4% to +25% as a result of climate change**. These impacts are more significant than those of changes in temperatures.

The biggest source of both P and N to the Baltic is cropland (including use of manure and of fertiliser). For N the second biggest source is forests: around half of the load from agriculture, because of low nutrient concentrations but high total flows (large areas). For P, wastewater plants are the second biggest source, but these emissions are expected to decrease only slightly under all the socioeconomic pathways considered.

The biggest load increase linked to climate change for phosphorus is from cropland, whereas for nitrogen the biggest load increase is from forests.

The four climate projections lead to **estimated increases of phosphorus loading to the Baltic of +6% to +20%** (14% average of the four projections), and for nitrogen +4% to +9% (average +8%).

"Future socioeconomic conditions may have a larger impact than climate change on nutrient loads to the Baltic Sea", A. Bartosova et al., Ambio 2019, 48:1325–1336 https://doi.org/10.1007/s13280-019-01243-5

Across Europe

Partly similar conclusions are reached in a study which models catchments across Europe. This also notes seasonal differences, and underlines differences between North and South Europe.

Eight river-systems across Europe were modelled and compared to real data. Real flows and nutrient concentrations tended to show higher variations than models.

Conclusions are that in **South Europe, both reduced precipitation and increased evaporation make climate change a major threat to freshwater ecosystems**. Overall impact in North Europe is smaller, as increased precipitation may counter evaporation resulting from higher temperatures, but with significant seasonal differences, and variation between catchments dominated by agricultural or by point sources.

Modelled lake chlorophyll levels are not proportional to changes in nutrient loading, with ecological changes predicted greater than changes in nutrients at some sites, but smaller than these changes at other sites. Large-scale change in agricultural practice could be effective to reduce eutrophication, despite climate change.

"A north-south divide in Europe: the future freshwater eutrophication response to land use and climate interaction", A. Wade et al., (conference poster) Geophysical Research Abstracts Vol. 20, EGU2018-6328, 2018 https://ui.adsabs.harvard.edu/abs/2018EGUGA..20.6328W/abstract *and REFRESH (FP7) D5.14 "Adaptive strategies to Mitigate the Impacts of Climate Change on European Freshwater Ecosystems" – "Integrated Catchment Biophysical Modelling: Synthesis Report" (March 2014)* http://www.refresh.ucl.ac.uk/webfm_send/2383

Canada

Climate change will increase stream flow and P loads, but not N loads, in Canada (*El Khoury et al. 2015*), suggests modelling of South Nations (SN) river basin, Ontario.

The SN basin covers 3 900 km^2, with around 115 000 population. Land use is around 2/3 cropland and 1/3 forest, and wetland area has been reduced from nearly 50% of land surface in the 1980s to around 15% today.

River total P regularly exceeds the provincial target of 0.03 mgP_{total}/l.

Modelling of climate change to 2050 suggests that mean water flow will increase by +11% and maximum monthly flow by +9%. Nitrate, nitrite and organic nitrogen loads do not significantly change with climate change, whereas **both mineral and organic phosphorus loads increase considerably (nearly +50%).**

The authors note that expected land use changes are likely to drive these variables in the same direction as climate change.

Modelling for two small watersheds in the Canada Great Lakes region (*Wang et al. 2018*), also suggests that climate change will lead to considerable increases in phosphorus run-off and some increase in nitrate.

The Green Lake watershed is 790 ha, with c. 90% cropland (mainly) and grassland. The Walworth watershed is 1 124 ha with c. 50% cropland (mainly) and grassland and c. 50% urbanisation. Three different climate scenarios were tested using the Water Erosion Prediction Project Water Quality (WEP-WQ) model.

With climate change, precipitation will increase, especially in the fall and winter, occurrence of extreme precipitation events will increase by +10 to +25% and air temperature will increase all year.

Annual total phosphorus losses to surface water are modelled to increase +25% to +110%, because of increased precipitation quantity and intensity and increased air temperature, with increases particularly in winter and spring.

Annual nitrate-N losses are also modelled to increase, but less markedly, by+1 to +40%.

Modelling of climate change (*Kalcic et al. 2019*) impacts suggest that despite higher rainfall, nutrient loads reaching Lake Erie may be lower because of warming.

This modelling study uses the hydrological and water quality model SWAT and a number of global and regional climate change models to estimate phosphorus loads from the **Maumee River** to 2065. This watershed, 17 000 km^2, in Ohio, Indiana and Michigan provides nearly 50% of nutrient loadings to Lake Erie's Western Basin. The watershed is dominated by row crop agriculture (mainly corn, soybean, winter wheat rotation), largely with tile drainage.

All the climate change models predicted, for the watershed, **increased intensity and overall quantity of precipitation, decreased snowfall and increased evapotranspiration** (with increased temperatures).

The different climate change models lead to **different results regarding water flow**, mostly however concluding that tile drainage flows are unchanged or increased, but surface water runoff is decreased.

The different climate models also gave varying results for nutrient loadings to the river, but generally predicted both **reduced nitrogen and phosphorus loads**, with averages of -2% nitrate, -11% organic-N, -11% total phosphorus, -6% dissolved reactive phosphorus (DRP). In particular, **all the climate models predicted both reduced annual P loadings, and reducing P loadings in March-July**, which is the critical period for algal blooms.

The authors conclude that, for Lake Erie, **water balance changes from increased temperature (evaporation) and reduced snowfall may outweigh increases in precipitation in terms of driving P flows** at least in the climate to 2050 which they studied.

Modelling of a Lake Erie (*Mehan et al. 2019*) stream suggests climate change will modify the form and route of agricultural nutrient losses.

The Matson Ditch watershed, Indiana, Western Lake Erie basin, covers 4 600 ha, of which 70% is cropland, mainly corn, soy and winter wheat. 42% of the total watershed has subsurface drainage.

Nine climate projections with two emissions scenarios (RCP 4.5 and 8.5) were modelled to 2099. These suggest that surface runoff could increase by +10% to +40% and subsurface drain flows by +70%.

For nutrient losses, the modelling shows high ranges in estimates, for example of -20% to +25% for soluble phosphorus losses but +5% to +15% increases for organic phosphorus, resulting in an overall increase in total phosphorus losses (surface plus drains). For N also, increases in organic and total N losses are higher than increases in soluble N losses (surface plus drains).

For P, organic P losses tend to increase whereas soluble P losses in subsurface drainage show -35% to -60% decreases. For nitrate-N, similarly, subsurface drainage losses tend to decrease and surface losses to increase.

The authors note that these differences in changes for different forms and routes of nutrient losses, are probably related (in the model) to increases in heavy precipitation events in which water does not have time to penetrate down to tile-drains and runs off the surface, and to low plant nutrient uptake during water stress periods.

"Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin", A. El-Khoury et al., Journal of Environmental Management 151 (2015) 76e86 http://dx.doi.org/10.1016/j.jenvman.2014.12.012 *and presentation of the South Nation river basin in El-Khoury et al. 2014* https://doi.org/10.1111/cag.12105 *Open Access.*

"Climate Change Impacts on Nutrient Losses of Two Watersheds in the Great Lakes Region", L. Wang et al., Water 2018, 10, 442 http://dx.doi.org/10.3390/w10040442

"Climate Change and Nutrient Loading in the Western Lake Erie Basin: Warming Can Counteract a Wetter Future", M. Kalcic et al., Environ. Sci. Technol. 2019, 53, 7543−7550 http://dx.doi.org/10.1021/acs.est.9b01274

"Assessment of hydrology and nutrient losses in a changing climate in a subsurface-drained watershed", S. Mehan et al., Science of the Total Environment 688 (2019) 1236–1251, https://doi.org/10.1016/j.scitotenv.2019.06.314

China

Modelling of climate change impacts suggests that river loads of dissolved phosphorus and nitrogen to China's coastal waters could increase by + 16% and + 24% by 2050.

Hydrology of the twelve rivers draining into China's coastal area was modelled, using the MARINA 2.0 (Model to Assess River Inputs of Nutrients to seAs) model, with different socio-economic and greenhouse gas scenarios (RCP2.6 and RCP8.5). These rivers cover 40% of China's land area (c. 4 million km^2) and include the Yangtze, Yellow and Pearl rivers.

The model takes into account human waste (based on protein intake), sewage connection and treatment, land use, fertiliser use and agricultural productivity, recycling of manure, direct discharges of manure to rivers, atmospheric nitrogen deposition, etc. Retentions and losses of nutrients in rivers as a result of denitrification, sedimentation, river damming and consumptive water use are taken into account. In particular, hotspots for nutrient pollution are identified, related to nutrient losses from agriculture or sewage.

The modelled hydrology suggests that river discharge may decrease (up to -68% in the low climate change scenario RCP2.6) or increase (up to +21% in the high climate change scenario RCP8.5) between 2012 and 2050, under the same socio-economic scenario SSP2. This leads to an increase in river export of **total dissolved phosphorus (TDP) by 16% and in river export of total dissolved nitrogen (TDN) by 24% to coastal waters** between 2010 and 2050.

The changes in river export of nutrients are, however, very different between the different river sub-basins, and also between different nutrient forms: e.g. +5% to +275% for dissolved inorganic phosphorus and +3% to +174% for dissolved organic phosphorus.

River export of nutrients to coastal waters may also be **considerably modified by policy decisions** (e.g. sewage and agriculture management), with modelling of the different socio-economic scenarios leading to + 56% or - 85% for river export of phosphorus (TDP) and + 52% or - 56% for river export of nitrogen (TDN) in 2050.

The authors conclude that climate change will make eutrophication management for China's coast more difficult, and that **nutrient policy management will be critical**.

"Global Change Can Make Coastal Eutrophication Control in China More Difficult", M. Wang et al., Earth's Future, 8, e2019EF001280 https://doi.org/10.1029/2019EF001280

How climate change will impact eutrophication

Increased algal blooms in the UK

Reports published by the UK Environment Agency conclude that days of algal bloom risk in UK rivers will increase by 2050 by a median of 8 days/year (c. 50/year currently) as a result of changes in river flow (reduced flows increase phosphorus concentrations in rivers where the main input is sewage discharge), sunlight and temperature increases.

The two reports were prepared by UK CEH (UK Centre for Ecology & Hydrology).

The first assesses impacts of changes in river flow at 117 sites across England. This looks at dilution of current phosphorus loadings (or scenarios with e.g. improved sewage treatment) but does not consider possible increases in land P runoff resulting from increases in storm events.

Increases in phosphorus concentrations resulting only from reductions in flow are considered unlikely to significantly modify water quality status, although reductions in summer flow may be more sensitive.

The second report assesses impacts of changes in sunlight, flow and temperature, which are known drivers for algal growth. 30 µg/l of chlorophyll was chosen as a threshold for algal blooms in most UK rivers, with higher thresholds in larger rivers. Based on nutrient limitation studies across the UK, a threshold of 30 µgP/l was fixed.

The report suggests that this phosphorus threshold is met at most sites despite the changes in river flows (as indicated above, this does not take into account possible increased phosphorus losses in storm events) but that **this phosphorus level does not prevent algal blooms**. Scenarios with further phosphorus removal in sewage treatment reduced algal bloom risk at very few sites.

By the 2050's, the number of days when algal blooms are likely are estimated to increase in 24 of the 26 sites modelled, from a current average of 50 days per year, median increase 8 and maximum 15 days/per year.

The report concludes that **reducing both sunlight and water temperature may be effective strategies in reducing risk of algal blooms**, for example by increasing riparian river shading.

"Climate change and eutrophication risk thresholds in English rivers" Reports SC140013/R *(2016) and –* SC140013/R2 *(2019), UK Environment Agency / CEH*

Combining UK catchment phosphorus flux data and climate change models suggests that increased P losses to surface waters will require major agricultural changes to prevent worsening of water quality.

The modelling is based on high frequency P flux data from three representative UK sub-catchments (in Cumbria, Norfolk and Hampshire), combined with a high-resolution climate model, uncertainty estimates from several future climate simulations, two P-transfer models and representations of agricultural scenarios based on expert opinion.

Climate models concur to predict **increased winter rainfall, resulting in significantly increased winter P losses to surface waters (c. +30%)**. Increased rainfall volume will increase loss of dissolved P, and increases in intensity will increase soil erosion, and so loss of particulate P. Effects of changes in temperature are comparatively smaller.

Effects of actions intended to mitigate P losses are buffered because of **stored "legacy P" in the soil** from high P inputs in the past. This means that very considerable changes in agricultural practice would be necessary to counteract the expected annual P losses, e.g. reductions in farm P inputs of 20 – 80%.

On the other hand, the modelling suggests that **summer river phosphorus levels would not increase significantly** where driven by agricultural P losses, so that impacts on eutrophication may not be proportional to the annual P-loss increase. However, where river P loads are driven by point sources, **eutrophication will increase as water flow decreases, so reducing dilution**.

"Major agricultural changes required to mitigate phosphorus losses under climate change", M. Ockenden, P. Haygarth et al., Nature Communications 8-161, 2017, Open Access
https://doi.org/10.1038/s41467-017-00232-0

See also: "The Phosphorus Transfer Continuum: A Framework for Exploring Effects of Climate Change", K. Forber, P. Withers, M. Ockenden, P. Haygarth, Agric. Environ. Lett. 3:180036 (2018)
https://doi.org/10.2134/ael2018.06.0036

Seine river, France: algal growth and oxygen depletion

Modelling of rainfall changes only (not considering temperature changes) suggests that climate change could result in +31% increase in algae and a -9% decrease in oxygen in the Seine river, France, as well as possible accentuated coastal eutrophication.

The Seine is France's second longest river, with a basin of nearly 76 000 km^2, including the Paris urban area and large areas of intensive agriculture.

The GR4-J-Cemaneige hydrological and pyNuts-Riverstrahler biogechimical models were used to analyse consequences of RCP 4.5 and 8.5 climate change scenarios.

The RCP4.5 stabilisation scenario shows low variations in both hydrology and water quality, whereas most results with the increasing carbon dioxide emissions scenario RCP8.5 lead to more intense spate flows and to longer lasting and lower minimum flows. The low flows in the driest RCP8.5 result in increased river residence time and **increased phosphate and nitrogen concentrations, leading to a +31% increase in river Spring algal bloom phytoplankton biomass**, a -23% decrease in silicic acid and downstream decreases of -9% in dissolved oxygen.

Both wet and dry scenarios led to increased total nutrient discharges from the Seine river to the sea (phosphorus, nitrogen and silicon) so accentuating coastal eutrophication risk.

"Landward Perspective of Coastal Eutrophication Potential Under Future Climate Change: The Seine River Case (France)", M. Raimonet et al., Front. Mar. Sci. 5:136
https://doi.org/10.3389/fmars.2018.00136

Accentuation of the Gulf of Mexico dead zone

Modelling suggests that climate change will worsen eutrophication, and so the "dead zone", of the Mexican Gulf, because of increases in ocean temperatures, freshwater discharge and atmospheric CO_2.

The continental shelf of the Northern Gulf of Mexico is today one of the world's largest hypoxia (low oxygen) and acidification zones with an average 14 000 km^2 impacted each year. This is the consequence of eutrophication, in particular fed by the Mississippi and Atchafalaya rivers.

The Regional Ocean Modelling System ROMS, configured for the Northern Gulf of Mexico shelf, was used to assess the effects of climate change by 2100. A 3°C air temperature increase was modelled, with a +10% increase in Mississippi river flow and unchanged nutrient loadings and an increase in atmospheric CO_2 to 936 µatm.

These scenarios led to bottom and surface water temperature increases in the Gulf of 2.2 - 2.7 °C. Bottom salinity decreased only marginally, whereas surface decreased by nearly 0.5 (PSU). Together, these two factors result in a bigger **decrease in water density at the surface** than near the bottom, so accentuating stratification (lack of vertical water mixing). This reduces oxygenation of bottom waters, so will **accentuate the hypoxic area** (oxygen-deprived "dead" zone).

The increase in water temperature reduces oxygen solubility, and this has an even greater impact in accentuating hypoxic conditions.

Results suggest an **increase in the hypoxic area of over 25%, and also that hypoxia will last for longer periods**, but with significant yearly variations.

Acidification is expected to be significantly accentuated, especially in hypoxic waters. This is driven mainly by the increase in atmospheric CO_2.

Because the model set nutrient discharge as unchanged, summer primary production (algal and plant growth) increased by only around 2.5% (total for the whole water column). Organic matter sinking to sediments is decomposed more rapidly with higher temperatures. In this unchanged nutrient discharge hypothesis, biological processes did not significantly modify the anoxic conditions.

"Climate Change Projected to Exacerbate Impacts of Coastal Eutrophication in the Northern Gulf of Mexico", A. Laurent et al., J Geophysical Research: Oceans, 123, 3408–3426
https://doi.org/10.1002/2017JC013583

Nutrients plus climate change drive algal growth

Laboratory testing of collected coastal water samples shows that nutrient inputs cause warming to have a much greater impact in driving phytoplankton production.

Eight surface water samples were collected from Shiwha Bay, Korea, from March to January, then each was bottle incubated with day-night cycles in different conditions for seven days (each in triplicate): **with or without additional nutrients, and at four temperatures (ambient water temperature as at sampling, +2°C, +4°C, +6°C).** Nutrients were added to reach 200 µMNO_3, 12 µMPO_4, 100 µMSiO_2, plus trace vitamins and minerals.

Initial chlorophyll-$_A$ varied from 3 to over 100 µg/l, and nutrient concentrations (without nutrient addition) were <0.05 to >100 µM NO_3/l and 0 to 0.5 µM PO_4/l depending on the month of sampling. These are considered typical of current levels in many coastal waters.

Without nutrient addition, the increased temperature resulted in increased phytoplankton growth some months, decreased for others, or no effect. However, **with nutrient addition, phytoplankton was significantly higher at temperature +2°C in all months** (except one when salinity was < 6.5), and continued to increase at °C and +6°C.

This shows that, in these laboratory conditions, nutrient inputs significantly accentuate eutrophication and algal bloom risks related to global warming temperature increases.

The authors note that the **initial nutrient : chlorophyll ratio** appears to define how phytoplankton will respond to increased temperature.

"Effects of warming and eutrophication on coastal phytoplankton production", K. H. Lee et al., Harmful Algae 81 (2019) 106–118
https://doi.org/10.1016/j.hal.2018.11.017

Climate change will hinder lake restoration

Climate change is likely to hinder lake recovery after phosphorus input reductions by extending stratification and modifying water residence times.

25 years of data is analysed for Rostherne Mere, Cheshire, UK (lake area 49 ha, max depth 31m, catchment 940 ha). The lake has been monitored since the early 20th century. It became hypereutrophic (water P_{total} > 100 µg/l) in the 1970's largely due to discharges from two sewage works, which were diverted away from the lake in 1991.

After sewage diversion, lake P_{total} levels fell from c. 600 µgP/l in 1992 to c. 200 in 2002 and c. 160 µgP/l in 2016, whereas lake dissolved organic nitrogen levels have not significantly changed. Reductions in P inputs are probably being partly nullified by release of 'legacy' phosphorus, stored in sediments in the past.

Chlorophyll data are not available 2002-2015, but available data suggest no significant change in chlorophyll levels since the 1990's. However, changes in the algal community are seen, with reductions in *Dolichospermum spp.* and *Microcystis spp.* blooms.

The authors consider that there is clear evidence that climate has driven changes over the last 43 years, with a weak trend of warming (for all seasons of the year) and a decrease in wind speeds. These trends could explain the **observed prolongation of the summer stratification of c. 6 weeks longer in the autumn**, so increasing risk or duration of algal blooms. The authors note that other lakes in the region have seen earlier onset of stratification. Recent improvements in flow monitoring show that lake water residence time is significantly shorter than previously thought. Flushing out of nutrients and algal biomass may thus be more important.

Climate change is leading to a national trend in lower summer rainfall across the UK, which will overall **reduce summer flushing of nutrients**, and a reduction in nutrient inflow from runoff, particularly of silicon. Warmer, wetter winters will lead to earlier stratification and increased flushing, possibly reducing abundance of siliceous diatoms. Also, an increase in high-intensity storm rainfall events may cause flushing pulses and turbulence which may reduce cyanobacteria.

The authors conclude that **climate change will significantly modify, and indeed has already modified, the lake's restoration trajectory and should be taken into account in catchment management**.

"The Influence of Climate Change on the Restoration Trajectory of a Nutrient-Rich Deep Lake", A. Radbourne et al., Ecosystems (2020) 23: 859–872, https://doi.org/10.1007/s10021-019-00442-1

Complexity of factors driving eutrophication

Two papers modelling factors impacting eutrophication and algae in Lake Taihu, China, show the complexity of attributing trends to possible causes: climate change, nutrients, land use, human activities.

Both papers analyse historic data from Meiliang Bay, Lake Taihu, subtropical, in the lower Yangtze River (lake surface 2 300 km^2, drainage basin 36 500 km^2). The lake provides drinking water to 30 million people and the Meilang Bay receives wastewater from Wuxi City, Jiangsu.

One study (Xu et al.) compares data for total N and total P from 1952 to 2010 to temperature and human activities (urban area, crop area, animal production, GDP). The second study (Guo et al.) compares N and P (total, soluble) and algae (biomass, species composition) from 1992 to 2017 to temperature, wind speed and sunlight.

The first study notes that, **over the long term, total N and P were positively correlated with temperature, GDP, urban area and animal production and negatively to crop area and precipitation**. Lower precipitation is noted to lead to lower lake water levels, probably increasing the concentrations of point source nutrients. The authors note abrupt changes in 2000, suggesting that this may relate to **major Yangtze floods in 1998** and to rapidly increasing urbanisation and industrial waste and sewage discharge at this time.

The second study concludes that **nutrients impacted algae more until 2007, but since then climate factors have had a greater impact**. In 2007 total N peaked, whereas total P continued to increase through to 2017 (but with high variation). **Algal biomass was three times higher in recent years than in the 1990's, with cyanobacteria dominating since 2011**. Both nutrients and climate changes (temperature, light) were (positively) correlated to algal biomass and linked algal community changes, with recently a consistently turbid state in the lake. Release of legacy phosphorus from sediments is noted as important.

Both papers conclude that **reducing both N and P inputs to the lake is necessary to reduce eutrophication, and that climate change will accentuate problems**.

"Influence of climate change and human activity on total nitrogen and total phosphorus: a case study of Lake Taihu, China", X. Xu et al., Lake and Reservoir Management, 36:2, 186-202, https://doi.org/10.1080/10402381.2019.1711471

"Climate exerts a greater modulating effect on the phytoplankton community after 2007 in eutrophic Lake Taihu, China: Evidence from 25 years of recordings", C. Guo et al., Ecological Indicators 105 (2019) 82–91 https://doi.org/10.1016/j.ecolind.2019.05.034

Soil iron, phosphorus and climate change

Iron levels in soil are strongly negatively correlated to lake and reservoir eutrophication. Climate change driven precipitation in tropical regions may thus reduce eutrophication, but worsen eutrophication in temperate regions.

Summer data for water total phosphorus and chlorophyll from 77 freshwater lakes and reservoirs across Eastern China was compared to regional data on precipitation, temperature and soil iron levels. Over this data set, **soil iron was strongly correlated to latitude** (higher in the South), more so than was temperature.

Soil iron content shows strong correlation to the relationships between precipitation and total P and between chlorophyll and total P, in both lakes and reservoirs, and appears to better explain latitudinal variations than does temperature.

Increased precipitation increases total P in reservoirs, and even more so in the lakes considered (mostly shallow). The lakes have generally higher total P than the reservoirs (probably because the reservoirs have more natural watersheds).

The data analysed suggest that **precipitation, accentuated by climate change, may decrease eutrophication effects (algal growth) in tropical and subtropical regions**, because of soil iron transported into the water, which then immobilises phosphorus in sediments. This may be less true in lakes than in reservoirs, because lakes already have high total P.

However, **in temperate regions, climate change driven precipitation is likely to accentuate eutrophication effects**.

"Total phosphorus-precipitation and Chlorophyll a-phosphorus relationships of lakes and reservoirs mediated by soil iron at regional scale", Q. Tang et al., Water Research 154 (2019) 136e143
https://doi.org/10.1016/j.watres.2019.01.038

Microplastics, climate change and eutrophication

Climate change will increase microplastics inputs to lakes, where they will accentuate sediment resuspension (which is already facilitated by climate change), so reinforcing eutrophication.

A concept review paper outlines the various interactions (and positive feedbacks) between climate change, microplastics, nutrients and algal blooms in shallow lakes.

Climate change will increase microplastics inputs to surface waters: in water, by increased precipitation and storm run-off; in air, with increased winds.

In lake water, microplastics tend to float (low density) and can **provide a matrix for biofilm and algal growth**. They can then be integrated into algal agglomerates, so **increasing the buoyancy of these algal agglomerates**, and so reducing their sedimentation, thus facilitating surface water algal blooms. Also, microplastics may interfere with the nutrition of algae-grazing zooplankton (e.g. daphnia) so reducing their capacity to control algal development.

In sediments, the low density of microplastics increases pore spaces, so facilitating nutrient mineralisation and diffusion. Also, **microplastics facilitate sediment resuspension**. Both these effects will increase nutrient release to the water column, accentuating eutrophication.

Microplastics may also accelerate or modify nutrient cycling in lakes. Nutrients can be adsorbed onto plastics and then released. Microplastics can accelerate mineralisation of organic matter, by release of organic molecules during plastics degradation, or via biofilms growing on microplastic particles.

Overall, it can be expected that climate change will increase microplastics inputs to lakes, which will accelerate nutrient release and algal development. The authors suggest that microplastics should therefore be taken into account in eutrophication management. They note that **further research is needed**, in particular into the impacts of microplastics on aquatic biochemistry and on sediments.

"How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: A review", Y. Zhang et al., Science of the Total Environment 705 (2020) 135979
https://doi.org/10.1016/j.scitotenv.2019.135979

Climate change and Harmful Algal Blooms (HABs)

Climate change and biology of eutrophication

An update review, based on some 250 publications, summarises the possible impacts of climate change on nutrient losses to surface waters and on aquatic biology of eutrophication.

A summary of nutrient loadings to surface waters from land and air, referencing numerous publications and models, notes the importance of fertiliser and manure but also that non-food sectors may account for a significant share of nutrient losses (e.g. cotton), and underlines that **changes in N:P ratios can significantly modify ecosystem response**.

Algal blooms are related not only to increases in nutrient loading, but also timing. This is impacted by retention in rivers, impoundments and in coastal waters. **Nutrient retention in reservoirs is estimated to have increased +60% worldwide in the twentieth century**, and modification of rivers is continuing worldwide. Phosphorus and silicon are retained by reservoirs much more than nitrogen, so causing nutrient imbalances.

Climate change will impact eutrophication in a number of ways. **Increased temperatures accelerate algal growth, but can also favour harmful species such as cyanobacteria and dinoflagellates**.

Higher temperature can **increase algal cell N:P ratio** (possibly as a consequence of lower cell P, *Yvon-Durocher et al. 2015*) and lead to smaller cell size, and increased CO_2 can increase C: nutrient ratios, deteriorating the food quality of the algae for zooplankton grazers which naturally control algae development and so help prevent blooms.

Increased temperature can also increase stratification, so reducing mixing of deeper with surface water (reducing upward nutrient fluxes) and increasing sinking rates for larger taxa. This tends to favour bloom-forming cyanobacteria, which can control their depth by internal buoyancy regulation.

Increased light intensity also favours smaller algal cells, which can more efficiently harvest sunlight, so may accentuate temperature effects.

Frequency of **extreme precipitation events**, linked to climate change are expected to lead directly to algal bloom risks (low flow periods), to increase the magnitude of nutrient release pulses (storm flows) and to modify the timing of these pulses (summer storms when waters are more sensitive to eutrophication). Climate change can also modify input to coastal lagoons from groundwater. Wildfires also result in high nutrient losses.

Warming and CO_2 are also associated with **water pH reductions** (acidification), and also with pH fluctuations, because algal blooms can lead to pH increases.

Overall, the authors suggest, **diatoms are likely to be disproportionately stressed by climate change**, leading to risk of replacement by taxa which are less attractive to zooplankton grazers (and so less controlled and more likely to develop blooms) or even toxic (cyanobacteria). Diatoms can be disadvantaged by: increasing temperatures, higher N:P ratios (because they have a low N:P ratio, *Mitra et al. 2014*), lower silicon availability (resulting from retention in reservoirs), rising CO_2, shifting nitrogen from nitrate to less oxidised forms.

Furthermore, **mixotrophs can be favoured by nutrient imbalances**. Mixotrophs both fix carbon by photosynthesis and also feed on other algae to supplement their nutrient intake (whereas diatom autotrophs photosynthesise but take up nutrients only directly from water). Mixotrophs include harmful dinoflagellates, haptophytes and raphidophytes.

The author concludes that **eutrophication's response to climate change is complex and that more research is needed on biology**, in particular factors such as cell size, grazing of algae and food chain interactions, allelopathy (algae releasing chemicals which influence the development of other species) and biochemical nutrient fluxes.

"Harmful algae at the complex nexus of eutrophication and climate change", P. Glibert, Harmful Algae 91 (2020) 101583, https://doi.org/10.1016/j.hal.2019.03.001

Exacerbation of blue-green algae blooms

A review paper based on over 150 references outlines mechanisms whereby climate change could accentuate cyanobacteria blooms (temperature, CO_2, stratification), concluding that nutrient limitation is essential.

Freshwaters are often supersaturated in CO_2, with most originating from carbon in watershed runoff. However, in algal bloom conditions, photosynthetic demand can transform conditions to undersaturation. Data from Lake Volkerak, The Netherlands, shows CO_2 below 1 µmol/l during algal blooms. H**igher atmospheric CO_2 will lead to increased CO_2 diffusion into the surface water, so feeding algal growth**. This has been demonstrated in experiments (*Verspagen 2014*).

Cyanobacteria can also use carbon from dissolved bicarbonate for photosynthesis, but this has an energy cost (compared to using dissolved CO_2) which can reduce growth rates by 20 – 65%.

Both cyanobacteria and green algae show a wide genetic range of different adaptation to higher CO_2 levels, so that increased atmospheric CO_2 may modify inter- or intra-species composition of algal blooms.

Temperature increase will also impact algal blooms, and **cyanobacteria often have higher optimal growth temperatures than green algae** (eukaryotic algae).

Climate change is likely to also increase stratification of lakes (periods when surface water and deeper waters do not mix). This may penalise eukaryotic algae which can be dependent on water movement to prevent them from sinking.

Climate change is also expected to extend the growing season, and so the duration of algal blooms.

Both increased temperature (related to limitation of metabolism by oxygen diffusion) and increased CO_2 may increase N_2 fixation by some cyanobacteria, again modifying balance of algal species during blooms.

Impacts of climate change (temperature, CO_2) on cyanobacterial release of toxins, however, seems to vary with different species, with no clear trend.

The authors conclude that **nutrient limitation is essential to prevent increasing cyanobacterial blooms with climate change**.

A book on marine harmful algal blooms (HABs) and "red tides", generally related to dinoflagellates and cyanobacteria, concludes that these are increasing worldwide, as a result of nutrient inputs, accentuated by climate change.

The 170-page book reviews current understanding of mechanisms and causes of marine HABs. A chapter on climate change concludes that HABs will increase with higher seawater temperatures and thermal stratification, and accentuated upwellings and local mixing (changing currents, wind), which bring nutrients to the ocean surface.

Time series studies have shown the **relation between climate variability, nutrient upwellings and marine algal blooms**. **Weather disturbances, such as high winds or typhoons, heavy rainfall or large temperature variations can drive algal blooms**, and such algal blooms have been related to toxic impacts on both marine mammals and human populations.

Coastal HABs, related to climate change and nutrient inputs from land and rivers, can lead to **dimethyl sulphide production (DMS),** from the biological precursor DMSP present in marine microalgae. DMS is related to methane emissions (see SCOPE Newsletter *n°135*) and is the most important natural source of reduced sulphur to the atmosphere, where it impacts atmospheric chemistry and so climate change.

The link between climate change related weather events and toxic algal blooms in lakes is explored in Liu et al. *2019*, based on laboratory simulations.

Turbulence promoted **increased algal biomass**, reduced algal diversity, and favoured the growth of colonial algae (*Microcystis*) – which plays an important role in freshwater algal blooms and favoured **toxin-producing strains**. The algae adapted to turbulence by increasing cell size and release of EPS (extracellular polymeric substances, which can agglomerate cells into colonies and blooms.

"How rising CO2 and global warming may stimulate harmful cyanobacterial blooms", P. Visser et al., Harmful Algae 54 (2016) 145–159 http://dx.doi.org/10.1016/j.hal.2015.12.006

"Marine Algal Bloom: Characteristics, Causes and Climate Change Impacts", S. Sarkar, book, Springer 2018, ISBN 978-981-10-8260-3 https://doi.org/10.1007/978-981-10-8261-0

"Strong turbulence benefits toxic and colonial cyanobacteria in water: A potential way of climate change impact on the expansion of Harmful Algal Blooms", M. Liu et al., Science of the Total Environment 670 (2019) 613–622 https://doi.org/10.1016/j.scitotenv.2019.03.253

USA: Higher winter temperature leads to blue-green blooms

Factors influencing cyanobacterial HABs in South-East of the USA are identified as winter temperature and land use (agriculture, impervious, forest).

Seventeen catchment parameters were compared to satellite data for cyanobacteria cell density (one date in summer, ESA Sentinel-2 MSI, reflecting cyanobacteria HAB risk – Harmful Algal Bloom) for 771 waterbodies in the State of Georgia, South-East USA.

Analysis showed that the satellite cyanobacteria density data corresponded accurately to water bodies known to have HABs.

Warmer winters were linked to high cyanobacteria counts (measured as max. winter temperature) and was the most influencing factor. This is expected, because higher winter temperatures allow cyanobacteria to remain active all year and to start development earlier in the spring.

Land use was clearly related to HAB risk: especially % agriculture, but also % developed (impervious) and % forest. The link to forests may be because of reforestation of land which has legacy soil nutrients (reforested soil has higher nutrient levels than mature forest).

The authors conclude that management actions to reduce losses of nutrients and sediment (soil erosion) to surface water are essential to reduce cyanobacteria algal bloom risks.

"Risks for cyanobacterial harmful algal blooms due to land management and climate interactions", S. Weber et al., Science of the Total Environment 703 (2020) 134608, https://doi.org/10.1016/j.scitotenv.2019.134608

Nitrogen

USA & China – nitrogen loadings

Sinha (2019) modelled river total nitrogen loadings for continental USA for 2100 for different socioeconomic and climate mitigation perspectives. **A combination of high climate mitigation and demand for domestic food production could increase total N runoff by +54%, resulting principally from increased bioenergy production and related fertiliser application**, and an expansion of agricultural land in the USA.

This exceeds the **increase of +19% in riverine N loadings expected to result from increased precipitation only, related to climate change,** for continental USA (Sinha 2017). On the other hand, some scenarios (SP1-2.6) can both address climate change and reduce nitrogen losses (net -7%), particularly by reducing food demand (dietary changes).

Yan (2019) modelled future (to 2065) total N loadings to the Miyun Reservoir, near Beijing (15 000 km^2 catchment) using the SWAT (Soil and Water Assessment Tool) model combined with CMIP5 climate models. Mean temperature is expected to increase +0.6°C by 2035 and +1.6°C to 2065, and annual precipitation to increase +5.4% to 2035 and +12.5% to 2065. Total nitrogen loading to the reservoir is modelled to increase in the same way as stream flow, but more so, that is **N_{-total} +14-19% by 2035 and +15-27% by 2065**, depending on the climate model. Highest total N increases are expected in the summer flood season.

"Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century", E. Sinha et al., Nature Communications (2019)10.939 https://doi.org/10.1038/s41467-019-08884-w

"Eutrophication will increase during the 21st century as a result of precipitation changes", E. Sinha et al., Science 357, 405–408 (2017) https://doi.org/10.1126/science.aan2409

"Future climate change impacts on streamflow and nitrogen exports based on CMIP5 projection in the Miyun Reservoir Basin, China", T. Yan, Ecohydrology & Hydrobiology 19 (2019) 266–278 https://doi.org/10.1016/j.ecohyd.2018.09.001

Stream N_2O emissions and agriculture

Sampling in nine Sweden streams suggests that N_2O emissions from headland watercourses may make a significant climate change contribution, and appear to be linked to nitrate concentrations and agricultural land use, but not to fertiliser use.

One site in each of nine streams in a 32 km^2 catchment was sampled monthly from December to August (9x9 samples). Sampling sites were not near tile drainage discharges. Water N_2O concentration was calculated using laboratory gas chromatography combined with stream water temperature and atmospheric pressure at the time of sampling. Stream nitrate, nitrite, ammonia, DOC and stream depth and velocity were also measured. Flow was calculated from flow at the catchment outlet flow x sub-catchment areas.

The streams were mostly channelised, with lengths varied from 1.3 to 23 km with slopes of 0.02 to 0.86 % and % agricultural land (mainly arable) of 0 (100% forest) to 61%. The whole catchment had a very low population density (10 person/km^2) and little livestock.

Stream N_2O saturations measured varied from 40 – 270 %.

Comparison both between sub-catchments, and at different months at the same site, suggested that **estimated N_2O emissions were correlated to water nitrate concentration, to the % arable land cover and to stream water discharge** (the latter two would be expected to be correlated to nitrate losses) but **not to DOC and not to nitrogen fertilisation rates** (data from Swedish Agricultural Monitoring Programme).

Nitrous oxide (N_2O) emissions from the streams were estimated at 108 - 175 kg N-N_2O/m^2/year, that is 12% - 36% higher than the IPCC Guidelines number.

However, estimation of the **N_2O emissions related to nitrogen fertiliser use in the catchment suggested that these were 25x higher than the total stream emissions**.

"Nitrous oxide emissions from streams in a Swedish agricultural Catchment", J. Audet et al., Agriculture, Ecosystems and Environment 236 (2017) 295–303
http://dx.doi.org/10.1016/j.agee.2016.12.012

N_2O emissions and eutrophication

A study of 101 small eutrophied waterbodies in the North America Great Plains (Saskatchewan, Canada) suggests that, in summer at least, these waters have the capacity to act as net sinks of nitrous oxide (N_2O). This is contrary to previous thinking that nitrogen polluted freshwaters are N_2O emitters.

The 101 waterbodies were artificially created reservoirs in agricultural catchments (grassland, cropland), with a mean area just over 1 300 m^2 (range 90 to 14 000 m^2) and mean depth 2.1 m. At the time of sampling (July or August 2017), mean total dissolved nitrogen was just over 3 000 µgTDN/l and total phosphorus mean 180 µgTP/l.

The reservoirs were eutrophic, with mean chlorophyll nearly 100 µgChl_{-a}/l (range 2 to 2 500).

Levels of N_2O in the surface water suggest that 2/3 of the sites were N_2O sinks, in the range of -2 to -12 µmol N_2O/day (in summer).

The mechanism for N_2O sink in these reservoirs is unclear, but data from this study suggests that it may be related to stratification and to algal development, both of which occur principally in summer (around 5 months per year in this region of Canada)

Generally, **nitrogen loadings to freshwaters and eutrophication are considered to increase N_2O greenhouse gas emissions,** but this is based mainly on studies on rivers and streams. The reservoirs studied may be representative of some 16 million small reservoirs in agricultural catchments worldwide, so may **question this general understanding**.

Further research is needed to assess the N_2O balance of these impoundments over the whole year, the relation to nitrogen inputs and to phosphorus, and the significance compared to N_2O emissions from other types of waterbody and their relation to nutrients.

"Widespread nitrous oxide undersaturation in farm waterbodies creates an unexpected greenhouse gas sink", J. Webb et al., 9814–9819 | PNAS | May 14, 2019 | vol. 116 | no. 20
http://dx.doi.org/10.5281/zenodo.2636099

Nutrients and climate carbon cycles

Nutrients, increased CO_2 and land biomass carbon uptake

Plants are expected to increase carbon uptake as atmospheric CO_2 increases. Analysis of experimental data suggests that this may be limited, by nutrient availability, to a +9% to +15% increase for land biomass.

This paper is based on data from **138 enhanced carbon dioxide experiments** in grassland, shrubland, cropland and forests, both FACE (free air CO_2 enrichment) and chamber trials. The study conclusions do not take account of changes in CO_2 uptake in freshwaters or oceans.

The principal factors impacting measured increases in vegetation carbon uptake were (in order): experimental method, **soil C:N ratio (indicative of soil nitrogen availability), soil P availability** and mycorrhizal type.

Global modelling suggests an increase of +9% to +15% in land biomass carbon uptake with an increase in atmospheric CO_2 concentration of +250 ppm (from 375 ppm currently to 625 ppm). Additional carbon sequestration would thus be equivalent to around 5-6 years of CO_2 emissions (intermediate emissions scenario).

Nutrient interactions are largely modulated by mycorrhiza (symbiotic association of soil fungi with plant roots).

The main sink for the increased carbon sequestration is tropical forests.

This is lower than some previous estimates because the effects of nutrient limitation are taken into account. The authors conclude that **impacts of ‘CO_2 fertilisation’ are limited by nitrogen for around 65% of global vegetation and by phosphorus for around 25%.**

Some mycorrhizal systems can fix atmospheric nitrogen, and atmospheric nitrogen deposition is widespread, so that phosphorus limitation may in fact be more important than this.

“Nitrogen and phosphorus constrain the CO_2 fertilization of global plant biomass”, C. Terrer et al., Nature Climate Change, vol. 9, Sept. 2020, 684–689 https://doi.org/10.1038/s41558-019-0545-2

Nutrients cause lakes to be carbon sinks

Analysis of data from over 500 lakes worldwide suggest that carbon sequestration has increased over the last 100 years, mainly as a result of increased nutrient inputs. This is estimated to offset around one fifth of annual CO_2 emissions from freshwaters, but the largest greenhouse gas contribution from freshwaters is considered to be from methane (see *SCOPE Newsletter n°135*).

Overall lakes’ net carbon emissions worldwide are estimated be about 1% of fossil fuel and industry emissions (correspondence with A. Heathcote 2020).

Lakes were selected where data from sediment core samples was available for both organic carbon and ^{210}Pb (necessary to harmonise data). Such sediment core data is mainly available from temperate and boreal regions, and efforts were made to balance with tropical and montane data by requesting raw data from Globocarb study sites. This resulted in data form 516 lakes worldwide.

Other data used for calculations include lake area data, global Mean Average Temperature (MAT), geolocalised fertiliser use data (NASA SEDAC) and (GRandD database).

The authors conclude that **lake carbon burial rates have increased significantly over the last hundred years**, with particularly high increases in tropical forest and grassland region lakes. Global lake carbon burial is today around 120 million tonnes carbon per year. This offsets around one fifth of freshwater CO_2 emissions, or around 30% if reservoirs are also considered.

Increasing global temperature, by stimulating primary production, may increase lake CO_2 uptake slightly. More significant is **carbon sequestration resulting from erosion of soil (with anthropogenic landscape use changes)** which contains organic carbon which is then buried in lake sediments.

Nonetheless, the authors conclude that **around 70% of the observed increase in lake carbon sequestration results from increasing nutrient levels**, resulting from nutrient runoff from land (from agriculture or with soil erosion), but also from atmospheric nitrogen deposition (which explains increases in lakes in non-agricultural catchments, e.g. boreal or tundra lakes).

Reservoirs have high carbon sequestration rates because of their high sediment accumulation rates (stocking organic carbon from soil erosion in sediments).

The authors note that organic carbon buried in lake or reservoir sediments is less susceptible to be cycled back to the atmosphere by metabolism than organic carbon in soils.

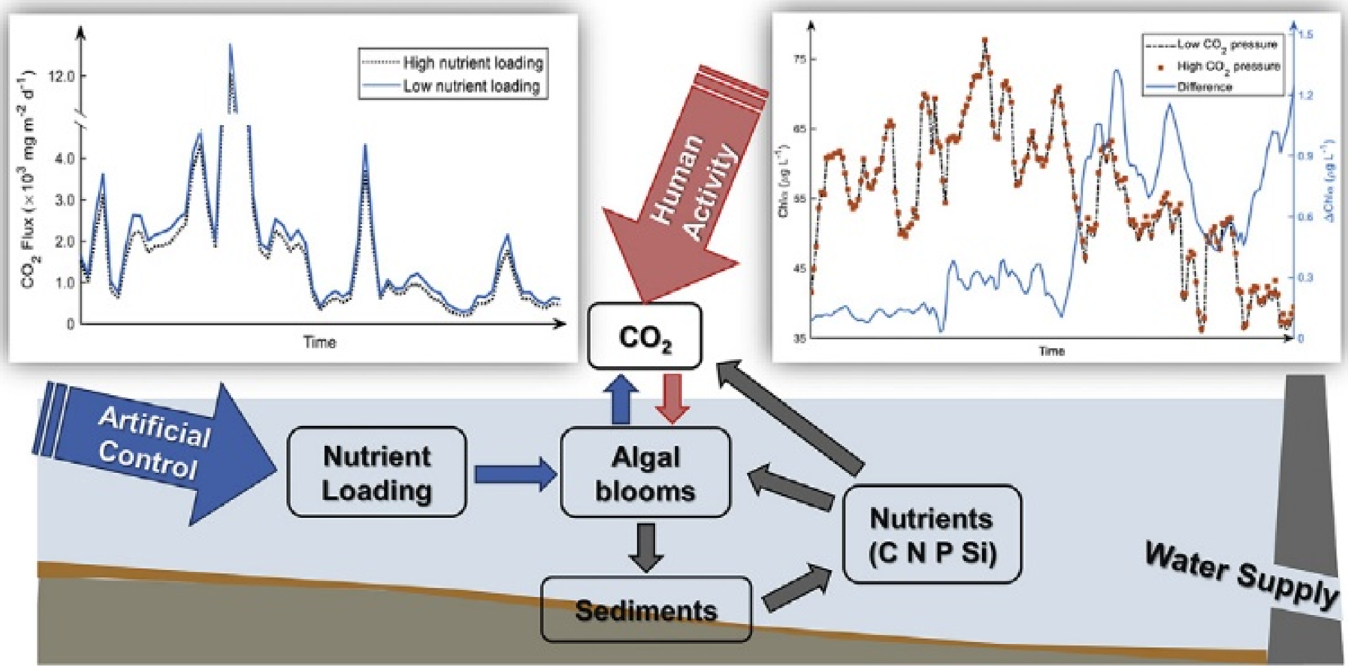
It is important to note that **the identified increase in lake carbon burial, related to nutrient inputs, may not mean a net “positive” result of nutrients on climate change emissions**: freshwater CO_2 emissions are much higher than CO_2 burial rates, and freshwaters also emit methane. The net CO_2 emissions from freshwaters and other freshwater greenhouse gas emissions are susceptible to increase with nutrient inputs.

“Anthropogenic alteration of nutrient supply increases the global freshwater carbon sink”, N. Anderson, A. Heathcote,, D. Engstrom et al., Sci Adv 6 (16), 2020 eaaw2145
https://doi.org/10.1126/sciadv.aaw2145

Nutrient – carbon interactions with eCO_2

Modelling of a sub-tropical reservoir levels suggest that increased atmospheric CO_2 (eCO_2) will increase algal biomass and that reduced nutrient loadings could result in CO_2 release.

Hydrodynamic and ecological modelling (Delft3D FLOW and WAQ) of the reservoir were based on local meteorological data (temperature, solar radiation, wind speed and direction, precipitation …) and monthly reservoir inflow data for nutrients, organic carbon, chlorophyll … (the reservoir is fed by flow from another reservoir upstream). Phytoplankton dynamics were based on lake species composition data (from the sampling below) and literature values for metabolism rates (laboratory monoculture studies).



Graphical abstract above : from Z. Chen et al., Sci. Total Environment 663 (2019)

Scenarios modelled included eCO_2 (increase to 540 ppm compared to 410 ppm 2019) and **-25% phosphorus input to the reservoir** (assuming future nutrient abatement measures).

Model results were calibrated and tested against sampling data from 8 sites in the reservoir, sampled twice monthly for six months in 2013 (water chemistry, phytoplankton).

Modelling results indicate that eCO_2 will considerably decrease net atmospheric CO_2 emissions (more than 60% reduction). **Reducing phosphorus inputs would increase net atmospheric CO_2 emissions (but by only 15 – 30 %).** This confirms studies suggesting that eutrophication causes temperate water bodies to become carbon sinks (Knoll et al. *2013*, Pacheco et al. *2014*)

Estimated burial of carbon to sediments in the reservoir is of the same order of magnitude as the net atmospheric emissions, but does not significantly vary in the different scenarios. Overall, burial and atmospheric emission represent around one third of input carbon into the reservoir (inorganic and organic in inflow water), the remainder leaves in outflow.

"Interaction between carbon dioxide emissions and eutrophication in a drinking water reservoir: A three-dimensional ecological modeling approach", Z. Chen et al., Sci. Total Environment 663 (2019) 369–379, https://doi.org/10.1016/j.scitotenv.2019.01.336

Nutrients and wetland carbon sequestration

Cheng (2020) assesses data from 473 wetland soil/sediment cores to estimate how climate and nutrients impact carbon sequestration rates.

Average carbon sequestration (calculated from core carbon contents) varied from 77 g/m^2/year in peatlands to 250 g/m^2/year in salt marsh. It increased with temperature and with precipitation.

Nitrogen was the primary controlling nutrient for carbon sequestration for all wetland types. **Phosphorus also increased carbon sequestration in saltmarsh and peatland**, but unexplainably not in the data for freshwater marshes.

The authors note that the low P levels in peatlands may limit the carbon sequestration of these soils.

"Impacts of Climate and Nutrients on Carbon Sequestration Rate by Wetlands: A Meta-analysis", C. Cheng et al., Chin. Geogra. Sci. 2020 Vol. 30 No. 3 pp. 483–492 https://doi.org/10.1007/s11769-020-1122-3

Climate change and sediment nutrient release

Comparison of nutrient levels in Lake Dianchi sediments to climate data and fertiliser use show that climate change has reduced burial of phosphorus and nitrogen in sediment.

Lake Dianchi is situated near Kunming, Yunnan, China, with an area of 310 km^2 and a watershed of nearly 3 000 km^2.

Three sediment cores were collected from different areas of the lake, sediment layers were dated by radioactive caesium and lead, and total P and N were analysed in each layer. From this data, sediment burial rates of P and N were calculated for 1951 to 2013, assuming no migration of nutrients up or down in sediment over this time.

Nutrient burial rates were compared to climate data (air temperature, precipitation, sunshine hours, wind velocity, relative humidity), to data on land use and fertiliser application rates, and to data on water quality (nutrient levels, chlorophyll …).

The burial of phosphorus and nitrogen decreased over this period, with increasing air temperature being the most important factor. Decreasing sunshine hours and fertiliser application were also significant factors. Increasing fertiliser application was correlated to increased water N and P, but - surprisingly - to decreasing sediment nutrient levels (whereas increasing water nutrient levels would be expected to increase algal production, and so sedimentation).

Increasing air temperature, the authors suggest, may increase the rate of chemical reactions, and increase the flux of nutrients out of sediments. Decreasing sunlight hours may lead to lower algal growth, so reduced algal biomass sinking with nutrients to the sediments.

The authors note that **climate change considerably reduces sediment nutrient burial**, and that this must be taken into account in water quality management.

"Climate change and human activities reduced the burial efficiency of nitrogen and phosphorus in sediment from Dianchi Lake, China", Q. Chen et al., Journal of Cleaner Production 274 (2020) 122839 https://doi.org/10.1016/j.jclepro.2020.122839

C - N- P interactions and climate change

Achat (2016) reviews models of how nutrients which affect terrestrial ecosystems will react to changes in carbon cycles under climate change.

182 relevant published studies were identified, concerning mainly forests, but also grass and cropland. Over 70 studies link C and N, but very few link C and P. The review identifies 12 research priorities for improving coupled C - N – P cycle models, including understanding plant adjustments to nutrient scarcity, changes in nutrient use efficiency, mineralisation of organic phosphorus, C - N – P ratios of soil organic matter (SOM) and microbes, P control of biological N fixation, release of P through soil weathering, losses of C- N- and P through leaching of organic materials.

"Future challenges in coupled C–N–P cycle models for terrestrial ecosystems under global change: a review", D. Achat et al., Biogeochemistry (2016) 131:173–202 https://doi.org/10.1007/s10533-016-0274-9

Soil C, P modify N_2O emissions from grassland

Data from long-term grassland trials in Ireland suggest that, if organic carbon is present in soil, then low soil P leads to N_2O emissions.

The data is from the long-term, non-grazed grassland trials at Johnstown Castle, Wexford, Ireland, ongoing since 1995. Plots were fertilised with different levels of phosphorus (0 – 45 kgP/ha/year). Grass was harvested eight times per year and nitrogen and potassium applied after each harvest (320 kgN/ha/y, 125 kgK/ha/y).

Results show that when the soil was not carbon limited (i.e. carbon substrate added during incubation), **cumulative N_2O release was significantly higher in the low-P soils**. When carbon was limited, this effect was not seen.

The authors suggest that in low P soils denitrification is by fungi releasing N_2O, whereas at higher soil P levels bacteria capable of fully reducing N_2O to N_2 may dominate (c.f. Kuypers 2018, Chen 2012, Randall 2019).

The trials highlight the **importance of organic fertiliser or manure in increasing the relative abundance of soil microbial carbon, phosphorus and nitrogen**. Optimising the soil microbial community could be a strategy to reduce greenhouse gas emissions.

"The effect of carbon availability on N_2O emissions is moderated by soil phosphorus", R. O'Neill et al., Soil Biology and Biochemistry 142 (2020) 107726 https://doi.org/10.1016/j.soilbio.2020.107726

A study of small agricultural impoundments in Australia found high greenhouse gas emissions, correlated to nitrate, but not to phosphorus.

77 farm dams in one catchment in Victoria, South-East Australia, were sampled once during the summer. Their mean area was just over 1 000 m^2. Carbon dioxide and methane emissions were measured.

Emissions were considerably higher per m^2 than for larger water bodies: c. 11 gCO_2-eq./m^2/day, that is >3 times higher than temperature reservoirs. Total emissions from such small impoundments in Victoria State were estimated to be nearly 5 000 gCO_2-eq./m^2/day, that is over 3 times total emissions from larger reservoirs across the State.

GHG emissions were significantly higher in farm dams with livestock than for cropping farms. Nitrate levels showed similar averages between livestock and crop farms (3.6 vs. 3.8 mgN-NO_3/l), as did water temperature and salinity, whereas average phosphate levels were significantly lower for the livestock farm dams (0.13 vs. 0.33 mgP-PO_4/l).

GHG emissions were correlated to nitrate concentrations measured in the dams, and also to water temperature and salinity, but not to measured soluble phosphate.

The authors note that the absence of correlation with phosphate is surprising, and requires further research.

They conclude that greenhouse gas emissions of small agricultural impoundments can be significant, and should be included global carbon budgets (whereas at present such small dams are not included). They suggest that measures to limit nitrate losses could significantly reduce GHG emissions: **a 25% reduction in nitrate could halve GHG emissions** from such small agricultural dams.

"Punching above their weight: Large release of greenhouse gases from small agricultural dams", Q. Ollivier et al., Glob Change Biol. 2019;25:721–732, http://dx.doi.org/10.1111/gcb.14477

Impacts on plants and plant P uptake

CO_2 and Phosphorus Use Efficiency

Bhattacharya (2019) provides a detailed analysis (60 pages) of how changing environmental conditions will impact Phosphorus Use Efficiency (PUE), as Chapter 5 in the book "Changing Climate and Resource Use Efficiency in Plants".

The chapter summarises the importance of phosphorus and of PUE in agriculture, P requirements of different crops, microbial mobilisation of soil P, impacts of P-application on PUE, interactions between CO_2 and N and PUE and different approaches to improve plant PUE.

Fifteen different definitions of PUE or similar terms are outlined and assessed, based on e.g. yield increase, biomass, grain P content, P uptake …

In the section on elevated CO_2 and PUE, it is emphasised that **the plant growth stimulation effect of increased atmospheric carbon dioxide (eCO_2) is likely to be severely constrained (maybe reduced by half) by nitrogen limitations.**

ESPP comment: this means that atmospheric CO_2 will not be "self-regulating": buffering of CO_2 emissions by plant uptake will be limited.

Studies also show limitation by bioavailable P (*BassiriRad 2001*, *Jin 2013*) or show increased P requirements with eCO_2 (*Lewis 2010*, *Jin 2012*).

Studies show diverging results concerning impacts of eCO_2 on plant tissue P concentration: increased, unchanged or reduced.

The author suggests that P transformations in soil will accelerate with eCO_2, including P mineralisation from organic material, because of accentuated vegetation processes. One study (*Jin 2014*) found that with eCO_2, P immobilisation by soil microbes was also accentuated.

In a review of nearly 200 publications, Jin (2015) concluded that eCO_2 will result in significantly increased plant P demand, because of stimulated photosynthesis and growth.

eCO_2 will result in changes in root morphology and increased root depth, as plants seek to access nutrients. Changes observed in a number of eCO_2 plant trials include increases in root biomass, root length, lateral roots and root clusters.

A few plant trials also show **increases in root exudates**, which are important for plant P uptake, with eCO_2, e.g. organic acids. Tests also show that eCO_2 can directly stimulate increased production of root exudates in plants, by changing carbon fluxes along the glycolic pathway.

eCO_2 has also been shown to modify soil conditions (e.g. decreasing pH) and soil micro-organisms. eCO_2 has been shown to **increase populations of P-solubilising micro-organisms and of AMF (arbuscular mycorrhizal fungi).** eCO_2 has also been shown to increase the activity of enzymes in the rhizosphere relevant to P cycling (e.g. protease, phosphomonesterase …).

Two tests have shown that eCO_2 led to increased plant available soil phosphorus in the rhizosphere (extractable P, one 5-year study - Khan et al., 2006, one 6 weeks – Jin et al. 2013).

The authors do however, like Bhattacharya above, note the **question of nitrogen limitation**. eCO_2 may reduce plant tissue N content, and so the decomposition rate of plant residues in soil, so reducing mineralisation and P availability.

In book "Changing Climate and Resource Use Efficiency in Plants" (324 pages), A. Bhattacharya, ISBN 9780128162095, chapter 5 (65 pages) "Changing Environmental Condition and Phosphorus-Use Efficiency in Plants", 2019 https://doi.org/10.1016/C2017-0-04681-5

"The impact of elevated carbon dioxide on the phosphorus nutrition of plants: a review", J. Jin et al., Annals of Botany 116: 987–999, in Special Issue on Plants and Climate Change, 2015 https://doi.org/10.1093/aob/mcv088

Changes in nutrient ratios in plant tissue

Xu (2020) analyses data on foliar C:N and N:P ratios to estimate effects of warming, increased precipitation, droughts, increased N input, increased CO_2.

Over 2 200 paired field data points from 123 publications include crops, mosses, trees and shrubs.

Foliar P increased with warming, precipitation and with N input but decreased with droughts. Warming and precipitation impacted foliar P more than foliar N.

Foliar N:P ratios did not change with precipitation or warming, declined with eCO_2 and increased under drought and N addition. However, the response magnitude of foliar N:P ratio to eCO_2 decreased with treatment duration.

This differs from Deng (2015) whose analysis of 112 studies concluded that increased atmospheric CO_2 leads to lower N:P ratios in terrestrial plants, possibly because of enhanced P mineralisation in soil (see summary of Deng 2017 in this SCOPE).

The authors note that further studies are needed concerning the impacts of droughts and of increased precipitation, and underline that **the availability of soil water (which is modified by these) strongly affects plant P uptake**.

"Variations in foliar carbon:nitrogen and nitrogen:phosphorus ratios under global change: a meta-analysis of experimental field studies", S. Xu, J. Sardans, J. Zhang, J. Peñuelas, Scientific Reports volume 10, Article number: 12156 (2020) https://doi.org/10.1038/s41598-020-68487-0

Increasing N increases plant P uptake

Deng (2017) analyses data from 288 study sites (in 192 publications) looking at how increased nitrogen input impacts various aspects of ecosystem phosphorus cycling.

N input led to increases in plant (+34%) and litter (+15%) biomass, resulting in an increase in total P present in plants (+17%) despite a decrease in plant P concentrations (-8%). Effects on litter and soil P were unclear because of data biases. N-induced changes both in biomass and in plant P concentration were significantly different between tropical and temperate forests, grasslands and wetlands, and also varied with different N forms and with soil pH.

Overall, N inputs led to modifications in P-cycling with increased P sequestration in plant and in litter biomass, and probably lower soil available P, but with high variation between different ecosystems.

"Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: A meta-analysis", Q. Deng et al., Global Ecol Biogeogr. 2017;26:713–728 https://doi.org/10.1111/geb.12576

See also "Down-regulation of tissue N:P ratios in terrestrial plants by elevated CO_2", Q. Deng et al., Ecology, 96(12), 2015, pp. 3354–3362 http://www.jstor.org/stable/24702592

Climate change will reduce soil available P …

Hou (2017) concluded from analysis of soil sample data that climate change factors (warming, precipitation changes) will significantly reduce soil available phosphorus.

Data from 802 soil samples (96 publications) are analysed, linking sequential P fractions (methods: Hedley; Tissen & Moir) to temperature and precipitation (both: mean annual).

Results suggest that **labile inorganic P in soil is significantly decreased with increased temperature**, and to a lesser extent with increased rainfall.

The authors suggest that increased temperature probably reduces soil P availability by increasing wind erosion of smaller soil particles, so increasing soil sand content. Also, increasing temperature accelerates microbial decomposition more than it increases plant growth, so tending to decrease soil organic carbon.

The authors conclude that **changes in soil P availability resulting from temperature and precipitation changes because of climate change** are likely to be of the same order as variations related to factors such as soil type, soil pH and vegetation.

This is demonstrated for temperate pastures by recent results from the New Zealand FACE showing decreased labile inorganic P and increased organic P in soil in response to long-term CO_2 enrichment (>20 years).

The **New Zealand FACE (Free Air CO_2 Enrichment) study** has been running on fertilised (according to agronomic recommendations) sheep grazed grassland since 1997, with three 12m eCO_2 rings (c. 500 ppm) and three control rings.

After more than twenty years of eCO_2, **Olsen P has decreased (by around one third)** as well as total N, nitrate-N and ammonia-N**.** On the other hand, soil total carbon and microbial biomass P (MBP) have increased. This has resulted in an **accumulation of organic P**.

"Effects of climate on soil phosphorus cycle and availability in natural terrestrial ecosystems", E. Hou et al., Glob Change Biol. 2018;24:3344–3356 https://doi.org/10.1111/gcb.14093

"Long-term atmospheric carbon dioxide enrichment decreases soil phosphorus availability in a grazed temperate pasture", D. Touhamia,et al., Geoderma 378 (2020) 114621 https://doi.org/10.1016/j.geoderma.2020.114621

… but may increase P losses

A meta-analysis of 79 studies (over 1 800 observations) suggests that increased drying and wetting of soil, susceptible to result from climate change, solubilises P in soil more than N, with consequences for plant nutrient supply and leaching.

Data covered mainly lab tests, with some field data, from across the world, but with most data points in Europe, Asia and North America.

Drying then rewetting tended to overall increase mineralisation of phosphorus, resulting in increased plant P availability and P leaching (more than doubling), but no net increase in N mineralisation (possibly because compensated by plant N uptake), and a significant reduction in leaching of nitrate, and an increase in atmospheric N_2O emissions. Effects increased with drying intensity. On the other hand, soil microbial processes recovered rapidly from drought after rewetting.

The authors conclude that drying then rewetting leads to a soil misbalance between N and P, with this effect more pronounced in forest than agricultural soils. They indicate that this may result in increased soil P losses to aquatic systems, as drought and rain cycles are accentuated by climate change, but that further research is needed in particular in realistic field conditions.

"Responses of soil nitrogen and phosphorus cycling to drying and rewetting cycles: A meta-analysis", D. Gao et al., Soil Biology and Biochemistry 148 (2020) 107896
https://doi.org/10.1016/j.soilbio.2020.107896

Climate change and phosphorus 'pools'

A meta-analysis of published data looks at how climate change and nutrient management may impact levels of phosphorus in soils and plants, concluding that effects are likely to be simply additive (rather than synergetic or antagonistic.

Over 1750 observations from over 280 published articles were analysed, after selection of data to limit to those with reliable and relevant results, and using only one data point from each primary study. Factors considered were: increased atmospheric CO_2, warming, increased rainfall and anthropogenic N or P input, and their impact on soil phosphorus levels (Olsen inorganic phosphorus in top 30 cm of soil, considered to be plant available), soil microbial biomass P and phosphorus in plants (at the single plant level and for the whole plant community).

The analysis concludes that phosphorus inputs increase both soil and plant P (unsurprisingly), whereas **nitrogen inputs have little impact on phosphorus pools**.

Atmospheric carbon dioxide appeared to reduce soil phosphorus (but only 6 - 7 data points) but did not show to impact plant P levels (69 data points). For plant P, these conclusions differ from the meta-analysis by Deng, 2015 (see summary of Deng 2017 in this SCOPE, whose authors suggest that eCO_2 may stimulate phosphatase activity in soil). The authors note that impacts or increased CO_2 vary widely between plant species, which may explain this difference.

Warming appeared to slightly increase soil available P, more significantly increase soil microbial P, but (contradictorily) slightly decrease total soil P (11 – 30 data points). Warming appeared to slightly decrease individual plant P (47 data points) but increase plant community P (only 4 data points). Again, the authors note that this may result from **variation between different plant species**.

"Individual and combined effects of multiple global change drivers on terrestrial phosphorus pools: A meta-analysis", K. Yue et al., Science of the Total Environment 630 (2018) 181–188
https://doi.org/10.1016/j.scitotenv.2018.02.213

Climate change and the food system

Climate change and nutrition

A review paper to the Nutrition Society underlines how much the food system contributes to climate change, questions current levels of protein intake, and underlines that both lower meat consumption and climate change impacts on crops may cause diet micronutrient deficiencies.

Climate change is a driver of increasing global hunger (*FAO 2018*). The number of extreme climate events which have impacted agricultural production has doubled since 1990. Conversely, **the food system (in the UK) accounts for 30% of greenhouse gas emissions, with nearly half of this related to agriculture** (the remainder from retail, catering, home cooking, food processing, packaging etc) (*Garnett 2011*).

Many studies conclude that to reduce food greenhouse impacts, it is necessary to reduce meat consumption (*Aleksandrowicz 2016*). This is often understood as replacing meat protein by plant protein. The authors suggest that **the question should instead be to reduce protein intake, which is currently around twice dietary requirement in the UK**. Meat is around 1/3 of UK protein intake, so the current without diet would provide adequate protein intake.

However, meat provides a significant proportion (16 - 37%) of UK dietary intake of the micronutrients iron and zinc, for which daily intake is already below the recommended level (LRNI) for a significant proportion of the population (e.g. over half of girls 11-18 years for iron). **Reducing meat intake therefore requires addressing micronutrient intake**.

One way to achieve this would be to **eat more wholegrain and less "white" flour**. The UK currently eats 2x more white bread than brown, and 4x more refined grains in breakfast cereals. This would also address fibre, for which the UK average intake is below the recommended level.

Another potential challenge linking climate change to nutrition is that staple crops growing under higher CO_2 levels may have lower contents of zinc, iron and protein (data from 41 staple crop FACE experiments = free air carbon dioxide enrichment in *Myers 2014* and *Smith 2018*).

"Nutrition from a climate change perspective", J. Macdiarmid & S. Whybrom,, Proceedings of the Nutrition Society, Nutrition Society Summer Meeting 10–12 July 2018
https://doi.org/10.1017/S0029665118002896

Eutrophication and climate change: export of New Zealand beef

Climate change and eutrophication impacts of import beef to Europe, from a region of New Zealand with specific nitrogen application limits, were estimated as lower than European beef.

A cradle-to-market assessment of **beef production in the Lake Taupö region of New Zealand** included impacts in production, processing and transport, using the FARMAX model for farm productivity and OVERSEER model for farm N, P). Greenhouse gas emissions and eutrophication impacts were modelled for six different beef farm systems using New Zealand regional LCA indicators. These were compared to published data for "average" European beef (Leip 2015 using CAPRI, nitrogen), Portuguese beef (Presumido 2018, phosphorus) and Italy (Bragaglio 2018, nitrogen).

Presumido 2018 published LCAs for two different beef production systems in North-East Portugal: semi intensive (feeding local hay and concentrated feeds) and organic extensive. The authors conclude that **phosphorus**

is the main 'Eutrophication Potential' contributor (50-70%), principally from manure nutrient losses either onto pasture or in feedlots (the feedlot slurry is indicated to be spread on fields). Overall Eutrophication Potential is estimated to be 25% higher for the semi-intensive systems, considering also nitrogen losses.

Bragaglio 2018, in an LCA of four different types of beef production in Italy (data from 25 farms), considered only nitrate losses for eutrophication effect (not phosphorus), with the main driver identified to be emissions from feed used in fattening.

Although Lake Taupö, New Zealand's largest lake, is still almost pristine there is slow deterioration of water quality, and so specific nitrogen leaching limits have been fixed for each farm.

Using standard eutrophication indicators (ReCiPe), based only on phosphorus release, then the farm systems using 100 kg nitrogen / ha / year appeared to show a lower freshwater eutrophication impact. However, **when nitrogen was also taken into account, the zero N fertiliser farms showed lower eutrophication impact. This is probably because the N fertiliser use enabled to increase farm cattle numbers.**

The greenhouse gas emission ranking of the farm systems was similar to that of nitrogen-related eutrophication. The farms using mineral fertiliser show higher estimated GHG impact, due to N_2O emissions estimated for fertiliser use. Dairy-farm beef shows lower GHG emissions only because part of the methane from the cows is allocated to the dairy products not to beef.

The study conclusions suggest that the eutrophication and climate change impact of this New Zealand beef, imported to Europe, is lower than for European beef production. ESPP notes that (a) the different LCAs used for reference Europe may not have comparable methodologies and (b) **the conclusion may not be valid to beef produced under comparable environmental constraints in Europe**.

"Eutrophication and climate change impacts of a case study of New Zealand beef to the European market", S. Payen et al., Science of the Total Environment 710 (2020) 136120
https://doi.org/10.1016/j.scitotenv.2019.136120

"Environmental Impacts of the Beef Production Chain in the Northeast of Portugal Using Life Cycle Assessment", P. Presumido Agriculture 2018, 8, 165;
http://dx.doi.org/10.3390/agriculture8100165

"Environmental impacts of Italian beef production: A comparison between different systems", A. Bragaglio et al., J. Cleaner Production 172 (2018) 4033e4043 http://dx.doi.org/10.1016/j.jclepro.2017.03.078

Climate change and nutrient management

Water basin management and greenhouse emissions

The potential for feasibly reducing greenhouse gas (GHG) emissions from surface waters and farmland, for a Netherlands water board, is estimated to be of the same order of magnitude as total net emissions related to the company's wastewater treatment operations.

The Dutch water authority *Amstel, Gooi and Vecht* (operated by Waternet) covers a 700 km^2 area and a population of c. 1.3 million. The board has an objective to reduce to zero the net total emissions from its business operations (water and sewage treatment, personnel transport, outsourced maintenance, materials …), estimated at 50 ktCO$_2$-eq./year (2014).

The **total GHG emissions from surface waters and farm peatlands in the Water Board area are estimated** from data on water bodies (ditches, lakes, canals, ponds) and soil types combined with literature data on methane (diffusive and ebullitive) and carbon dioxide emissions (adequate data was not available on nitrous oxide emissions). Total GHG emissions from water bodies are estimated at 230 ktCO$_2$-eq./year, principally from ditches (51%) and lakes (39%). Additionally, drained agricultural peat meadows (nearly 20 000 ha) are estimated to emit a total of 470 ktCO$_2$-eq./year (24 t/ha/year), mainly as CO_2 but with some methane and N_2O.

Literature-based estimates are given for potential GHG emission reductions for different possible management actions.

For **lakes and ponds**, it is expected that reducing nutrient inputs would reduce net GHG emissions, because these are estimated to be net emitters of GHG (carbon dioxide and methane). However, reductions possible by management measures are uncertain and so are not estimated.

Most of the region's **ditches** are eutrophic or hypertrophic. Their GHG emissions could be reduced by dredging out sludge containing organic matter and by reducing soil erosion and organic matter input from the surrounding agricultural peat soils. Deeper ditches, with less (labile) organic matter in the sediment, are expected to have lower methane and carbon dioxide emissions, due to higher oxygen concentrations and improved submerged vegetation. Deeper water columns may also lower sediment temperature, so reducing methane production. It should however be ensured that deepening ditches, that is the water level in the ditches should be kept the same or higher. Overall, it is estimated that a **50% reduction in total methane emissions from ditches** would reduce GHG by around 26 ktCO_2-eq./year.

For the agricultural land, **100% reduction of CO_2-eq. emissions is estimated for reconversion back to natural habitat,** c. 63% for paludiculture (growing plants on waterlogged land), c. 21% by increasing summer groundwater levels by 20 cm. Subsurface irrigation makes little difference to CO_2-eq. emissions (each of these estimates is considered to be conservative). Based on the surfaces of agricultural land for which these different measures are considered technically or socially feasible (a total of only 17% of the 19 400 ha), a GHG emission reduction of 27 ktCO_2-eq./year is estimated.

The authors underline that the figures derived are very estimative, but show that **GHG emissions reductions from improved water and land management are potentially as high or higher than total net emissions from sewage and drinking water collection and treatment**. They underline that the proposed actions to reduce agricultural land and water body GHG emissions would have **other benefits, such as improving water quality, reducing soil erosion and restoring biodiversity**.

"The potential impact of measures taken by water authorities on greenhouse gas emissions", A-M. Motelica-Wagenaar et al., Proc. IAHS, 382, 635–642, 2020, https://doi.org/10.5194/piahs-382-635-2020

Agriculture BMPs, nutrient losses & GHGs

A conference abstract suggests that analysis is needed of the possible greenhouse gas impacts of certain agricultural BMPs (Best Management Practices) recommended to reduce nitrogen losses.

Tests were carried out on a US farm using "**conventional no-till**" corn – soybean rotation, with a radish crop in the non-growing season, using GMO crops and herbicides. ESPP note: this is "conventional" in the US, not in Europe.

For three years, two fields used **Drainage Water Management (DWM),** that is boards installed in drainage ditches to slow and control runoff, and two controls were without DWM. This practice is recommended to reduce dissolved nitrogen and trap particulate phosphorus. Soil nitrate content and moisture were monitored at points in the field and nutrients were measured in the drain discharge water (flow, nutrients: dissolved nitrogen, total P).

Results suggest a small **increase in nitrous oxide (greenhouse gas, N_2O) losses from soil in the DWM fields** (to be expected with increased humidity, but not significant), no significant change in methane emissions, significant reductions in total dissolved nitrogen release, but an **increase in total phosphorus release**. The P release may result from humidity reducing soil oxygen, leading to reducing conditions which cause iron-bound phosphorus to be released.

The authors conclude that impacts on different nutrient releases and possible impacts on greenhouse gas emissions should be considered when considering agricultural BMP (best management practices) for nutrient management.

"Pollution Swapping of N_2O and CH_4 Emissions with Dissolved Nitrogen and Phosphorus Export in Drainage Water Managed Agricultural Fields", J. Hagedorn et al., AGU2019 – ESSOAr https://doi.org/10.1002/essoar.10501940.1

China: climate change means tighter nutrient limits

Modelling based on lake and reservoir data in China suggest that, with climate change, water nutrient concentration targets will need to be reduced by 46% for N and 15% for P by 2100.

Modelling was based on data from 17 lakes and 9 reservoirs in China (mainly central Eastern China) for phosphorus, nitrogen and chlorophyll-α (monthly monitoring 2006-2010). Three climate models (GISS-E2-H, HadGEM2-ES, MRI-CGCM3) were used with four greenhouse gas emission scenarios were used to predict changes in air temperature.

'Nutrient criteria', defined as the maximum water nutrient concentrations necessary that do not threaten waterbody functions (using General Additive Models, GAMs), were determined as 880 µgTN/l for total nitrogen and 21 µgTP/l for total phosphorus.

The models used suggest that, **with climate change, these water nutrient criteria would have to be reduced by 6 - 46% for TN and 4 - 15% for TP.** Although these lakes and reservoirs are currently phosphorus-limited, both P and N, with surface temperature, were used to predict chlorophyll. It is noted however that strict control of phosphorus would probably suffice to limit algal development. Also, the reduction in TP criteria required is significantly smaller than for TN, suggesting that **policy should target reducing phosphorus loads**.

"Stricter nutrient criteria are required to mitigate the impact of climate change on harmful cyanobacterial blooms", S. Huo et al., Journal of Hydrology 569 (2019)
https://doi.org/10.1016/j.jhydrol.2018.12.030