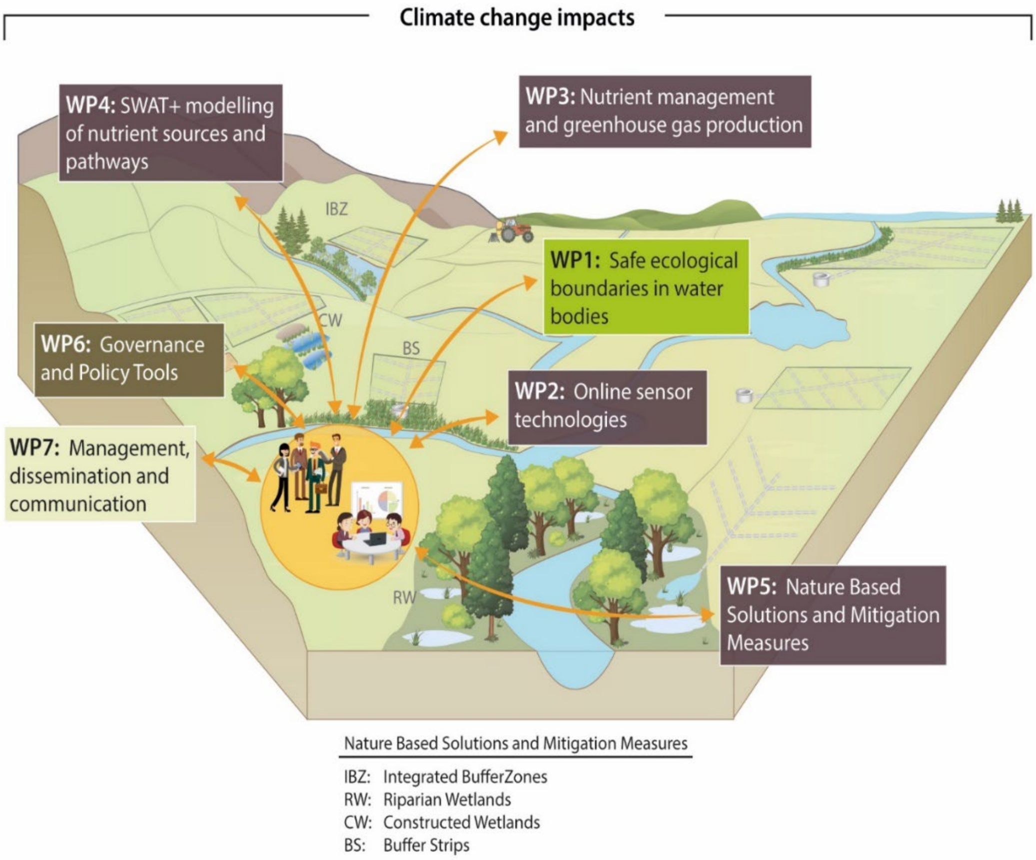

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NORDBALT ECOSAFE

Nitrogen and phosphorus load reduction approach within safe ecological boundaries for the Nordic-Baltic region

https://projects.au.dk/nordbalt-ecosafe

POLICY BRIEF NO. 7

Northern Nordic river mouth N:P:Si stoichiometry: spatio-temporal patterns and implications for eutrophication management

Background: Stoichiometry vs. Single Element Approaches

Analysis of 88 Nordic river mouths draining to the Baltic and North Seas suggests limitations in current single- nutrient management approaches and indicates potential benefits of multi-element strategies for marine eutrophication management. These findings from Norwegian, Swedish, and Finnish monitoring programs may offer insights for European river systems with similar characteristics. In the Nordic region and across Europe, human activities have altered natural element cycles in ways that can lead to marine eutrophication. Agricultural practices, particularly widespread use of nitrogen (N) and phosphorus (P) fertilizers, have increased nutrient fluxes from land to sea. Simultaneously, water regulation and damming may have decreased silicon (Si) fluxes from terrestrial to marine systems. This combination can create stoichiometric imbalances with ecological consequences. The ecological significance of these imbalances relates to algal community composition. When sufficient Si is available relative to other nutrients (N and P), diatoms may dominate algal communities. However, when Si is depleted relative to N and P, conditions may favor other algal groups, including potentially harmful cyanobacteria. This relationship suggests that managing nutrient stoichiometry, rather than individual nutrients alone, may be relevant for controlling harmful algal blooms. There is growing recognition that new approaches to managing multiple element cycles may help to address environmental challenges, including reducing negative impacts of surface water eutrophication.

Our findings suggest resource allocation could be informed by distinguishing between rivers that may benefit from phosphorus reduction (the majority), nitrogen reduction (4 rivers in the study), or joint N-P management (39 rivers). This targeting capability could help direct conservation funding toward interventions that may address limiting nutrients rather than implementing broad approaches based on single-element thresholds. Additionally, identifying the potentially limiting nutrient may help target reduction measures and potentially increase the acceptability of management measures to affected stakeholders by focusing efforts where they may be most effective.

Element cycles can be considered either in isolation or jointly with other elements—the latter approach is known as stoichiometry. Stoichiometric analyses ideally consider both the relative proportions of different elements and their absolute concentrations, providing a more comprehensive understanding of nutrient dynamics than single-element assessments. Most current water quality management programs, including the EU Water Framework Directive, set targets for individual nutrient concentrations or loads. However, such single-element approaches may not fully account for environmentally relevant interactions between nutrients, including consideration of limiting nutrients and their ecological consequences. Current approaches, including EU Water Framework Directive classifications and indices like the Carlson Trophic State Index, evaluate nutrients individually and focus on absolute concentrations or loads. These methods may not fully capture stoichiometric imbalances that could influence algal community composition.

The stoichiometric approach is based on the Redfield ratio, derived from Alfred Redfield's 1930s observations of marine phytoplankton elemental composition. While most studies have focused on carbon (C), N and P (C:N:P) ratios, Redfield also developed ratios incorporating silicon (Si), with the commonly used molar ratio of C:N:P:Si being 106:16:1:16 for marine systems. There are ongoing debates in eutrophication management as to whether prioritizing N or P reductions is more likely to improve environmental conditions. Multi-element N:P:Si approaches may complement single-nutrient strategies by helping identify which nutrient could potentially limit harmful algal bloom development and inform this longstanding question.

The Redfield ratio approach considers Si availability to support diatom communities. When silicon becomes depleted relative to other nutrients—a condition that single-element monitoring may not detect—algal community composition may shift. The Nordic findings suggest that this framework could help identify rivers where stoichiometric conditions may influence algal bloom risk. N:P:Si monitoring in Nordic river systems shows that nutrient limitation varies across the Baltic and North Sea regions. The Carlson Trophic State Index might suggest similar eutrophication potential between two rivers with identical phosphorus concentrations, yet stoichiometric conditions could differ due to Si availability. For example, a river might meet Water Framework Directive phosphorus standards yet still experience conditions that could favor certain harmful algal groups if Si levels are depleted relative to N inputs.

By measuring all three elements, managers may better understand which nutrient management approaches could potentially influence algal community composition.

Datasets

The analysis presented here draws on data from 88 river mouths across three Nordic countries: 20 in Finland, 21 in Norway, and 47 in Sweden, with observations collected between 2017 and 2024 (Figure1,3). These data come from established national monitoring programmes that collect monthly samples for water quality analysis and HELCOM/OSPAR reporting. The Swedish programme has been operational since the mid- 1960s and represents one of the longest-running water quality monitoring efforts in the region. The Norwegian programme includes rivers monitored since 1990, with an expanded programme for minimally impacted catchments beginning in 2017. Finnish data were available from the 1990s to present from the national monitoring programme, focusing on rivers without large lakes or significant point sources of nutrients in their catchments. All programmes collect surface water samples (typically <1 meter depth) have at least six observations per year.

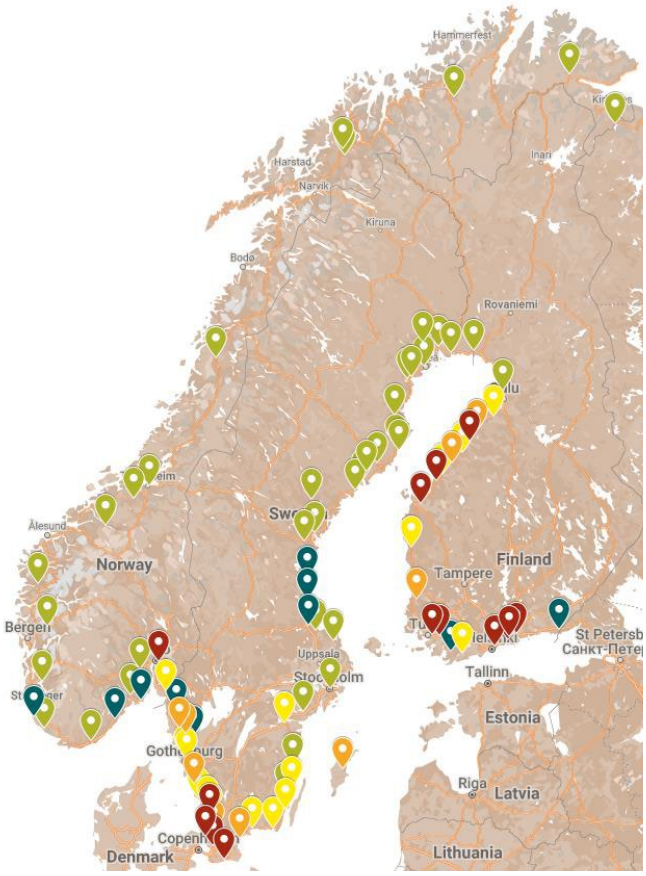

Figure 1: Locations of river mouth monitoring sites in Norway, Sweden and Finland. Locations are colour coded by the trophic status index (TSI) class of the Redfield depleted nutrient (i.e., molar N:P < 16 reports TSI(DIN), molar N:P > 16 reports TSI(TP). Light green represents ultra-oligotrophic conditions (TSI < 30), dark green shows oligotrophic river mouths (30 < TSI < 40), yellow represents mesotrophic conditions (40 < TSI < 50) while orange indicates eutrophic conditions (50 < TSI < 60) and red indicates hyper-eutrophic conditions (TSI > 60).

Ternary Diagrams as Communication Tools

Ternary diagrams offer visualization capabilities for communicating stoichiometric relationships to stake- holders (figures 2,3). These plots display relative nutrient proportions and deviations from Redfield ratios, potentially making technical assessments more accessible to policymakers and the public. The diagrams can help identify nutrient depletion patterns across river systems and facilitate assessment of regional management priorities. They distinguish between phosphorus-depleted, nitrogen-depleted, jointly-depleted, and balanced systems, which may support resource allocation decisions. The visual format enables comparative analysis between catchments and tracking of management outcomes. However, ternary diagrams require interpretation training and may simplify complex ecological interactions. They represent relative rather than absolute concentrations, potentially masking situations where all nutrients are simultaneously elevated or depleted. Additionally, the diagrams show stoichiometric conditions rather than actual ecological outcomes, which depend on additional factors like temperature and light availability.

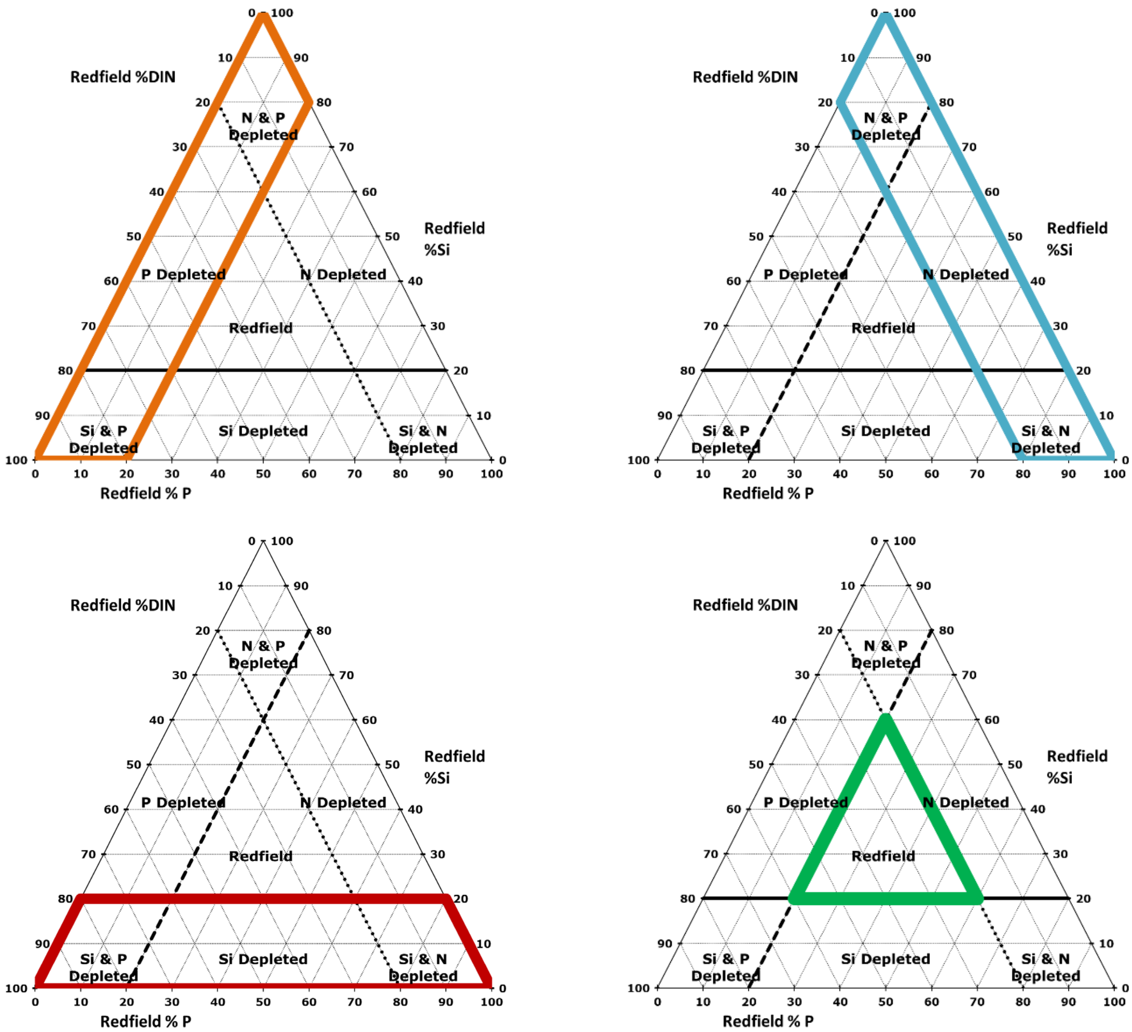

Figure 2: Ternary diagram for representing N:P:Si Redfield ratios showing zones of relative nutrient depletion. The point at the centre of the ternary diagram (33.33, 33.33, 33.33) corresponds to the Redfield molar ratio of N:P:Si = 16:1:20. The horizontal lines represent the proportion of Si in a sample scaled to the Redfield ratio (Redfield %Si). The diagonal lines running from bottom left to top right represent the proportion of total phosphorus in a sample relative to the Redfield ratio (Redfield %P). The diagonal lines running from bottom right to top left represent the proportion of inorganic nitrogen in a sample scaled to the Redfield ratio (Redfield %DIN). The upper left panel (orange lines) shows the zone of relative P depletion. The upper right panel (blue lines) shows the zone of relative N depletion while the lower left panel (red lines) shows the zone of relative Si depletion. The lower right panel (green lines) shows the zone of “balanced” nutrient concentrations.

Results

Overall arithmetic average river mouth N:P:Si values and their deviations from the Redfield ratio were calculated for all Nordic river mouth monitoring locations based on measurements made between 2017 and 2024 (below). There was a relationship between Redfield ratios and trophic status, with more oligotrophic river mouths typically showing N, P or joint NP depletion and more eutrophic sites typically showed lower levels of N, P or NP depletion relative to Si.

Most rivers (n=77) were P depleted relative to the N:P:Si Redfield ratio (Figure 3). Of these, 39 showed evidence of joint N, P depletion (plotting in the diamond at the top of Figure 3). Most of these rivers are in northern Sweden as well as Norwegian rivers draining to the Arctic Ocean. Three rivers in Sweden and one in Finland were N depleted relative to P and Si. Four rivers in Finland, two in Sweden and one in Norway fell into the "balanced" Redfield zone at the centre of the plot where each nutrient had a Redfield percentage >20%. No rivers showed evidence of overall Si depletion (i.e., Redfield Si percentage < 20%).

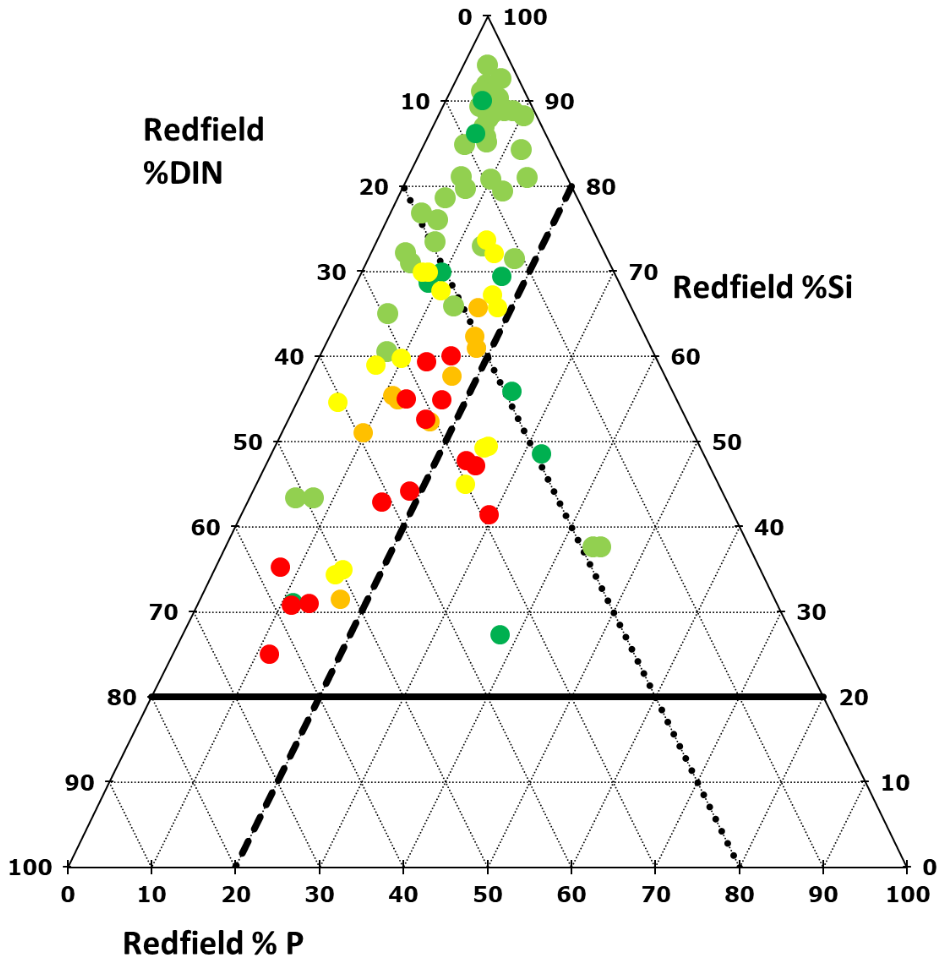

Figure 3: Average (2017-2024) molar N:P:Si ratios relative to the16:1:20 Redfield ratio observed at Nordic river mouths. Locations are colour coded according to the trophic status index (TSI) of the Redfield depleted nutrient (i.e., molar N:P < 16 reports TSI(DIN), molar N:P > 16 reports TSI(TotP)). Light green represents ultra-oligotrophic conditions (TSI < 30), dark green shows oligotrophic river mouths (30 < TSI < 40), yellow represents mesotrophic conditions (40 < TSI < 50) while orange indicates eutrophic conditions (50 < TSI < 60) and red indicates hyper-eutrophic conditions (TSI > 60).

European water quality monitoring programs could consider integrating silicon measurements into existing protocols, particularly where such data are currently lacking for Baltic tributaries. The Nordic study suggests that without silicon data, assessments may not capture potential harmful algal bloom risk factors. Regional adaptation of management strategies based on stoichiometric patterns could potentially improve management effectiveness while maintaining compatibility with international reporting requirements under, e.g., UN SDG 14.1.1a frameworks. The Nordic study identified variation in silicon depletion patterns, with southern and eastern Baltic regions showing greater silicon depletion relative to nutrients.

This approach represents one tool among many for eutrophication management and should be considered alongside other assessment methods. The relationship between stoichiometric ratios and actual harmful algal bloom occurrence requires further validation. Additional research is needed to understand how seasonal variations in stoichiometry relate to ecological outcomes and to validate findings across different geographic regions and water body types.

Policy Recommendations

Incorporate or maintain silicon measurements in water quality monitoring

European surface water monitoring programs should consider adding silicon measurements to complement existing monitoring. Our study indicates that Si depletion relative to N and P may influence algal community composition, with potential implications for harmful algal bloom development.

Adopt nutrient-specific reduction strategies based on stoichiometric analysis:

Consider targeting the limiting nutrient rather than implementing broad-spectrum nutrient reductions. Analysis of Nordic river mouths indicates that 77 of 88 Baltic/North Sea tributaries show P depletion relative to the Redfield ratio, with 39 showing joint NP depletion (Figure 3). Targeting the appropriate nutrient based on stoichiometric analysis may improve management effectiveness compared to reducing non-limiting nutrients.

Develop region-specific management targets

Tailor nutrient management strategies to regional stoichiometric patterns rather than applying uniform approaches. Our study shows variation across regions—Finnish and eastern Baltic rivers generally appear to require P reduction, while only 4 rivers were N-limited. Management strategies should accommodate this geographic variation in stoichiometric conditions.

The NORDBALT-ECOSAFE consortium will develop and demonstrate innovative methods and establish best practices to improve current river basin management and governance by reaching the following major aims: i) setting ecologically safe nutrient boundaries in different types of water bodies; ii) improving monitoring of nutrient concentrations by comparing benefits of novel high-frequency online sensors with traditional monitoring; iii) establishing nutrient loading tipping points for carbon sequestration and emissions in water bodies; iv) establishing a harmonised river basin modelling tool for precise estimation of nutrient sources, pathways and transport; v) demonstrating novel Nature Based Solutions (NBSs) and Mitigation Measures (MMs) for reaching the required nutrient load reductions; and vi) developing advanced solutions supporting regional governance structures to implement the most suitable measures to meet the ecological nutrient boundaries. A conceptual diagram is shows the links between different parts of the project and a map shows our working platform consisting of six river basins and riverine monitoring points under HELCOM and OSPAR. https://projects.au.dk/nordbalt-ecosafe