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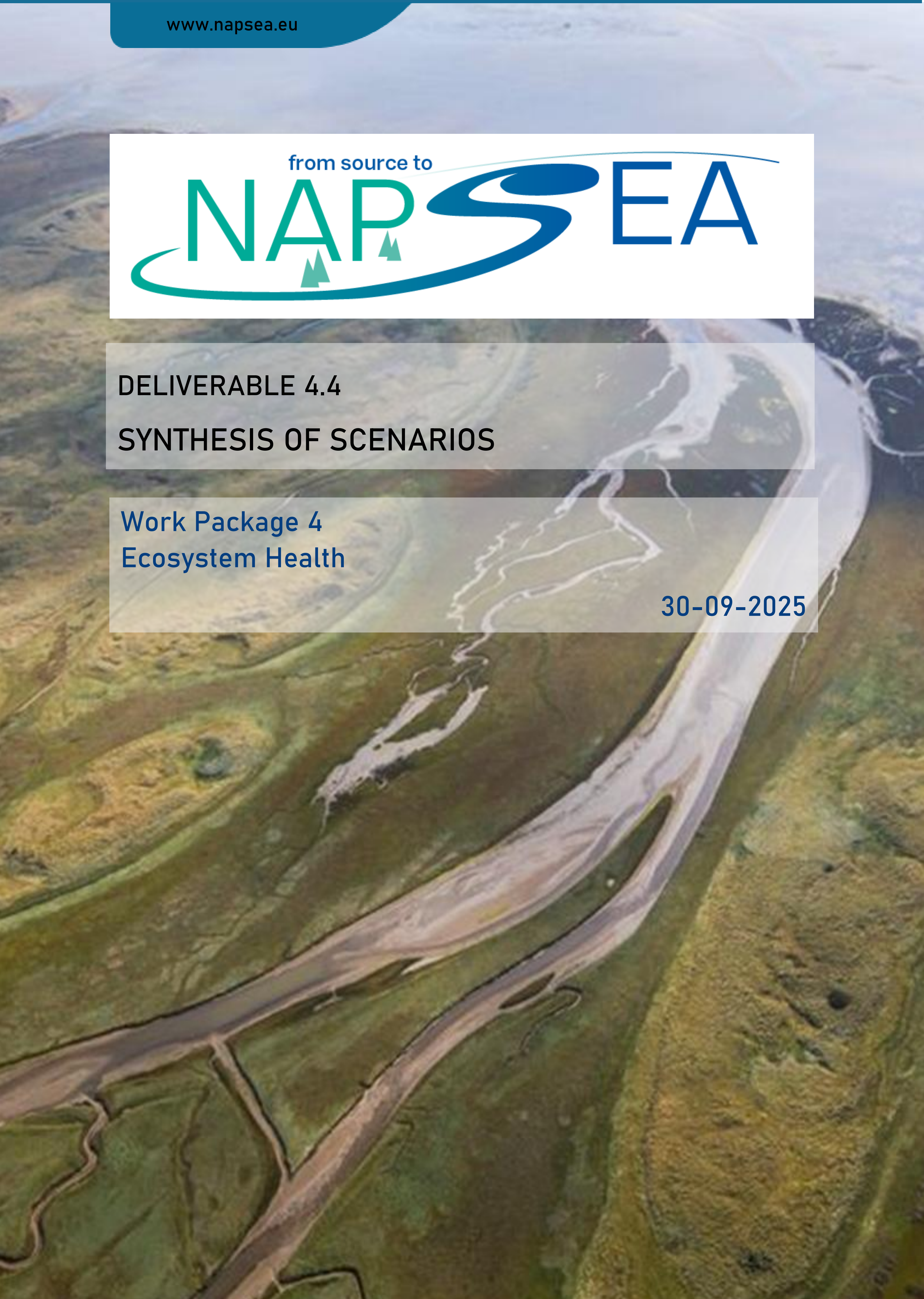

DELIVERABLE 4.4

SYNTHESIS OF SCENARIOS

Work Package 4
Ecosystem Health

30-09-2025

Grant Agreement number	**101060418**
Project title	**NAPSEA: the effectiveness of Nitrogen And Phosphorus load reduction measures from Source to sEA, considering the effects of climate change**
Project DOI	[10.3030/101060418](10.3030/101060418)
Deliverable title	Synthesis of scenarios
Deliverable number	D 4.4
Deliverable version	Concept 1
Contractual date of delivery	July 31, 2025
Actual date of delivery	September 30, 2025
Document status	Concept
Document version	1.0
Online access	Yes
Diffusion	Public
Nature of deliverable	Report/presentation
Work Package	WP 4 + Synthesis of scenarios
Partner responsible	HEREON
Contributing Partners	Deltares, Fresh Thoughts, UBA, Rijkswaterstaat
Author(s)	Van Beusekom, J.E.E, van der Heijden, L.H., Blauw, A., Gericke, A., Dworak, T., Geidel, T., Plette, S.
Editor	van der Heijden, L.H.
Approved by	van der Heijden, L.H.
Project Officer	Blanca Saez-Lacava
Abstract	This deliverable synthesizes the work on safe ecological limits, scenarios to reach the proposed reduction, and societal aspects linked to the acceptance of proposed reduction scenarios. Recommendations for policies are formulated.
Keywords	Synthesis; scenarios; reduction; nutrient reduction targets; safe ecological boundaries

Contents

Acronyms

Chl-a	Chlorophyll-a
C^nANDY	Coupled Complex Algal-Nutrient Dynamics
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
EU	European Union
GE	Germany
mHM	mesoscale Hydrological Model
MSFD	Marine Strategy Framework Directive
mQM	multiscale water Quality Model
N	Nitrogen
ND	Nitrates Directive
NECD	National Emission Reductions Commitment Directive
NL	Netherlands
O_2	Oxygen
OSPAR	Oslo-Paris Convention
P	Phosphorus
RCP	Representative Concentration Pathway
Si	Silicon
SRP	Soluble Reactive Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
UWWTD	Urban Wastewater Treatment Directive
WFD	Water Framework Directive
WP	Work Package

NAPSEA project approach

Measures adopted since the late 1970's to combat eutrophication e.g. in the OSPAR- and EU-frameworks (among others WFD, MSFD) resulted in a clear reduction of nutrient emissions and in healthier ecosystems in the North Sea and adjacent Wadden Sea (e.g. de Jong, 2007; van Beusekom et al., 2019).

Although nutrient reductions have led to improvements in ecosystem health, the specific targets for growing season average chlorophyll-a concentrations and near-bottom oxygen levels have not yet been fully achieved across all assessment areas. It is important to note that chlorophyll-a is used as a proxy for algal biomass rather than algal blooms, and the targets are based on seasonal averages rather than peak values. Regional differences also play a role: while several areas meet the targets, locations such as the Northern Delta coast, river plumes of the Scheldt, Meuse, and Rhine, and parts of the German Bight including the Wadden Sea still exceed chlorophyll-a thresholds, and oxygen deficits persist in offshore zones like the Eastern North Sea due to summer stratification.

In marine areas strongly influenced by riverine nutrient loads, current eutrophication targets have not been fully reached. Past measures have already addressed the most accessible sources of nutrient pollution, resulting in substantial load reductions. However, further progress—particularly in regional inland waters—requires more ambitious and costly interventions, and the pace of improvement is slowing down.

At the same time, societal fatigue around nitrogen-related issues has grown, and the topic has become increasingly politicized. This makes it more challenging to maintain momentum for additional measures. To support continued efforts and improve ecological relevance, we are exploring the development of more coherent, transparent, and science-based (eutrophication) measures and targets—moving beyond the current benchmark of historical levels plus 50%—to better reflect ecosystem functioning and resilience.

The NAPSEA project aims at supporting national and local authorities in selecting effective nutrient load reduction measures and policies and in gaining societal support for their implementation. The project's geographical scope covered the catchment of the Wadden Sea, with case studies for the Rhine, Elbe, and Hunze catchments and the Wadden Sea itself. NAPSEA uses an integrated approach to address nutrient pollution from source to sea, combining three complementary perspectives: governance and social acceptance, nutrient pathways and measures and ecosystem health, as illustrated in Figure 1:

1. For the perspective of **ecosystem health,** we analysed currently used indicators as well as their thresholds and explored the development of additional more comprehensive indicators—moving beyond the current targets for chlorophyll-a aiming at a better reflect the benefits of nutrient reduction measures for ecosystem functioning and resilience.
2. The perspective of **pathways and measures** quantifies nutrient emission sources and their pathways to the Wadden Sea with models, to assess how nutrient loads are affected by various scenarios of nutrient reduction measures and climate change.
3. The **governance and social acceptance and acceptability** perspectives assess the coherence of the relevant policy frameworks across scales and the public and farmer support for nutrient reduction measures.

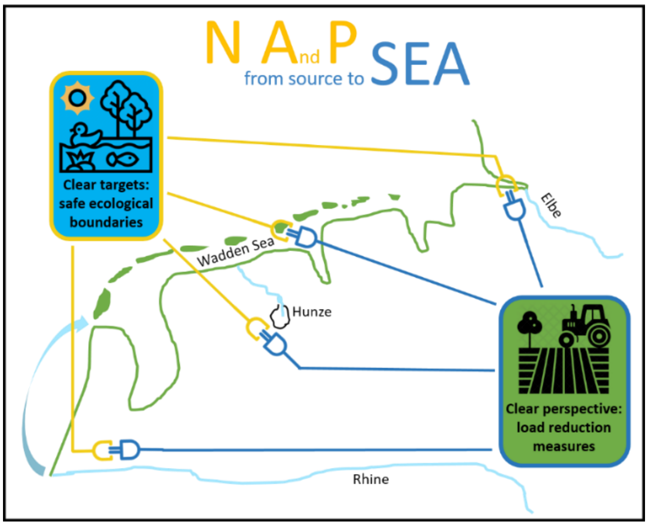

Figure 1. NAPSEA outline: connecting clear targets (safe ecological limits) with clear perspectives on load reduction measures.

Clear alternative targets: safe ecological limits

Current targets and policy frameworks

Current water quality objectives and water improvement measures come from multiple policy frameworks (WFD, MSFD, ND, UWWTD, NECD, etc.) and are not coherent. For example, the coherency in terms of monitoring along the source-to-sea domain/continuum needs to be improved as demonstrated by Table 1 (Enserink et al., 2024).

For the North Sea and Wadden Sea, a strong focus is on chlorophyll-a as a proxy for algal biomass. In addition, the ecological context of why a certain threshold value to determine eutrophication status is chosen is not clear: for instance, a 50% elevation (threshold value) compared to historic conditions (baseline) is often used but lacks a clear ecological concept. OSPAR uses the nutrient concentrations around 1900, which is before the introduction of mineral fertilizer in agriculture, as a baseline. The 50% allowable elevation considers the growth of the human population and intensified agriculture since 1900.

According to the MSFD Descriptor 5 (eutrophication) assessments, which build on the joint and coherent eutrophication assessment in OSPAR, reduction in eutrophication has been achieved through management measures, following the Recommendation 88/2 in OSPAR to reduce nutrient inputs to the sea by 50% compared to 1985. Along the Dutch and German coasts there are still assessment areas that are not in good status and the trend towards reaching the threshold values for N and chlorophyll-a is levelling off (ref to OSPAR COMP4 assessment).

The Wadden Sea is not yet in a good state although progress has been made: seagrass trends in the northern part of the German Wadden Sea (Lower Saxony) show a recovery and a good status, but not yet in the southern part (Lower Saxonian and the Dutch Wadden Sea). Chlorophyll concentrations show a downward trend in the entire Wadden Sea, but recent chlorophyll-a still are above the good/moderate boundary suggesting a reduction need in the Dutch Wadden Sea by approximately 50%, in the Lower Saxonian Wadden Sea by up to 77% and in the Schleswig-Holstein Wadden Sea by around 40% to comply with the current WFD threshold for chlorophyll-a.

Table 1. Eutrophication indicators used across policy frameworks and countries. For these indicators, the evolution across the limnic-marine border is analysed. More information in Enserink et al., (2024).

Policy	Water type	Country	Indicator			
			DIN Winter	Total N Summer	Total N Year	Chl-*a* Summer
OSPAR/MSFD	river plume	NL	x			x
		GE	x		x	x
WFD	coastal	NL	x			x
		GE	x		x	x
	transitional	NL	x			x
		GE	x		x	
	river	NL		x		
		GE			x	x
	lake	NL		x		x

Alternative targets

To better communicate how ecosystems can benefit from combatting eutrophication and to support continued efforts and improve ecological relevance, we developed alternative targets based on discontinuities in the response of the Wadden Sea to increasing eutrophication: 1) the transition from

N limited spring diatom blooms to Si limited spring blooms, leading to a shift in phytoplankton species (e.g. *Phaeocystis* blooms) and 2) the recovery of seagrass at certain riverine N loads.

At present, an oversupply of N especially during the winter leads to high N/Si ratios in winter and early spring. During the spring bloom, diatoms dominate. After Si is depleted, enough N is left over to enable non-diatom blooms like *Phaeocystis* – an algae responsible for substantial amounts of foam on our beaches in late spring. To restore pre-eutrophic conditions, a first step is to aim at maximum winter N concentrations at a similar level as winter Si concentrations as diatoms take up N and Si in a ratio of about 1:1. Winter N/Si ratios are river-specific depending on both the Si concentrations and N concentrations. Reductions needed to reach an N/Si ratio of about one range between 30-55% (Table 2 and Figure 2). This implies that winter concentrations must be explicitly taken into account in future assessments of riverine nutrient loads and that dissolved Si should be included in all monitoring programmes.

In the northern Wadden Sea, seagrass decreased to eutrophication but recovered from eutrophication since the 2000s. Currently, efforts to replant seagrass in the Dutch Wadden Sea have often failed because the seagrass was overgrown by macrophytes (van Katwijk et al., 2024). This suggests eutrophication hampers the recovery of seagrass. Based on comparison with areas in the Wadden Sea where seagrass successfully recovered it was estimated that the eutrophication indicator ‘summer mean chlorophyll-a’ should not exceed 8,4 µg/L, which would require a nitrogen load reduction from the Rhine, Meuse and Ems of approximately 35-45% (van Katwijk et al., 2024).

The reduction of nitrogen loads needed to reach our alternative targets for the Wadden Sea (balanced nitrogen to silicate loads, to enable seagrass recovery) are in a similar range of about 30-55%. (Table 2 and Figure 2). Nutrient loads from smaller rivers impacting the Wadden Sea should be reduced in a similar magnitude. Winter Si concentrations and winter N/Si ratios may guide reduction needs.

The above range of 30-55% compares well to reductions needed to prevent upstream ecological problems like oxygen depletion in the Elbe estuary (45%).

The above-mentioned reduction needs to reach the Alternative Targets compare well to reductions needed to reach WFD goals: The chlorophyll-a concentrations in the Dutch and German Wadden Sea would need to be reduced by approximately 40% - 77% to comply with the current WFD threshold for chlorophyll-a in the Wadden Sea and with a 63% reduction in riverine loads to reach the WFD threshold values for chlorophyll-a in the Elbe.

The above reduction of 30-55% for seagrass recovery and balanced N/Si ratios is higher than the N load reduction of 0% and 23% for the rivers Rhine and Elbe respectively based on current WFD threshold values for nitrogen. Riverine winter concentrations and loads from the large European rivers like Rhine and Elbe dominate the total nutrient load to the Wadden Sea. Consequently, compliance with WFD threshold values for nitrogen in the Rhine, is not sufficient for reaching our alternative safe ecological boundaries for the Wadden Sea.

In recent years (2018 – 2023) part of the additional reduction has already been achieved. In the Rhine winter mean nitrogen concentrations reduced by approximately 7% and the annual nitrogen loads reduced by even 17%, due to a decrease in river discharges. In the Elbe annual mean total nitrogen concentrations decreased by 12% and the annual nitrogen loads reduced by 38% due to a decrease in river discharges. The large decrease in river discharges between 2010 – 2017 and 2018 – 2023 may be due to climate change or natural variability. Drier years lead to lower volumes of river water and to longer residence time in the catchment, with higher nitrogen losses due to denitrification.

Present riverine reduction targets use annual or seasonal summer means of nutrient concentrations. For the Wadden Sea and adjacent North Sea coast, however, winter loads determine the initial growth conditions. Therefore, we suggest that reduction goals also mention maximum winter loads, as is standard practice in OSPAR, and concentrations. For instance, for the Elbe, it is important to reduce the summer phytoplankton blooms as they drive the oxygen dynamics in the upper estuary during summer. But to reach balanced N/Si ratios along the northern Wadden Sea, winter N loads must be reduced. The Hunze case study also exemplifies this: to reach a good environmental status in the Hunze catchment, summer P loads must be reduced. But no goals have been formulated for the winter conditions. Yet the winter N loads impact the phytoplankton growth potential in the Wadden Sea necessitating additional N targets for the winter loads from the Hunze catchment.

At present, only targets for either N or P are formulated. Given the 1) focus on P in freshwater policies and 2) the fact that P is removed much easier from wastewater, this has led to an increase in N/P ratios. High N/P ratios are detrimental for all aquatic food webs (Sterner and Elser, 2002) and have led to an increase of harmful algae in the North Sea (Brandenburg et al., 2025).

If reduction measures are taken, effects of changes in nutrient ratios and their effect on aquatic food webs should be taken into account. As mentioned above, a sole reduction of P and not N will probably negatively affect aquatic food webs. Conversely, a stronger reduction of N compared to P may lead to N limitation of phytoplankton blooms. This may be relevant for the Elbe blooms: our first estimate was that both N and P had to be reduced by 63% to reach the WFD goals. The envisioned N reductions may potentially lead to an N limitation, more efficient food webs, reduced phytoplankton blooms and thus a lower overall reduction need of less then 63%.

In summary, N/P ratios are not evaluated in the WFD and MSFD and we strongly suggest including nutrient ratios in future updates of the WFD and MSFD and in research supporting these directives.

Table 2. Safe ecological limits with related N and P reductions for the four case studies (Hunze, Rhine basin, Elbe lower river and upper estuary, Wadden Sea). See van Beusekom et al. (2024) for more information. For certain ranges average is provided between brackets.

Source	Case study	Indicator	Mainly impacted by:	Reduction needs for:	N reduction:	P reduction:
NAPSEA (Van Katwijk et al. 2024)	**Wadden Sea**	Seagrass recovery Western Dutch Wadden Sea	Riverine TN loads	Rhine/ Meuse/Ems	34-43% (~38%)	
		Seagrass recovery Lower Saxonian Wadden Sea	Riverine TN loads	Rhine/ Meuse/Ems	39-46% (~43%)	
NAPSEA	**Wadden Sea**	Minimize blooms by non-silicifying algae (e.g. *Phaeocystis*)	Winter riverine Si:N ratio	Rhine	50%	
				Ems	55%	
				Weser	40%	
				Elbe	30%	
NAPSEA	**Elbe estuary**	O_2 >7 mg/l	Import riverine organic matter (phytoplankton)	Elbe	~45%	~45%
NAPSEA	**Elbe river**	Phytoplankton biomass < 40 µg Chl-a/l	Organic matter loads	Elbe	63%	63%
WFD	**Elbe river**	Annual mean total nitrogen		Elbe	23%	
NAPSEA	**Hunze**	Recovery of submersed vegetation in the Zuidlaardermeer	Incoming TP load	Hunze		40%
NAPSEA	**Hunze**	Reduction need for Wadden Sea (sea grass recovery)	TN loads (mainly winter)	Hunze	34-43%	
WFD-NL	**Rhine catchment**	Winter mean DIN concentrations		Rhine mouth	0%	
				Rhine NL-GE border	0%*	
NAPSEA	**Rhine catchment**	N and P concentrations below safe ecological boundaries from literature		Rhine tributaries	44%	50%?

* No further reduction is required for N in the Rhine according to Dutch and German WFD thresholds. It is currently already below the threshold value.

Visualizations of required reductions and linked outcomes

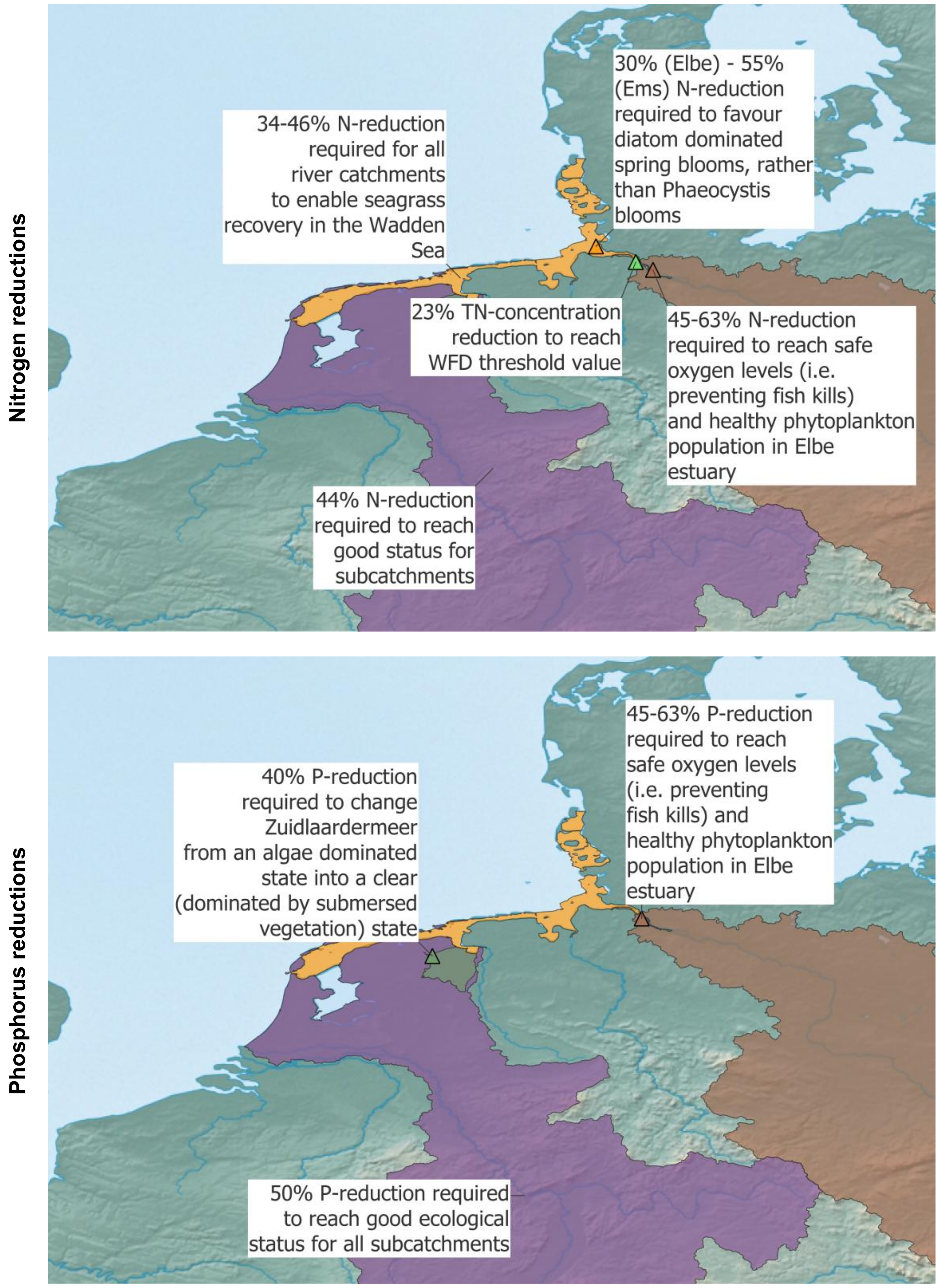

Figure 2. NAPSEA estimates (in %) of required N-reductions (top) and P reductions (bottom) and linked outcomes for ecosystems and catchments.

Clear perspective: Policy targets and measures to reduce loads

Scenario definitions

In NAPSEA, we considered two types of scenarios: policy-based scenarios for the large river basins of Rhine and Elbe and more detailed measure-based scenarios for the small Hunze catchment.

Scenarios for Rhine and Elbe

We defined a set of scenarios to evaluate how the reductions required for the safe ecological boundaries can be reached in the basins of the rivers Rhine and Elbe (Tables 2 and **Error! Reference source not found.**). Given the wide range of possible measures and the large uncertainty in effects of specific measures on future N and P fluxes at the basin-scale, we used policy-based scenarios as a kind of 'best case' scenarios – which also indirectly demonstrate the importance of enforcement for ambitious targets as they assume that the respective measure programmes are sufficiently implemented (Gericke and Leujak, 2023). Our scenarios address major nutrient sources as well as nature-based solution to increase the nutrient retention under a moderate climate change until 2050 (Table 3). Apart from the business-as-usual scenario as baseline (scenario 6), we assessed current sector-specific policy goals (scenarios 1-5) and explored more ambitious policy targets (scenarios 7A-C).

The main purposes of the 7 scenarios were:

- 1-4: sector-specific effects of policy targets under climate change
- 5: overall effect of considered policy targets under climate change
- 6: impact of climate change alone
- 7A-7C: overall effect of increasingly ambitious policy targets under climate change

These scenarios were implemented by modifying the input data of the models mQM and C^nANDY (cf. Musolff et al., 2025). In line with the model setup for past and current conditions (cf. Jomaa & Musolff, 2023), international or national datasets (only Germany and the Netherlands) were used either directly or as input for to derive the model inputs (Table 4). The N model mQM required a continuous time-series until 2050 which was derived by linear interpolation. The P model C^nANDY was applied around the scenario years 2030 and 2050 (for technical details see Musolff et al., 2025).

Table 3. Narratives of NAPSEA scenarios (Musolff et al., 2025).

Scenario		Target	Narrative
1		Wastewater treatment	UWWTD implemented
2[1]		Agricultural input	ND implemented (in NL and GE)[2]
3[1]		Atmospheric deposition	Current EU and national legislation implemented including e.g. the Dutch regulations to protect Natura 2000 areas
4		Nature-based solutions for nutrient retention	e.g., Biodiversity Strategy 2030 addressed by restoring riparian areas and reactivating floodplains which potentially also fulfils water-related goals of the EU Nature Restoration Law, stopped Dutch ND derogation
5		All	Scenarios 1-4 jointly implemented
6		None	Business as usual. Scenarios 1-4 not implemented. Projected hydrological state represents emission scenario RCP4.5
7	A	All except nature-based solutions	Intensification of scenarios
	B	Nature-based solutions (floodplains)	More active floodplains for German rivers. Turning "green rivers" into "blue rivers" in Dutch Rhine sub-basins
	C	Scenario 7B + more drastic measures in scenarios 2-3	50% reduction of livestock in the Netherlands (de Vries et al., 2023) and reduction of nitrogen fertilizer to 80% of plant uptake in Germany (Häußermann et al., in prep)

[1] The scenarios 2 and 3 were only implemented for N as no suitable policy targets exists for the modelling of soluble (dissolved) P. The threshold for soil erosion rate on agricultural land in the proposed Soil Health Law is

assumed to (partly) affect the input of particulate and total P (cf. Gericke and Leujak (2023) and Gericke and Leujak (2024)) but not of soluble P.
[2] Soil Health Law with threshold for soil erosion rate excluded as the P model did not consider particulate P inputs.

Scenarios for the Wadden Sea

To check in which parts of the Wadden Sea the simulated riverine nutrient load reductions would be sufficient to reduce eutrophication so that seagrass can recover, we calculated summer mean chlorophyll-a concentrations with the 3D coupled biogeochemical model DCSM. This model has been used extensively to evaluate impacts of riverine nutrient loads in the North Sea and Wadden Sea (for example: van Leeuwen et al., 2023; Rönn et al., 2023). It has a spatial resolution of 800 m in the Wadden Sea. As input, we used the river loads of the Rhine and Elbe described above and their extrapolated load estimates of other rivers to the Wadden Sea (appendix B). simulations were conducted covering the period 2015–2017, excluding the spin-up years 2012–2014. The reference run represents current conditions, scenario 5 reflects the combined effects of scenarios 1–4 (Table 2) and scenario 7c represents the most drastic societal changes.

Scenarios for the Hunze

Owing to the small extent of the case study compared to the Rhine and Elbe basins, a more detailed model setup was possible using a SWAT model. In addition, scenarios were derived with bottom-up input from the local water authority: the Water Board Hunze and Aa's (Table A.1 in Appendix A). These scenarios offered a more detailed assessment of the local efficiency of both planned and extended measures in the Hunze catchment, including an evaluation of the feasibility of meeting local and downstream safe ecological limits. In addition to the moderate climate scenario (RCP 4.5), following the approach for rivers Rhine and Elbe, a worst-case scenario (RCP 8.5) in 2050 was considered. For the scenarios, monthly national averages of climatological variables were derived for the period 2050–2055. In addition to the climate projections, thirteen measure-based scenarios were implemented which can be categorized by the type of intervention:

- 1–5: land use changes: (extreme) land conversions (e.g. all arable land to nature)
- 6–7: wastewater treatment improvement
- 8–9: agricultural management: best agricultural land management practices
- 10–13: nature-based solutions: retention in the main streams, riparian buffers, wetland

The scenarios 6 (technical upgrades of the wastewater treatment plant), 9 (reduction of surface runoff from arable land), and 13 (extension of the wetland) reflect measures that are already planned. The selection and model implementation of the remaining scenarios were developed in consultation with the local water board.

Translation from scenarios to pathways and safe ecological limits

Rhine and Elbe

The analysis of N and P reduction strategies reveals that current policy measures are inadequate to achieve safe ecologically nutrient levels in, and coming from, major river basins such as the Rhine and Elbe (Figure 3). Both nutrients require substantial reductions in emissions from agriculture, wastewater, and atmospheric sources, alongside the adoption of nature-based solutions, to reach the safe ecological limits. While planned interventions show moderate progress (Figure 3; Scenario 1-5), only more ambitious and integrated policy scenarios demonstrate the potential to meet long-term ecological goals (Scenario 7A-C; Figure 3-4 and Figure B.1 in Appendix B).

Additionally, climate change is expected to change river discharges, something which is not demonstrated in the same way by concentrations (Figure B.2 in Appendix B), which may in turn affect nutrient loads reaching downstream ecosystems. Since reduced water flow can also exacerbate ecological stress in receiving waters there is clear need for proactive nutrient management. These findings highlight the urgency of adopting more comprehensive and adaptive strategies to safeguard water quality under changing environmental conditions.

Wadden Sea

Model results for the Wadden Sea (Figure 4) suggest that in the current situation (2015 – 2017) parts of the Dutch western Wadden Sea should already be suitable for seagrass recovery. This aligns with preliminary successful results of seagrass recovery in this area. The eastern Dutch Wadden Sea and Lower Saxony waters are still too eutrophic. With planned measures (scenario 5) a large part of these areas should already become more suitable for seagrass recovery. In the most drastic scenario (7c) eutrophication should be sufficiently reduced for seagrass recovery in most of the Wadden Sea except close to the river mouths of the Ems and Elbe.

Hunze

Scenario results in the Hunze catchment (Figure 5 and A.1 in Appendix A) showed that land use changes are expected to have the strongest impact on the loads of total N and total P from the Hunze catchment. Conversion of all agriculture land to nature, mammut grass cultivation, dairy production or bean cultivation would each be sufficient to reach the N-load reduction required. However, land use change from dairy to arable land would lead to a strong increase of nitrogen loads. Other measures, such as improved wastewater management, optimised agriculture practices and nature-based solutions lead to more modest nutrient load reductions that are insufficient to reach the required load reductions by themselves. But if several of these measures are combined, they are likely to reach the required nutrient load reductions. Climate change scenarios predict a 7-13% increase of TN and TP loads from the Hunze catchment to the Wadden Sea in winter due to increased precipitation.

Table 4. Overview of scenario implementation for the basins of rivers Rhine and Elbe (based on Gericke & Leujak (2024) and Musolff et al., 2025).

Target	Implementation, assumption	Scenario Table 3	Spatial extent	Nutrient	Own calculations
Climate change	Hydrology based on RCP 4.5	1-6, 7A-C	all	N, P	
Wastewater treatment			all	N, P	load per treatment plant from adjusted retention and/or outflow concentration
	Target retention and outflow concentrations based on the revised (recast) UWWTD	1, 5			
	Size-specific median retention and outflow concentration as benchmark, plants with 2000-10000 PE included	7A-C			
Agricultural input				N	
	Fertilizer Ordinance[1] 2021	2, 5	GE		
	7th Action Program, Dutch Taskforce Agricultural Water Management[2] measures, no derogation and overfertilization	2, 5	NL		relative change N surplus as change in nitrate concentration under agricultural land
	Scenario 2 + site-specific fertilization	7A, 7B	GE		
	All sets of measures in de Vries et al. (2023)	7A, 7B	NL		
	Scenario 2 + fertilizer application limited to 80% plant demand	7C	GE		
	Scenario 7A/B + 50% livestock reduction	7C	NL		
Atmospheric deposition			all	N	
	Existing EU (NECD, Green Deal) and national policies	3, 5			
	Scenario 3 + maximum technically feasible reductions	7A, 7B			
	Scenario 7B + climate policy including lower livestock density	7C			
Nature-based solutions					
	§38a Federal Water Act[3], extent: arable land next to rivers if slope above 5%, 50% retention of N fluxes younger than 1 year	4, 5, 7A-C	GE	N	potential area of new riparian buffers, average retention (literature)
	Same but with 50% retention of diffuse input	4, 5, 7A-C		P	
	Buffer strips on agricultural fields in compliance with regulation since 2024 related to stopped derogation	4, 5, 7A-C	NL	N, P	average retention (literature)
	20% more active floodplains	4, 5, 7A	GE	N, P	mean area-specific retention
	Polders reactivated according to Environmental Quality Decree[4]	4, 5, 7A	NL	N, P	mean area-specific retention
	Maximum 30% of former floodplain reactivated and scenario 7B	7B, 7C	GE	N, P	mean area-specific retention
	Turning "green rivers" to "blue rivers" increases area-specific retention	7B, 7C	NL	N, P	Same increase to scenario 4 as for German Rhine

[1] Düngeverordnung (DüV), [2] Deltaplan Agrarisch Waterbeheer (DAW), [3] Wasserhaushaltsgesetz (WHG), [4] Besluit Kwaliteit Leefomgeving (Bkl)

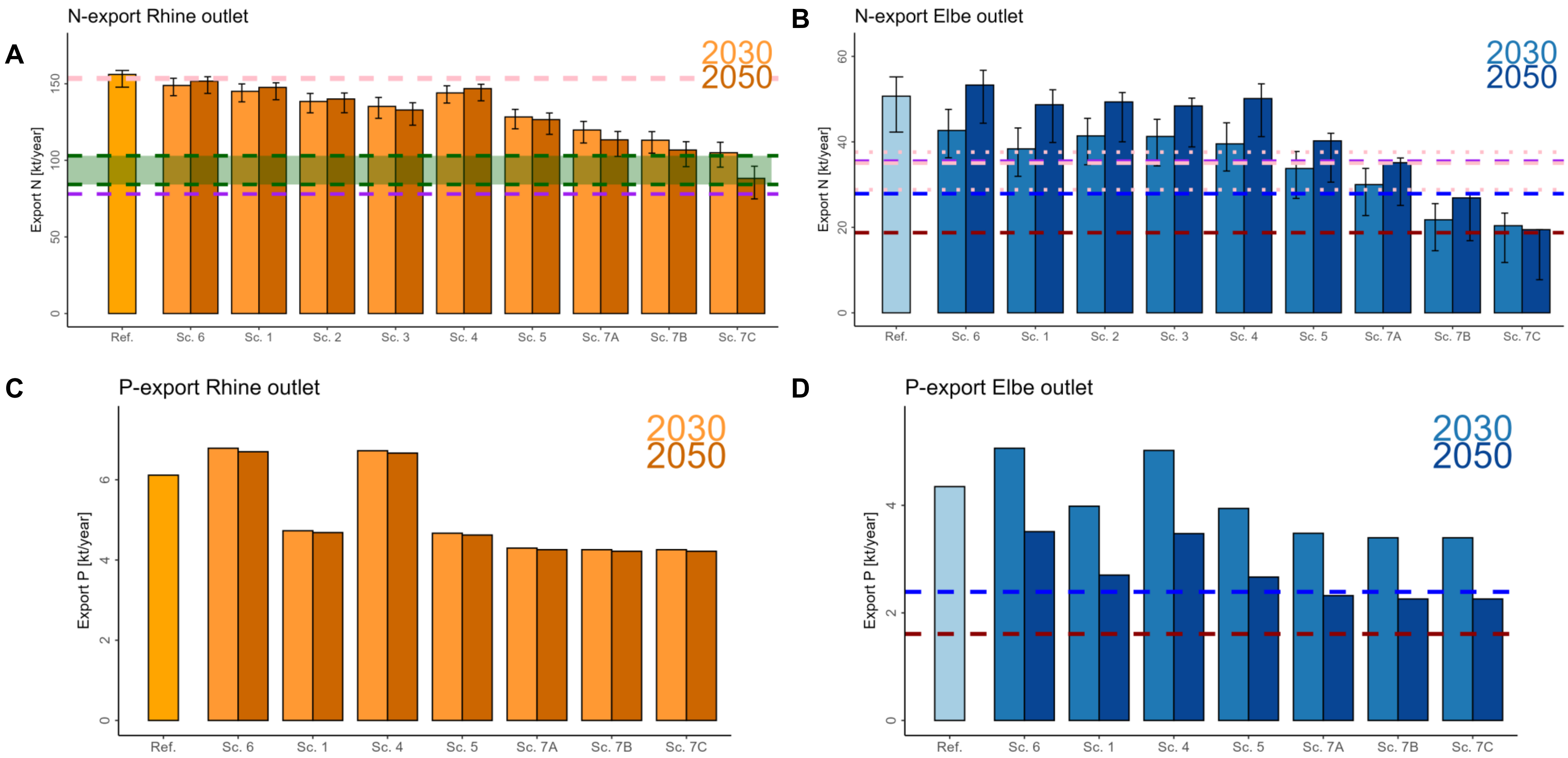

Figure 3. Nutrient export at the Rhine Lobith (nitrate in A and total P in C) and Elbe (nitrate in B and total P in D) outlet considering the different scenarios and the reference (ref, 2010-2020) including the required reduction (see Table 2) for seagrass recovery (green shaded area), natural nitrogen to silicate ratios preventing blooms of non-silicifying phytoplankton in the Wadden Sea (purple), preventing oxygen depletion (blue), phytoplankton biomass below WFD threshold (red), and WFD threshold for which modelled discharges where used for the reference (dashed pink) year as well as 2030 and 2050 (dotted pink). Ref – reference period 2010-2020, lighter colours in scenarios – average 2028-2032, darker colours – average 2046-2050, whiskers – 5-95 confidence interval of 100 model realizations (see Musolff et al., 2025 and van Beusekom et al., 2025 for more details).

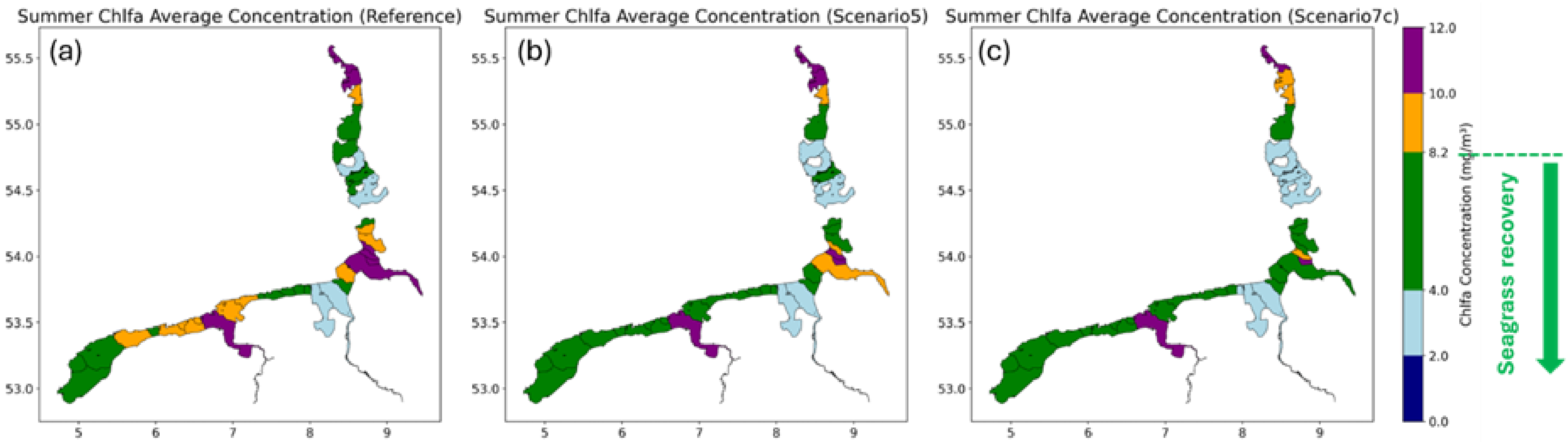

Figure 4. Simulated marine eutrophication responses (summers of 2015–2017) across three scenarios: baseline reference conditions (a), combined reduced riverine nutrient input under scenario 5 (b), and extreme riverine nutrient reduction under scenario 7c (c). The green dotted line denotes a Chl-a threshold (<8.2), indicating a high potential for seagrass recovery.

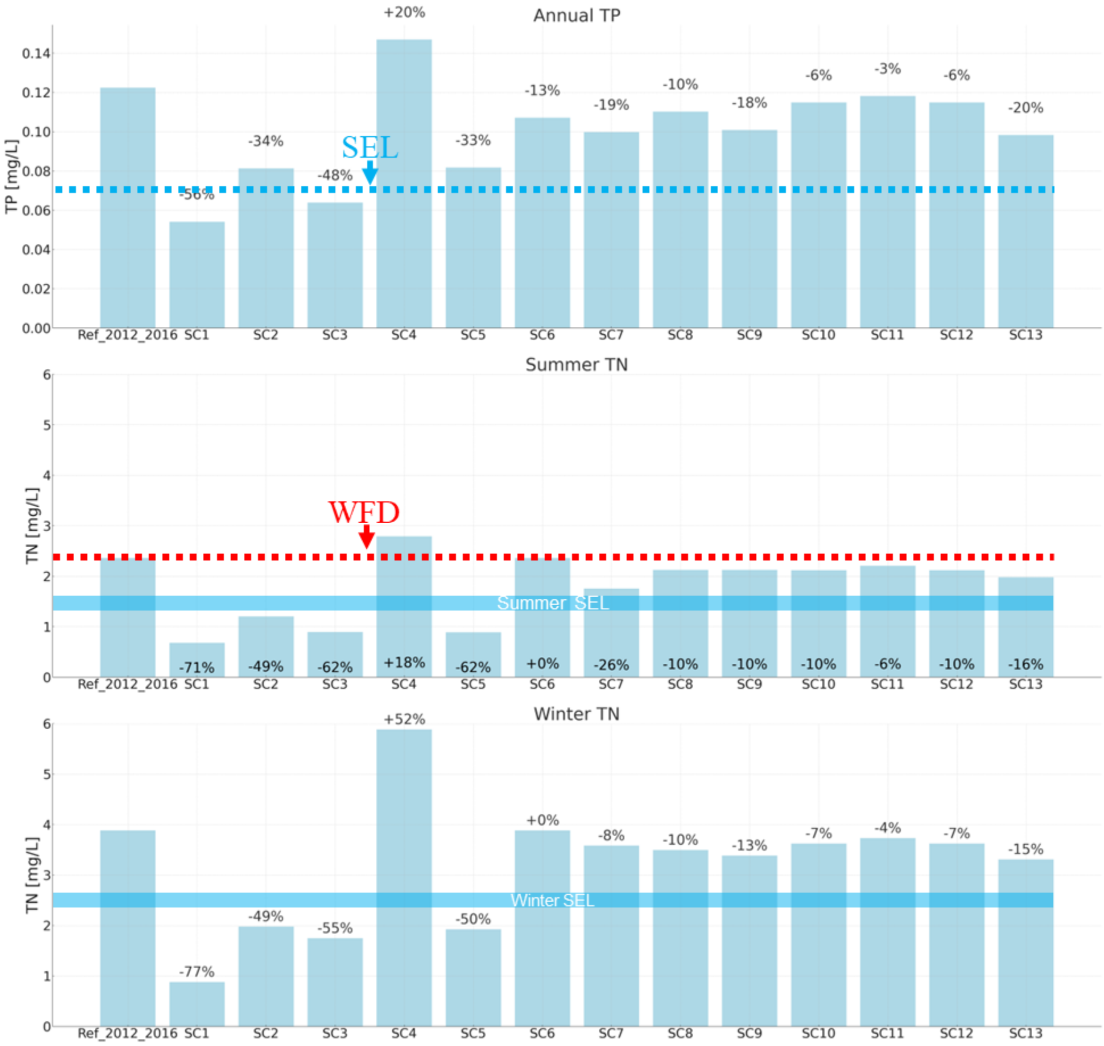

Figure 5. TN and TP concentration results for all scenarios in the Hunze catchment. SEL is the Safe Ecological Limit target. WFD refers to the Water Framework Directive target. Note that the upper (TP) graph gives annual average concentrations; while the middle and lower plots give summer and winter average TN concentrations, respectively.

Policy feasibility and social/societal acceptance

Policy feasibility

As an outcome of D2.3 it needs to be stated that as regard to scenario 1-5 the legal background exists, and the main challenge is the full implementation and enforcement of it. Although the EU level framework is set at the Member State level there is not enough political will to take sufficient action. While the pressures on the water system in the Netherlands and Germany are well understood, water authorities often lack a clear course of action to address them due to lack of formal instruments to impose measures.

For scenario 7, some parts of the measures proposed (e.g. More active floodplains) will be implemented by the newly agreed Nature restoration regulation[1]. It addresses nutrient pollution by promoting measures like reducing chemical pesticides and fertilizers and improving nutrient management in agricultural ecosystems. This integrated approach aims to restore natural ecosystems, such as rewetting drained peatlands, to improve water quality by processing nutrients.

Considering the current Common Agricultural Policy Proposal[2] more stricter rules for fertilizer application and/or livestock density are highly unlikely. Further due to a reduced budget and more freedom of MS to design agri-environmental and climate actions it can be assumed that the application rate of such voluntary measures will drop, making a full implementation of scenario 7 highly unlikely.

Social acceptance

Social acceptance of nutrient reduction measures is essential, because the more the measures are accepted, the more and/ or better they will be implemented. Work Package 2 of this project examines the social acceptance of nutrient reduction measures in the Rhine River Basin among farmers (through interviews) and citizens (through surveys). The objective of the study was to assess the social acceptability of a measure, identify barriers and enabling factors affecting its implementation, and evaluate the awareness among farmers and citizens regarding the impact of their activities on the Wadden Sea – including potential differences based on their geographical proximity. While stricter measures, such as those proposed within scenario 7, may be highly effective in theory, their successful implementation depends on broad societal support.

The survey results show that citizens are generally in favour of the measures. Of the three common nutrient-reducing measures mentioned in the survey, buffer strips are the most popular. The reduction of livestock intensity and stricter fertilization management are slightly less popular. Most farmers, by contrast, tend to adopt measures they perceive as logical and practical from an agricultural standpoint. Farmers demonstrate high engagement with debates over nutrients, and they recognise their role in nitrate and phosphorus loading to the environment, but they also feel that they are disproportionally blamed compared to other sectors such as industry, municipal wastewater, and households. Both citizens and farmers acknowledge the risks of eutrophication, especially for biodiversity and for future generations. However, citizens appear to be more concerned about the downstream effects on the Wadden Sea than farmers, who focus more on local soils and groundwater. Some of the farmers also shared ideas for additional measures or good practices to reduce nutrients, but there was no way to check how much they approved of the additional ideas.

From the citizen side, the data showed that citizens are concerned about nutrient pollution and identified agriculture as the primary contributor to high nutrient loads in rivers. However, they also acknowledge that there are trade-offs for farmers when they implement nutrient reduction measures. They particularly expect a higher financial and administrative burden for farmers if measures were stricter. The survey with citizens included two questions related to their willingness to decrease the consumption of animal products (meat and dairy), and willingness to pay more for them. The responses revealed that citizens (especially female respondents) are willing to make dietary changes for nutrient reduction, but it was

[1] https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-regulation_en
[2] https://commission.europa.eu/publications/common-agricultural-policy_en

not measured whether the claims were put into practice. To realise scenario 7 and beyond, the study participants believe that more exchange and contact amongst farmers and citizens as consumers is essential.

Farmers' acceptance of nutrient-reducing measures is more conditional, often driven by economic and agronomic logic rather than societal expectations, and shaped by frustrations with rigid regulations, administrative burdens, and insufficient compensation. Many highlight the need for policies that strike a balance between environmental goals and financial viability, as well as practical farming realities. Farmers mentioned the following enabling factors for socially acceptable nutrient reduction policies: fairer subsidies, long-term planning security, advisory support, and stronger cooperation across sectors. The findings underscore the importance of bridging the gap between public expectations and the reality of farmers to ensure both ecological effectiveness and social acceptance of nutrient reduction strategies.

Reflections

Coherence with reduction needs for terrestrial targets

To combat eutrophication in freshwater systems, focus has been on reducing P input, whereas in marine systems N is the ultimate limiting element. However, N is an important element contributing to the diversity loss in many terrestrial ecosystems (e.g. Bobbink et al., 2010). Reductions needed to bring terrestrial ecosystems within safe limits necessitate a strong reduction in N input. De Vries et al. (2021) estimated that about 30-40% (Europe-wide) reduction is needed to bring terrestrial and freshwater systems within safe boundaries. These reduction needs are in the same order of magnitude as proposed in our study. This calls for a coherent strategy to shape and design an integrated view on safe limits for terrestrial, freshwater, and marine ecosystems.

Towards a holistic view on nutrient ratios: An option to link N and P reduction scenarios?

Planned nutrient reduction measures have reduced N and P loads, but they have also unintentionally increased N/P ratios, which can negatively affect aquatic ecosystems. Since the 1980s, P loads have been reduced more effectively than N, leading to elevated N/P ratios in rivers like the Rhine and Elbe. These imbalances can alter phytoplankton dynamics and harm higher trophic levels, as shown by increased harmful algal blooms and with potential effects on higher trophic levels in both marine and freshwater systems. Current policies often treat N and P separately, overlooking the ecological importance of their ratio. To reach safe ecological limits, future strategies must address both nutrients simultaneously and aim to more balance N/P ratios to protect food web integrity.

Linking N and P biogeochemical cycles is a major challenge: Whereas N can be easily removed from the biogeochemical cycles due to denitrification, P remains available for much longer time scales. In certain environments like the Baltic Sea or in lakes, a surplus of P may lead to N fixation by cyanobacteria. P adsorption in marine sediments may reduce P limitation as was shown for the Wadden Sea (van Beusekom et al., 2025).

Given the complexity of the N and P cycles, setting goals for N/P ratios will be a major challenge. However, at present a further increase in N/P ratios should be avoided.

Ecological uncertainties in nutrient reduction: implications for the Elbe river

The reduction target for the Elbe River, set at 63% for nitrogen and phosphorus, is based on a simplified dose-response analysis linking current and desired levels of oxygen concentration and phytoplankton biomass. While this approach provides a quantitative foundation for policy development, it does not fully account for the ecological complexities that may arise from such a substantial nutrient reduction. In particular, the response of phytoplankton communities to nitrogen limitation remains uncertain. A shift in nutrient availability could alter bloom dynamics, potentially leading to changes in species composition, timing, and intensity. Moreover, adjustments in the N:P ratio may have unintended consequences for ecosystem functioning, including the risk of promoting harmful algal blooms. These knowledge gaps underscore the need for further research to better understand the ecological implications of nutrient reductions and to refine management strategies that are both effective and adaptive under changing environmental conditions.

Future research should investigate how phytoplankton communities in the Elbe River respond to nitrogen limitation, including shifts in species composition, bloom dynamics, and seasonal variability. Particular attention should be given to the ecological effects of altered N:P ratios and their potential to trigger harmful algal blooms or disrupt oxygen levels.

Impact of climate change on the effectiveness of reduction scenarios

Climate change significantly influences the effectiveness of nutrient reduction measures by altering hydrological and biogeochemical processes. Changes in discharge patterns affect N and P differently: wetter years tend to increase N mobilization and reduce P retention, while drier years enhance P removal through algal uptake and sedimentation. These dynamics suggest that climate variability can either amplify or diminish the impact of mitigation strategies, depending on timing and intensity. Climate change also affects the residence time in the catchment as well as the stream network which is explicitly considered in process-based models like mQM for nitrogen. Moreover, extreme events like the 2018 drought reveal how climate-induced shifts in oxygen and phytoplankton dynamics can disrupt aquatic ecosystems, potentially requiring revised nutrient targets. Understanding and modelling these complex interactions is essential for developing resilient and adaptive water quality policies.

Our business-as-usual scenario underlines that climate change effects vary in space and time. The Alpine Rhine, whose discharge is (partly) influenced by snowmelt, showed only minor changes to reference conditions, while the lowland river Elbe may experience decreasing discharges and nutrient exports to the sea followed by an increase towards 2050. Accordingly, scenario results for one river basin cannot simply be extrapolated to other river basins.

Reliability of model results

Different kind of model were used to derive reduction needs and to quantify scenario effects in the case studies. Each of the models comes with its own limitations and uncertainties. Our model applications and assessments of model scenarios at the basin scale have been challenged e.g. the complex hydrology of the Dutch Rhine and the complex and variable effects of planned measures which depend e.g. on natural and farm characteristics. We addressed these challenges by using existing national datasets and different model setups for NL and GE or by assessing policy-based which implicitly assumed a full implementation of measures.

The model uncertainties could partly be exemplarily quantified for some reduction needs (cf. Table 2) and the mQM model for nitrogen. Running the mQM model with the best 100 parameter sets after the model calibration showed that the model uncertainty was larger for river Elbe than for river Rhine (range of whiskers relative bar heights in Figure 3 A–B). Published data showed that applying the reduction needs to riverine concentrations reported by Germany that our findings with a median of 1.8 mg / l N are plausible and consistent (Gericke et al. 2025). Future work should extend these assessments to raise awareness of uncertainties among policymakers and stakeholders. Such an effort also requires applying different models and further developing existing models e.g. to explicitly consider effect of nutrient legacy which decouples the status of water bodies from measures in the catchments (e.g. Ascott et al. 2021) and to account for seasonal variability in climate change as precipitation and river discharge may increase in winter and decrease in summer.

Further recommendations

- Create more transparency about the aims and narratives of nutrient reduction targets by:
    - Developing separate nutrient thresholds to prevent **local and downstream** eutrophication problems and use the minimum of both thresholds to design nutrient reduction scenarios.
    - For the thresholds to prevent downstream eutrophication, nutrient loads and concentrations should be included for the **entire year**, including specific winter goals.
    - Developing thresholds for both **nitrogen and phosphorus** and their ratios for each water body, so that downstream eutrophication impacts and ecological impacts of imbalanced nutrient ratios can be taken into account.
    - Given that N/Si ratios impact phytoplankton composition, we suggested N/Si of about one as a goal in riverine winter concentrations. This necessitates the inclusion of Si in current monitoring programs.
    - Taking into account **multiple ecological impacts** of eutrophication and their specific nutrient reduction needs.
- Support a better understanding of current nutrient loads and pathways by:
    - Aligning and extending the **monitoring locations** for water flows and nutrient concentrations

- Adopt an **integrated source-to-sea approach** for selecting and implementing nutrient reduction measures across the entire catchment areas, including all countries involved.
  - Reliable models and data are crucial for a science-based and quantitative coherent analysis.
  - Compare different model approaches for more insight in the uncertainties of model outcomes.
- Use **ecological indicators that resonate with the public**, such as seagrass recovery, to build support for nutrient reduction strategies.
- Gain more support for nutrient reduction measures by collaborating with other policies aiming at climate adaptation and terrestrial biodiversity.
- The selection of measures should be more aligned with farmers motivation to pick up measures, such as planning security and low bureaucratic burden.

References

Ascott, M. J., D. C. Gooddy, O. Fenton, S. Vero, R. S. Ward, N. B. Basu, F. Worrall, K. Van Meter, B. W. J. Surridge 2021. The need to integrate legacy nitrogen storage dynamics and time lags into policy and practice. Science of The Total Environment 781: 146698. DOI: 10.1016/j.scitotenv.2021.146698.

Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, M. Bustamante, S. Cinderby, E. Davidson, F. Dentener (2010). Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecological Applications 20:30-59, DOI: 10.1890/08-1140.1

Brandenburg, K. M., J. Merder, A. Budiša, A. M. Power, C. J. Philippart, A. M. Michalak, T. J. van den Broek, D. B. Van de Waal. (2025). Multiple global change factors and the long-term dynamics of harmful algal blooms in the North Sea. Limnology and Oceanography 70:1267-1282, DOI: 10.1002/lno.70025

Brockmann, U., D. Topçu, M. Schütt, W. Leujak (2021). Third assessment of the eutrophication status of German coastal and marine waters 2006 – 2014 in the North Sea according to the OSPAR Comprehensive Procedure. UBA Texte 37/2021

De Jong, F. (2007). Marine eutrophication in perspective: on the relevance of ecology for environmental policy. Springer Science & Business Media.

De Vries, W., L. Schulte-Uebbing, H. Kros, J. C. Voogd, G. Louwagie (2021). Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Science of the Total Environment 786:147283, DOI: 10.1016/j.scitotenv.2021.147283

De Vries, W., J. Kros, J. C. Voogd, G. H. Ros (2023). Integrated assessment of agricultural practices on large scale losses of ammonia, greenhouse gases, nutrients and heavy metals to air and water. Science of the Total Environment 857:159220, DOI: 10.1016/j.scitotenv.2022.159220

Enserink, L., S. Plette, J. van Beusekom, W. Leujak, A. Gericke, T. Prins (2024). Review of currently used indicators, direct and indirect effects and nutrient targets. EC report of grant 101060418 Deliverable 4.1; https://napsea.eu/wp-content/uploads/2024/03/D4.1_Review_of_indicators_NAPSEA.pdf

Gericke, A., W. Leujak (2023). Feasibility of measures to reduce nutrient inputs in rivers Elbe and Rhine. EC report of grant 101060418 Deliverable 2.2; https://napsea.eu/wp-content/uploads/2024/02/D2.2.-Feasibility_of_measures_NAPSEA_final-1.pdf

Gericke, A., W. Leujak (2024). Model input of selected scenarios. EC report of grant 101060418 Deliverable 3.4; https://napsea.eu/wp-content/uploads/2024/10/D3.4_Model-input-of-selected-scenarios.pdf

Gericke, A., K. Morling, I. Haag, M. Gebel, J. Krumm, G. Bruns, J. E. E. van Beusekom, S. Fuchs, W. Leujak 2025. Are historical conditions reference conditions? Revising the modeled riverine nutrient input into the German North Sea and Baltic Sea around 1880. Environmental Sciences Europe 37: 133. DOI: 10.1186/s12302-025-01185-8.

Häußermann, U., Dreisbach, N., Bach, M., Breuer, L. (in prep). Evaluierung der novellierten Düngegesetzgebung auf deren Umwelt- und Klimawirkung, UBA: Dessau-Roßlau

Musolff, A., J. Ledesma, A. Gericke, J. Rozemeijer, T. Troost, X. Liu (2025). Effectiveness of measures, updated. EC report of grant 101060418 Deliverable 3.5; https://napsea.eu/wp-content/uploads/2025/09/D3.5_Effectiveness-of-scenarios_update_incl_appendix.pdf

Musolff, A. (2025). Transfer of model results. EC report of grant 101060418 Deliverable 3.6; https://napsea.eu/wp-content/uploads/2025/05/D3.6_Transfer_of_model_results.pdf

Jomaa, S., A. Musolff (2023). Data collection. EC report of grant 101060418 Deliverable 3.1; https://napsea.eu/wp-content/uploads/2024/02/D3.1_Data_overview_NAPSEA_final.pdf

Sterner, R. W., J. J. Elser (2002). Ecological stoichiometry: the biology of elements from molecules to the biosphere. Princeton University Press.

Van Beusekom, J. E. E., J. Carstensen, T. Dolch, A. Grage, R. Hofmeister, H. Lenhart, O. Kerimoglu, K. Kolbe, J. Pätsch, J. Rick, L. Rönn, and H. Ruiter. 2019. Wadden Sea Eutrophication: Long-Term Trends and Regional Differences. Frontiers in Marine Science 6.

Van Beusekom, J. E. E., G. Schulz, J. Pein, A. Musolff, J. Rozemeijer (2024). Safe Ecological Limits. EC report of grant 101060418 Deliverable 4.2; https://napsea.eu/wp-content/uploads/2025/02/D4.2_Safe_Ecological_Limits.pdf

Van Beusekom, J., Gericke, A., Musolff, A., Rozemeijer, J., Biederbick, J., Pein, J., Liu, X., Troost, T., van der Heijden, L.H. (2025). Implications of reduction scenarios for the Safe Ecological Status of the Rhine Basin, Hunze river, Elbe lower river and upper estuary and Wadden Sea. EC report of grant 101060418 Deliverable 4.3; D4.3_Impact-of-reduction-scenarios-on-the-Safe-Ecological-Limits_NAPSEA.pdf

van Katwijk, M. M., J. E. E. van Beusekom, E. O. Folmer, K. Kolbe, D. J. de Jong, and T. Dolch. 2024. Seagrass recovery trajectories and recovery potential in relation to nutrient reduction. Journal of Applied Ecology 61:1784-1804.

Appendix

Appendix A: Table of scenarios for Hunze case study

Table A.1. Hunze-specific scenarios and their implementation in the SWAT model (Musolff et al., 2025). Scenarios 6, 9, and 13 are already planned, the remaining scenarios were developed in consultation with the local water board.

	Scenario	Narrative	Model implementation
1	Convert agriculture to nature	All agricultural land used is converted to nature	Agricultural land use types changed into natural grassland, fertilizer input and drainage removed, improved soil quality, reduced erosion
2	Convert agriculture to Mammoth grass cultivation	Mammoth grass cultivation for bio-based building materials, co-benefits for soil quality, water quality, C sequestration	Agricultural land use types changed into Mammoth grass, improved soil quality, reduced fertilizer input, reduced erosion
3	Convert arable into dairy	Arable farming is replaced by dairy farming (grass-maize rotation)	Change arable land use types into grass and maize, improved soil quality, reduced fertilizer input, reduced erosion
4	Convert dairy into arable	Dairy farming (grass-maize rotation) is replaced by arable farming	Change grass and maize land use types into the most common row crops, reduced soil quality, increased fertilizer input, increased erosion
5	Convert arable to beans	Land use change related to the protein transition; change arable crops to beans like field bean (Vicia faba)	Change arable agricultural land use types into beans, improved soil quality, reduced fertilizer input, reduced erosion
6	WWTP improved	Improved wastewater treatment for P, effluent concentrations reduce from max. 0.5 mg/l to max. 0.27 mg/l	Limit total P concentration in effluent to 0.27 mg/l. No effect on total N.
7	WWTP enhanced purification / summer peak buffering	Enhanced purification, e.g. by increased buffering of extreme events	Reduction N and P load of 20% in summer and 10% in winter
8	Optimize crop nutrient uptake efficiency	Combination of measures to improve nutrient uptake (soil quality, fertilization method (timing, dosing, type)	Increase crop uptake in all arable area by 10%
9	Optimize infiltration and reduce overland flow in arable areas	Reduce overland flow by optimized infiltration (improved soil structure, infiltration trenches, dams between crop rows)	Reduce model parameters CN2 (75 to 55) and USLE_C (0.20 to 0.10) enhanced infiltration, decreases runoff, reduced soil erosion, and P loss

10	Optimize in-stream retention	More in-stream retention in main streams, e.g. by longer residence times by re-meandering, more N/P capture in vegetation/sediment, more denitrification (N)	Increase the in-stream N and P retention by 10%
11	Optimize riparian retention 20m	Riparian buffer zones around main streams, more retention of water, nutrients, sediments	Riparian 'strip buffer' activated in SWAT for larger surface water system, reduced overland flow, no fertilizer input around streams
12	Optimize riparian retention 100m	Riparian buffer zones around main streams, more retention of water, nutrients, sediments	Riparian 'strip buffer' activated in SWAT for larger surface water system, reduced overland flow, no fertilizer input around streams
13	Extend purification wetland	The 230-ha marsh area Tusschenwater will be extended by 90 ha, so a part of the Hunze storm water runoff can flow over into this buffer	Land use changed from agriculture (mainly grassland) to marsh. Reduction of storm water load peaks in the Hunze stream

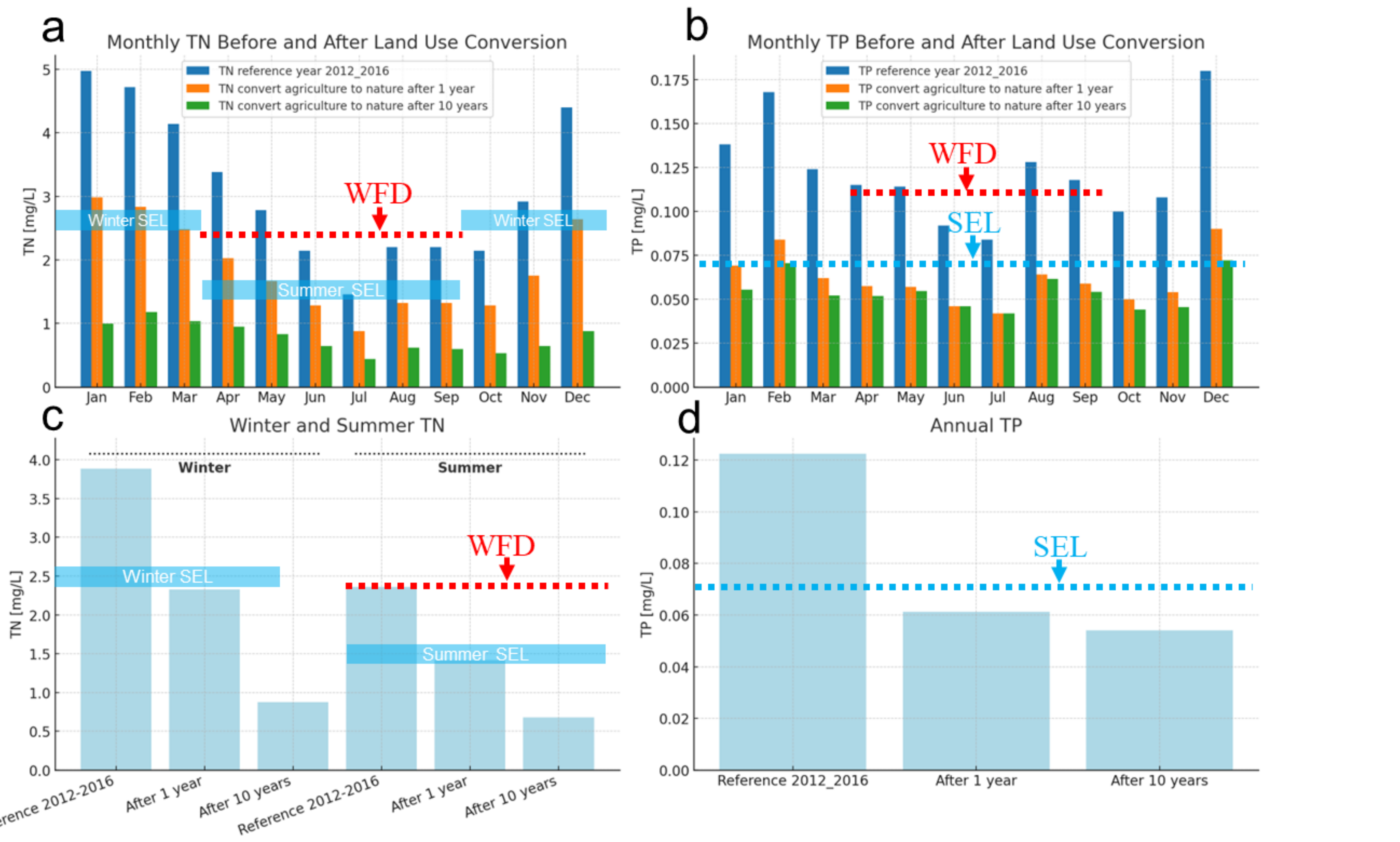

Figure A.1. TN and TP concentration under the land use change scenario from agriculture to nature. SEL is the Safe Ecological Limit, WFD refers to the Water Framework Directive target.

Appendix B: Figures on nutrient reduction scenario as well as reductions in concentrations and extrapolation of other German and Dutch rivers

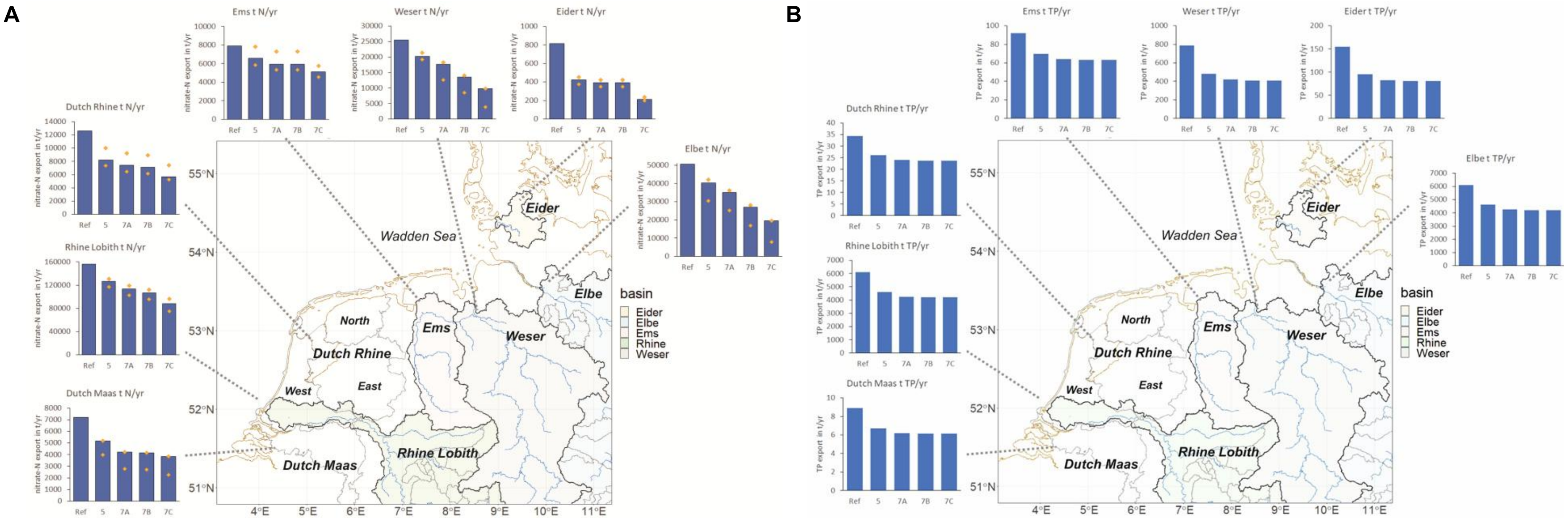

Figure B.1. Nitrate-N (A) and total P (B) exports from the different basins and regions contributing to the Wadden Sea eutrophication. Light grey lines are modelled subcatchments in Elbe and Rhine basin and modelled subregions of Rhine and Maas in NL. The blue bars are based on the best modelled realisations, the yellow dots depict the 5th and 95th percentiles of solutions or the min and max of estimated solutions (see Table 7 in Musolff, 2025).

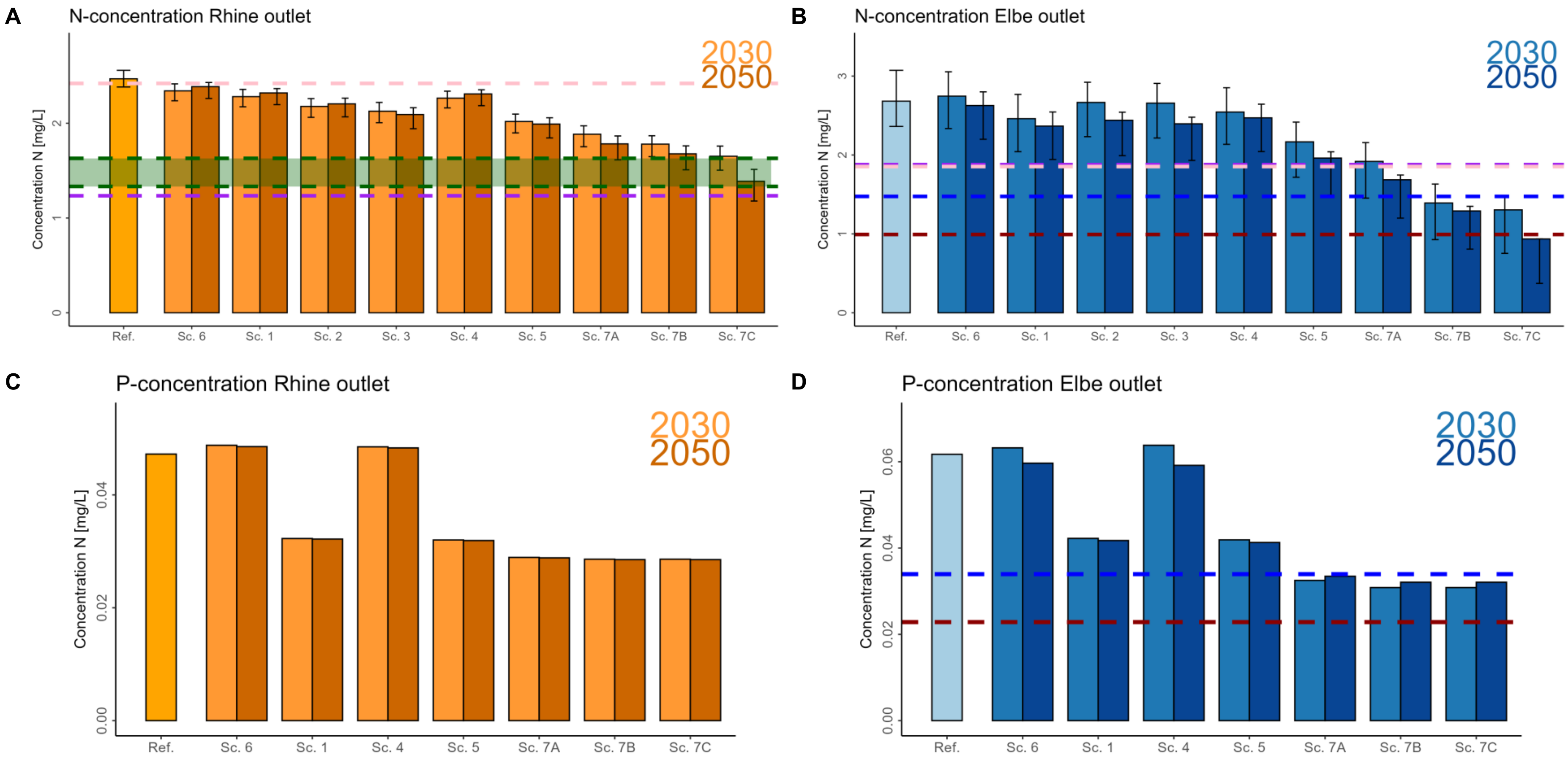

Figure B.2. Nitrogen and Soluble Reactive Phosphorus (SRP) concentrations the Rhine (A = nitrogen and C = phosphorus) and Elbe (B = nitrogen and D = phosphorus) outlet considering the different scenarios including the required reduction (see Table 2) for seagrass recovery (green shaded area), natural nitrogen to silicate ratios preventing blooms of non-silicifying phytoplankton in the Wadden Sea (purple), preventing oxygen depletion (blue), phytoplankton biomass below WFD threshold (red), and WFD threshold (converted TN to NO_3; dashed pink). Ref – reference period 2010-2020, lighter colours in scenarios – average 2028-2032, darker colours –average 2046-2050, whiskers – 5-95 confidence interval of 100 model realizations (see Musolff et al., 2025 and van Beusekom et al., 2025 for more details).