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DELIVERABLE 2.2

FEASIBILITY OF MEASURES

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Abstract	The planned measures until 2027 according to e.g. the river basin management plans and their potential impacts on the dominant pathways of nitrogen and phosphorus in the basins of rivers Elbe and Rhine are evaluated. This was complemented by scenario analyses on policy implementation. The overview confirms the important role of agricultural measures for the reduction of nutrient inputs. The local and basin-wide potentials of measures to reduce nutrient inputs are highly variable. Various reports indicate that the planned measures are insufficient to achieve the environmental targets. We discuss criteria for the upcoming scenario definition in WP 3.
Keywords	Nitrogen, nutrient input, phosphorus, policy, reduction measures, scenarios

Contents

LIST OF ABBREVIATIONS

AECM .... *agri-environment-climate measures*
AP .... *Action Program*
C factor ..*Factor of the universal soil loss equation which expresses the interplay of seasonal rainfall erosivity and soil coverage*
CAP .... *Common Agricultural Policy*
DAW .... *Deltaplan Agrarisch Waterbeheer*
DIN .... *dissolved inorganic nitrogen*
DIP .... *dissolved inorganic phosphorus*
GAEC .... *good agricultural and environmental condition*
KTM .... *Key Type of Measures*
MSFD .... *Marine Strategy Framework Directive*
N .... *nitrogen*
ND .... *Nitrates Directive*
NECD .... *National Emissions Reduction Commitments Directive*
Nmin .... *amount of soil mineral N content*
P .... *phosphorus*
p.e. .... *population equivalent*
RBMP .... *river basin management plan*
TN .... *total nitrogen*
TP .... *total phosphorus*
USLE .... *universal soil loss equation*
UWWTD .... *Urban Wastewater Treatment Directive*
UWWTP .... *urban wastewater treatment plant*
WFD .... *Water Framework Directive*

EXECUTIVE SUMMARY

This report evaluates the potential effects of often planned measures of policies on local and basin-wide inputs of nitrogen and phosphorus to water bodies in the German and Dutch parts of the catchments of rivers Elbe and Rhine. Due to the intensive agriculture with its high nitrogen surplus on agricultural soils, tile drainage and subsurface flow are the dominant pathways for nitrogen, while for phosphorus urban sources including wastewater treatment plants as point sources are at least equally important as the agricultural input. Atmospheric nitrogen deposition is relevant for Dutch surface waters and the marine system. The aim is to provide an overview of local and basin-wide measure effects and nutrient-relevant policies for the definition and selection of scenarios for the nutrient modelling in WP 3.

The large-scale assessment relied on scientific and 'grey' literature from Germany and the Netherlands as well as various datasets including the current river basin management plans and other programs of measures. The study addresses various policies ranging from the Water Framework Directive, Marine Strategy Framework Directive, Nitrates Directive, NEC Directive to the Urban Wastewater Treatment Directive and the Common Agricultural Policy. We also briefly explored the reduction potential of the proposed Soil Health Law.

The focus was on frequent measures addressing the important pathways and sources as they have the highest overall potential impact to reduce nutrient inputs in the study area. 'Measures' were rather loosely defined as (groups of) practices or actions which directly or indirectly target nutrient input. It was based on published (meta-) studies, published model outcomes, and data analyses, while modelling was out of scope. Measures were primarily taken from the extended national reporting within the Water Framework Directive. This collection was complemented by measures from the recent Action Programmes of the Nitrates Directive, the Programs of Measures of the Marine Strategy Framework Directive and the NEC Directive, the Common Agricultural Policy, as well as measures listed in the Dutch Deltaplan Agrarisch Waterbeheer. The data analyses focused on scenarios on the implementation (targets) of the Urban Wastewater Treatment Directive, the NEC Directive, and the Soil Health Law.

The most frequent measures address the key sources. They are related to agricultural pollution (KTM 2), soil erosion and surface runoff (KTM 17), and point sources (KTM 1). Measures addressing hydrology and hydromorphology were also dominant but do mostly not affect nutrient input but instream retention. These measures were excluded from our analysis. The potential effect of conceptual measures is exemplarily discussed in the context of advisory services (KTM 12) which contributed in various regions to lower N balances and erosion rates.

According to the evaluated literature and published scenario results, many agricultural options exist to reduce nutrient input to water bodies locally as well as at the basin-scale. Their reduction potentials vary widely depending on site and farm characteristics. At large scales, their effect can also be counterbalanced by antagonistic changes in agricultural production especially if measures are poorly designed and controlled. It has been argued that the voluntariness of measures in combination with a low participation rate hampers the achievement of environmental goals. Nonetheless, the flexibility also adds to the acceptance, together with institutionalized collaborations of agriculture and water agencies at national scale (Netherlands) and regional scale (Germany). Accordingly, 'Cooperation for water protection' is a prominent keyword for KTM 14 (research, improvement of knowledge base) in the German river basin management plan. Agricultural training and advice are factors which positively influence the participation rate. From an environmental perspective, regional, landscape-oriented funding schemes rather than individual schemes would be beneficial. The Dutch agri-environment-climate measures programme uses a collective approach and the farmers perceive advantages to individual approaches, also for ecology. In Germany, support for co-operation is seemingly appreciated only by part-time farmers and farmers without formal training but not experienced farmers.

The evaluation of scenarios complemented the analyses of measures in case of missing data on measure effects on atmospheric deposition (NEC Directive) and point sources (Urban Wastewater Treatment Directive). The available data revealed that the implementation of policies can significantly reduce the nutrient input. Based on the current trends of atmospheric emissions of NH_3 from agriculture and NOx from traffic and industry, reaching the national emission targets seems feasible. Benchmark scenarios for wastewater treatment indicate that substantial reductions can be achieved by optimizing according to common treatment standards. According to the available European data, substantial reductions in soil erosion are needed to achieve the threshold of 'tolerable' soil loss on all arable land. However, further model development is needed to estimate the effect on nutrient input.

The measure descriptions do not provide sufficient details about specific measures. For the nutrient modelling in the basins of rivers Elbe and Rhine we recommend that input-related scenarios broadly address

- Fertilizer management to reduce the nitrogen surplus and atmospheric losses,
- Lower livestock density and stable management to reduce nutrient balances and atmospheric losses,
- Conservation tillage to reduce soil erosion,
- Organic farming to reduce N surplus and soil erosion,
- Adaptation of crop rotation including more catch/cover crops to reduce N surplus and soil erosion,

- Riparian buffers to retain particulate and dissolved nutrient input although Dutch studies indicate a low efficiency under Dutch conditions,
- Optimization of urban wastewater treatment plants.

If possible, this set of scenarios should be complemented by more detailed scenarios in the Hunze case study which could better consider the complex dependencies among different measures as well as to site and farm characteristics. The scenarios should also address measures on hydrology and hydromorphology as they alter the in-stream retention and eventually nutrient concentrations and loads. The literature provides evidence that measures matching these scenarios also match the goal of NAPSEA to promote mitigation options with co-benefits for other policy goals, although these goals are likely not reached until 2030.

The current trends towards more organic farming, more catch/cover crops, less tillage, lower livestock densities, lower N surplus (in Germany), and lower atmospheric emissions indicate that the above-mentioned measures are already attractive, and certain policy targets feasible. For instance, the results of the benchmark scenarios indicate that substantial reductions are achievable by adopting the most effective technology. However, the implementation of scenarios needs to be discussed in terms of how to

- Integrate the uncertainty in measure effects,
- Combine measures whose expected effects are spatially disjunct, or which are otherwise complementary,
- Consider complex interactions, e.g. the compensation of less manure by more mineral fertilizers,
- Integrate voluntary measures or participation/implementation rates, and
- Spatially locate measures.

The literature strongly suggests that achieving the targets of the Nitrates Directive would be pivotal for achieving marine targets. Despite all efforts, achieving these policy targets is unlikely with the current set of planned measures. Even more stringent agricultural measures are likely insufficient to reach the environmental goals. This limitation calls for ambitious (‘best case’) scenarios which could consider a general adoption of voluntary measures, a substantial change in the agri-food systems with dietary changes (much lower meat production), and the use of best technology in wastewater treatment.

1. INTRODUCTION

1.1. The NAPSEA project

This project addresses the effectiveness of 'Nitrogen And Phosphorus load reduction measures from Source to sEA, considering the effects of climate change' (NAPSEA). The primary objectives of NAPSEA are to support national and local authorities in the selection of effective measures to reduce nutrient loads and to create political support for their execution. The project employs an integrated approach spanning from pollution sources to sea, considering governance, nutrient pathways and measures, as well as ecosystem health. Geographically, the project focuses on the Wadden Sea catchment area, with specific case studies for the Rhine, Elbe, Hunze, and the Wadden Sea itself. NAPSEA serves as a platform to show practices in the implementation of socially acceptable, sustainable, and efficient measures.

The envisaged outcome of Work Package (WP) 2 is an improved support, with a set of guidelines, for the policy vision of clean European seas by 2030. Efforts to combat eutrophication have significantly advanced in Europe, but certain challenges remain, such as disjointed policies, adverse effects of high nutrient inputs, and limited public acceptance of measures. WP2 aims to analyse the policy and socio-economic aspects of nutrient management. This includes analysing barriers and highlighting good practices for implementing sustainable and effective strategies to reduce marine pollution – encompassing administrative, legal, financial, technical, and social dimensions.

1.2. OBJECTIVES

Nutrients enter lakes, rivers, and ultimately the sea via different pathways (e.g. atmospheric deposition, soil erosion) which are linked to different sources (e.g. agriculture, point sources). Their mobilisation, transport, and transformation towards and within water bodies depend on complex interactions of site conditions and human activities (including countermeasures) at different scales. Likewise, the impacts of measures on nutrient fluxes vary considerably and are influenced by how (long), where, and when such measures are implemented as well as how relevant the addressed process, pathway, and/or source is. Moreover, there is a lag between the implementation of measures and its impact on the state of downstream water bodies. This makes nutrient inputs, loads, and concentrations in water bodies highly variable in space and time, and their quantification challenging.

The overarching objective of this report (Deliverable 2.2) is to analyse the set of planned measures across relevant policies and programmes of measures and to provide an overview of their potentials to reduce nitrogen (N) and phosphorus (P) inputs to rivers Rhine and Elbe. This assessment addresses the questions: Which measures are most often planned? Which nutrient reductions can be expected locally and at the basin scale? The (local) efficiency of measures is often expressed as kg nutrient per ha utilized agricultural land / animal / farm or as % of nutrient concentration or input. The basin-wide reduction of nutrient input does not only depend on the local efficiency but also on the spatial extent, the livestock density, and the number of participants. Likewise, the effect will be higher if measures address the important nutrient pathways and sources, as well as the largest reduction needs due to policy targets. Given the huge uncertainty on where which measures will be implemented and on the missing evidence of basin-wide effects, we complement the assessment of individual measures by existing evaluations / scenarios of policy targets.

To give (preliminary) answers to the questions above, we relied on published model outputs, meta-analyses, and data analyses. These answers are needed as criteria for the selection and implementation of scenarios in WP 3. For the scenario modelling in WP 3, it is necessary to e.g. estimate the effect of the selected measures on relevant model variables and parameters.

1.3. STUDY AREA

The study area consists of the German and Dutch parts of the Elbe and Rhine catchments, i.e. two thirds of their total basin area. Figure 1 demonstrates that the relative importance of nutrient pathways not only varies among the two river basins – soil erosion by water is more important for P inputs in the steeper Rhine catchment than in the flatter Elbe catchment – but also among different model applications. Tile drainage is a more important pathway of N in the Elbe catchment according to the MoRE model (Fuchs, Kaiser, et al. 2017) compared to the AGRUM-DE model system (Schmidt et al. 2022). The recent update of the MoRE model resulted in higher soil loss but lower P input via soil erosion than before and, accordingly, in more dominant urban and point sources. These differences have to be considered as uncertainty. Nonetheless, the overall picture remains consistent: the intensive agriculture with its high N surplus on agricultural soils causes high N input via tile drainage and subsurface flow, while for P urban sources including wastewater treatment are at least equally important as the agricultural input, e.g. via soil erosion. Despite the differences, e.g. the share of atmospheric N deposition in the Netherlands is larger than in Germany due to the larger surface area of surface waters, the apportionment for the

Netherlands similarly reveals that agriculture is the most important nutrient source in surface waters and that urban sources are more important for P than for N (Figure 2).

On average, about 20% of the P input and 30% of the N input are retained in the German parts of the two river catchments, i.e. before they reach the limnic-marine and national borders (Zinnbauer et al. 2023). Local conditions such as the flow velocity or water temperature affect the in-stream retention. Accordingly, upstream sub-catchments in steeper terrain may have a lower local retention than downstream areas in flat terrain. Nonetheless, their impact on marine target concentrations is lower given the larger distance to the sea.

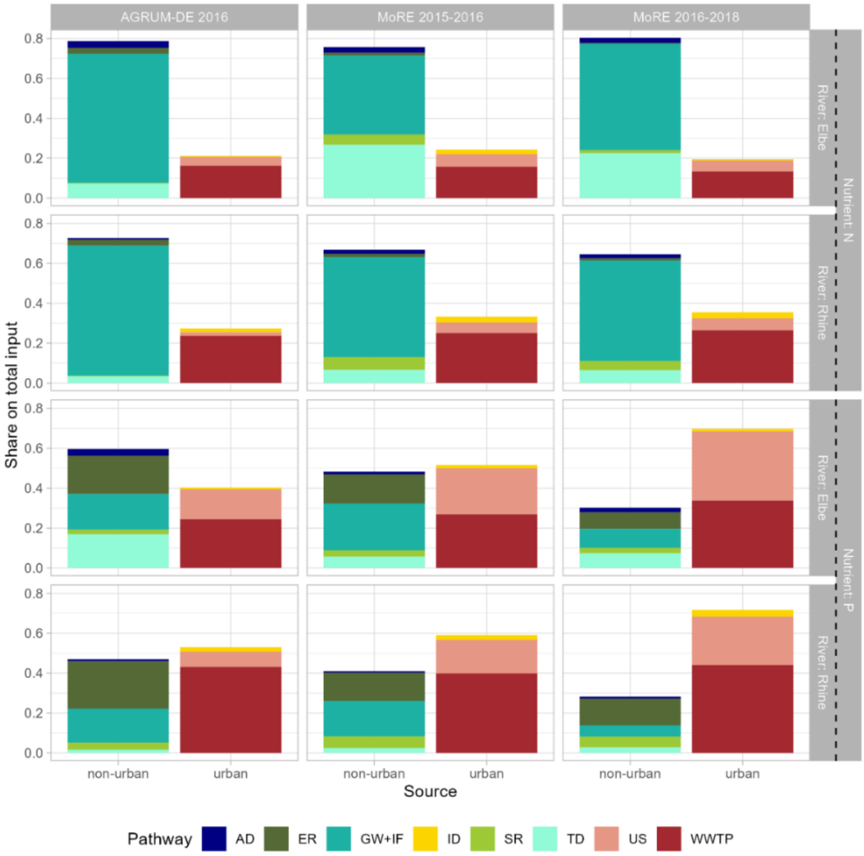


Figure 1. Share of different pathways on the nitrogen (N, top) and phosphorus (P, bottom) inputs to the German parts of rivers Elbe and Rhine. The first two columns compare the outcomes of the two established model frameworks AGRUM-DE and MoRE (LAWA 2021) with revised MoRE approaches for P (Fuchs et al. 2022) (A. Ullrich, pers. comm.). Pathways: atmospheric deposition (AD), soil erosion by water (ER), subsurface flow (GW+IF), industrial discharges (ID), surface flow (SR), tile drainage (TR), urban systems (US), and wastewater treatment plants (WWTP). Model results reflect different model assumptions, input data, and modelling periods.

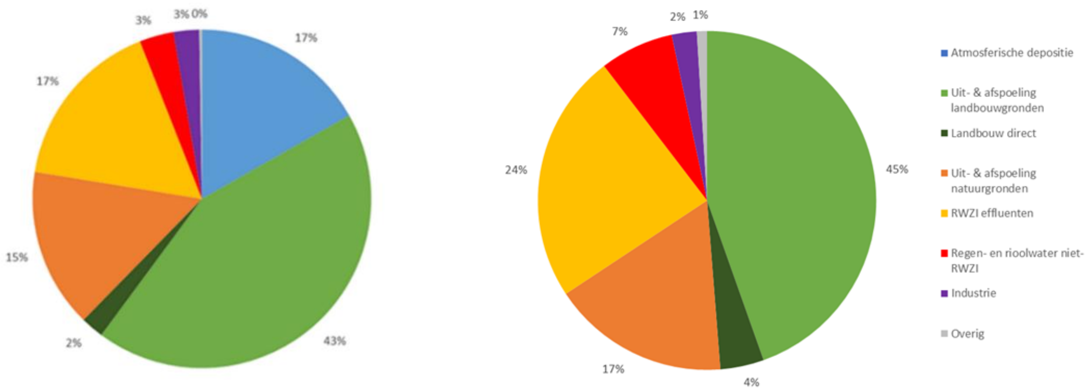


Figure 2. Sources of N (left) and P loads (right) of Dutch surface water. Preliminary figures for the upcoming Nitrate report of the Netherlands (S. Pletten, pers. comm.). Previous figures showed similar distributions (e.g. Fraters et al. 2020), however did not separate natural areas ('natuurgronden') and agricultural areas ('landbouwgronden').

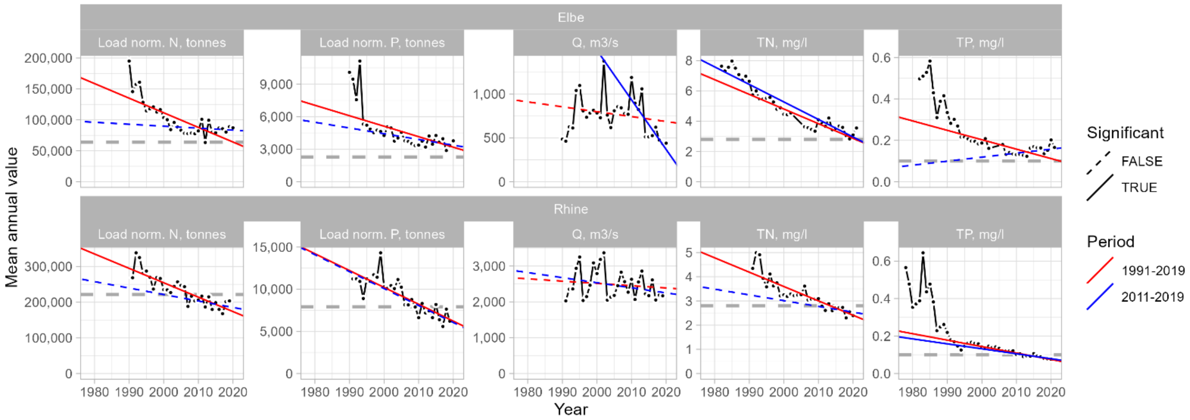


Figure 3. Change in annual normalised load (left), discharge (Q, middle) and concentration (right) for total nitrogen (TN) and phosphorus (TP) with the respective target values at the German gauges at Seemannshöft (Elbe, top) and Bimmen (Rhine, bottom, Table 2). Q measured at Neu Darchau (Elbe) and Rees (Rhine) adjusted for the catchment area. Trend lines for 1991-2019 (red) and 2011-2019 (blue) based on Mann-Kendall trend tests. Dashed lines represent non-significant trends (Sen's slope) (Data sources: FGG Elbe n.d.; ICPR 2023). Target load from target concentration and long-term average Q (Elbe 724 m^3 s^{-1}, Rhine 2508 m^3 s^{-1}).

Since the 1990s, the nutrient inputs and the resultant concentrations and loads decreased significantly in both river basins (Figure 3). During the 2010s, this decrease was less pronounced and even turned into a (albeit statistically not significant) increase in total P (TP) concentrations in r. Elbe. While r. Rhine achieved the current target values according to the Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD)[1], the concentration (normalized load) of r. Elbe needs to be reduced by 20% (25%) for TN and 35% (37%) for TP.

The OSPAR region 'Greater North Sea' – to which the Wadden Sea belongs – receives about one third of its N and P from both river systems, other rivers, and atmospheric deposition (Figure 4). Their relative contributions vary with the distance to the river mouths and terrestrial sources. Since 2000, the declining N load of the Greater North Sea is driven by decreasing atmospheric N inputs which underlines the high importance of this source compared to the river basins.

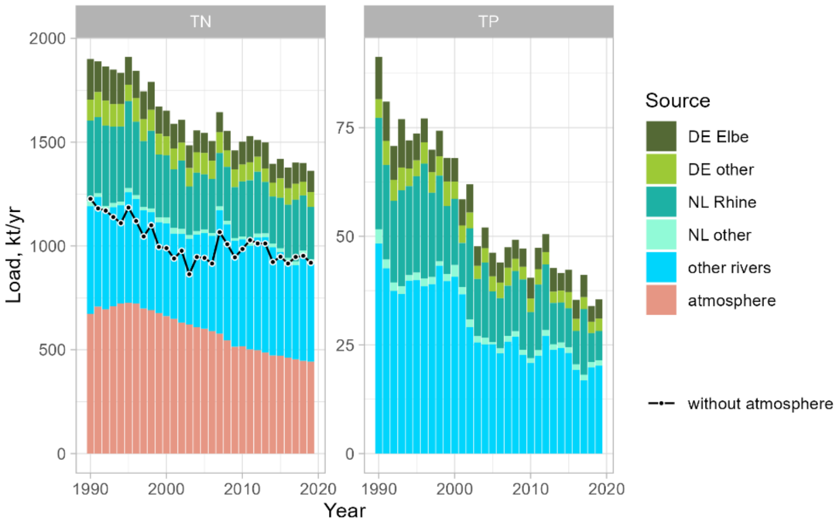


Figure 4. Normalised water- and airborne inputs of total N and P to the Greater North Sea from different regions. Elbe consists of the regions 'Elbe Estuary' and 'Elbe tributaries', Rhine of 'Closed Holland Coast', 'Northern Delta Coast', and 'Wadden Coast' (Data source: OSPAR Commission 2022). The broken line reveals that the decline in N loads is less pronounced if the atmospheric deposition is excluded.

[1] The eutrophication thresholds in OSPAR were recently harmonised which results in lower targets for dissolved inorganic N (DIN), and thus additional reductions needs of river loads to the North Sea. The Netherlands agreed, provided that these new targets will not be applied before 2027. So, until then, the present targets (i.e. annual average TN concentration of 2.8 mg L^{-1}, 2.5 mg L^{-1} summer average for r. Rhine) will be used (S. Plette, pers. comm.).

2. METHODS AND POLICIES

2.1. Background

There is a plethora of literature on measures to reduce directly or indirectly nutrient inputs to water bodies. Meta-analyses reveal that their efficiency depends on e.g. the type of measure, duration, management, or site characteristics (e.g. Gericke et al. 2020; Li et al. 2023; Osterburg and Runge 2007; Velthof et al. 2020). Since these conditions vary considerably in space and time, the efficiency of measures to retain nutrients is also highly variable (Figure 5, Table 24). The scale-dependency of processes may also hamper the expected efficiency of policies and measures. For instance, experimental studies on riparian buffers are dominantly conducted at the plot scale where flow concentration and preferential flow paths hardly occur. In natural terrain, however, flow concentration can create short-cuts which reduce the residence time in riparian buffers and thus the nutrient retention. At the same time, the increased transport capacity may favour high nutrient input to the riparian buffers (and the water bodies). Groenendijk et al. (2021) discuss these, and other concerns based on their literature review (cf. Table 20), including

- Empirical data is needed on the effectiveness of many measures,
- Effects of measures are site-specific and cannot easily be transferred to countries like the Netherlands due to high fertilization levels and other site conditions,
- Measures are not always clearly defined and can overlap,
- Measures may not involve specific actions but e.g. business strategies with variable success, or
- Effects of measures can target more than just nutrients. They may have a big impact e.g. on biology rather than nutrients.

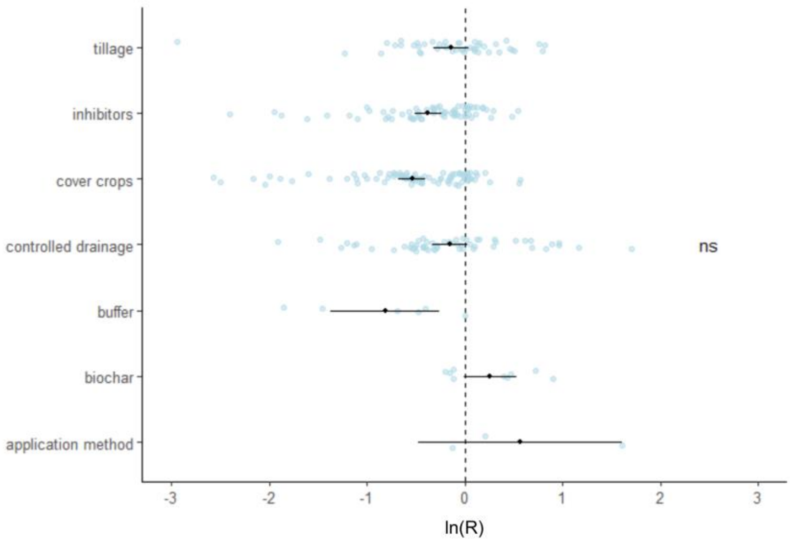


Figure 5. Exemplary results of a meta-analysis on the effect of various agricultural measures, here on nitrate loss to water bodies. Black dots show the mean logarithm of the response ratio R of the means of the treatment group and the means of the control group, blue dots the individual observations, and the error bars the 95% confidence interval (Source: Velthof et al. 2020, 33). Note: A negative value means that the loss is on average lower with than without the measure.

Apart from effectiveness, measures (and their implementation) have aspects like costs, adoptability, and (unwanted) side-effects (Velthof et al. 2020). Even in principle effective measures may fail when the acceptance and motivation of adopters are low (Auerswald et al. 2018; Hasler et al. 2019) in combination with insufficient design, inspections and enforcement (Klages et al. 2022). For instance, only 1% of the applying farms in Germany were subject to on-site inspections regarding cross-compliance between 2015 and 2018. In about 15% of the cases, non-compliance with the requirements of the EU Nitrates Directive were penalized (BMEL and BMU 2020). At the same time, the share of non-compliance and the penalty sums increased significantly in the Netherlands with the higher number of inspections (Fraters et al. 2020). On the other hand, cooperation with farmers including training can be helpful to achieve the legal commitments (Ortmeyer, Hansen, and Banning 2023), and regional and national programs like the Dutch DAW program (see Chapter 2.3) specifically address this issue. Insufficient policy support (Kathage et al. 2022; Stuhr et al. 2021), spatial mismatches of payments for agri-environmental measures and pressures (Früh-Müller et al. 2019; Tzemi and Mennig 2022), different views on ambitions, achievements, and necessary actions even within organizations (Wuijts et al. 2023), or unfavourable producer prices (Katte 2023) may also affect the adoption of measures and their (expected) impacts. To achieve the ambitious policy targets, measures likely need to be complemented by further research (Paulsen, Mahlberg, and Hahn 2023) as well as behavioural and cultural changes of our society (Leip et al. 2022; Desmit et al. 2018) in order to be effective.

Given the many factors and their interactions, similar statuses of water bodies (as addressed by the WFD and MSFD, see Chapter 2.4.1) or nutrient concentrations can thus be the result of different reasons. Disentangling the effect of measures or prioritizing the pressures for management is difficult (Bieroza, Bol, and Glendell 2021). Simulation models and scenarios are well-established tools to provide such input for river basin management plans (ICPDR 2021) or policy assessments (e.g. Fuchs, Weber, et al. 2017; Zinnbauer et al. 2023). Their results will necessarily deviate due to different model assumptions, input data, and assumptions on the efficacy of measures. Deviations such as in Figure 1 should be seen as uncertainty inherent to any assessment of measures. These uncertainties can hardly be quantified, even more so for planned and voluntary measures.

Table 1. Overview of nutrient-related targets of measures, policies, and core data considered in this study.

Pressure	Nutrient	Pathway/process	Target measures	Relevant policy[a]	Data
Point sources	N, P	Wastewater treatment plants (WWTP)	Retention, outflow concentration	UWWTD	WWTP inventory
Diffuse sources	N	Subsurface flow, tile drainage	N surplus	ND, CAP, DAW	Model results
	N	Atmospheric deposition	Atmospheric N emission	NECD	Model results, reported emissions
	P	Soil erosion	Soil coverage, soil loss	CAP, DAW, EU Soil Health Law	Model results
	N, P	(Sub-)surface flow, soil erosion	Riparian buffers	CAP, (WFD)	
Hydrological / hydro-morphological change	N, P	In-stream retention	Residence time	WFD	-
High nutrient load / concentration	N, P	-	State water bodies	WFD, MSFD	Programme of measures, monitoring data, model results

[a] Policy abbreviation: Common Agricultural Policy (CAP), Marine Strategy Framework Directive (MSFD), National Emission Ceilings Directive (NECD), Nitrates Directive (ND), Urban Wastewater Treatment Directive (UWWTD), Water Framework Directive (WFD), Deltaplan Agrarisch Waterbeheer (DAW).

2.2. General approach

For this large-scale assessment and the available data which do not contain sufficient implementation details, we consider ‘measures’ rather loosely as (groups of) practices or actions (e.g. as in Tables 20 and 24) which directly or indirectly target nutrient inputs. For instance, the conversion to organic farming e.g. consists of multiple site-specific measures to replace mineral fertilizer with manure: establish pasture or integrate legumes in the crop rotation for farm-grown fodder, higher N use efficiency, and lower infestation risk (Reckling et al. 2016; Barbieri, Pellerin, and Nesme 2017). For the same reasons, we focus on frequent measures which address the key pathways and sources of nutrients in the catchments of rivers Elbe and Rhine as well as the Wadden Sea as they have the highest overall potential impact to reduce nutrient inputs (Table 1). As we cannot anticipate when, where, and how the planned measures will be implemented, we also considered scenario assessments of policy implementation and other data to assess potential basin-wide impacts on path-specific and total inputs of N and P. The focus is on actions with a physical impact on water bodies. The positive effect of advisory services as conceptual measure is briefly demonstrated. Financial and other measures are out of scope.

This simplified approach can neither disentangle the multiple effects of different measures nor the interactions of multiple stressors (Lemm et al. 2021). For instance, lowering the N surplus to improve the state of terrestrial water bodies also reduces the N losses to the atmosphere and eventually the atmospheric deposition. Riparian buffers may connect habitats but also retain nutrients. No-till helps to maintain soil functions by reducing the soil erosion but may favour N leaching (cf. Li et al. 2023). Given the uncertainties in any input data, the results can only indicate what can be expected by implementing nutrient-related measures policies. The model-based scenario analyses in WP 3 will extend these findings and previous scenario assessments.

2.3. Assessment of planned measures

We analysed national data tables of the measures planned for the 3rd River Basin Management Plans (RBMP, 2021-27) within the Water Framework Directive (Informatiehuis Water 2023; Umweltbundesamt 2022; as used for Völker et al. 2023). The data tables were pre-processed (spelling harmonized, translation, merge tables where required) to assign the measures to individual water bodies within the catchments of rivers Elbe and Rhine. The final tables contained quantitative data on the number, area, and length of measures as well as national measure codes with further attributes such as a description and the Key Type of Measures (KTM, Table 21) for the EU reporting. The quantitative data for the German federal state Nordrhein-Westfalen were either 1 or 0. In the Netherlands, measures were assigned to multiple water bodies, and it remained unclear how they are distributed. So, we evaluated for both countries the number of water bodies the measures were assigned to. The additional attributes of the measures as well as the type of water body (surface = river, lake; subsurface = groundwater, transitional, coastal, territorial = coastal/marine) were used to group the results.

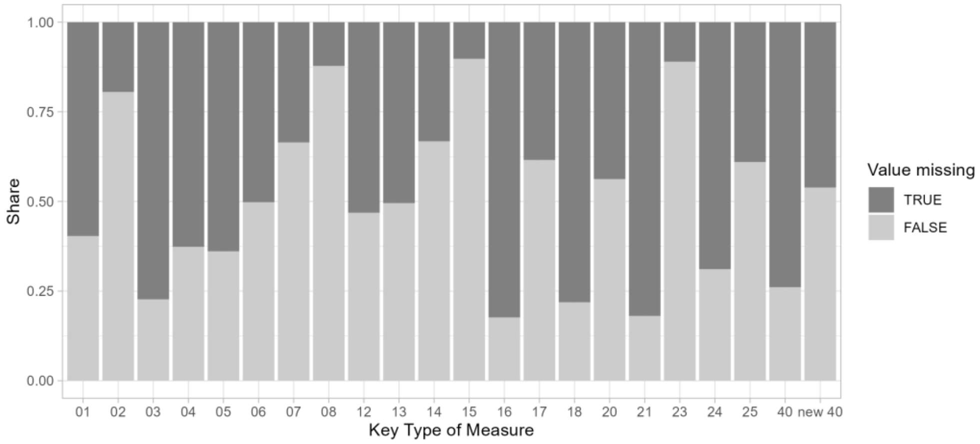


Figure 6. Share of records with empty COMMENTS attribute of the German data table. Note: Values consists of records which were completely excluded (e.g. measure ids) or are meaningless ('AW' for wastewater).

While Germany uses a set of national measure codes which are uniquely assigned to KTM (Table 21), the Netherlands uses more generic measure codes (KRWmaatregel_Code, LokaalID) whose combination is uniquely assigned to KTM. However, the number of these combinations was too high for the evaluation (n=1163). So, we assessed the results at KTM level and explored the context of the most frequent KTM, i.e. the most common keywords and phrases in the 'COMMENTS' (DE) and 'Naam' (NL) attributes. These 'tokens' were obtained with the R library tidytext (Silge and Robinson 2016) which contains language-specific lists of stop words. Further pre-processing and post-processing were needed to account for misspellings and grammatical differences between plural/singular and verb/noun (e.g. 'ontwikkelen'/'ontwikkeling') as well as to glue words and to avoid double counting (e.g. 'Deltaplan Agrarisch Waterbeheer (DAW)'). Remaining unspecific words and abbreviations like 'benutten', 'i.c.m.', and 'BVP-ID' were manually excluded. A minimum frequency of 5 was chosen to exclude e.g. names of places. Unlike the Netherlands, Germany does not systematically use its attribute (Figure 6). Despite the common KTM, the data tables were independently evaluated due to the different table structures. The Dutch tables were translated with deepl, and the translation revised (J. Rozemeijer, pers. comm.).

This set of planned measures was complemented by the database of measures related to the National Emission Reduction Commitments Directive as reported by the EU Member States (EEA 2023a), the reporting under Article 13 of the Marine Strategy Framework Directive for Descriptor 5 (Eutrophication) (BMUV 2022a; IenW 2022), as well as an overview of the measures listed in the Action Programmes for the Nitrates Directive (BMEL and BMU 2020; LNV and IenW 2021) and the BOOT list of the Dutch Taskforce Agricultural Water Management (Deltaplan Agrarisch Waterbeheer, DAW).

2.4. Nutrient-relevant policies and measures

The comprehensive policy framework of the European Union comprises environmental and agricultural policies, Circular Economy, as well as the European Green Deal (EEA 2020). Most fundamental for our analyses are the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). The WFD aims at achieving the good ecological and chemical status of surface water, the MSFD at the good environmental state of marine waters. Using a holistic approach, both Directives target the ecological impact of nutrient inputs which is one end of the pollution continuum (Bieroza, Bol, and Glendell 2021). They are complemented by source-oriented policies on nutrient (and other pollutants) inputs from wastewater, atmosphere, and agriculture (Figure 7,

Table 1). We also included in our assessment measures linked to the Common Agricultural Policy – the central agricultural EU policy to influence farming activities and to subsidize agricultural measures to reach the goals of the WFD and the MSFD (and, especially in Germany, the Nitrates Directive).

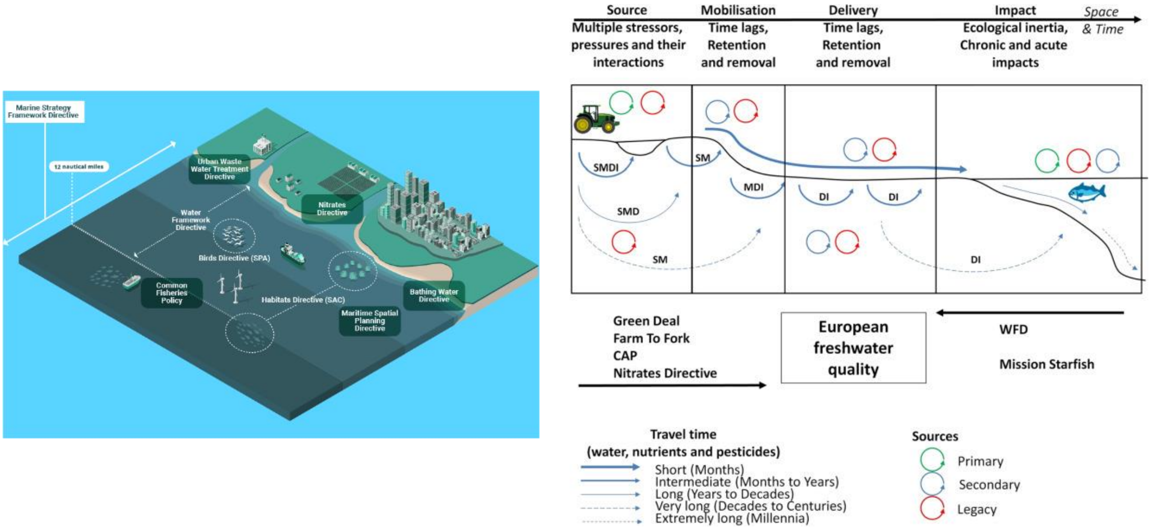


Figure 7. Marine Policies Schema (left, © EEA-ETC/ICM) and water pollution continuum and European strategies to improve freshwater quality representing travel times (arrow width) and extent (letters Source, Mobilisation, Delivery, and Impact, right). Each step involves complex processes controlling diffuse pollution mobilisation, retention and transfer to the downstream compartment. European freshwater quality is regulated by the Water Framework Directive (and the Marine Strategy Framework Directive) focussing on impact while CAP, Nitrates Directive, and other policies focus on sources and the mobilisation of nutrients (Source: Bieroza, Bol, and Glendell 2021).

2.4.1. Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD)

The Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) are the fundamental environmental policies to protect freshwater, transitional, coastal, and marine ecosystems from pollution and ensure their ecological quality (European Parliament and European Council 2000; 2008). Since 2000 (WFD) and 2008 (MSFD), Member States are obliged to use RBMP and Programs of Measures to originally achieve the good status until 2015 (WFD) and 2020 (MSFD). To assess the status of water bodies, the Directives prescribe various quality elements (WFD) and descriptors (MSFD) for which the Member States defined environmental quality standards (Poikane et al. 2019; Araújo et al. 2019). The nutrient conditions are chemical elements supporting the biological element according to the WFD, and a primary criterion of Descriptor 5 (Eutrophication) in MSFD as well as the OSPAR Common Procedure (ICG EUT and ICG EMO 2022).

Despite all the improvements so far – the EU-wide model assessment of Vigiak et al. (2023) exemplarily demonstrates that the inputs of N and P as well as their loads to the seas declined in most marine regions since the 1990s – the WFD and MSFD targets are not achieved. Accordingly, the WFD status of the nutrient conditions for many water bodies in the Rhine and Elbe basins is still insufficient (Figure 8). While r. Rhine meet the current WFD targets at the German-Dutch border, substantial reductions are still needed at the limnic-marine border of r. Elbe (see Figure 3 and Chapter 1.3). Accordingly, only the 6 offshore areas out of the 12 Dutch and German reporting units in the North Sea were in ‘good’ nutrient conditions (based on the winter concentration of dissolved inorganic N and P) according to the 2018 Reporting under MSFD Article 8 (EEA n.d.). The recent OSPAR Quality Status Report 2023 revealed in the OSPAR region II (Greater North Sea) that many assessment areas are in a moderate to poor status for dissolved inorganic N (DIN, Figure 9) and 4 assessment areas are in a moderate status for dissolved inorganic P (DIP).

Table 2. Indicators used for quality assessment of coastal and transitional waters in Germany and the Netherlands (based on Poikane et al. 2019; Araújo et al. 2019).

Country	**DE (North Sea)**	**NL**
WFD, MSFD	Winter DIN, Winter DIP, TN, TP	Winter DIN, winter DIP
Target concentration limnic-marine border	2.8 mg L^{-1} TN, 0.1 mg L^{-1} TP	2.8 mg L^{-1} TN (annual)*
OSPAR	Winter DIN, Winter DIP, TN, TP	Winter DIN, Winter DIP
	* See Footnote 1 on p. 9	

Figure 8. WFD status of water bodies as reported by the countries (data sources: EEA 2018b; 2018a; Informatiehuis Water 2023; data used for Völker et al. 2023). The EEA for the 2nd River Basin Management Plans complements the marine data. Note: The Netherlands does not use P target for transitional and coastal waters.

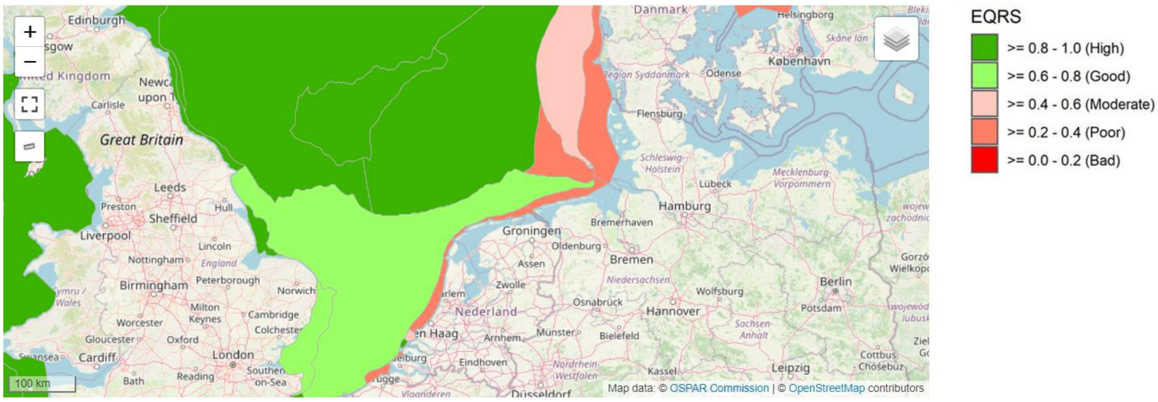


Figure 9. Assessment for winter DIN of the fourth application of the OSPAR common procedure (2015–2020) (source: Heyden and Leujak 2022, detail). The status is based on the scaled ecological quality ratio (EQRS) ranging from 0 to 1.

For the evaluation of how the implementation of measures and policy compliance contribute to the goals of the WFD and MSFD, we used published model assessments. A recent Germany-wide study modelled the reduction needs for 2014–2016 and for an assumed compliance with the Nitrates Directive to achieve the targets for groundwater bodies and the coastal waters (Zinnbauer et al. 2023; Schmidt et al. 2022). The ongoing DüngEval project used the methods established by Häußermann et al. (2019), the agri-economic projections for Germany 2022–2032 (Haß et al. 2022), and the recent Fertilizer Ordinance to assess how the Ordinance contributes to the environmental targets for water quality (WFD, Nitrates Directive) and atmospheric N emissions for climate and biodiversity (Häußermann et al., unpublished). Van Grinsven et al. (2016) evaluated the WFD, as well as the NEC Directive and Nitrates Directive, regarding target achievement, effectiveness, costs and benefits in the Netherlands. More recently, the effect of implemented and planned measures in the Dutch RBMP 2016–2021 as well as 2022–2027 on the status of waterbodies in 2027 was modelled (van Gaalen, Osté, and van Boekel 2020). Both studies are based on the previous Dutch Action Program for the Nitrates Directive. For the ex-ante analysis of the Dutch RBMP 2022–2027, various policy scenarios were evaluated including the current 7th Action Program (2022–2025), RBMP 2022–2027, and the DAW (van der Linden, Altena, and van den Roovaart 2021). As an extension, two ‘target scenarios’ and one ‘realistic’ scenario for rivers Rhine and Meuse were evaluated regarding the status of the Dutch coastal and marine waters in 2027 (van den Roovaart et al. 2021).

2.4.2. National Emissions Reduction Commitments Directive (NECD)

The National Emissions Reduction Commitments (NEC) Directive sets national commitments to reduce the emission of 5 main air pollutants with quantitative reduction targets for the years 2020 to 2029 and for 2030 onwards (European Parliament and European Council 2016). The new NEC Directive (NECD) goes beyond earlier legislation which defined emission targets for 2010 to achieve air-quality levels which do not harm human health and the environment.

Among the 5 pollutants, oxidized and reduced N forms (NOx, NH_3) are relevant sources of nutrient fluxes to water bodies (cf. Figures 1–2). While the traffic and industry are the main emitters of NOx, agriculture is by far the main source of NH_3 emissions to the atmosphere throughout European countries (Figure 10). The figure also reveals that the emissions greatly decreased since the 1990s and that Germany and the Netherlands already reach their emission targets for the years 2020–2029. However, more efforts are needed to reach reduction commitments for 2030. This is especially true for Germany as it has slightly higher commitments until 2030 but lower commitments until 2020 compared to the Netherlands (Table 19).

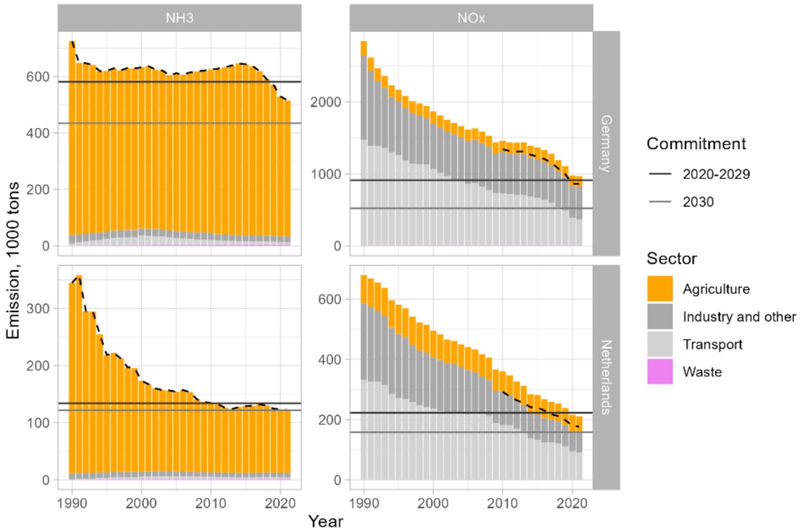


Figure 10. Atmospheric N emissions for Germany and the Netherlands according to main sectors with the legal commitments according to the NEC Directive. For compliance, agricultural NOx emissions are not fully counted (broken line) (source: EEA 2023a).

The assessments on an integrated N indicator for Germany revealed that the NECD requires more than 80% of the German reduction which is needed to fulfil legal obligations (Bach et al. 2020; Häußermann et al. 2021). The reduction needs for NH_3 are above 40% which underlines the importance of agricultural measures. Accordingly, Annex III on the content of national air pollution control programmes of the Directive refers to the ‘good agricultural practice’ to control NH_3 emissions related to livestock and fertilizer application including the spreading of manure and slurry.

The atmospheric N is deposited on soils, freshwater, marine waters and thus contribute to the N soil-surface balances, to N leaching to groundwater, and to N input to surface waters. In Germany, atmospheric N deposition contributes 17% to the N surplus on agricultural land (Häußermann et al. 2020), about 2% to the N inputs directly to surface waters (Figure 1), but 17% to Dutch surface waters (Figure 2), and 33% to the marine system (Figure 4). However, agricultural measures target at emissions / losses not the deposition elsewhere. To link the effect of reduction measures to N input to water bodies, we evaluated recent, unpublished scenario calculations for Germany conducted with the LOTOS-EUROS model within the PINETI-IV project (A. Moravek, pers. comm.). Pan-European simulations combined with ‘zoom runs’ at higher resolution to cover the sea basins near Germany were performed for the years 2019 and 2030. The model tracked the spatial and sectoral origins of the N deposition.

The soil-surface balance was legally binding for farmers in Germany until 2020 to meet the requirements of the Nitrates Directive (Chapter 2.4.4) and the NECD but was recently replaced by fertilization planning – which is in line with most EU countries including the Netherlands (Löw, Osterburg, and Klages 2021). The soil-surface balance is the difference between the applied to soils and the removed (harvested) nutrients. Any surplus poses a risk of nutrient losses to the atmosphere but also surface and groundwater bodies (cf. Chapter 2.4.4). Its parameters are identical to the fertilizer planning except for the nutrient demand and supply from the soil. The patterns of both indicators are similar across farm-types (Löw, Osterburg, and Klages 2021). 27% of the farms assessed by the authors have to reduce their N surplus by on average 10 kg N ha^{-1} based on the fertilizer planning in contrast to 23% (9 kg N ha^{-1}) based on the soil-surface balance (Figure 11).

In addition to the reduction needs according to the NECD, the Dutch Ministry of Agriculture, Nature and Food Quality intends to induce actions of the 3000 top peak emitters to reduce N deposition on Natura 2000 areas (van der Maas, Jones, and Hazelhorst 2023). Apart from a few industrial sites, livestock farming exceeds the derived threshold of 2500 mol (van der Maas, Jones, and Hazelhorst 2023). We evaluated the AERIUS 2023 dataset with tracked N deposition on Natura 2000 sites to compare the deposition for the years 2021 and 2030 for the selected areas 'Waddenzee', 'Noordzeekustzone', and 'IJsselmeer' (RIVM 2023) which are close to the Rhine basin. The scenarios for foreign emissions are based on the NEC Directive (Romeijn et al. 2023). Due to an error in the published scenario results for foreign sources, the original values were divided by 2 (Helpdesk Stikstof & Natura2000, pers. comm.).

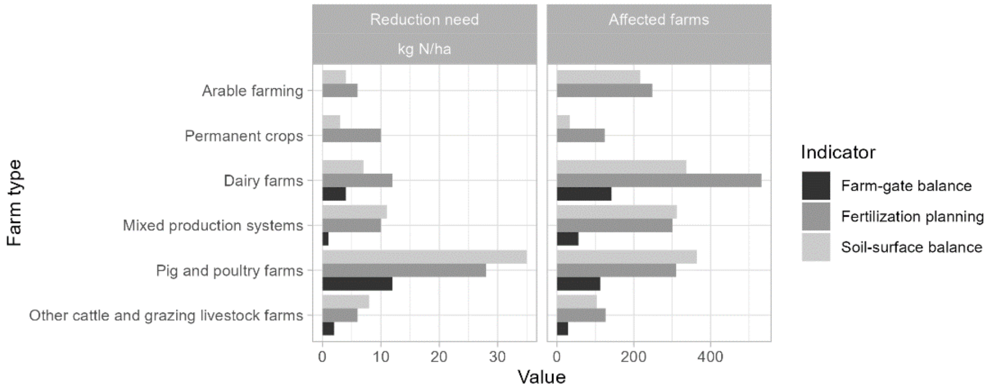


Figure 11. Mean reduction needs (left) and number of affected farms according to fertilization planning and soil-surface balance for different farm types in Germany. For visual comparison, the farm-gate balance (black) – one indicator of the German Sustainable Development Strategy (data: Löw, Osterburg, and Klages 2021).

2.4.3. Urban Wastewater Treatment Directive (UWWTD)

The Urban Wastewater Treatment Directive (UWWTD) was adopted in 1991 to protect humans and the environment from the adverse effects of untreated wastewater. Since 2005, Member States are required to provide collecting systems and at least secondary treatment for wastewater in agglomerations above 2000 population equivalents (p.e., Figure 12). The Directive defines minimum target values for N and P retention and concentrations in the outflow for agglomerations above 10000 p.e. To address the remaining nutrient pollution from urban wastewater treatment plants (UWWTP), an update was proposed in 2022 (Directorate-General for Environment 2022) with stricter rules (Table 3). Agglomerations above 1000 p.e. should be equipped with collection systems, above 10000 p.e. tertiary treatment should be mandatory.

For assessing how optimizing UWWTP may affect the nutrient inputs to surface waters, we selected all discharge points of active Dutch and German UWWTP within the study area. The reported data to the EU contained annual inflow and outflow loads of N and P as well as treatment level and design capacity of UWWTP above 2000 p.e. but no water discharge to derive concentrations (EEA 2023b). In order to assess the latter, we linked it to German data tables (Umweltbundesamt n.d.). All 4122 selected UWWTP were found to have secondary treatment, and 3990 UWWTP have tertiary treatment, mostly N and P removal (3185 UWWTP). The 136 UWWTP without tertiary treatment have design capacities below or equal to 10000 p.e., except for Burghausen (30000 p.e.) and Panheel (22500 p.e.).

Table 3. Minimum values for concentration and retention according to the current and the proposed new UWWTD. Note: the new UWWTD refers to tertiary treatment.

Pollutant	**Treatment size, p.e.**	**Current UWWTD**		**Proposed new UWWTD**	
		Concentration, mg/l	**Retention, %**	**Concentration, mg/l**	**Retention, %**
Phosphorus	10–100000	2	80	0.5	90
	>100000	1	80	0.5	90
Nitrogen	10–100000	15 mg/l	70–80	6	85
	>100000	10	70–80	6	85

On average, the UWWTP in the study area meet the targets (N: about 85% retention, P: 88% retention in the Netherlands and 94% in Germany)[2]. Despite the same treatment level, the outflow concentration and nutrient retention (calculated as ratio of outflow load and inflow load) can vary significantly (Figure 13). As it is not feasible to assess the effect of measures on individual UWWTP, we assessed the potential of optimizing UWWTP under current legislation following the approach of Fuchs et al. (2017) for Germany. For 4 classes of design capacity (2000–5000 p.e., 5000–10000 p.e., 10000–100000 p.e., and more than 100000 p.e.), we applied quantiles of retention and concentration as technological benchmarks. To assess the potential of the proposed UWWTD, we

[2] Based on the data used for this study. The missing treatment plants below 2000 p.e. will only slightly reduce these values.

applied the new minimum values to UWWTP connected to agglomerations above 10000 p.e. UWWTP already below these target values remained unchanged.

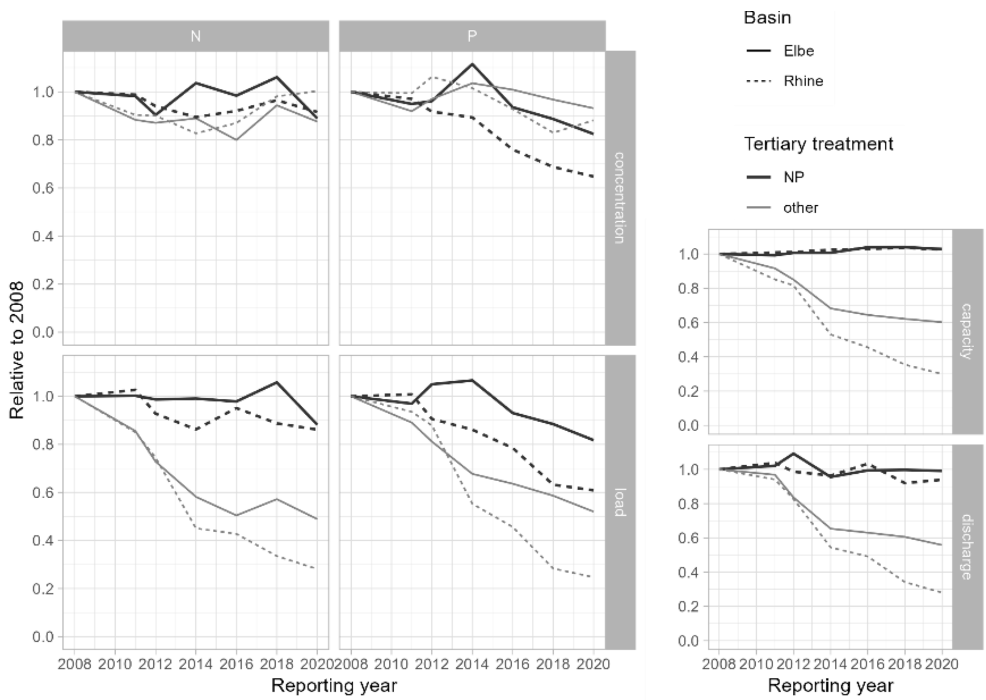


Figure 12. Change in average outflow concentration and total load (left) and capacity and discharge (right) of urban WWTP in the German parts of r. Elbe (solid) and Rhine (broken line) for UWWTP with tertiary treatment for N and P (NP, dark) and other treatment levels (light) (data: Umweltbundesamt n.d.). The capacity of UWWTP with NP treatment increased after 2008 at the cost of other UWWTP. Unlike N, the P retention improved resulting in lower outflow concentration (and load).

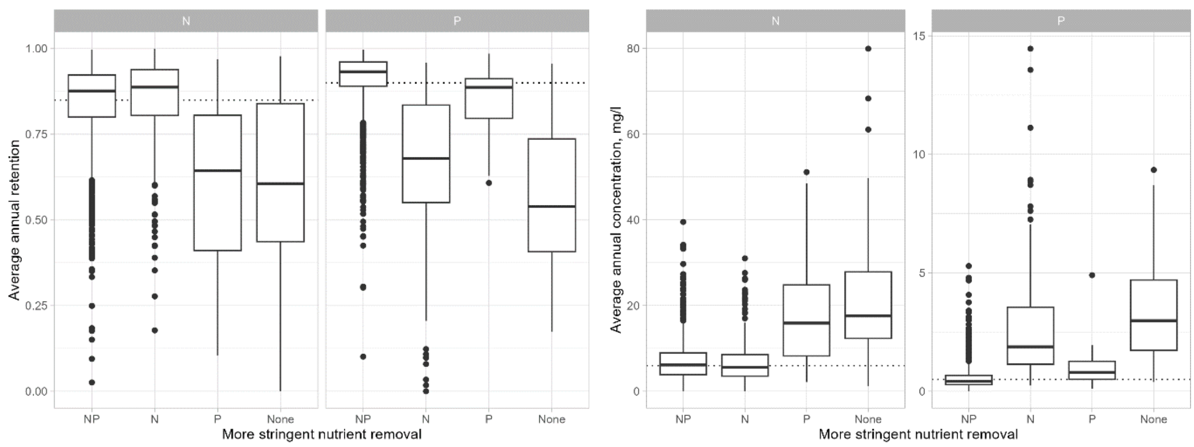


Figure 13. Distribution of nutrient retention (left) and outflow concentration (right) for active urban WWTP in the Rhine and Elbe basins for different types of tertiary treatment. Concentration only available for German UWWTP. Broken line indicates the target values according to the UWWTD. Note: The majority of UWWTP have NP treatments, no tertiary treatment (None) occurred only for UWWTP with incoming loads below 10000 p.e.

2.4.4. Nitrates Directive (ND)

Adopted in 1991, the Nitrates Directive (ND) aims at reducing and preventing the pollution of water bodies by nitrate from agricultural sources (European Council 1991). Despite all achievements, nitrate pollution remains a key environmental pressure in the European Union, especially from agricultural sources (Fermeglia 2023) which makes the ND an integral part of the WFD. The ND requires EU Member States to establish and revise Action Programs (AP) in designated Nitrate Vulnerable Zones, if not the whole territory as in Germany and the Netherlands. To achieve the target concentrations of 50 mg L^{-1} in groundwater and avoid eutrophic surface waters, good farming practices are promoted including periods of inappropriate fertilizer applications, minimum quantity of vegetation to take up (excess) nitrate (intercropping), and fertilizer plans at farm level.

Intensive fertilizer application with high soil-surface N balances is the main driver for nitrate losses to water bodies. N balances are positive ('surplus') when the (fertilizer) input exceeds the output, i.e. the uptake by (harvested) plants and the microbial degradation leading to atmospheric losses of nitrous oxide or N (denitrification). The excess N leaches to tile drainage and the interflow and groundwater. Germany and the Netherlands are among the EU countries with the highest N surplus, although the values dropped significantly during the 1990s (Figure 14) which lowered the NH_3 losses to the atmosphere (Figure 10). The unsustainable surplus, however, makes these pathways still most important for the N input to rivers, lakes, and marine water bodies in the study area (Figures 1–2). The same pattern – no further decline of N surplus after the initial reduction during the 1990s – holds true for large parts of Europe (EEA 2020).

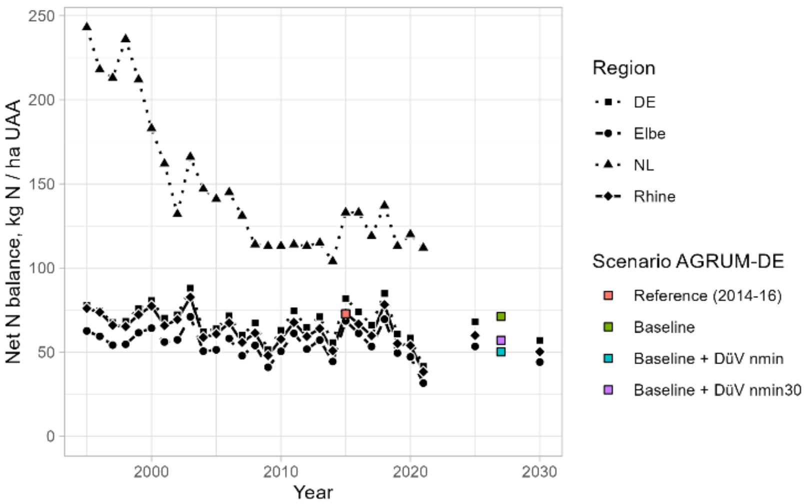


Figure 14. Area-weighted regional N soil-surface balances for the German parts of rivers Rhine and Elbe (Häußermann et al. 2023, pers. comm.) compared to the national average from the AGRUM-DE model (Zinnbauer et al. 2023) (plus an atmospheric deposition of 14.5 kg ha^{-1}, red square) and the national N balance for the Netherlands (CBS 2022) (triangles). The expected change in the AGRUM-DE scenarios (other squares) is within the current range of values. Note: Methodical differences and inherent uncertainties limit the comparison of the time-series.

The interplay of land use and land management, livestock density, soil and groundwater properties make the N balances as well as the N input to water bodies variable in space and time (Figures 14–15). Both figures also support the notion that limited plant growth and nutrient uptake during drought years such as 2018 can cause higher N surplus and subsequently higher N concentration in water leaching the root zone. However, high N leaching may also occur without a high N surplus due to sandy soils and low groundwater depths (cf. Figure 15).

A comparison across the EU revealed methodical deviations in N budgets which hamper the comparison of N balances and concluded that N budgets cannot be readily used as legal requirement for the ND and other environmental policies (Klages et al. 2020). Nonetheless, farm-level budgets are suitable indicators for best management practices.

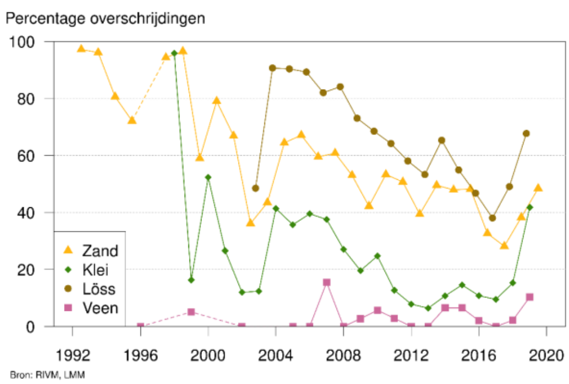


Figure 15. Inter-annual variability of area-weighted percentage of farms exceeding the EU standard of 50 mg/l nitrate in groundwater in different soil regions in the Netherlands (sand, clay, loess, and peat). The increase after 2017 could be related to droughts (source: Fraters et al. 2020).

Both countries do not yet achieve the targets of the ND (e.g. Figure 15). For the assessment of possible measure effects, we relied on national model-based scenario assessments of basin- or nation-wide effects of the Dutch AP and the German Fertilizer Ordinance which both implement the ND (Groenendijk et al. 2021; Zinnbauer et al. 2023; van Boekel et al. 2021; van Gaalen, Osté, and van Boekel 2020). This was complemented by published (local) effects (Osterburg and Runge 2007; Groenendijk et al. 2021) (see also Figure 5). Osterburg and Runge (2007) provide an extensive overview of measures addressing nitrogen including their efficiency, acceptance, and applicability. The efficiency is reported for 3 complementary indicators: calculated N balances for the long-term risk of N losses to the environment, measured Nmin in autumn as amount of soil mineral N content which can readily leach during winter, and calculated N loads as the annual amount of N in the leachate.

The national fertilizer regulations also address phosphorus. High P contents in soil increase the risk of P losses via soil erosion (cf. Chapter 2.4.5) or via surface runoff (cf. Figure 1). Like N, P was excessively applied to agricultural soils in the past which resulted in highly saturated soils and a high risk of diffuse losses to German and Dutch water bodies (Fischer, Pöthig, and Venohr 2017; Schoumans and Chardon 2015). The nutrient balances decreased significantly since the 1990s. Unlike N, the P inputs and outputs converged leading already to closed balances (Figure 16).

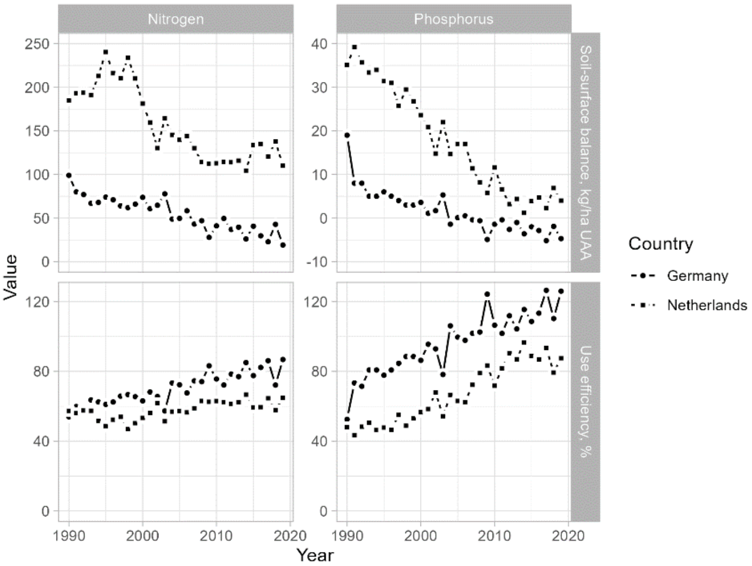


Figure 16. N and P soil-surface balance (top) as difference of (net) input and output as well as the use efficiency (bottom) as ratio of nutrient output to nutrient input in Germany and the Netherlands. Note: The German N balance differs from Figure 14 due to different approaches (Eurostat 2023a).

2.4.5. Common Agricultural Policy (CAP)

The Common Agricultural Policy (CAP) was established in 1962 to promote agricultural production and rural development in the EU. Since its implementation, the CAP was reformed multiple times. The most recent CAP 2023-2029 entered into force in 2023.

The funding schemes of the CAP are the key instrument to guide agriculture and its sustainable development (EEA 2020). It consists of two 'pillars': income and market support (Pillar I) and rural development (Pillar II). Farmers and stakeholders are subsidized according to the approved national CAP Strategic Plans (European Commission 2023b; 2023a). Under the CAP, beneficiaries have to obey basic standards and societal expectations concerning e.g. the statutory management requirements (SMR) and good agricultural and environmental condition of the land (GAEC, Table 4). This cross-compliance links the CAP with the WFD and ND. These requirements, or 'conditionalities' in the recent CAP, are complemented by voluntary 'eco-schemes' which go beyond the conditionalities and other legal requirements (European Parliament and European Council 2021).

The requirements SMR 1, SMR 2, and GAEC 4 directly address water quality, while the other GAEC in Table 4 primarily address soils (GAEC 5-7) and biodiversity (GAEC 8) but also indirectly affect water quality. The conditions for the eco-schemes and expenditures are specified in the national CAP Strategic Plans. In contrast to Germany, the Netherlands opted for a complex, multi-dimensional, score-based eco-scheme across farm-types (Figure 17). Farmers need a minimum score for climate, soil and air, water, biodiversity, and landscape.

Table 4. Relevant requirements of conditionality related to nutrients (European Parliament and European Council 2021; Heyl et al. 2023).

Requirement	Target / Reference	Effect on nutrient management
SMR 1	Water Framework Directive	Reduce phosphate input to water bodies
SMR 2	Nitrates Directive	Reduce nitrate input to water bodies
GAEC 4	Buffer strips along water courses	Reduce nutrient input to water bodies
GAEC 5	Tillage management	Limit soil erosion
GAEC 6	Minimum soil cover	Limit soil erosion, fertilizer input, nutrient leaching
GAEC 7	Crop rotation in arable land	Preserve soil potential, limit soil erosion, fertilizer input
GAEC 8	Non-productive areas	Reduce soil erosion, fertilizer input

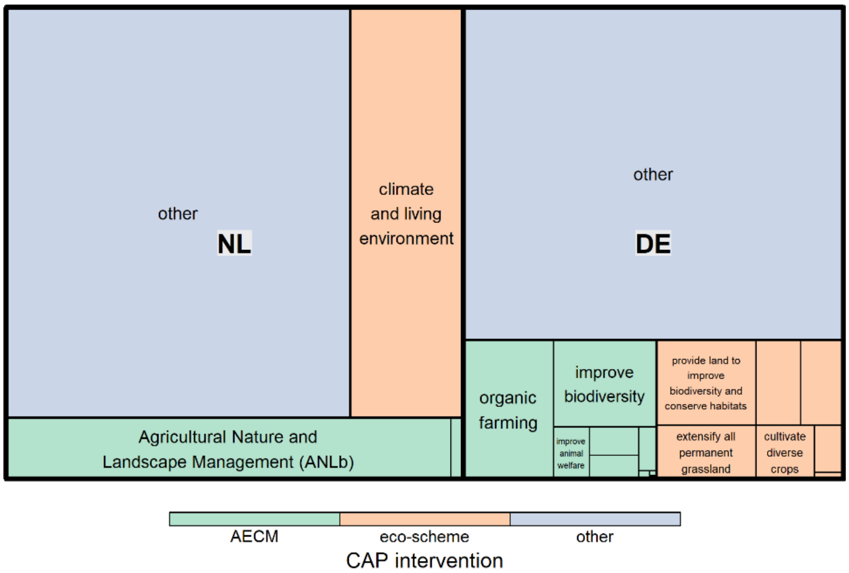


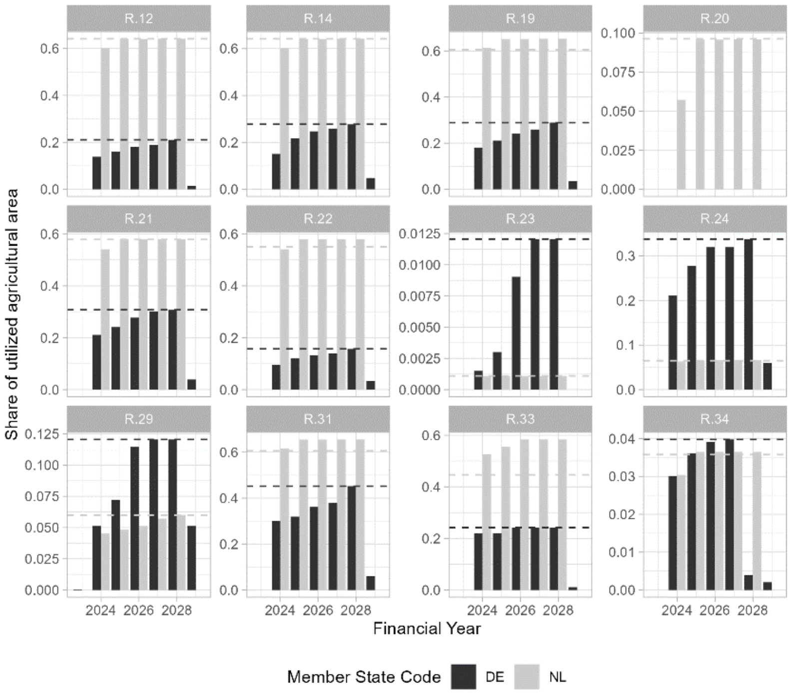
Figure 17. Total public expenditure (2023-2029) for agri-environment-climate measures (AECM, green), eco-schemes (orange), and other measures (blue) according to the CAP Strategic Plans for Germany and the Netherlands (data: European Commission, Directorate-General for Agriculture and Rural Development 2023a). The area is proportional to the expenditure in Euro per utilized agricultural area in 2021 (data: European Commission, Directorate-General for Agriculture and Rural Development 2023b).

The eco-schemes in Germany and other countries were already available as agri-environment-climate measures (AECM) in previous CAP and the ND. However, with the new CAP, there is a substantial financial shift from the multi-annual AECM to the annual eco-schemes (Figure 17). The previous CAP already lacked the ambition and sufficient implementation to achieve water-related goals, and data to assess the effectiveness of the CAP (EEA 2020; UBA 2021) which is also in line with the achieved status of water bodies (Chapter 2.4.1) as well as the stable N balances and unclear trend in N leaching (cf. Chapter 2.4.4). Although the new CAP gives Member States more flexibility, countries such as Germany do not use it for more ambitious standards than the minimum requirements (Heyl et al. 2023). Scenario calculations indicate that the CAP subsidies may have aggravated the quality of the Baltic Sea (Jansson et al. 2019). The voluntariness, the short time period and the minimum funding (in Germany) of the new eco-schemes, in combination with the funding cuts of AECM restrict the effectiveness of the CAP to achieve the envisaged nutrient losses by 2030 (Bieroza, Bol, and Glendell 2021; Heyl et al. 2023). The limitations of voluntary measures to improve water quality at regional and national scales – high participation rates are required for a significant impact – were also recently stressed in Dutch studies (van den Brink et al. 2021; Wuijts et al. 2023). Nonetheless, voluntariness may also raise the motivation of participants (DAW 2021).

We focused on measures related to the GAEC in Table 4 and the Specific Objective 5[3], i.e. riparian buffers, reduced tillage, and adapted crop rotation. The latter includes the use of cover crops and the switch to organic farming. The CAP uses a group of indicators to evaluate these measures. These indicators are linked to the goals of the European Green Deal, Farm-to-Fork Strategy, or Biodiversity Strategy for 2030 (e.g. Englund et al. 2021). However, the national target values differ widely (Figure 18). Soil coverage on arable land without permanent crops is dominant in Germany and the Netherlands, unlike organic farming and conservation tillage (Figure 19). In the Netherlands, these measures are not only less common than in Germany but also below the

[3] Foster sustainable development and efficient management of natural resources such as water, soil and air, including by reducing chemical dependency

EU average. In addition, the ambitious Farm-to-Fork Strategy envisions organic farming on 25% of agricultural land by 2030 in the EU. The German Sustainable Development Strategy 2021 aims at 20% by 2030 (German Government 2020) but the ruling coalition increased the target to 30% (BMEL n.d.).



Indicators (R codes) related to
12 climate adaptation
14 carbon storage
19 soil quality and biota such as tillage, soil cover, and leguminous crops
20 ammonia emissions to the atmosphere
21 water quality
22 nutrient management
23 water balance
24 use of pesticides
29 organic farming
31 biodiversity and High-Nature-Value farming
33 Natura 2000 management
34 landscape elements like tree and hedgerows

Figure 18. Overview of national milestones and targets for result indicators in the recent CAP Strategic Plans (European Commission, Directorate-General for Agriculture and Rural Development 2023c) assigned to the areal measures addressing the GAEC in Table 4 or the Specific Objective 5 (Soil, water, air).

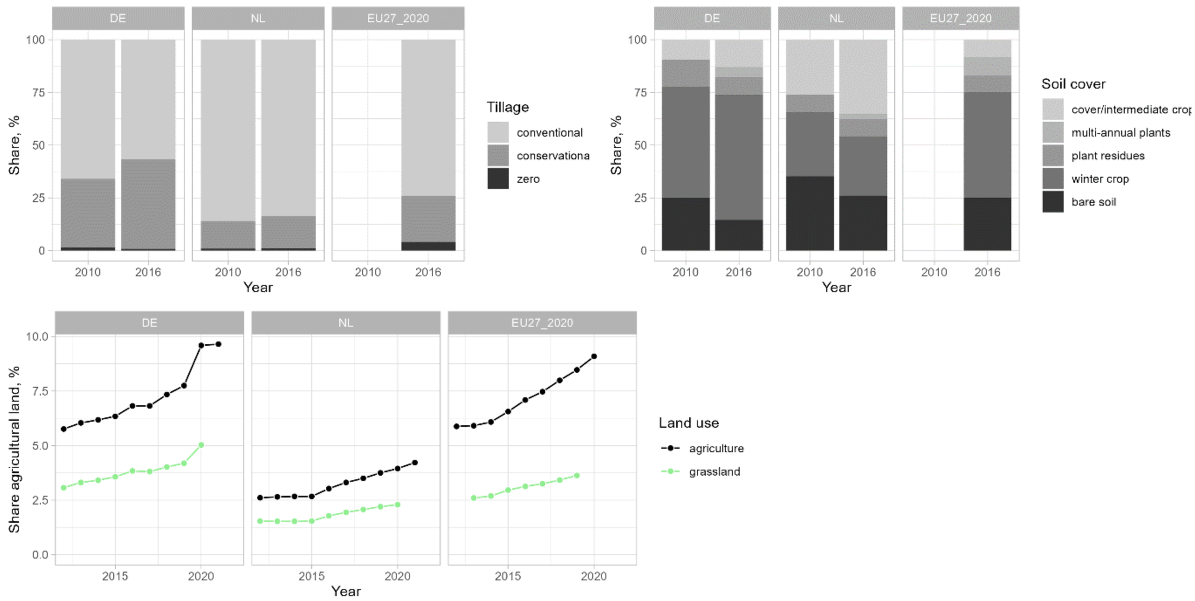


Figure 19. Tillage practices and soil cover on arable land (top row) as well as development of organic farming on agricultural (black) and grassland (green, bottom row) in Germany, the Netherlands, and the EU27 (Eurostat 2020a; 2020b; 2023c). The EU values for tillage and soil cover were calculated from the national values. The ambitious target of the Farm-to-Fork Strategy is 25% organic farming by 2030. Note: Conservation tillage dominantly applied on large farms (not shown).

For the assessment of possible measure effects, we used published (meta-)analyses on the efficiency of riparian buffers to retain nutrients (Gericke et al. 2020; Walton et al. 2020) and national studies (Noij, Heinen, and Groenendijk 2012; Schipper et al. 2021), on how organic farming affect water quality (Sanders and Heß 2019), and on the effect of crop management and tillage on soil erosion by water (Auerswald et al. 2021) as an important pathway for P (cf. Figure 1). This was complemented by modelled measure effects on N balances (Bach and Klement 2015) and nutrient inputs (Fuchs, Weber, et al. 2017; Englund et al. 2021).

2.4.6. Soil Health Law

In support of the Green Deal, the EU Soil Strategy for 2030 (European Commission 2021) provided a framework to target land degradation in a comprehensive way. In accordance with the Farm-to-Fork Strategy, nutrient losses should be halved by 2030 and healthy soil conditions reached by 2050. One of the actions announced by the Strategy is the proposal of a Soil Health Law by the EU Commission which was accomplished in July 2023 by the proposal for the Directive on Soil Monitoring and Resilience (Directorate-General for Environment 2023).

The Soil Health Law of the EU lists 6 soil descriptors with criteria for healthy soils, 3 of which to be established at Union level including the soil erosion rate on agricultural land. Soil erosion has been extensively studied during decades and soil erosion models are routinely applied albeit with a strong preference of water erosion (e.g. to model nutrient fluxes) and individual processes (Borrelli et al. 2021; 2022). The Soil Health Law, however, requires that the estimation of soil erosion rates considers all relevant processes and countermeasures. It proposes a fixed threshold of 2 t ha^{-1} yr^{-1}, although the range of natural soil formation rates and soil properties suggests site-specific thresholds (e.g. Di Stefano et al. 2023; Rippel 2010). It can be argued that the proposed threshold is too high for European soils (Verheijen et al. 2009). The authors advocate 1 t ha^{-1} yr^{-1} as 'tolerable' if water quality is considered.

Despite all research and conceptual flaws, the empirical universal soil loss equation (USLE) and its many derivatives still dominate assessments of soil erosion risk and rates, especially at large scales (Schmaltz et al. 2024; Borrelli et al. 2021). The USLE is mostly used to predict the long-term average of sheet and rill erosion by water. The gross erosion is estimated as product of various factors which consider the effect of rainfall and runoff (R factor), field size and terrain (L and S factors), soil erodibility (K factor), interplay of seasonal rainfall erosivity and soil coverage (C factor), and other management for soil protection (e.g. contour farming, terracing, P factor). The C factor reflects the effect of crop rotation and crop management. Its wide value range makes it most relevant for farmers to tackle soil erosion. For the input of nutrients, the gross soil erosion has to be adjusted for the sediment transport as typically only a small part of the mobilized soil particles in a river catchment reaches the water bodies in the given time period (sediment delivery or net erosion) as well as the content and relative enrichment of nutrients as the transport of soil particles is particle-size selective and P is adsorbed to clay minerals.

The calculation of soil erosion rates and particulate nutrient inputs requires detailed information which is typically unavailable for regional and national assessments. So, simplified approaches to estimate the erosion factors prevail. Even if the same modelling framework is used, the parameterization and the data base differ widely not only among EU countries (Schmaltz et al. 2024) but also among the German federal states (Plambeck 2020). Regarding the C factor, however, such simplifications may not consider the complexity of (modern) crop rotations and effect of measures (Auerswald et al. 2021) as well as the impact of climate change (Auerswald and Menzel 2021). The lack of harmonization hampers not only the comparison of model results but may also foster the inconsistent implementation of countermeasures and, in combination with the lack of empirical evidence, the mismanagement of nutrients in river basins (Schmaltz et al. 2024).

In absence of national consistent datasets on concurrent soil erosion processes in the study area, we used gridded datasets of (gross) soil erosion rates on arable land due to wind, water, tillage, and crop harvesting (Borrelli et al. 2022) for a rough estimation of potential reduction effect of the Soil Health Law. The total average soil erosion rates and the share of the individual processes were determined without and with upper limits of 1–2 t ha^{-1} yr^{-1}.

3. RESULTS AND DISCUSSION

3.1. Overview of planned measures

3.1.1. Water Framework Directive in Germany

The German RBMP strongly focus on lateral connectivity and hydromorphology (KTM 5 and 6), diffuse nutrient inputs (KTM 2 and 17), and conceptual measures (KTM 12 and 14, Figure 20 top). Point sources and urban inputs (KTM 1 and 21) are only of relevance in the Rhine basin. Most measures supplement legal requirements Figure 20 bottom).

KTM 5 and 6 are dominated by construction measures except for riparian buffers to improve the structure of surface waters and to connect habitats (KTM 6, national code 73). These buffers are distinguished from riparian buffers to retain diffuse and particulate nutrient input via surface runoff (KTM 17, national code 28). KTM 17 also consists of erosion protection beyond the 'good agricultural practice' (national code 29) which complements measures against N leaching (KTM 2, national code 30, until 2027). After 2027, KTM 2 mainly addresses the nutrient input via drainage systems in the Elbe basin (national code 31). The conceptual measures address research on pressures and measure efficiency (KTM 14) as well as advisory services for farmers (KTM 12). The latter is especially relevant in the Rhine basin.

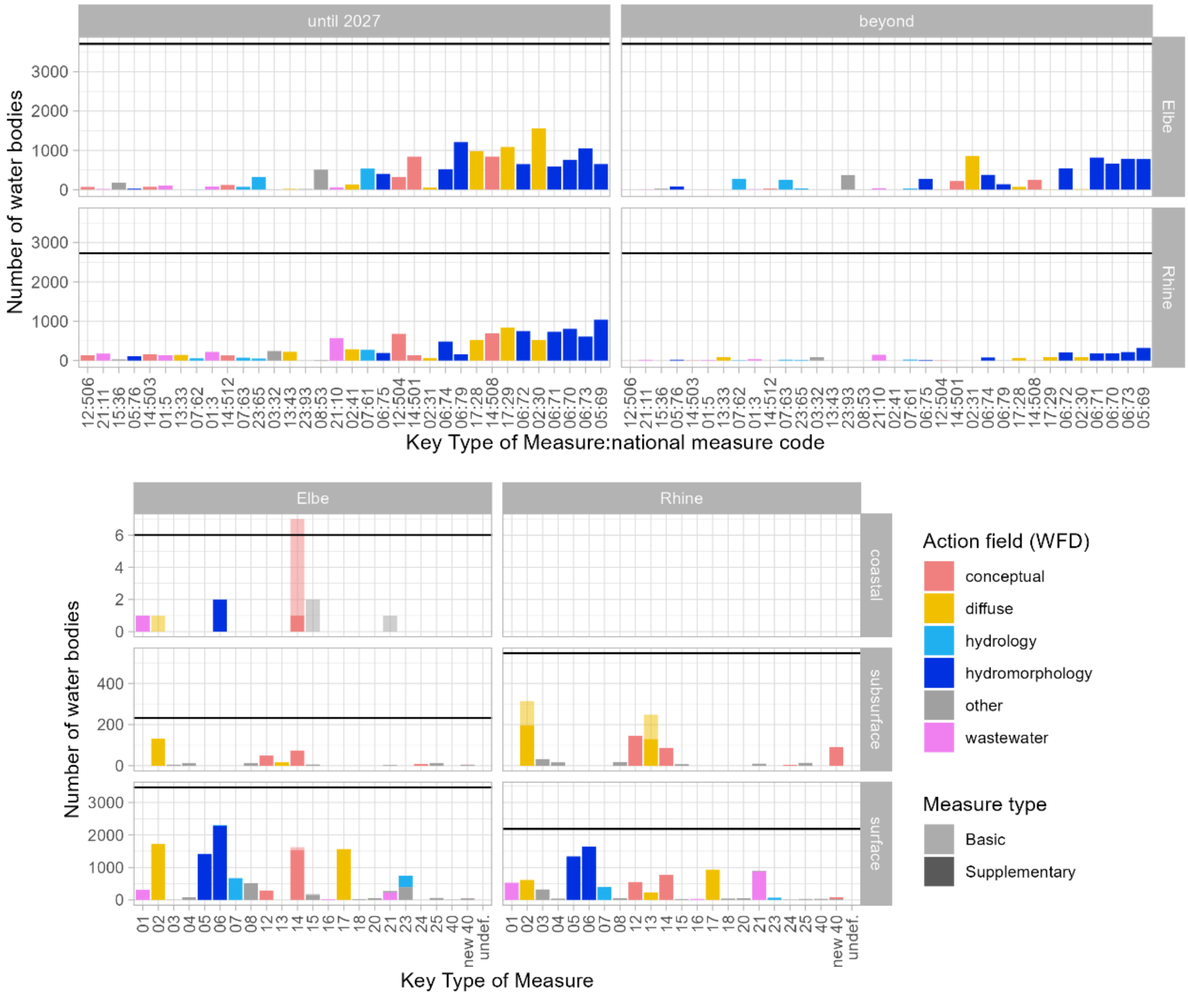


Figure 20. Water bodies with WFD measures planned until 2027 and beyond ('full planning') in the German parts of rivers Elbe and Rhine compared to the number of water bodies (horizontal line). Separated by action field and national measure code (top, Table 21) as well as water-body type and measure type (bottom). Note: Water bodies may have basic and supplementary measures assigned to the same KTM.

The measure descriptions are highly aggregated, and do not specifically mention e.g. organic farming. Instead, KTM 2 and 17 refer to the (previous) CAP ('RL AUK/2015', 'Agrarumweltmaßnahme' (AEM) and 'AUKM' (AECM), 'ökologische Vorrangflächen' (ecological focus areas, EFA) which are replaced by the new conditionality), and, in case of groundwater bodies, also to the Fertilizer Ordinance (Figure 21 top). KTM 12 focus on advice and cooperation for water protection (‘Gewässerschutzberatung’, ‘Gewässerschutzkooperationen’) and, more specifically, on herbicides (‘PSM’, ‘Diflufenican’). In contrast to the other KTM, KTM 14 has much more variable terms with a focus on water chemistry (e.g. herbicides, PFOS, metals) and hydromorphology (‘HYMO’). Unspecific measures are linked to DPSIR (assessments), regional working groups (‘rAG-Maßnahme’), existing plans (‘Teil-VoSa’), and inspections within areas of excess P (‘Fachrechtskontrollen’, ‘P-Überschussgebiete’). Likewise, there is a wide range of nutrient-related terms such as water protection (‘Gewässerschutz’), nutrient balances (‘Nährstoffbilanzen’); seepage water (‘Sickerwasser’), and wastewater treatment (‘KKA’, ‘KA’, ‘AW’). The KTM 1 is quite generic (‘rAG-Maßnahme’, ‘Abwassermaßnahme’) with references to more detailed state programs on water protection (‘Landesprogramm Gewässerschutz’, not shown).

Figure 21. Word clouds of the COMMENTS attribute of measures assigned to KTM 2 (top left), KTM 17 (top right), KTM 12 (bottom left), and KTM 14 (bottom right) for all planned measures (‘full planning’). Font size represents the relative frequency within each cloud. Generic terms dominate.

3.1.2. Water Framework Directive in the Netherlands

Similar to Germany, the Dutch RBMP focuses on the lateral connectivity and hydromorphology, diffuse nutrient inputs, and conceptual measures (KTM, Figure 22). Point sources and urban inputs (KTM 1 and 21) are also relevant. The major differences to Germany are the missing KTM 17 and the many measures not assigned to KTM. The absence of KTM 17 can be explained with the low importance of water erosion in the Netherlands (cf. Chapter 3.3.3) and the assignment of riparian buffers (‘oeverbegroeiing’, ‘begroeiing van bomen (en struiken)’) to KTM 6, if any (‘Behoud en beheer oeverbegroeiing’). The missing reference to nutrient retention seemingly fits the expected low efficiency of riparian buffers under Dutch conditions (see Table 20 and Chapter 3.2).

The descriptions of the relevant nutrient-related measures are in general more variable than in Germany. Nonetheless, the terms are also aggregated, and do not refer to specific measures. KTM 2 measures refer, in line with the KTM description, to agricultural measures to reduce nutrients (Figure 23). More specifically, the measures refer to the DAW, to measures beyond legal requirements (‘Landbouw bovenwettelijke maatregelen (nutriënten)’), and ammonium. The measures not assigned to KTM cover a broad range of topics. They link to the WFD measures to the CAP (‘GLB’) and its agri-environment climate funding scheme (‘Agrarisch Natuur- en Landschapsbeheer’, ‘ANLB’), as well the DAW. KTM 1 measures aim at reducing loads of nutrients, (heavy) metals, and micropollutants (‘microverontreinigingen’) from UWWTP (‘RWZI’) while KTM 21 often only generally refers to appropriate measures against stormwater (‘passende maatregelen bij afkoppelen regenwater’) and the good management of urban water (‘goede stedelijk waterbeheerpraktijk’). KTM 14 has a strong focus on research and assessments of (heavy) metals rather than nutrients.

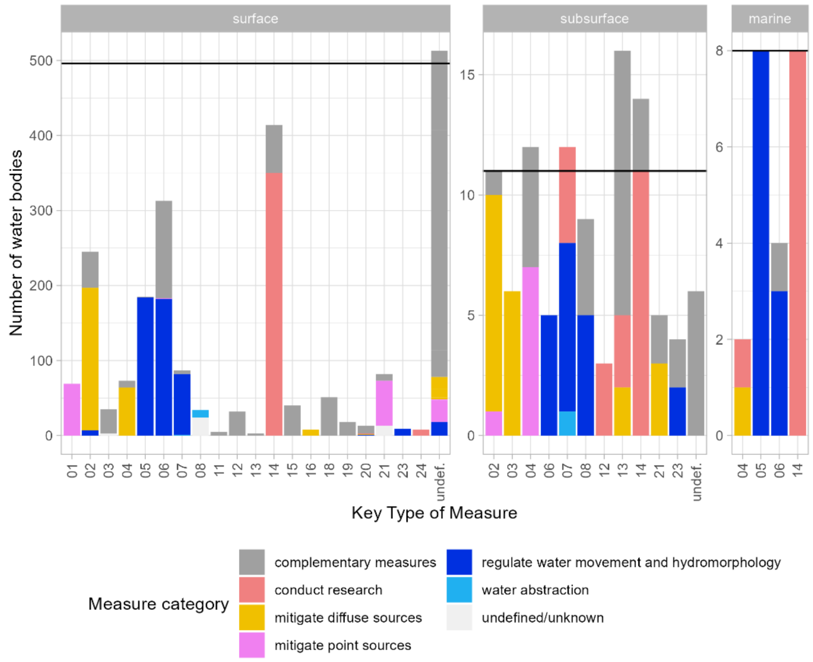


Figure 22. Water bodies with WFD measures planned until 2027 in the Dutch parts of river Rhine compared to the number of water bodies (horizontal line), separated by water-body type and main category. The main category is the translated attribute 'SGBP_Hoofdcategorie'. Note: national measures with different measure categories can be assigned to different KTM.

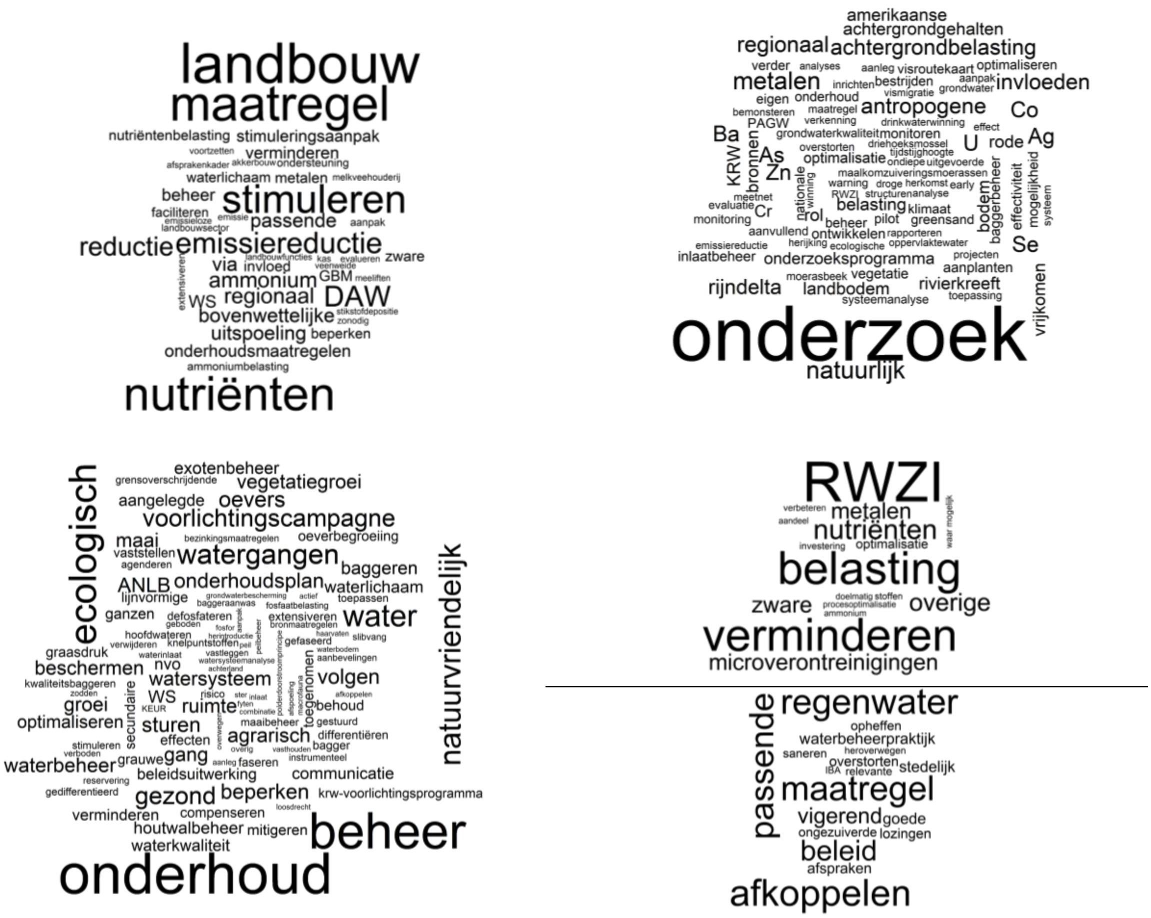


Figure 23. Word clouds of the Naam attribute of measures assigned to KTM 2 (top left), KTM 14 (conduct research, top right), no KTM (bottom left), as well as KTM 1 (above the line) and KTM 21 (below the line). Font size represents the relative frequency within each cloud.

3.1.3. Other policies

The Program of Measures within the NECD was only available for Germany. The expected emission reductions to meet the national targets are highest for the agricultural measures followed by measures in the energy sector, i.e. the implementation of the Medium Combustion Plant Directive and the coal exit, and climate-related measures (Figure 24). The 12 agricultural measure to reduce NH_3 emissions to the atmosphere address the nutrition and housing of livestock (5 measures), the application and storage of slurry and manure (6 measures), as well as the reduction of the soil N balance by 20 kg N ha^{-1}. All these agricultural measures refer to the good agricultural measures to reduce NH_3 emissions (UN ECE 2015) except for the change of N balances and the change of subfloor slurry storage to covered storage systems. The reduction of N balances mitigates the potential conflict between the NECD and the ND / WFD as reducing atmospheric losses may increase the N content of manure and the net N soil balances and subsequently the risk of N losses to water bodies.

The German Program of Measures 2022–2027 within the MSFD subsumes the nutrient-related measures under the environmental target UZ1 (Seas unaffected by eutrophication) with its operational targets: reduction of riverine nutrient inputs, reduction of transboundary nutrient inputs, and reduction of atmospheric nutrient inputs need to be further reduced. Ten MSFD measures complement measures linked to other policies like WFD and ND (KTM 1, 2, 12–14, 16, 17, 23), and international agreements (NECD, MARPOL, and OSPAR, Table 22).

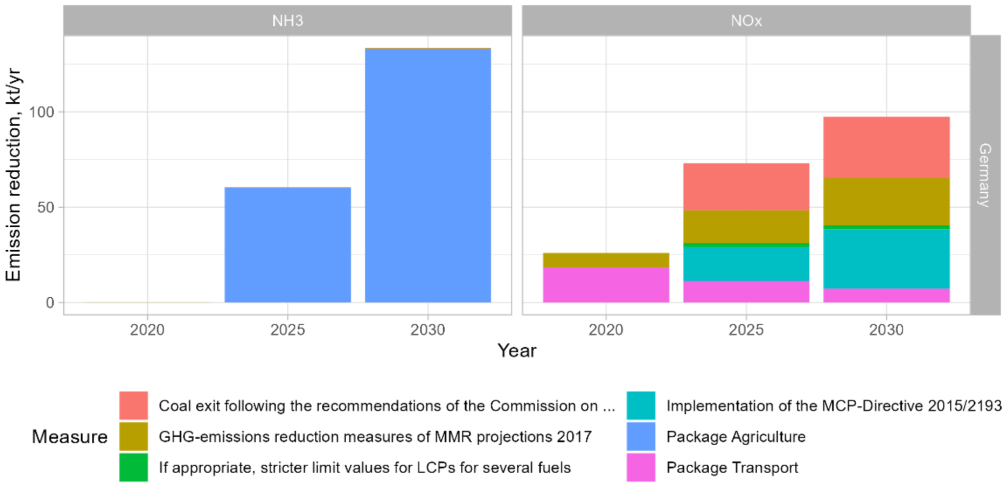


Figure 24. Expected emission reduction according to the NECD Program of Measures. Measure names slightly modified. The MCP-Directive is the Medium Combustion Plant Directive of the EU. Only available for Germany.

Only a few of these measures address nutrient inputs to rivers in the study area. The measure DE-M401-UZ1-01 is already implemented. Its aim was to improve the communication and cooperation with the agricultural sector to foster ‘best practice’, the implementation of AECM, a more efficient use of fertilizers, and improved drainage systems in the catchment of r. Jade. Given the small catchment area, the direct contributions to the operational targets of Descriptor 5 (reduction of riverine and atmospheric inputs) are expected to be marginal. Assuming that a broad implementation of voluntary measures is currently not feasible, the indirect contributions are considered limited (BMUV 2022b). The measure DE-M434-UZ1-07 is about the revision of target values to which NAPSEA contributes. The measure is expected to be implemented in 2027 and will thus affect future WFD and MSFD management plans.

The current Dutch Program of Measures does not list any technical measures addressing Descriptor 5 (IenW 2022). It rather relies on the implementation of measures on land under other policies.

In Germany, the good practice for fertilization and the measures of the AP for the ND are regulated nationwide in the Fertilizer Ordinance (Table 5) and the Ordinance on Installations for the Handling of Substances Hazardous to Water. The rules for the good agricultural practice and the measures of the action program are largely identical and applied on a mandatory basis throughout Germany (BMEL and BMU 2020). The good practice is extended by the Soil Law albeit without specific measures: site- and weather-adapted tillage, maintaining and improving soil structure, avoiding soil compaction and soil erosion, preserving natural features of fields (hedges, terraces), as well as maintaining soil biology through appropriate crop rotation and soil organic matter through sufficient supply or reducing tillage intensity.

The 7th Dutch AP (2022–2025) is based on 5 pillars: a) sustainable cultivation plans to improve soil quality and water quality, b) additional measures in areas with insufficient water quality, c) other regulatory measures, d) knowledge, communication and pilot studies, as well as e) additional measures linked to surface water quality and N pollution. A 6th pillar is about control and enforcement. These pillars consist of various mandatory and enabling measures (Table 6) and are strongly based on existing policies such as the CAP or DAW (cf. Table 20).

Table 5. Overview of main measures in the German Fertilizer Ordinance.

Category	Measure
Fertilizer planning	Clearly defined and compulsory
Determination of fertilizer demand	Yield level of the cultivated crop of the last 5 years
Organic N application threshold	170 kg N ha^{-1} yr^{-1}
Blocking periods – fixed	Grassland 1.11.–31.1., arable land 1.10.–31.1., no fertilizers on frozen soils
Blocking periods – after harvest of the main crop	Total nutrient application restricted to 30 kg Ammonia N and 60 kg total N for catch crops, winter rapeseed, field forage and winter barley after cereals
Reduced ammonia emission application techniques	Organic fertilizer without Urease inhibitor to be incorporated within 4 h, after February 2025 within 1 h, broadcast spreaders banned on arable land, 2025 on grassland
Minimum manure storage capacity	6 months, 9 months for farms >3 livestock units ha^{-1}
Minimum distance from surface water for fertilizer application	4 m, 1 m with precision spreaders, 3–10 m depending on slope
Additional measures in pollution hotspots	Intercropping mandatory, N fertilization 20% below calculated needs, 170 kg $ha^{-1}\cdot yr^{-1}$ N cap per management unit, extended blocking period, 60 kg ha-1 of liquid organic fertilizer in autumn

Table 6. Overview of measures in the 7th Dutch Action Program.

Pillar	Measure
A	catch crops in crop rotation ('rustgewas', 'vanggewas') on sandy soils and loess
	minimum share of (permanent) grassland for cattle farms
B	stimulate awareness and initiatives by farmers who are responsible for the choice of measure
	voluntary participation with agreement on targets, mandatory measures in the 8th AP are possible if results are insufficient
C	implementation of EU regulation fertilizer, update soil maps
	support the use of recycled N fertilizer from livestock manure (Renure)
	stimulate the use of organic fertilizers
	restrict fertilizer application on arable land between 1.8. and 15.9. to 60 kg N ha^{-1}
	integrated riparian buffers: 5 m width along ecologically sensitive and WFD water bodies, 2 m along other water courses (up to 5% of the plot area), grazing is allowed
	extend ban of slurry application on arable land from 15.2. to 15.3.
	reduce effects of droughts on water quality (hydrological measures, more efficient irrigation, drought-resistant crops, adjust fertilization, reduce N leaching with buffer strips or catch crops)

In Germany, the voluntary measures subsidized by the CAP mainly aim at organic farming and at biodiversity (Figure 17). The measures which may directly and indirectly contribute to lower nutrient input into rivers consist of

- Organic farming: establish and maintain organic agriculture,
- Improve biodiversity: nature conservation-oriented agriculture, fallow land as well as strips of flowers and old grass to foster biodiversity and conservation of habitats,
- Soil protection: measures against soil erosion, more diverse crop rotation e.g. with more legumes,
- Water quality: riparian buffers, less / no mineral fertilizers and chemical weed control, extensive farming along water bodies, in wetlands, and other sensitive areas,
- Climate protection: conversion of arable land to grassland, protection of peat soils, water retention,
- Productive and non-productive investments: irrigation, reduced water pollution, development of water bodies with minimal environmental impact, protection of natural resources,
- Extensification of permanent grassland.

The Dutch BOOT list of the DAW comprises 85 voluntary agricultural measures (see Table 20) to support the goals of the WFD, ND, the eco-schemes of the CAP, and other policies (DAW 2022). These measures are grouped into

- Farm management: e.g. extensive grazing (maximum 1.5 LU ha^{-1}, fertilization planning, agroforestry, circular agriculture to minimize the use and loss in of nutrients etc., good soil management and reuse of residues, broader crop rotation with intercropping beyond the 7th AP,

- Soil improvement: e.g. level depressions, tillage perpendicular to slope, conservation tillage or no-till, improved soil structure,
- Crop protection / pest control: e.g. use of pesticides with low risk profile, non-chemical weed control,
- Land management: e.g. no fallow land in winter, optimized grazing to improve grass cover, adjusted crop rotation to reduce N leaching on susceptible soils, crops to uptake P from P-rich soils,
- Use of nutrients: e.g. manure replaced by mineral fertilizers or treated manure, fertilizer application adjusted to N mineralization, shorter period of manure application in spring and autumn, more legumes in crop rotation,
- Water management: e.g. retain and reuse (drainage, residual, or rain) water, optimize irrigation, provide agricultural land for water storage, use gauge-controlled drainage systems,
- Pollution control, waterways: e.g. manage riparian buffers, avoid bank erosion, treat drainage water.

3.2. Feasibility of common measures to reduce local nutrient input

The potential effects of UWWTP optimization (KTM 1) are discussed in the evaluation of the UWWTD scenarios in chapter 3.3, together with the scenario for the NECD and the Soil Health Law.

3.2.1. Reduce nutrient pollution from agriculture (KTM 2)

Measure effects in the are either reported as absolute differences (e.g. in kg ha^{-1}, Table 24) or as relative values or response ratios (Table 7, Figure 5). In any case, the value range indicates not only a wide range of measure efficiencies but also the large uncertainty in measure efficiencies. Suitable measure combinations can improve both aspects. For instance, the combination of catch crops, mulching, and summer crops (measures 1, 2, 4, and 16 in Table 24) reduces Nmin (autumn) and the risk of water pollution better than catch crops alone (Osterburg and Runge 2007).

Table 7. Measure effects on nitrate and N leaching to ground and surface water (Groenendijk et al. 2021, slightly modified). The response ratio is the ratio of the concentrations or fluxes measured on treated plots or fields and the measured reference values on untreated plots or fields. Lower values show stronger measure effects.

Measure	Studies	Response ratio (±sd)	Comparisons	Outliers
Nitrogen input control	14	0.67 (0.29)	33	1
Fertilization type and method	15	1.04 (0.36)	25	1
Timing of application	3	0.99 (0.43)	16	0
Nitrification inhibitor	2	0.50 (0.16)	10	0
Crop type and crop rotation	20	0.56 (0.36)	27	7
Catch crop	12	0.61 (0.36)	32	0
Mulching/tillage	9	0.66 (0.22)	16	1
Irrigation	4	0.98 (0.69)	13	0

Based on their literature review on N leaching, Groenendijk (2021) consider as most effective: controlling N input, adjusting crop rotations, cultivating catch crops, adjusting tillage, and use nitrification inhibitors (Table 7). Taking cost effectiveness into consideration, Osterburg and Runge (2007) propose grassland without ploughing, stricter timing of application, more catch crops, and adjusted crop rotations as optimal. For lower N balances and water protection, nutrient management planning is recommended as better option for farmers (Table 8). The decision for the measure target is important for the measure efficiency and the cost effectiveness as measures not necessarily perform equally well for all indicators. If cost efficiency and acceptance are neglected, adjusting crop rotation, integrating catch crops, switching to organic farming, converting arable land to grassland, and hydrological measures including riparian buffers are most effective if all indicators are considered (Table 24). Experimental studies confirm the high variability (see Chapter 3.2.2 for riparian buffers). For organic farming, a meta-analysis showed 28% (median) lower N losses under organic agriculture compared to conventional agriculture, however with a range from -82% to +167% (Sanders and Heß 2019). In addition, a random forest model from 48 farms in nitrate sensitive zones revealed that the crop is the most important factor influencing Nmin autumn along a transect from north to south Germany, followed by soil properties and precipitation in October (Dieser et al. 2023). This result supports that adjusting crop rotation is suitable for reducing the risk of N losses. It also shows that weather and soil properties can mask the importance of factors like the timing and rate of N fertilisation which may explain why measure efficiencies differ. Similarly, the effect of tillage depends on duration as well as the content of soil organic carbon (and other factors) (Li et al. 2023). Switching from conventional tillage to no-till very likely increase nitrate leaching if the measure is of short duration (<5 years) and the content of soil organic carbon is low (<1%) but reduce it if the measure has been implemented longer and if the soil contains more organic carbon.

The meta-analysis of Velthof et al. (2020) within the FAIRWAY project suggests that buffer strips, of (non-legume) catch crops, and nitrification inhibitors are significantly reducing nitrate losses. Again, the efficiency is highly variable. Only for these measures, the 95% confidence interval of the mean response ratio is negative (Figure 5). However, the questionnaire in the case studies of the FAIRWAY project revealed that national experts preferred to optimize the rate and timing of fertilizer and manure applications which was ranked as (cost) effective, applicable, and adoptable (Table 23) while nitrification inhibitors were not reported at all. Catch crops were also not reported for the German and Dutch case studies, instead crop rotation including grassed buffer strips between maize (NL) and improved information transfer (for the latter see also Chapter 3.2.3).

Table 8. Frequency of measures with best cost effectiveness (in € kg^{-1} N) for different indicators (Osterburg and Runge 2007). Measure groups refer to Table 24. The measures per measure group differ among the indicators. Nmin is the soil mineral N content in autumn.

Measure group	N balance	N balance, cash crop farms	Nmin autumn	Water protection on grassland
Greening (catch crops)			4	
Crop rotation	3	4	2	
Grassland	1		1	2
Mineral fertilizer		1		
Organic fertilizer	4		2	1
Hydrology			2	2
Fertilizer management	2	2		1

3.2.2. Reduce sediment from soil erosion and surface run-off (KTM 17)

Measures in Chapter 3.2.1 which increase the soil cover on arable land are in principle also effective against soil erosion. The effects of organic farming, cover crops, tillage management, and crop rotations is conceptually represented by the C factor of the USLE, a correction factor between 0 and 1 which combines the seasonality of rainfall erosivity and soil cover. The USLE estimates long-term average erosion rates, so C factors are calculated for crop rotations rather than individual crops.

As these crop rotations have changed, and will likely do so in the future, summable crop-specific C factors which integrate rotation-related effects were recently calculated using a dense German dataset of crop stages and extrapolated climate data for the year 2025 (Auerswald et al. 2021). Their results exhibit a wide range for different crops and tillage practices (Figure 33). For instance, the C factors for row crops under conservation tillage (with mulch) were on average 0.086 lower than under conventional tillage. The values for no-till were generally around 0.047. Adapting tillage management is not only helpful against soil erosion by water but against wind and tillage erosion as well (cf. Chapter 3.3.3). Organic farming was not specifically addressed in this study, but data allow to derive the reduction effect because typical European organic crop rotations differ significantly from conventional rotations by including more (temporary) fodder and (undersown) cover crops (Barbieri, Pellerin, and Nesme 2017). According to Auerswald et al. (2021), organic crop rotations are more effective against soil erosion than any conventional rotation – even without targeting at soil protection – by integrating sod (e.g. clover-grass).[4] So, the actual measure against erosion for conventional farmers would be ‘integrate sod into the crop rotation’, e.g. to produce biogas, rather than ‘switch to organic farming’. Although organic farming (and conservation farming with minimum mechanical soil disturbance) has multiple benefits as it enhances various regulating and supporting ecosystem services compared to conventional farming by supporting biodiversity, soil health, as well as climate protection and mitigation (Wittwer et al. 2021; Sanders and Heß 2019). Compared to the national average (C=0.124), the typical organic rotation (C=0.05, close to no-till) lowers the erosion risk by 60%. Reducing soil erosion, like any sustainable soil management, helps to preserve or even increase soil organic matter which is pivotal not only for soil health but also climate adaptation (Montanarella and Panagos 2021). However, reducing soil erosion is only one aspect of how crop rotation can support soil health (Yang, Siddique, and Liu 2020).

Although these summable C factors were calculated across Germany, the authors expect that the values are also valid for neighbouring countries like the Netherlands. Long-term empirical data confirm that erosion rates can be reduced by adjusting crop rotation and tillage management (e.g. Steinhoff-Knopp and Burkhard 2018; Deumlich et al. 2006 in the Elbe basin).

Meta-analyses of published experimental data demonstrate the efficient yet variable nutrient retention in riparian buffers (e.g. Figure 5, Table 9). Accordingly, reported literature values depend on selected set of studies. For instance, the median of retention rates collected by Gericke (2020) ranged from 58% for dissolved nutrients to

[4] The example given by Auerswald et al. (2021): The optimal conventional rotation – but hardly used in Germany – would alternate small grain crops followed by a frost-intolerant cover crop with direct drill (no-till) row crops (C=0.060). A typical organic crop rotation consists of sod (2 years) as well as a row crop, a cereal, and a grain legume (each 1 year, C=0.05 with undersowing).

85% for sediment and particulate P. Tsai et al. (2022) analysed the P retention by riparian buffer only located in the USA and Canada and reported a mean of 51.3% with a 95% confidence interval from 19.6% to 71.2%.

The efficiency of riparian buffers is positively related to buffer width, and national regulations use buffer widths as easy rules, for instance 5–10 m according to the water laws of the German states. However, the optimum buffer width depends on the pollutant, water flow, other buffer and site characteristics, management, as well as the productivity of adjacent land which may favour conflicts (Cole, Stockan, and Helliwell 2020; Walton et al. 2020; Hill 2019) (e.g. Table 10). On agricultural land in the Netherlands, 5 m wide grassed buffer strips – which were considered most representative for the country – may have only small effects given site specific hydrogeological factors (Noij, Heinen, and Groenendijk 2012). However, and independent of their efficiency, riparian buffers can provide many other benefits and ecosystem services (Kail et al. 2021; Palt et al. 2022; Zak et al. 2019; Cole, Stockan, and Helliwell 2020).

Table 9. Nutrient retention in and efficiency of riparian buffers, with mean ± standard deviation (sample size) (Walton et al. 2020). Soil erosion is a relevant source for the particulate fraction of TP. Sedimentation is an important process for the retention of sediments and particulate nutrients in riparian buffers. Note: The values were collected from different publications which may not contain all values.

Pollutant	Load, kg N/P ha^{-1} yr^{-1}	Loss, kg N/P ha^{-1} yr^{-1}	Retention, kg N/P ha^{-1} yr^{-1}	Efficiency, %
NH_4+	18 ± 19 (23)	26 ± 39 (21)	−8 ± 42 (21)	−90 ± 294 (21)
NO_3−	560 ± 523 (46)	255 ± 253 (37)	177 ± 137 (45)	51 ± 31 (56)
DON	148 ± 196 (20)	142 ± 148 (21)	−1 ± 76 (20)	−112 ± 291 (17)
TN	523 ± 557 (56)	383 ± 495 (56)	149 ± 133 (63)	43 ± 30 (58)
SRP	8 ± 8 (28)	4 ± 5 (20)	2 ± 6 (30)	−5 ± 74 (31)
TP	20 ± 30 (48)	14 ± 24 (48)	7 ± 14 (49)	21 ± 72 (55)

[1] NH_4+ = ammonium, NO_3− = nitrate, DON = dissolved organic N, TN = total N, SRP = soluble reactive P, TP = total P

Table 10. Buffer width (m) required to achieve 90% nitrate removal efficiency in relation to the predominant riparian sediment texture and depth to a confining layer with number of sites in brackets (Hill 2019).

Soil texture	Permeable sediment depth		
	<2 m	**2–4 m**	**4–8 m**
Gravel/sand	19–37 (6) 60 (1)	15 (1) 33–56 (7)	128–225 (5)
Loamy sand/sandy loam	6–14 (3) 39 (1)	15–22 (5) 45 (1)	53–56 (2) 128 (1)
Loam/silt loam/silt clay loam	5–13 (3)	5–10 (2) 28 (1)	13–26 (2) 64 (1)

The risk of low retention asks for complementing buffer restoration with agricultural measures to effectively reduce nutrient input to water bodies. Such limitations may occur when preferential flow reduces the residence time of nutrients in the buffer, or even bypasses the buffer. Many empirical studies were conducted on the plot scale where preferential flow is negligible unlike natural terrain in river basins (Gericke et al. 2020). High runoff can also result in high N load. The inverse relationship between N retention and N load reveals the saturation of the denitrification capacity is a key factor for lower N retention rates (Walton et al. 2020). Despite its effectiveness against soil erosion, conservation and no-till may favour preferential flow in macropores and N leaching (Blanchy et al. 2023; Li et al. 2023), e.g. by reducing the efficiency of riparian buffers. In addition to subsurface preferential flow, lower soil erosion and particulate P losses from arable land may accumulate labile P in topsoil. The shift from particulate to dissolved P does not only lower the average efficiency of riparian buffers but also the risk of eutrophication due to the increased bioavailability (cf. references in Gericke et al. 2020).

3.2.3. An outlook to conceptual measures: Advisory services for agriculture (KTM 12)

There is a range of measures which farmers can apply to serve water quality with consistently positive effects on multiple environmental areas environmental targets (Baaken 2022). The positive effect of advice and support for agriculture is implicitly addressed in the previous chapters because the more farmers apply these measures, the higher their basin-wide efficiency. However, measures against high nutrient input may affect crop yield and may not automatically serve environmental targets if not implemented appropriately. For instance, switching to organic crop rotations can significantly increase product-based nutrient losses compared to conventional rotations if farms solely strive for maximum yield and not for a more integrated, more diverse production (Biernat et al. 2020). In the Netherlands, van Balen et al. (2023) obtained similar or even higher crop yields with conservation tillage compared to conventional tillage. They recommend more research and exchange with farmers to promote the adoption because farmers perceive high yields under conservation tillage as challenging.

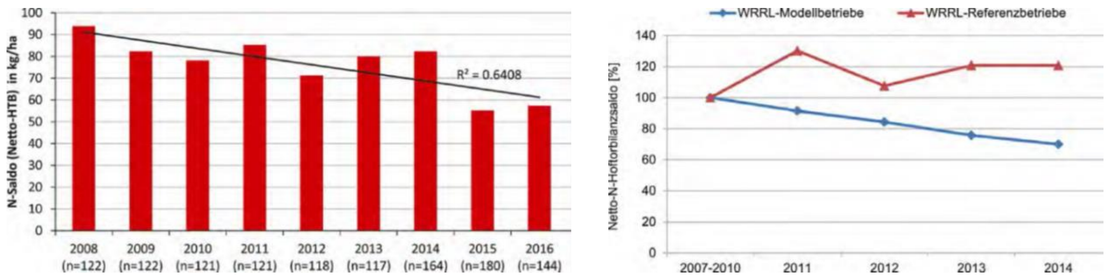


Figure 25. Average net farm-gate N balance in intensively advised farms in Schleswig-Holstein (left) and change for model and reference farms in Niedersachsen (2007–10=100%, right) (source: FGG Elbe 2023).

The cooperation between agriculture and water agencies is at the core of the Dutch DAW but also of various regional programs in Germany (e.g. StMELF 2023; AG Wasserrahmenrichtlinie & Landwirtschaft 2023; Allianz für den Gewässerschutz 2023). Such activities contributed to lower N (farm-gate) balances in the coastal states of Schleswig-Holstein and Niedersachsen (Figure 25), to lower soil erosion in Switzerland (Prasuhn 2020) and the Elbe basin (Chapter 3.2.2), and to increase the length of riparian buffers by 31% since 2014 in Schleswig-Holstein (Allianz für den Gewässerschutz 2023).

The main limitation of such voluntary programs is the participation rate. Behavioural factors like agricultural training, advice, and positive perception of agri-environmental schemes as well as opportunity costs including market conditions, implementation efforts, and contract flexibility are consistently linked to participation rate. This differs from factors like environmental attitude, trust, and farm size which therefore require context-specific interpretation (Schaub et al. 2023). The Netherlands changed its national AECM programme to a collective approach in 2016 (farmers have to join collectives to apply for AECM but remain responsible for the implementation) – as the only country in the EU (Reichenspurner, Barghusen, and Matzdorf 2023). The authors found a strong preference of a collective-oriented view among Dutch farmers rather than business-oriented or environment-oriented perspectives as they perceive advantages compared to the previous individual scheme, including the ecological effects. Such co-operative schemes within the CAP are also needed in Germany to implement measures at the scale of landscapes rather than farms (ZALF 2020). However, a questionnaire among farmers managing peat land in northern Germany revealed that part-time farmers and farmers without formal agricultural training prefer support for co-operation, unlike more professional farmers (Häfner and Piorr 2021).

3.3. Feasibility of measures to reduce nutrient input at the basin scale

3.3.1. NEC scenarios and atmospheric deposition

According to the scenario calculations for Germany and the Netherlands, the policy goals to reduce the atmospheric N emissions will lower the N deposition on coastal and marine areas in and around the case study by about 10% (Figure 26). The relative impact of agricultural measures is higher in Germany than in the Netherlands. This difference can be explained by the high reduction needs in Germany (cf. Figure 10) and the focus on peak emitters in the Dutch scenario. The contribution of the German agriculture is highest for coastal areas (Figure 27). Nonetheless, the implementation of the NECD in foreign countries is the most important step to achieve the reductions as foreign sources dominate the deposition on the German areas in absolute terms and dominate the absolute and relative changes in the Netherlands. A recent analysis for the Netherland reveals that the policy goals on NH_3 emission and deposition – based on the Birds and Habitats Directives – will likely be achieved with the planned agricultural measures but not the goals on greenhouse gas emissions (Figure 32 in chapter 3.4).

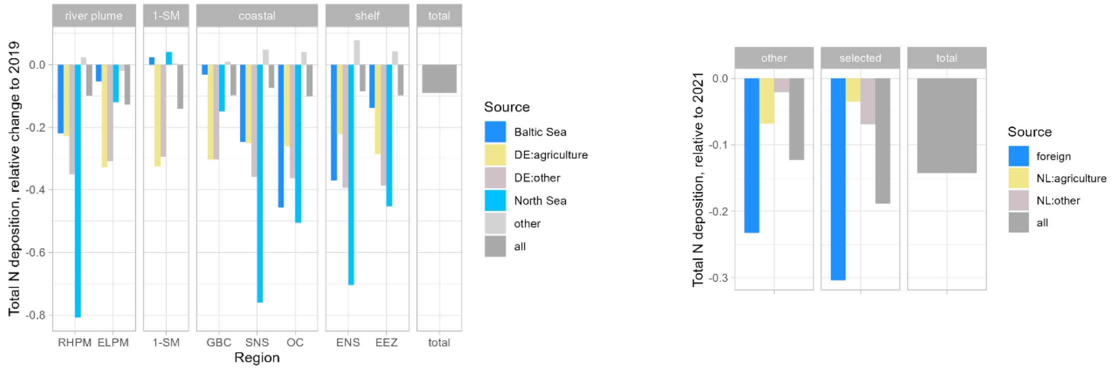


Figure 26. Total N deposition from different sources in 2030 on German coastal and marine areas in the North Sea (left) and Dutch Natura 2000 areas (right), relative to the current situation. Left: OSPAR regions Elbe Plume (ELPM), Rhine Plume (RHPM), 1-nautical mile along the coast (1-SM), German Bight Central (GBC), Southern North Sea (SNS), Outer Coastal (OC), Eastern North Sea (ENS), and the exclusive economic zone (EEZ), right: Natura 2000 areas 'Waddenzee', 'Noordzeekustzone', and 'IJsselmeer' (selected), and other Natura 2000 areas.

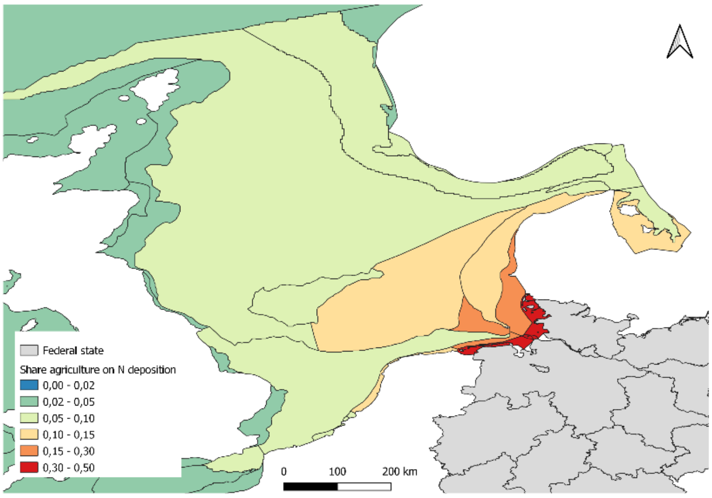


Figure 27. Relative share of German agriculture on atmospheric N deposition on coastal and marine areas (based on unpublished PINETI-IV results, A. Moravek, pers. comm.).

3.3.2. UWWTD scenarios and point sources

The stricter target values of the proposed new UWWTD decreased the N load of UWWTP in the study area on average by 22% and the P load by 15%. However, the reduction potential differs significantly among the countries, river basins, and the policy target (retention, concentration, Figure 28 left). The highest reduction potential for N occurs in the Elbe basin if the concentration target is used, while the maximum for P occurs in the Dutch part of the Rhine basin for which only the retention target could be applied.

The effect of the new proposed targets would be stricter than the concentration targets suggested by a German expert group (Figure 28 right, A. Ullrich, pers. comm.). However, the benchmark scenarios reveal that the average UWWTP performance in the study area is already above the proposed targets (Figure 13, Table 11). Striving for the current median retention or concentration in the 4 assessed size classes would result in load reductions above the UWWTD. However, the reduction of nutrient inputs at the basin scale is smaller. Using the same approach, Fuchs et al. (2017) modelled 3.6% lower N input and 6.5% lower P input if the median is used as technological benchmark which would be (slightly) higher than the optimization of the N management in agriculture (3.5% N).

Germany and the Netherlands also have very high levels of wastewater collection. Fuchs et al. (2017) already obtained low overall reduction potentials for increasing connection rates compared to optimizing UWWTP (the relative impact is higher for parts of the German states Sachsen and Thüringen, both located in the upper Elbe catchment). Since then, the population connected to independent wastewater treatment further dropped from 3.6% to 2.0% in 2019 in Germany and from 0.7% to 0.5% in the Netherlands (Eurostat 2023b) which likely decreased future reduction potentials. Nonetheless, additional measures to mitigate stormwater overflow in combined sewers and exfiltration from aging sewers may help to reduce urban emissions – both are more relevant for the Rhine than the Elbe basin (Zinnbauer et al. 2023). Compared to UWWTP, the estimated inputs to the rivers are small considering the additional retention of leaking wastewater during the soil passage and residence time in groundwater (Table 12). The dominance of point sources was also derived for the Netherlands (Figure 2). However, alternative model applications for Germany indicate similar contributions of urban and point source to P input (Figure 1).

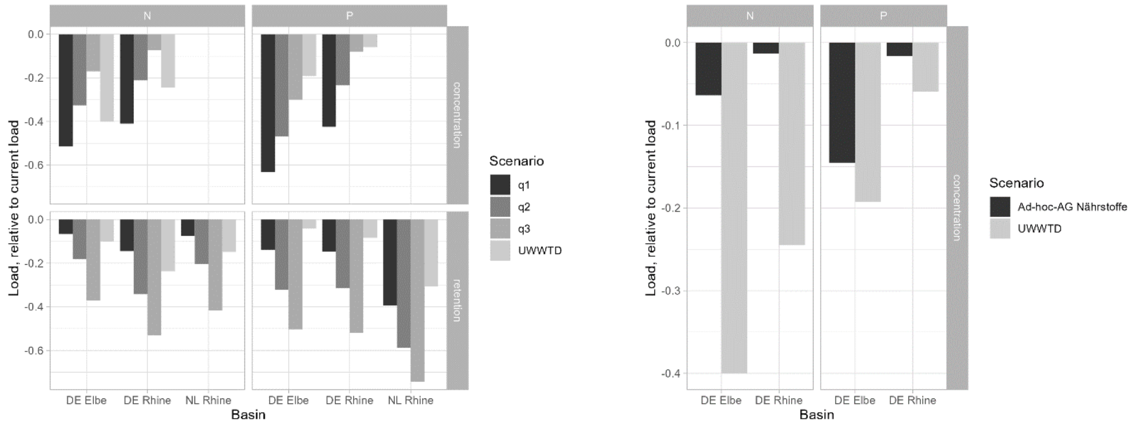


Figure 28. Nutrient load of UWWTP >2000 p.e. relative to current load (report year 2020 for Germany and 2022 for the Netherlands) for the implementation of the new UWWTD and quartiles 1–3 as benchmarks (q2 = median, left) as well for applying target concentrations as suggested by a German expert group (A. Ullrich, pers. comm.). Note: q1 scenario (1st quartile, 25% percentile) is most stringent for concentrations but laxest for retention values.

Table 11. Concentration (in mg L^{-1}) and relative retention values derived for UWWTP of the different size classes (in p.e.), and the values used by Fuchs et al. (2017). Note: Our values were derived for the case study and without UWWTP <2000 p.e. Concentration only for Germany.

Scenario	**50-1000**		**1000-5000**		**5000-10000**		**10000-100000**		**>100000**	
(Quartile)	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**
Concentration										
q1			4.08	0.583	3.50	0.368	4.00	0.270	5.38	0.203
q2			6.60	1.08	5.15	0.579	6.30	0.400	7.70	0.306
q3			11.5	2.11	7.76	1.12	9.25	0.636	10.1	0.425
Retention										
q1			0.740	0.656	0.805	0.814	0.794	0.899	0.806	0.928
q2			0.864	0.845	0.882	0.898	0.873	0.937	0.868	0.957
q3			0.922	0.918	0.932	0.945	0.925	0.962	0.907	0.975
Concentration, Fuchs et al. (2017)										
q1	8	1.7	4.19	1	3.6	0.58	4.4	0.42	5.88	0.3
q2	13	2.9	7	1.71	5.5	0.9	7	0.66	8.46	0.4
q3	20.9	5	12.33	2.73	8.7	1.3	9.75	0.9	10.92	0.56

Table 12. Nutrient input from urban sources and point sources via different pathways in t yr^{-1} within Germany (Zinnbauer et al. 2023). Population equivalents (p.e.) represent UWWTP of the given size class. Note: N inputs to soils and groundwaters are subject to denitrification which reduces the input to surface water.

Basin	**Pollutant**	**Urban to surface water**		**Urban to soil/groundwater**				**Point source**		
		Combined sewers	**Separate sewers**	**< 50 p.e.**		**Exfiltration**	**No sewer**	**50–2000 p.e.**	**> 2000 p.e.**	**Industry**
Rhine	N	1200	1600	400	260	6200	120	1900	39000	3200
	P	210	240	70	50	1100	20	400	2500	150
Elbe	N	160	1800	1470	720	2700	360	790	12000	510
	P	30	300	260	120	470	80	170	800	40

3.3.3. Soil Health Law and soil erosion

The modelled soil erosion rate on arable land in the study area is 4.45 t ha^{-1} yr^{-1} which is well above the target value proposed by the new Soil Health Law, and even more so the threshold recommended by Verheijen et al. (2009) (Figure 29). The soil erosion would decrease by 65% if the policy target would everywhere be achieved. However, the modelled area covered about 25% of the EU and the United Kingdom (Borrelli et al. 2022). So, the basin-wide effect (of any measure against soil erosion) on soil erosion is significantly lower given the low erosion rates on grasslands and forests.

Only a small part of the mobilized soil particles and the attached nutrients reach the surface water. Water and wind erosion are the most relevant processes, but other forms of soil degradation can alter the susceptibility by changing soil properties, the terrain, and plant growth. The effect of measures against soil erosion in the field (on-site) might differ from the effect on nutrient input (off-site) – depending on the purpose and selection of measures. Firstly, erosion processes complement each other in space – tillage erosion occurs in locations of low risk of water erosion – and time – tillage erosion occurs regularly but water and wind erosion often during (extreme) events (Van Oost et al. 2006). Measures against tillage erosion may not directly reduce sediment and nutrient inputs to surface waters. However, the sediment is usually deposited where the risk of water erosion is high (Quinton and Fiener 2023) and where it can be re-mobilized and delivered to surface water. Secondly, while on-site measures might serve both soil and water quality (e.g. by reducing tillage or increasing the soil organic content), off-site measures like riparian buffers favour water quality. To quantify these effects in the context of nutrient input in river basins require further model development as the national nutrient models in Germany and the Netherlands consider only soil erosion by water (cf. Figures 1 and 2).

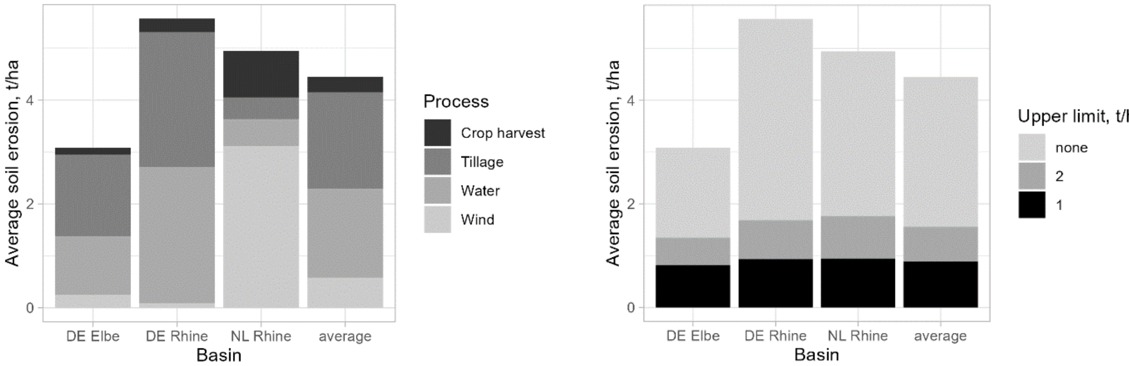


Figure 29. Average soil erosion rates an arable land for different processes within the study area (data: Borrelli et al. 2022) (left, light grey in the right panel) and after applying the upper limits of 2 t ha^{-1} yr^{-1} according to the Soil Health Law (dark grey) and 1 t ha^{-1} yr^{-1} after Verheijen et al. (2009) (black, right). Note: Model assumptions and input data differ from national assessments of soil erosion rates by water and wind.

Runoff and erosion processes are scale dependent and highly variable, so measured local erosion rates cannot be simply extrapolated. In fact, there is a lack of suitable data to assess soil erosion at the watershed scale and beyond (Fiener, Wilken, and Auerswald 2019). Hence there is no alternative to modelling, especially at large scales and for assessing measure effects. However, large-scale model assessments of soil erosion suffer from the data availability which can result in significant deviations to monitoring data (Bircher, Liniger, and Prasuhn 2022). The use of inconsistent approaches to estimate USLE factors also results in inconsistent results across administrative boundaries (e.g. Fiener et al. 2020). The authors demonstrate that European maps such as used for Figure 29 underestimate the high and mean erosion rate by water compared to their regional estimates. Data availability also hampers the calculation of erosion-related factors. Especially literature on harvest erosion is scarce (Kuhwald et al. 2022). Accordingly, simple assumptions and fixed values prevail. An example is the pan-European assessment of the effect of the CAP on soil erosion (Borrelli and Panagos 2020). The authors report 20% lower soil erosion by water (reference year 2016) compared to a potential pre-CAP scenario without soil conservation. Their study relied on fixed management factors between 1 (conventional tillage) and 0.25 for no-till as well as 0.8–0.9 for winter crops. The calculated average measure (or policy) reduction effect for the Netherlands and for Germany was rather small (3%). In contrast, a more detailed assessment in Germany suggests that the effect of measures was counterbalanced by more erosive crops in erosion-prone areas which resulted in a net increase of 5% between 2010 and 2016/17 in north-western Germany (Röder et al. 2022).

Similarly, simple empirical relationships and fixed values are also used to assess the impact of riparian buffers on the catchment-scale (Schipper et al. 2021; Lam, Schmalz, and Fohrer 2011) and beyond (Englund et al. 2021; Weissteiner, Bouraoui, and Aloe 2013). The model parameters may not consider the relevant processes like preferential flow but the data demand of process-based models typically prohibitive. Lam et al. (2011) assessed best-management practices including 10-m riparian buffers on arable land and pasture along the main channel in a small catchment in northern Germany. The scenario resulted in -13% TN and -5% TP input. However, the trap efficiency of the buffers was calculated with an empirical relationship from the US. Schipper et al. (2021) modelled the effect of riparian buffers of dominantly 2 m width for areas which are connected to the IJsselmeer and the Wadden Sea. The N and P losses in the suitable areas are lowered by 12–13%. The values were derived from buffer length and, for (only P) buffer width and runoff. The pan-European assessments of the impact of riparian buffers and windbreaks on e.g. N input to rivers as well as soil erosion by water and wind (Englund et al. 2021) and nutrient input to rivers (Weissteiner, Bouraoui, and Aloe 2013) are also based on fixed values and simple width-dependent equations. Despite their inherent limitations, such models can reveal the regional pattern of suitable areas for measures and of nutrient pathways, and in this way, can shed some light on the variability of measure effects for river basin management.

3.3.4. Agricultural scenarios and nutrient input

The implementation of the ND is pivotal to reduce nutrient inputs, not only in the Netherlands (Table 13) but also in Germany. To achieve the good status of German groundwaters, N reductions of 100 kt yr^{-1} are currently required (Zinnbauer et al. 2023; Schmidt et al. 2022) which reduces to 20 kt yr^{-1} in 2027 if the Fertilizer Ordinance would be fully implemented. The remaining reduction needs for the German WFD and MSFD targets (i.e. target of 2.8 mg L^{-1} at the limnic-marine border to the North Sea) are 53 kt N yr^{-1} (11% of the input) and 5.5 kt P yr^{-1} (28%) without, and 2.8 kt N yr^{-1} (1%) after achieving the good status of groundwater bodies (Table 14). In the cited study, the Fertilizer Ordinance was translated into a required reduction of N surplus as the key factor of N input to surface waters. Table 13 depicts that regional mitigation options like wetlands have a high reduction potential for N and P while being more cost-effective (for P) than restricting nutrient application.

Table 13. Cost efficiency and reduction potential (target year 2027) and indication of ecological effectiveness of measures to reduce N and P loads to surface waters according to various studies. Wet buffer zones are assumed to have a width of 5 m around WFD waterbodies (Van Grinsven, Tiktak, and Rougoor 2016).

Measure	Cost efficiency, € kg^{-1}		Emission reduction, kt yr^{-1}		Ecological impact
	P	N	P	N	
Action Plans ND	1100	16	0.4	24.4	Slow P response, high for N
Improved wastewater treatment	150	40	0.6	2.0	Low, mainly downstream
Wet buffer zones	650	50	0.6	7.2	High
Wetlands (helophyte filters)	350	20	1.6	27.0	High, only downstream
P mining	400	–	0.7	–	Slow P response
(Controlled) drainage	700	–	0.6	–	High but only in low-lying areas
Maximum NH_3 emission reduction application	–	5			
Maximum NH_3 emission reduction housing	–	10	–	5	Modest, only N
Improved feeding	–	10			

Table 14. Reduction needs in 2027 in the German part of the study area and in Germany to achieve the target concentrations of the WFD and MSFD (Zinnbauer et al. 2023). The policy scenario assumes that the agricultural N surplus is reduced by implementing the Fertilizer Ordinance and that the good status of groundwater bodies is achieved.

	Pollutant	Nutrient input, kt yr^{-1}			Reduction need, kt yr^{-1} (% input)		
		Rhine	Elbe	Germany	Rhine	Elbe	Germany
Current	N	180	82	477	5.5 (3)	13 (16)	53 (11)
	P	6.8	3.9	19.1	1.5 (22)	1.6 (41)	5.5 (28)
Policy scenario	N	140	56	329	1.3 (1)	0 (0)	2.8 (1)

In the Netherlands, the full ensemble of DAW measures is expected to reduce N input to surface water by 19% in sandy areas (where the nitrate concentration is highest) and by 10% in clay and peat areas – if implemented in all farms (van Boekel et al. 2021). Nonetheless, the study also shows the minor effect of the source-oriented DAW measures on P input as well as the insufficiency of planned measures to achieve the goals of the ND. With more stringent measures, the area-average nitrate concentrations would achieve the target value of 50 mg L^{-1} in most regions. These findings are in line with the latest assessments (Kros et al. 2024). Non-fertilized field edges (5 m from WFD water bodies and 2 m elsewhere in scenario B and 7.5 m and 3 m in scenario C) are found to be especially effective (Table 15).

For Germany, Bach and Klement (2015) as well as Häußermann et al. (2019) calculated how measures may change the N soil-surface balance in Germany (Table 16). Although organic farming is locally a very effective reduction measure (Table 23), optimizing the fertilizer management has a stronger reduction potential on N balances and eventually on the N input to rivers as the measure affects more farms (agricultural land). Preliminary outcomes of the DüngEval project (Häußermann et al., unpublished) show that the structural changes in the German agriculture (reduction of livestock density and biogas production) will strongly affect N soil-surface balances as well as potential N losses to the atmosphere and the groundwater. And the measures of the Fertilizer Ordinance will add to this reduction. Nonetheless, the environmental targets for groundwater, climate, air quality, and biodiversity will require additional measures. In addition, contrary measure effects on environmental targets require combination of measures and comprehensive evaluations (e.g. to avoid that lower atmospheric losses will result in higher net N balances).

In the coastal states Schleswig-Holstein and Niedersachsen, ex-post analyses show that the AECM contributed most to the decrease in state-wide N balances between 20007 and 2013 by 2.8 kg N ha^{-1} (3.4%) and 5.8 kg ha^{-1} (6.5%), respectively (BMEL and BMU 2020). Organic farming and advisory services were found to be (cost-) effective (cf. Figure 25). At the same time, however, N balances stagnated due to antagonistic changes in exogenous factors which masked the effects of the CAP in Nordrhein-Westfalen (Grajewski 2016).

Table 15. Measure effects in two ambitious scenarios on the area-averaged N and P leaching in 2027 compared to the reference (van Boekel et al. 2021, slightly modified).

Measure	Scenario	Impact on N and P leaching from agricultural soils
Reduction of N-use standard in case of intensive cultivation plan	B	Area averaged N leaching: -0.6%, -0.1%, and -0.3% in Sand North, Sand Middle, and Sand South. No effect in Loess. Negligible for P.
	C	Not determined
Reduction N-use standard for non-break crops	B	Not available
	C	N: -2.6%, -1.6%, -2.8%, and -1.23% in Sand North, Sand Central, Sand South, and Loess regions respectively. Negligible for P.
Non-fertilized field edges	B	N: -4%, -6%, -6%, -14%, and -1% in the sand, river clay, marine clay, peat and loess regions, P: -3%, -5%, -3%, -7%, and -2%
	C	N: -6%, -9%, -20%, and -2% in the sand, river clay, marine clay, peat and loess region, P: -4%, -6%, -6%, -14% and -1%
Thresholds in ridge cultivation	B	Impact on N minor. P: reduction ≤0.02 kg ha^{-1} yr^{-1} P, a few percent for the marine clay and loess region. Local effects may be larger.
	C	Like B. P: reduction below 0.01 kg ha^{-1} yr^{-1}, a few percent for the sand, river clay and peat region

Table 16. Overview of N soil-surface balances as well as reduction of N input to rivers in Germany for various scenarios. Values between the two studies cannot be compared due to different reference years and methodical changes. Häußermann et al. (2019) calculated additional scenarios, e.g. limit of livestock density, but did not provide aggregated numbers. The scenario 'More efficient use of manure' was their most efficient one. Note: The calculated effect of measures is spatially variable, with unique pattern. The results will be complemented by the ongoing DüngEval and EMoll projects (Häußermann et al. unpublished).

Study	Measure / Scenario	Germany, kg ha^{-1}	Coastal states, kg ha^{-1}	Reduction N input (Fuchs, Weber, et al. 2017)
Bach and Klement (2015)	Reference	68	73	
	10% organic farming	65.4	71.7	0.4
	20% organic farming	59.2	65.8	1.3
	Optimized N management in conventional agriculture	46.9	50.7	3.5
Häußermann et al. (2019)	Reference	73.8		
	NEC (2016)	68.9		
	NEC (2030)	62.8		
	80% intercropping	72.1		
	100% intercropping	71.7		
	More efficient use of manure	58.2		

Similar to soil erosion, such large-scale assessments of measure effects on N balances and nutrient input are limited by data availability and strongly depend on the definition of the measures (or the model assumptions). 'Fertilizer management' is a very general measure description for which farmers have a range of options (cf. Table 24). Firstly, the farm type and its specific conditions (e.g. soil, climate, staff) determine the (combinations of) specific measures which are applied and how specifically they are designed. It is not feasible to adequately consider all the relevant factors in regional and national analyses. Secondly, it can be assumed that implementing a measure like 'reduction of livestock' at large scales will likely reduce the current transport of manure but may also be compensated by different crop rotations or more mineral fertilizer. The calculated measure effect – the average values and the spatial pattern – depends on what is (or can be) considered in the calculation of the N balances. Finally, it is important to keep in mind that these balances are theoretical and cannot be validated. Regional data such as parameters like the input of the mineral fertilizer are not known. Estimations based on trade statistics and on the fertilizer demand-based approach of the Fertilizer Ordinance result in different value ranges and spatial pattern (Häußermann et al. unpublished).

In general, the basin-wide effect of measures depends on how easily the measure is (can be adopted) and how widely the measure is (or can be) applied. Expert knowledge from the nine European case studies of the FAIRWAY project (Velthof et al. 2020) shows that optimizing the rate and timing of fertilizer and manure applications are widely applicable, easy to be adopted, of low cost, and rated as highly effectivity (Table 23). In comparison, riparian buffer, cover crops, crop rotation, and tillage are considered less optimal for reducing N losses, but these measures may provide additional benefits such as reduction of erosive inputs, higher content of soil organic matter and better soil health in general, as well more diverse landscapes. Nonetheless, even wide-spread measures which can be easily implemented and controlled may only poorly contribute to water protection if the measure design is insufficient, control is lacking, and antagonistic trends prevail like catch and cover crops in Niedersachsen (Klages et al. 2022).

3.4. Feasibility of measures to achieve the WFD and MSFD targets at large scales

The outcome of the German AGRUM-DE and DüngEval projects (Chapter 3.3.4), the German WFD measures planned after 2027 (Chapter 3.1.1), and various ex-ante assessments for the Netherlands indicated that the planned measures of the relevant nutrient-related policies are likely insufficient to achieve the (nutrient-related) targets of the WFD (Figure 30). However, the ‘one-out all-out’-principle hides e.g. the (expected) reductions in nutrient input. Unlike the earlier assessments (top left and right panels in Figure 30), a more recent assessment of the RBMP 2022–2027 considered the recent 7th AP 2022–2025, the Subbasin Management Plans 2022–2027, and the (potential) DAW measures (van der Linden, Altena, and van den Roovaart 2021). The authors compared the policy scenarios ‘NAP7+DAW 2027’ (7th AP, DAW implementation), ‘Voorzien 2027’ (Sub-basin Management Plans 2022–2027 (RBMP 2022–2027), targets of foreign countries reached), and ‘MMA 2027’ (plus further reduced N, higher DAW implementation) to the 6th AP as ‘Referentie’ scenario (Figure 30 bottom left). According to their findings, the impact of agricultural measures remains small: Even substantial investments would not ensure to achieve the WFD targets until 2027 which confirms earlier findings of van Gaalen et al. (2020) (Figure 30 right). However, an ambitious mix of regional management, technical, and structural measures in agriculture could be sufficient to achieve the WFD target for N at the national level albeit not for P, and not necessarily for other policy goals (Kros et al. 2024) (Figure 32).

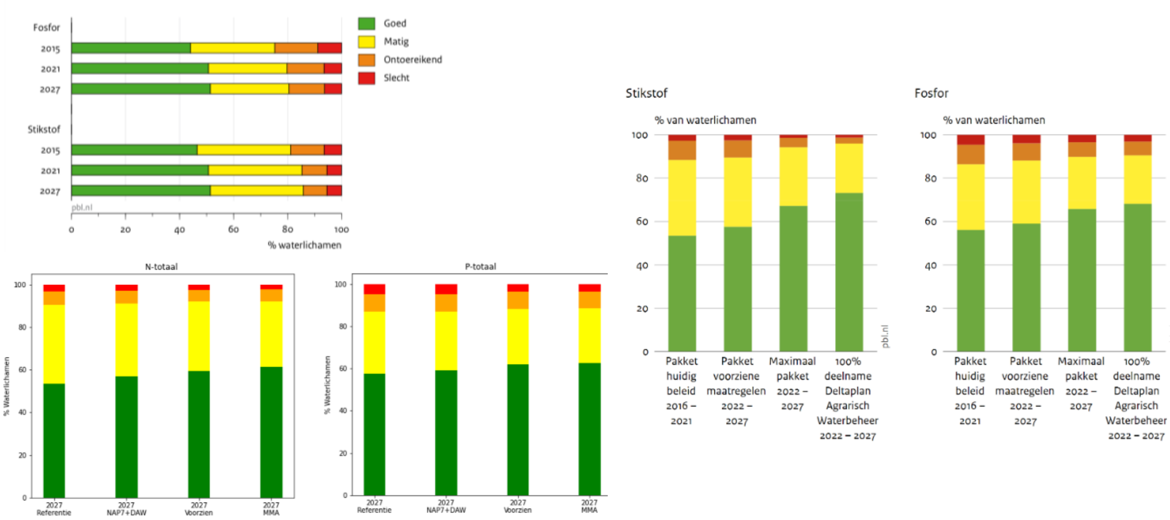


Figure 30. Change of WFD status for N and P in Dutch surface waters according to ex-ante analyses for different years (top left) and with increasing measure implementation until 2027 (bottom left and right). Top left: 2016–2021 (van Gaalen et al. 2016), right: 2022–2027, scenarios ‘huidig beleid’ (6th AP, 2nd RBMP, ongoing DAW projects), ‘‘voorziene maatregelen’ (3rd RBMP 2022–2027, DAW participation under current conditions, manure policy of 6th AP, implementation of planned measures abroad), ‘maximal’ (additional measures which require substantial investments, DAW participation according to available subsidies, foreign countries meet their targets), and ‘100% deelname Deltaplan Agrarisch Waterbeheer’ (‘maximum’ with full DAW participation) (van Gaalen, Osté, and van Boekel 2020), bottom left: 2022 – 2027, scenarios ‘Referentie’, ‘‘NAP7+DAW’, ‘Voorzien’, and ‘MMA’ (details in text). The WFD aims at 100% ‘good’ status (green) until 2027.

Table 17. Scenarios used by van den Roovaart et al (2021). The intended measures considered measure related to e.g. agriculture, UWWTP, atmospheric deposition, and hydromorphology.

Code	**Name**	**Definition**
A	Reference	Dutch part of river basins a 'no measure' scenario, transboundary water bodies 2015 data as measured by the Netherlands
A+	Reference	Dutch part of river basins a 'no measure' scenario, the transboundary water bodies the 2015 data as measured or modelled by the upstream partners
B	Dutch targets	Dutch part of river basins an 'intended measures' scenario, transboundary water bodies concentrations meeting the Dutch water quality targets
C	Upstream targets	Dutch part of river basins an 'intended measures' scenario, transboundary water bodies concentrations meeting the targets of the upstream partners
D	Realistic	Dutch part of river basins an 'intended measures' scenario, transboundary water bodies realistic expected concentrations in 2027 by upstream partners as the result of measures planned in the 3rd RBMP

Van den Roovart et al. (2021) compared the WFD and OSPAR statuses among different scenarios and different areas (Table 17). The scenario effect was stronger for the transboundary than for the inland waters (Figure 31, left). As expected, the model assumptions resulted in reduced riverine loads and lower nutrient concentrations in coastal and marine waters. Nonetheless, the WFD and OSPAR statuses hardly changed. For instance, no effect was observed for monitoring stations in the Wadden Sea (Figure 31, right). The study confirmed that the status of coastal areas is not necessarily identical to the status of contributing rivers (e.g. 'Holland coast' and the Rhine).

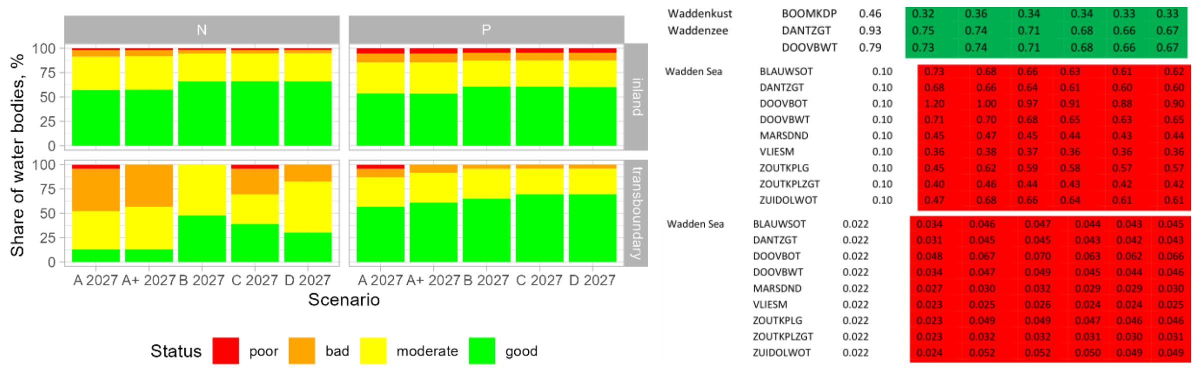


Figure 31. Change of WFD status of inland and transboundary freshwater in the Rhine basin (left) and concentrations in mg L^{-1} and status at monitoring stations in the Wadden Sea (right, green below, red above the target value in the 3rd column) (van den Roovaart et al. 2021). The right panel shows the classification according to WFD (top: DIN) and OSPAR (middle: DIN, bottom: DIP).

These results are line with European assessments which suggest that substantial changes in system of food production and consumption are needed to achieve the ambitious environmental goals of the EU. The goal of the Farm-to-Fork Strategy is to half the N losses by 2030 from the European agri-food system which can be achieved by better management in agriculture (lower N input), less waste and better waste treatment (lower N loss in the food system), or dietary changes (lower energy and protein demand as well as less animal products) (Leip et al. 2022). The authors identified 12 out of 144 combinations of interventions and ambition levels to achieve this goal, and 11 of which included dietary changes. Such systemic changes may also be needed to reduce the riverine nutrient fluxes to coastal and marine areas (Table 18) and the areas affected by eutrophication (Desmit et al. 2018). Likewise, Grizzetti et al. (2021) conclude that the agri-food system needs to be tackled for the goals of EU water policy. They analysed 3 policy scenarios of nutrient reduction: measures currently planned in the Rural Development Programs and under the UWWTD, full UWWTD implementation without derogation in the ND, as well as best technology in wastewater treatment and optimal fertilization. The latter resulted in 14% (N) to 20% (P) lower riverine input to the seas across the EU which may not be sufficient to reduce eutrophication. In fact, the significant decrease of the N surplus in Germany (cf. Figure 19) is caused by the decrease in livestock, especially in the hotspot areas (Häußermann et al. unpublished). Agri-economic projects foresee that the German meat production will further decrease due to changing consumer habits in combination with more stringent environmental and animal welfare standards (Haß et al. 2022). Systemic changes require but may also stimulate the trust of consumers in food (production) which is currently low in countries like Germany (Murphy et al. 2021; 2022).

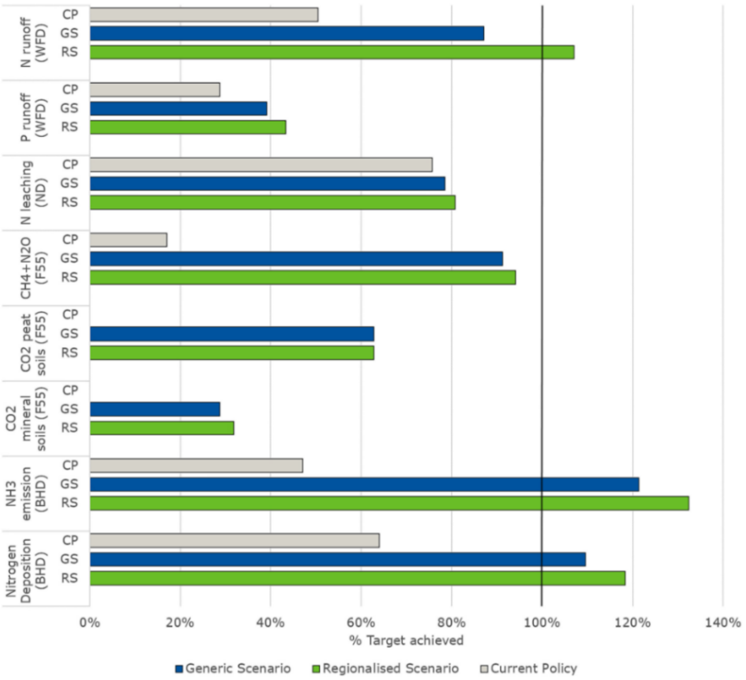


Figure 32. Degree of achievement of the national 2030 targets of different policies including the Water Framework Directive and the Nitrates Directive for the 'Current Policy' scenario (grey) as well as the more stringent 'Generic' (blue) and 'Regionalised' (green) scenarios (source: Kros et al. 2024). Note: Achieving the national N target of the WFD does not mean that the goal is achieved in all provinces. The EU Fit for 55 package (F55) is implemented by the National Climate Agreement, the Birds and Habitats Directives (BHD) by the National Rural Area Programme.

Table 18. Scenarios defined by Desmit et al. (2018) and their effect on nutrient fluxes to the coastal area of rivers Rhine and Scheldt. The future scenarios assume the application of the UWWTD, of good agricultural practices (GAP) with lower N balances and leaching, and of deep changes in the agro-food system (LocOrgDem) with less consumption of meat, less waste, local food for livestock, and organic farming.

Sector	Pristine	Reference	UWWTD	GAP	LocOrgDerm
Population	None	Current	Current	Current	Current
Wastewater	-	Current	UWWTD	UWWTD	UWWTD
Agriculture	-	Current	Current	GAP	LocOrgDerm
Fluxes (Rhine-Scheldt) relative to Reference, %					
N	-92.6		-0.3	-17.1	-51.2
P	-82.0		-3.6	-3.6	-3.6

4. CONCLUDING REMARKS

Intensive agriculture is a key source of nitrogen and phosphorus in the German and Dutch parts of the basins of rivers Elbe and Rhine. Nitrogen enters both rivers dominantly via subsurface flow and drainage due to high N soil-surface balances, while soil erosion (by water) is important for phosphorus. Input from point sources is also relevant, as well as the atmospheric N deposition on costal and marine areas. Therefore, we evaluated the effect of often planned measures addressing these key sources / pathways as they have the highest reduction potential.

The evaluated scientific and 'grey' literature from Germany and the Netherlands lists numerous specific measures as options for farmers to reduce nutrient input to water bodies. These measures differ widely in efficiency, applicability, and adoptability. The programs of measures do not provide enough implementation details but rather general action targets. The most frequent measures in the current river basin management plans discussed in this study are linked to KTM 2 (reducing agricultural pollution), KTM 17 (only in Germany, reducing input via soil erosion and surface runoff), and KTM 12 (advisory services) as an example for conceptual measures. These broadly defined measures cover most nutrient-related measures planned within the Marine Strategy Framework Directive, Nitrates Directive, and the Common Agricultural Policy. The Program of Measures of the NEC Directive (only available for Germany) adds measure against atmospheric NH_3 losses related to livestock and storage of manure. Measures against urban and point sources (KTM 1 and 21) are of certain relevance for the Rhine basin.

Considering specific measures for the upcoming nutrient modelling in the basins of rivers Elbe and Rhine is not feasible given the low resolution of available model input. Instead, we recommend that the scenarios should generally address

- Fertilizer management to reduce the N surplus and atmospheric losses,
- Lower livestock density and stable management to reduce nutrient balances and atmospheric losses,
- Conservation tillage to reduce soil erosion,
- Organic farming to reduce N surplus and soil erosion,
- Adaptation of crop rotation including more catch/cover crops to reduce N surplus and soil erosion,
- Riparian buffers to retain particulate and dissolved nutrient input although Dutch studies indicate a low efficiency under Dutch conditions,
- Optimization of UWWTP (KTM 1, construction and upgrades of wastewater treatment plants).

The Hunze case study is likely more suitable to explore specific measures, their interactions and dependencies to site and farm characteristics, as well as possible target conflicts (e.g. conservation tillage and the use of herbicides).

Model assessments indicate that the contribution of diffuse urban sources to nutrient input is lower compared to point sources. As the current level of wastewater collection is already high, measures against nutrient leakages from sewers have likely superior reduction potential than measures against stormwater flow which are restricted to combined sewers. However, a national assessment is only available for Germany (Nguyen, Peche, and Venohr 2021).

The current study focused on nutrient input and therefore neglected the frequent measures on hydrology and hydromorphology. Therefore, the scenarios should also cover KTM 5 and 6 as they likely affect the residence time of nutrients in surface waters and thus the in-stream retention. These measures are also important for climate adaptation (Garack et al. 2022). These scenarios could also include floodplain restoration as nature-based solution. Kaden et al. (2023) estimated for the active floodplains of both rivers Elbe and Rhine similar nitrate retention values about 7000–7400 t yr^{-1} which corresponds to 3–10% of the total instream retention.

The ranges of efficiency of different measures can overlap. NAPSEA should promote mitigation options with co-benefits for other policy goals. And there is evidence that measures matching these scenarios also match this criterion, although policy goals may not be reached with the planned measures (cf. Chapter 3.4). These scenarios can rely on existing or upcoming N balance scenarios from e.g. the German DüngEval and EMoll projects both coordinated by UBA. These projects translated the bundle of existing and more stringent measures into a spatial pattern of nitrogen soil-surface balance – a key input parameter for the modelling. Their scenarios cover the above-mentioned scenarios. These scenarios should be complemented by Dutch nitrogen balances and scenarios, as well as the outcomes of the policy scenarios discussed in Chapter 3.3 on point sources, atmospheric deposition, and – with limitations – soil erosion. Although not strictly 'measures', using (data based on) policy targets may serve as 'best case' scenarios in NAPSEA and demonstrate how important enforcement is for ambitious targets. Methodical differences between (scenarios of) N balances and atmospheric deposition will increase the inconsistencies in model results for the two countries. Phosphorus balances are underrepresented in this study as they are already almost closed, and partly even negative. It can be assumed that lower N input from fertilizer also lowers the input of dissolved P.

The current trends towards more organic farming, more catch/cover crops, less tillage, lower livestock densities, lower N surplus (in Germany), and lower atmospheric emissions indicate that the above-mentioned measures are already attractive, and certain policy targets feasible. For instance, the results of the benchmark scenarios indicate that substantial reductions are achievable by adopting the most effective technology. However, the discussion and the implementation of such measures faces various challenges:

- How do we to integrate the uncertainty in measure effects?
- Do we combine measures whose expected effects do not spatially overlap, or which are otherwise complementary? For instance, reducing atmospheric N losses in N balances increases the soil-surface surplus if the use of fertilizer is not reduced.
- To which degree do we consider dependencies? For instance, an ambitious cap of livestock density reduces the availability of manure which might be compensated by more mineral fertilizers.
- How do we represent voluntary measures or the participation / implementation rate of measures/policies? An approach could be to use different levels of ambition.

Existing model assessments strongly suggest that achieving the targets of the Nitrates Directive would be pivotal for achieving the marine targets of the Water Framework Directive, i.e. the target concentrations at the limnic-marine border. Despite all efforts, achieving these policy targets is unlikely with the current set of planned measures. That even more stringent agricultural measures are likely insufficient to reach the environmental goals calls for ambitious ('best case') scenarios. Such a scenario could consider the general adoption of voluntary measures, a substantial change in the agri-food systems including dietary changes (i.e. much lower meat production), and the use of best technology in wastewater treatment (Chapter 3.4). The scenarios also have a spatial dimension as the effect of measures varies regionally depending on site and farm characteristics (e.g. Chapter 3.3.4). Combining multiple measures will thus likely improve the basin-wide effect. Furthermore, the effect of measures on target concentrations depends on the spatial pattern of measures as the in-stream retention adds to the local retention. Regarding the planned measures, only the river basin management plans provide sufficiently detailed spatial information. They should be complemented by existing spatial scenario outcomes on policy or measure implementations (e.g. the regional N balances from the German DüngEval project) or by different ambition scenarios (e.g. measure implementation primarily in hotspot areas or everywhere).

It remains unclear to which degree measure effects are counterbalanced by legacy effects. The long history of nutrient imbalance resulted in an accumulation of phosphorus in topsoil causing an elevated risk of phosphorus leaching to water bodies (Fischer, Pöthig, and Venohr 2017). Soil data reveal that the accumulation in the Rhine basin is high compared to the Elbe basin (Panagos et al. 2022). According to the current classification, most agricultural soils in Germany are already ideally or even over-supplied (Gocke et al. 2021; Fischer, Pöthig, and Venohr 2017). Agricultural demand dominates the German P balance, and runoff from agricultural soils to water bodies is the main sink which can be reduced by fertilizer management and healthy soils (Mayer and Kaltschmitt 2022).

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ANNEX

Table 19. National emissions reduction commitments in % for NOx and NH_3 according to the EU NEC Directive (European Parliament and European Council 2016).

Country	NOx reduction compared to 2005			NH_3 reduction compared to 2005		
	2020–2029	2030 onwards	Difference	2020–2029	2030 onwards	Difference
Austria	37	69	32	1	12	11
Belgium	41	59	18	2	13	11
Bulgaria	41	58	17	3	12	9
Croatia	31	57	26	1	25	24
Cyprus	44	55	11	10	20	10
Czech Rep.	35	64	29	7	22	15
Denmark	56	68	12	24	24	0
Germany	39	65	26	5	29	24
Estonia	18	30	12	1	1	0
Finland	35	47	12	20	20	0
France	50	69	19	4	13	9
Greece	31	55	24	7	10	3
Hungary	34	66	32	10	32	22
Ireland	49	69	20	1	5	4
Italy	40	65	25	5	16	11
Latvia	32	34	2	1	1	0
Lithuania	48	51	3	10	10	0
Luxembourg	43	83	40	1	22	21
Malta	42	79	37	4	24	20
Netherlands	45	61	16	13	21	8
Poland	30	39	9	1	17	16
Portugal	36	63	27	7	15	8
Romania	45	60	15	13	25	12
Slovenia	39	65	26	1	15	14
Slovakia	36	50	14	15	30	15
Spain	41	62	21	3	16	13
Sweden	36	66	30	15	17	2
UK	55	73	18	8	16	8
EU-28	42	63	21	6	19	13

Table 20. Assessment of clarity of measure definitions, possible overlap with other measures, and extent to which effects of measures are empirically substantiated by research (source: Groenendijk et al. (2021), adjusted translation of the original Table 4.1 with deepl.com).

Category	Measure	6th AP	DAW	Definition[a]	Measure code study	Effect substantiated by field studies[b]
manure amount	1. Adjust conditions and utilization standards for grassland tearing on sand and loess soils	6		++	14	++
	2A. Adjust classification of phosphate classes and associated application standards	2a		++		
	2B. Increase P norm for application of organic fertilizer on arable land	2b		+	11	o
	3. Adjust fertilization to N mineralization		13	o	7, 8, 11, 13B	o
manure application	4. Row fertilization of maize on sandy and loess soils	1		++		++
	5. Shifting the application period for slurry on arable land	5a		++	7	?
	6. Extended application period for slurry on grassland	5b		++		o
	7. Later application of livestock manure on grass and maize in spring		10, E1	++	5	o
	8. Optimize nitrogen efficiency of manure		11	o	4, 5, 7, 9, 12	o
	9. Dilute slurry before application		24	+	8	+
manure composition	10. Application of less leaching-prone mineral N fertilizers		12	+		o
	11. Application of compost and organic manure		20	+	2B, 13B	+
crops	12. Requirements for growing catch crops and green manures	4a, 4b		++	8, 16	++
	13A. Optimizing land use with grass and corn		5	+	13B, 14, 15	+
	13B. Application of crop rotation on a dairy farm to preserve and build up organic matter		19	o	13A, 14, 15	+
	14. Extending the lifespan of grassland		6	++	13A, 13B	+
	15. Use deep rooting crops and residual crops		18	o	13A, 13B, 14	+
	16. Timely sowing and proper care of a catch crops		21	+	12, 17	++
	17. Soil cover by application of green manure, catch crops, and intermediate crops		22	+	12, 16	+
tillage	18. Applying thresholds for ridge crops on clay and loess (6th AP) and other soils (DAW)	9	14	+		NL: o, International: +
	19. Preventing soil compaction by adjusting wheel load		29	+		o
water management	20. Applying underwater drainage in peatlands		31	+		++ (discussion)
other	21. Preventing soil runoff of nutrients	8		o		Concentration: +, Load: o
design	22. Unfertilized strips along watercourses	7	7	o		NL: +, International: ++
	23. Wet buffer strips		8	o		NL: +, International: ++
end-of-pipe	24. Use dredge pump for effective ditch dredging		15	o		o
	25. Removal of phosphate from drainage water		9B	+		Local

[a] ++ clearly and quantitatively described, + description leaves room for different interpretations, 0 qualitative description where assumptions have to be made; [b] ++ substantiated with reported/published field research; + some field research with summarized information; 0 not substantiated with field research, effect reasoned based on e.g. expert judgement, ? no evidence

Table 21. Key Type of Measures for the EU reporting within the Water Framework Directive and Marine Strategy Framework Directive (LAWA 2022, slightly modified). Unlike the Netherlands, Germany uses measure codes which are uniquely assigned to these KTM.

KTM	Description	German measure code
Water Framework Directive		
1	Construction or upgrades of wastewater treatment plants	1–7
2	Reduce nutrient pollution from agriculture	27, 30, 31, 41, 100
3	Reduce pesticides pollution from agriculture	32, 42
4	Remediation of contaminated sites (historical pollution including sediments, groundwater, soil)	16, 20–22, 25, 101
5	Improving longitudinal continuity (e.g. establishing fish passes, demolishing old dams)	68, 69, 76
6	Improving hydromorphological conditions of water bodies other than longitudinal continuity (e.g. river restoration, improvement of riparian areas, reconnecting rivers to floodplains, etc.)	70–75, 66, 77–87
7	Improvements in flow regime and/or establishment of ecological flows	61, 62, 63, 64, 67
8	Water efficiency, technical measures for irrigation, industry, energy and households	45–60
9	Water pricing policy measures for the implementation of the recovery of cost of water services from households	
10	Water pricing policy measures for the implementation of the recovery of cost of water services from industry	
11	Water pricing policy measures for the implementation of the recovery of cost of water services from agriculture	
12	Advisory services for agriculture	504, 506, 507
13	Drinking water protection measures (e.g. establishment of safeguard zones, buffer zones etc.)	33, 43, 97, 98
14	Research, improvement of knowledge base reducing uncertainty	501–503, 508
15	Measures for the phasing-out of emissions, discharges and losses of Priority Hazardous Substances or for the reduction of emissions, discharges and losses of Priority Substances	23, 36, 44
16	Upgrades or improvements of industrial wastewater treatment plants (including farms)	13–15
17	Measures to reduce sediment from soil erosion and surface run-off	28, 29
18	Measures to prevent or control the adverse impacts of invasive alien species and introduced diseases	94
19	Measures to prevent or control the adverse impacts of recreation including angling	95
20	Measures to prevent or control the adverse impacts of fishing and other exploitation/removal of animal and plants	88–92, 410
21	Measures to prevent or control the input of pollution from urban areas, transport and built infrastructure	8–12, 18, 19, 26, 35, 39, 40
22	Measures to prevent or control the input of pollution from forestry	
23	Natural water retention measures	65, 93
24	Adaptation to climate change	17, 509
25	Measures to counteract acidification	24, 34, 37, 38, 102
new 40	Measures to prevent or control the adverse impacts of other human activities	95, 96, 99, 505
Marine Strategy Framework Directive		
26	Measures to reduce physical loss of seabed habitats in marine waters (and not reported under KTM 6)	408, 430
27	Measures to reduce physical damage in marine waters (and not reported under KTM 6)	408, 410–414, 430
28	Measures to reduce inputs of energy, including underwater noise, to the marine environment	404, 407, 425–429
29	Measures to reduce litter in the marine environment	404, 415–423
30	Measures to reduce interferences with hydrological processes in the marine environment (and not reported under KTM 6)	
31	Measures to reduce contamination by hazardous substances (synthetic substances, non-synthetic substances, radionuclides) and the systematic and/or intentional release of substances in the marine environment from sea-based or air-based sources	401, 404, 405, 407

KTM	Description	German measure code
32	Measures to reduce sea-based accidental pollution	406
33	Measures to reduce nutrient and organic matter inputs to the marine environment from sea-based or air-based sources	400–404
34	Measures to reduce the introduction and spread of non-indigenous species in the marine environment and for their control	404, 411, 412, 428
35	Measures to reduce biological disturbances in the marine environment from the extraction of species	410–412
36	Measures to reduce other types of biological disturbance, including death, injury, disturbance, translocation of native marine species, the introduction of microbial pathogens and the introduction of genetically modified individuals of marine species	409
37	Measures to restore and conserve marine ecosystems, including habitats and species	401, 407–409, 419–421, 424, 427, 430
38	Measures related to Spatial Protection Measures for the marine environment (not reported under another KTM)	409, 412, 427
39	Other measures	400, 401

Table 22. List of MSFD measures in the German Program of Measures 2022–2027 (BMUV 2022b; 2022a), slightly modified. The previous code links the measure to the previous Program of Measures.

Measure code	Measure name	Previous code	KTM	Target[2]	Mode[3]
DE-M401-UZ1-01	Agricultural cooperation project on reducing direct inputs into coastal waters via drainage systems[1]	ANSDE-M401-UZ1-01	33, 39	1.1, 1.3	T, E
DE-M402-UZ1-02	Strengthening the assimilative capacity of estuaries, example of river Ems[1]	ANSDE-M402-UZ1-02	31, 33, 37, 39	1.1	T
DE-M403-UZ1-03	Promoting sustainable measures to reduce NOx inputs from shipping	ANSDE-M403-UZ1-03	33	1.3	L, T, P, E
DE-M404-UZ1-04	Support the designation of a Nitrogen Emission Control Area in the North and Baltic Seas	ANSDE-M404-UZ1-04	33	1.3	L, T, P, E
DE-M432-UZ1-05	Revision of the Gothenburg Protocol to the Convention on Long-range Transboundary Air Pollution as it relates to the seas		33	1.3	L, P
DE-M433-UZ1-06	Implementation of National Air Pollution Control Program as related to the sea		33	1.3	L, T, P
DE-M434-UZ1-07	Development of ocean-related target values for reductions in inputs of P etc. at the limnic-marine border (management in accordance with WFD)		29, 31, 33	1.1	L, T
DE-M435-UZ1-08	Restoration and conservation of seagrass beds[1]		33, 37	1.1	T
DE-M436-UZ1-09	Pilot study of environmentally friendly ways of handling fertilizers in ports		33	1.1–3	L, T
DE-M437-UZ1-10	Criteria, conditions and procedures for sustainable mariculture systems		31, 33, 34	1.2	L, T

[1] outside study area, [2] nutrient-related operational targets: 1.1 = reduction of riverine inputs, 1.2 = reduction of transboundary inputs, 1.3 = reduction of atmospheric inputs, [3] mode of action: L = Legislative, T = Technical, E = Economic, P = Policy-driven

Table 23. Overview of measure types applied and studied within the FAIRWAY case studies (Velthof et al. 2020).

Measure type (Changes in)	Country	Target[1]	Effectivity[2]	Cost[3]	Applicability[4]	Adoptability[4]	Notes
Cropping system or crop rotation	NL, SI	GW, SW, NUE	Moderate	Low	Partly	Partly	May improve soil health/quality, lower disease risk
Fertilization timing	NL, DK, GR, RO, SI	GW, SW	High	Low	Yes	Yes	e.g. no manure spreading in fall or split fertilizer applications. Expense may increase if more labour-demanding or additional manure storage required
Application method	DE, DK	GW	Moderate	Low	Partly	Partly	Effectivity may depend on farm; may decrease other N losses such as greenhouse gases
Application dose (reduced input, balanced or optimal fertilization)	NO, PT, DE, DK, GR, SI	GW, SW, NUE	Moderate	Low	Yes	Yes	May require soil testing. May be mandatory
Cover crops	DK, GR, RO, SI	GW, SW	High	Moderate	Partly	Partly	May increase content of soil organic matter. Cost depends on farm type
Reduced tillage	NO	SW	Moderate	Moderate	Yes	Partly	May prevent soil erosion.
Buffer strips (either between crops and waterways, or between rows of crops)	NL, FR, GR, RO, SI	GW, SW	Moderate	Moderate	Partly	No	May contribute to landscape diversity but decrease crop yield. Costs vary among countries
Grassed waterways	NO	SW	High	Very high	No	No	May reduce erosion and contribute to landscape diversity. Reduce amount of cropland.
Farm-scale nutrient management tools	DE	NUE	Variable	Low	Yes	Yes	Farmers may be obliged to use these tools
Outreach and information events	DE	NUE	Variable	Low	Partly	Partly	Effectivity depends on farm type and farmer knowledge

[1] Groundwater (GW), surface water (SW), nitrogen use efficiency (NUE), [2] Low (5–10% load reduction), Moderate (10–25% load reduction), High (>25% load reduction), [3] Low (<10 € ha^{-1}), Moderate (10–50 € ha^{-1}), High (50–100 € ha^{-1}), Very high (> 100 € ha^{-1}), [4] No (<25% of the land/cases), Partly (25–75% of the land/cases), Yes (>75% of the land/cases).

Table 24. Efficiency of measures in kg N ha^{-1} regarding Nmin autumn, N balance, and N load (Osterburg and Runge 2007). These indicators complement each other. N balance represent the long-term effect of measures, the soil mineral N content Nmin and the N load in leachate the short-term effects on the N losses to groundwater. Suitable combination of these measures can improve the efficiency and make the efficiency more certainty.

No.	Measure	N balance	Nmin autumn	N load	Applicability	Acceptance
Greening						
1	Cover crop, early plough down	0–40	20–60	15–25	++	+++
2	Cover crop, late plough down	0–40	30–60	25–50	++	+++
3	Turnip rape before winter wheat	0–20	20–40	10–30	++	++
4	Frost-tolerant cover crop, late plough down	0–40	30–60	30–60	++	++
5	Cover crop between main crops	0–15	10–40	5–20	++	+
Crop rotation						
6	Annual grass fallow crop, with plough down in autumn	40–80	30–60	30–60	+++	++
7	Two-year grass fallow crop, with plough down in autumn	40–80	30–70	30–70	+++	++
8	Multiple-year grass fallow crop, with plough down in autumn	40–80	40–80	40–80	+++	+
9	Annual rotation summer / winter crops	20–40	10–30	10–30	++	++
10	Early harvest of maize followed by cover crop	0–40	20–40	20–40	++	+
11	Cover crop after rapeseed	0–40	30–70	30–70	++	+
12	Cover crop after potatoes	0–40	30–60	30–60	++	+
13	Cover crop after vegetables	0–40	40–80	40–80	++	+
14	Less N demanding crops	20–60	0–20	0–20	+	++
Seeding						
15	Increasing density of maize plants	0–20	0–15	0–10	++	+
Tillage						
16	Mulching of crop residues (summer crops)	0	0–20	0–25	++	++
17	Zero tillage (no-till)	0–10	0–20	0–20	+++	+
18	Minimum tillage after rapeseed	0–20	0–40	0–30	+++	+
19	No tillage in autumn after cereals	0–10	0–20	5–15	+++	++
20	No tillage in autumn after maize before summer crop	0–10	0–20	5–15	+++	++
Grassland						
21	Extensification of grassland	10–60	0–20	0–20	++	+
22	Extensification of pasture, restricted grazing in autumn	20–60	0–40	0–20	+	++
23	No ploughing of grassland	0	40–80	40–80	++	++
Mineral fertilizer						
24	Reduction of N fertilization of arable crops	20–40	0–10	0–10	0	+
25	No N fertilization of arable crops in late summer and autumn	0–20	0–20	0–20	0	++
26	Use stabilized fertilizers, including nitrification inhibitors	0–20	0–20	0–20	++	++
27	Use of CULTAN; injection of liquid fertilizers	0–20	0–20	0–20	+++	++
28	Improved fertilizer spreading	0–20	0–10	0–10	++	++
29	Application of fertilizer in rows (potatoes)	0–20	0–15	0–15	+	++
30	Precision N fertilization	10–50	0–20	0–20	+++	+

No.	Measure	N balance	Nmin autumn	N load	Applicability	Acceptance
Organic fertilizer						
31	Covering manure storages	1–3	?	?	+++	++
32	Low-emission slurry application	10–40	0–20	0–20	+++	+++
33	Improved application technique for solid manure	10–30	0–10	0–10	+++	+++
34	No manure application to land after 15 September	20–40	20–40	5–30	++	++
35	Ban of manure application from 1 October to 15 February	10–30	10–20	5–15	++	++
36	Manure export to reduce manure application rate to 150 kg ha^{-1}	4	?	?	++	++
Land-use change						
39	Convert arable land into grassland	30–80	30–70	30–70	+++	0
40	Buffer strips	?	?	?	+++	+
Hydrology						
41	Construction measures to retain surface runoff to streams	?	?	?	+++	0
42	Reduced drainage	30–80	30–70	30–70	+++	0
43	Establish riparian zones	30–80	50–300	50–>300	+++	0
44	Re-establish of wetlands	30–80	50–300	50–>300	+++	0
Fertilizer management						
45	Transformation to organic farming	30–120	20–80	0–50	+++	+
46	Nutrient management planning	10–60	0–30	0–30	+++	+++
47	Using soil mineral N analyses for nutrient management planning	0–50	0–30	0–30	+++	++
48	Using plant N analyses for nutrient management planning	–10–40	0–20	0–20	+++	+++
49	Using manure N analyses for nutrient management planning	0–40	0–40	0–40	+++	++

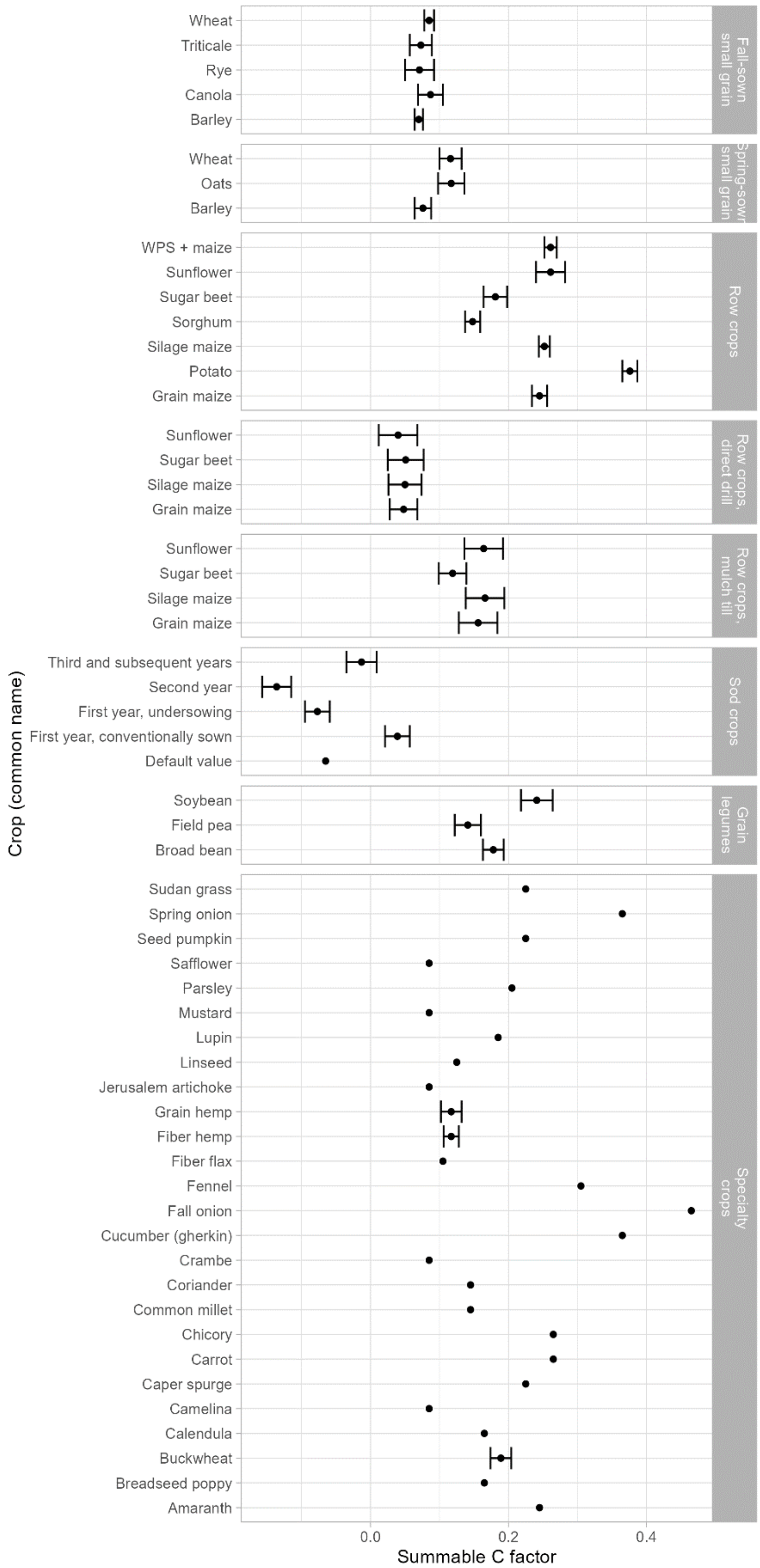

Figure 33. Average summable C factors of different crop groups according to crop type calculated for Germany (Auerswald et al. 2021). Higher values mean higher soil erosion. Ranges depict 95% confidence intervals. Specialty crops without range were adjusted from a previous publication. Note: Negative values for sod crops mean that the carry-over effect is larger than the erosion during the year of sod growing. These C factors are different from the C factors of the universal soil loss equation (and its derivatives) which represent crop rotations, sequences, or monocultures. The C factor of a specific field, farm, or region with m crops can be calculated from the fractions f_i of the individual crops i and the summable C factors γ_i as $C = \sum_{i=1}^{m} f_i \gamma_i$.