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Groundwater nitrate problem and countermeasures in strongly affected EU countries – a comparison between Germany, Denmark and Ireland

Nitratproblematik im Grundwasser und Gegenmaßnahmen in stark betroffenen EU-Ländern – ein Vergleich zwischen Deutschland, Dänemark und Irland

Header: Groundwater nitrate: EU countries comparison

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Abstract

Water resources protection co-occurring with intensive agriculture brings major challenges in Europe including groundwater contamination with nitrate (NO_3^-). Due to non-compliance with the EU Nitrates Directive, some intensive agricultural member states have been penalized by European jurisdiction, putting them under great pressure to reduce groundwater NO_3^- concentrations. This review summarizes the situation of groundwater NO_3^- pollution in Germany, Denmark and Ireland, critically compares the measures taken to improve it, and identifies potentials for improvement and mutual learning. Denmark is often considered a leader in the field with the NO_3^- countermeasures program being continuously developed since 1985. However, impacts on agriculture productivity and crop quality are evident. Also Ireland considers NO_3^- one of the decisive water quality problems, but differs in hydrogeological setting and drinking water management. Climate change is expected to massively aggravate

challenges to all affected countries by causing scarcity of water resources and increasing the pressure on water quality.

Kurzfassung

Der Schutz der Wasserressourcen in Verbindung mit intensiver Landwirtschaft und daraus folgenden Nitratbelastungen bringt in Europa große Herausforderungen mit sich. Aufgrund der Nichteinhaltung der EU-Nitratrichtlinie wurden einige Mitgliedstaaten mit intensiver Landwirtschaft von der europäischen Rechtsprechung bestraft, was sie unter großen Druck setzt, die Nitratkonzentrationen im Grundwasser zu reduzieren. Diese Übersichtsarbeit fasst die Situation der Nitratverschmutzung des Grundwassers in Deutschland, Dänemark und Irland zusammen, vergleicht kritisch die Maßnahmen, die zur Verbesserung ergriffen wurden, und zeigt Potenziale für Verbesserungen und gegenseitiges Lernen auf. Dänemark gilt als führend auf diesem Gebiet, da das Nitratmaßnahmenprogramm seit 1985 kontinuierlich weiterentwickelt wird. Auswirkungen auf die landwirtschaftliche Produktivität und Erntequalität sind jedoch offensichtlich. Auch Irland betrachtet NO_3^- als ein entscheidendes Wasserqualitätsproblem, unterscheidet sich jedoch in hydrogeologischer Gegebenheit und Trinkwasserbewirtschaftung. Es wird erwartet, dass der Klimawandel die Herausforderungen für alle betroffenen Länder massiv verschärfen wird, da dieser zu einer Verknappung der Wasserressourcen führt und den Druck auf die Wasserqualität erhöht.

Keywords

Groundwater, nitrate pollution, nitrate measures, agriculture, climate change

Schlagworte

Grundwasser, Nitratbelastung, Nitratmaßnahmen, Landwirtschaft, Klimawandel

Introduction

Nitrogen (N) is one of the most important nutrients for organisms, a crucial component of molecules, proteins and DNA. For plants, N is often a limiting factor for growth (Bernhard

2010). With the development of the Haber-Bosch process in the early 20th century, mankind found a way to produce N fertilizer synthetically by accessing the vast atmospheric N pool (The European Nitrogen Assessment 2011). Nitrogen fertilizers are used in agriculture to increase productivity and food yields (Hosono et al. 2013), but nearly half of the N applied to cropland worldwide is lost through leaching or ammonia emissions (Lassaletta et al. 2014; Sutton et al. 2011). Humans contribute about three times more reactive N to terrestrial ecosystems than natural sources (Fowler et al. 2013). Excess N not used by plants, degraded in the unsaturated zone, or stored in soil, is then transported to groundwater as nitrate (NO_3^-) (Sebilo et al. 2013; Baram et al. 2017), leading to NO_3^- contamination and a global NO_3^- problem (Almasri 2007). This has serious consequences as NO_3^- has adverse effects on human health (Schullehner and Hansen 2014). The World Health Organization (WHO 2011) and the European Drinking Water Directive (98/83/EC 1998) set the limit for NO_3^- in drinking water at 50 mg/L because high NO_3^- consumption can cause methemoglobinemia in infants up to 6 months of age (Ward et al. 2018). Elevated cancer risk (thyroid, kidney, colorectal and rectal cancer) for adults is also discussed (Inoue-Choi et al. 2015; Jones et al. 2017; Espejo-Herrera et al. 2016; Schullehner et al. 2018). Nitrogen inputs can lead to eutrophication threatening aquatic life (Dodds and Smith 2016) as excessive plant and algal growth degrades water quality (Chislock et al. 2013). Elevated NO_3^- concentrations are also major threats to biodiversity (Díaz-Alvarez et al. 2018; Payne et al. 2017). For example, growth (McGurk et al. 2006), activity levels and reproductive output of organisms may be reduced (Alonzo and Camargo 2013; Soucek and Dickinson 2016).

In aquifers, NO_3^- can be degraded by sulfide minerals and organic carbon (C) (Rivett et al. 2008). This NO_3^- degradation capacity varies from aquifer to aquifer. If NO_3^- is degraded, the sulfide minerals and organic C are also consumed, so degradation capacities decrease and are finite (Knowles 1982). Denitrification occurs when denitrifying microorganisms (for catalysis) are present at low oxygen concentrations (Korom 1992). Denitrification can be divided into two predominant reactions:

Chemo-organotrophic NO_3^- reduction (also referred to as heterotrophic denitrification):

$$5\ CH_2O + 4\ NO_3^- \longrightarrow 2\ N_2 + 4\ HCO_3^- + CO_2 + 3\ H_2O \qquad \text{(Eq.1)}$$

Chemo-lithotrophic NO_3^- reduction (also referred to as autotrophic denitrification):

$$5\ FeS_2 + 14\ NO_3^- + 4\ H^+ \longrightarrow 7\ N_2 + 10\ SO_4^{2-} + 5\ Fe^{2+} + 2\ H_2O \qquad \text{(Eq.2)}$$

Moreover, NO_3^- can be reduced by Fe^{2+}, Mn^{2+} and methane. Further information on denitrification can be found in Rivett et al. (2008), Appelo and Postma (2005), Wisotzky et al. (2018), DWA (2015) and Wisotzky and Strobel (2009).

Despite the NO_3^- degradation capacity of some aquifers, NO_3^- pollution is present in many countries and regions worldwide (European Commission 2018; Shukla and Saxena 2018; Zhou 2015; Cheong et al. 2012). With the Nitrates Directive (91/676/EEC), the European Union aims to protect waters from pollution by agricultural NO_3^-. This directive includes detailed monitoring of NO_3^- concentrations, designation of NO_3^- vulnerable zones, establishment of good agricultural practice rules, and action programs to reduce NO_3^- concentrations. A key regulation is the maximum input of 170 kg N/ha*a. Article 10 of the Nitrates Directive makes Member States report to the EU Commission on the progress in implementing the Directives every four years. Due to non-compliance and too unambitious measures, some Member States, including Germany, have been penalized by the European Court of Justice (European Court of Justice 2010; European Court of Justice 2018). An overview map of EU member states and their designated NO_3^- vulnerable zones is presented in Figure 1. Member states can decide whether to designate NO_3^- vulnerable zones or to apply the Directive to their entire territory.

Figure 1: Nitrate Vulnerable Zones (NVZ) subdivided into designated areas (dark blue) and applied to the entire country (light blue)"; Germany, Denmark and Ireland highlighted (European Commission 2022)

Abbildung 1: Nitratgefährdete Gebiete (NVZ) unterteilt in ausgewiesene Gebiete (dunkelblau) und angewandt auf das gesamte Land (hellblau); Deutschland, Dänemark und Irland hervorgehoben (European Commission 2022)

This review paper presents the current situation of NO_3^- pollution of the strongly affected EU countries Germany, Denmark and Ireland, and the specific measures taken by the countries to manage the problem. A critical comparison of measures and impacts is made and provides potential for improvement and aspects of mutual learning. In an outlook, climate change and a probable shortage of water resources are also considered. These impacts pose further challenges for all countries concerned.

Nitrate in Germany

Geologically, Germany is very diverse and has many different geological units. Thus, the geology can be divided from N to S into the lowlands, among others the Rheinisches Schiefergebirge, the Erzgebirge, the Upper Rhine Graben, the Molasse Basin and at the southernmost edge a small part of the Alps belongs to Germany. The north is characterized by glacial and periglacial sediments due to the ice ages. In the center and in the south of Germany karst aquifers are common (Meschede and Warr 2019).

High NO_3^- pollution in Germany occurs in regions with intensive agriculture (Umweltbundesamt 2022a). With a total of 357,581 km^2, 50.6 % of the area were used for agriculture in 2020. The other land uses were 31.0 % forests and woods, 14.5 % urban areas and traffic, 2.3 % lakes, rivers, canals and near coastal waters, and 2.8 % "other areas" (Umweltbundesamt 2021). The European Environment Agency (EEA) groundwater monitoring network with 1215 monitoring wells was selected to record NO_3^- pollution in Germany. This corresponds to a network density of 3.4 monitoring wells per 1000 km^2 (Figure 2). Some member states (including Germany) apply the EU Nitrates Directive to their entire national territory (BMEL and BMU 2020, Figure 2). Thus, the entire national territory is considered a NO_3^- vulnerable area. Nitrate concentrations > 50 mg/L are detected at 17.3 % of the monitoring wells of the EEA monitoring network. 17.7 % have a concentration between 25 and 50 mg/L (Umweltbundesamt 2022a, Figure 2).

Figure 2: Distribution of groundwater NO_3^- contamination in Germany; monitoring wells of the EEA groundwater monitoring network subdivided into < 25 mg/L, > 25 to 50 mg/L and > 50 mg/L (modified according to Umweltbundesamt 2022a)

Abbildung 2: Verteilung der Nitratbelastung des Grundwassers in Deutschland; Messstellen des Grundwassermessnetzes der EUA unterteilt in < 25 mg/L, > 25 bis 50 mg/L und > 50 mg/L (modifiziert nach Umweltbundesamt 2022a)

Monitoring wells influenced by agricultural land use exceed the limit value at 26.7 %. Compared to the previous NO_3^- report, the NO_3^- concentration decreased minimally in 1.3 % of the monitoring wells (BMEL and BMU 2020). In the assessment of groundwater status according to the EU Water Framework Directive, 27.1 % of German groundwater bodies showed NO_3^- concentrations above 50 mg/L, corresponding to poor chemical status (Umweltbundesamt 2022a). Especially in Lower Saxony, the near-surface aquifers are polluted with NO_3^- due to intensive livestock farming (Kastens and Newig 2007). Nitrate pollution in North Rhine-Westphalia and Bavaria also results from a large proportion of intensive livestock farming. In forest areas, only 2 % of the groundwater monitoring wells are polluted. Urban areas contain 6.3 % and grassland (meadows and pastures) 8.6 % polluted groundwater monitoring wells. Thus, the greatest contamination is found in agricultural areas. However, not only the extent of arable land is decisive, also the crops cultivated. For example, the cultivation of maize or vegetables is very fertilizer-intensive (BUND 2019, Umweltbundesamt 2022a). A major problem is the high standards of food retailers (and customers) in terms of product size and flawlessness. Here is some potential to save fertilizer. Furthermore, not the amount of N fertilization is decisive, but the difference between N supply and N uptake by plants, consequently the N balance. In 1990, the N surplus was 141 kg/ha, which was reduced until today by 26 % on a 5-year average. Surpluses of the N balances of the federal states (average 2015 to 2017) range from 51 kg N/ha for Brandenburg to 108 kg N/ha for Lower Saxony. The goal is to reduce the N surplus throughout Germany to 70 kg/ha on average between 2028 and 2032 (Umweltbundesamt 2022b, Umweltbundesamt 2019, Eulenstein et al. 2018).

Besides fertilization behavior, site conditions have an influence on NO_3^- input to groundwater: N mineralization potential, soil NO_3^- retention capacity, soil NO_3^- denitrification capacity groundwater recharge rate, groundwater flow velocity and depth to groundwater table

(Umweltbundesamt 2022a). Nitrate leaching occurs primarily in regions with high precipitation on sandy soils with low retention potential (Köhler et al. 2006; Meissner et al. 1996). However, there are numerous studies that investigate the conditions of aquifers, identifying NO_3^- degradation processes, degradation potential and subsequent reactions such as trace element mobilization or well clogging (Table 1). In the publications of the last few years, the effects of climate change are also increasingly being investigated. There are first projects that apply machine learning. In addition, a recent BMBF research call and a newly established FH-DGGV (German Association for Hydrogeology) work group underline the ongoing demand for groundwater NO_3^- research in Germany.

Table 1: Overview of selected NO_3^- research and effects of climate change projects in Germany

Tabelle 1: Übersicht über ausgewählte Nitratforschungsprojekte und Projekte der Auswirkungen des Klimawandels in Deutschland

Countermeasures Germany

The implementation of the Nitrates Directive in Germany is regulated by the Fertilizer Regulation (BMJ 2020). As specified by the Nitrates Directive, the maximum use of organic fertilizer is 170 kg/ha*a. Since the Fertilizer Regulation of 2017 became effective, this limit applies to all organic and organic-mineral fertilizers (Landwirtschaftskammer NRW 2021). Kuhn (2017) compares the changes in the Fertilizer Regulations of 2007 and 2017. It was amended again in 2020 due to the judgement of the European Court of Justice against Germany for insufficient and unambitious measures against NO_3^- pollution (Umweltbundesamt 2022a; BMEL and BMU 2020). The updated measures (valid since May 2020) of the German Fertilizer Regulation 2020 (BMJ 2020) are shown in Table 2.

Table 2: Updated measures of the German Fertilizer Regulation 2020 (BMJ 2020; BMEL and BMU 2020; Landwirtschaftskammer NRW 2021)

Tabelle 2: Aktualisierte Maßnahmen der Düngeverordnung 2020 (BMJ 2020; BMEL und BMU 2020; Landwirtschaftskammer NRW 2021)

Further measures are included for polluted areas to improve the water quality (Table 3). This is one of the fundamental innovations in the Fertilizer Regulation 2020. These measures are valid since January 2021 (BMJ 2020).

Table 3: Measures of the German Fertilizer Regulation for NO_3^- polluted areas (BMJ 2020; BMEL and BMU 2020; Landwirtschaftskammer NRW 2021)

Tabelle 3: Maßnahmen der Düngeverordnung für NO_3^- belastete Gebiete (BMJ 2020; BMEL und BMU 2020; Landwirtschaftskammer NRW 2021)

Besides the legally required measures for agriculture, the water suppliers take further measures to comply with the limit value of 50 mg/L. There are cooperations with agriculture to reduce the application of fertilizers and liquid manure (with varying success), and advisory services for agricultural businesses. Other methods include buying agricultural land, infiltrating low NO_3^- water, mixing NO_3^- polluted water with low NO_3^- water, or moving to deeper aquifers and less polluted regions (BUND 2019; Umweltbundesamt 2017b). These measures by water suppliers result in extra costs, increasing in drinking water prizes between 32 to 62 % depending on the pollution situation (BUND 2019).

Examples of local solutions developed at individual waterworks include the Broichhof waterworks of the Neuss municipality which is operating the world's first treatment scheme for NO_3^- polluted water since 1983. The groundwater contaminated with NO_3^- is transferred to a biofiltration facility to which acetic acid and phosphate are added to trigger bacterial reduction of NO_3^- to N_2. After the denitrification, the treated water is infiltrated back into the subsurface and then extracted at the wells of the waterworks (Banning et al. 2017; Mohseni-Bandpi 2013).

Nitrate in Denmark

The upper geologic layers in Denmark containing aquifers consist of either 50-200 m thick Quaternary unconsolidated sands and gravels or fractured limestone and chalk. An exception is the island Bornholm south of Sweden, where the hydrogeology resembles the Swedish geology, due to the crystalline bedrock. The unconsolidated sediments are underlain by Paleogene and Neogene deposits or Cretaceous limestone and chalk (Kitterød, 2022).

Denmark is one of the most intensively farmed countries in the world. 59.9 % of the state's territory is used for agriculture (Statistics Denmark 2022). Thereby, food production is specialized, technology-oriented and focused on innovative thinking. Thus, food production is three times larger than the country's demand (Nygaard et al. 2022). Other land use is divided into 13.1 % forest, 12.8 % urban areas and traffic, 9 % nature, 2.7 % lakes and rivers, and 2.5 % other (Statistics Denmark 2022). Monitoring of NO_3^- pollution in Denmark is done with groundwater observation wells from three categories: GRUMO (widespread groundwater monitoring wells), LOOP (groundwater monitoring wells in top 5 meters in 5 small agricultural catchments), and water supply wells. Groundwater NO_3^- concentrations have been measured at 1277 monitoring wells, 95 LOOP monitoring wells, and 6.111 water supply wells in the period from 2016 to 2020 (Thorling et al. 2021). With an area of 43,094 km² (excluding the Faroe Islands and Greenland), we calculate a GRUMO monitoring well density of 29.7 monitoring wells per 1000 km^2 (Figure 3), over 8 times higher than in Germany. Also the monitoring well density in the Danish Nitrate report to the EU is 18.7 monitoring wells per 1000 km^2. Figure 3 shows the location of the GRUMO and water supply wells with NO_3^- analyses in the period from 2016 to 2020. At 14.4 % of the GRUMO monitoring wells, 23.2 % of the LOOP wells, and only 0.4% of the water supply wells the limit value of 50 mg/L was exceeded in the period from 2016 to 2020 (Thorling et al. 2021). The monitoring wells with > 50 mg/L are distributed all over Denmark, so no area with a particular NO_3^- pollution can be identified (Thorling et al. 2021; Jung-Madsen et al. 2021). Like Germany, Denmark also applies the action program of the EU Nitrates Directive throughout their territory and therefore regards the whole territory as vulnerable (Ministry of Environment of Denmark 2021; Dalgaard et al. 2014). In addition, Denmark has a derogation from the Nitrate directive maximum level of 170 kg N/ha*a. Danish cattle holdings are allowed to apply livestock manure corresponding to up to 230 kg N/ha*a if more than 80 per cent of the area available for manure application was cultivated with beets, grass or grass catch crops. Furthermore, derogation holdings have to comply with several other conditions laid down in the decision. In 2020, the average NO_3^- concentration in oxic groundwater in the GRUMO monitoring wells was about 42 mg/L (Thorling et al. 2021). In the

water supply wells, NO_3^- concentration is mainly found in Northern Jutland, Thy, Himmerland and Djursland (Thorling et al. 2021). These areas are particularly vulnerable because of a poor natural protection from upper geologic layers and a relative deep NO_3^- interface in the sediments.

Figure 3: Groundwater NO_3^- concentration in Denmark. Left: Average NO_3^- concentrations in 1.276 GRUMO monitoring wells; Right: Average NO_3^- concentrations in 6.111 water supply wells from 2016 to 2020 (Thorling et al. 2021)

Abbildung 3: Nitratkonzentration im Grundwasser in Dänemark. Links: Durchschnittliche Nitratkonzentrationen in 1.276 GRUMO-Messstellen; Rechts: Durchschnittliche Nitratkonzentrationen in 6.111 Wasserversorgungsbrunnen von 2016 bis 2020 (Thorling et al. 2021)

Nitrate is present in the upper parts of aquifers almost everywhere in Denmark (Thorling et al. 2021). In 2020, the shallow LOOP monitoring points showed that NO_3^- concentrations are considerably higher in catchments with sandy soils than in catchments with clay soils (Thorling et al. 2021, Jung-Madsen et al. 2021). N surplus in Danish agriculture increased from 1946 to 1985 from approx. 28-185 kg N/ha*a. Nevertheless, by 2012, the N surplus had decreased to about 100 kg N/ha*a (Hansen et al 2017). However, in addition to NO_3^- pollution of groundwater, the main problem in Denmark is NO_3^- pollution in rivers, lakes, and the sea (Petersen et al. 2021, Murray et al. 2019). Similar to Germany (too unambitious implementation of the Nitrates Directive), Denmark has been penalized by the European Court of Justice for poor implementation of the Water Framework Directive with respect to nutrient discharges to coastal waters (European Commission 2014).

Countermeasures Denmark

Despite some exceedances of the limit value for NO_3^-, Denmark is considered a role model for measures against the NO_3^- problem. Denmark consistently ranks high in comparisons evaluating the environmental policies of EU member states (Knill et al. 2012). In the mid-1980s, there was a turnaround in N use efficiency and surplus in agriculture, and a corresponding trend reversal in the NO_3^- content of oxic groundwater (Hansen et al. 2017; Hansen et al. 2011;

Dalgaard et al. 2014). It was possible to reduce N surplus in agriculture by 40 % already by 2011 (Hansen et al. 2011), however still not meeting the environmental demands of the Danish and EU legislation (Hansen et al. 2017). Therefore, there is a need for N management to be further strengthened, and changed, and the application of N in agriculture might have to be reduced (Bowles et al. 2018; Zhang et al. 2015). Unlike Germany with its Fertilizer Regulation (BMJ 2020), the Nitrates Directive and the EU Groundwater Directive in Denmark is implemented in several legislations as part of the different Danish Action Programmes. Further information on the legislations and the regulations in preparation can be found in the Danish Nitrates Report to the European Commission (Ministry of Environment of Denmark 2021). Overall, Denmark has one of the most developed environmental regulatory systems in the world (van Grinsven et al. 2012). An overview of the measures of the Danish Action Program and their development from 1985 until today are presented in Table 4.

Table 4: Major N policy measures in Denmark (Hansen et al. 2017; Dalgaard et al. 2014)

Tabelle 4: Bedeutende Maßnahmen der Stickstoffpolitik in Dänemark (Hansen et al. 2017; Dalgaard et al. 2014)

It is important to emphasize that for a long time, regulations focused on the N-input side; output-based regulations have appeared since 2004 (Dalgaard et al. 2014). In addition, fertilizer accounting by individual farmers should be mentioned. Failure to comply with maximum fertilizer rates results in detentions, fines, or court notices (Ministry of Environment of Denmark 2021). Moreover, the cultivation of catch crops is monitored with satellite images (Ministry of Environment of Denmark 2021). The Danish groundwater monitoring program shows that measures reduce NO_3^- pollution of groundwater with a decline in monitoring points with statistical significant upward trends, and an increase in monitoring points with statistical significant downward trends (Hansen et al., 2017). However, the concentration of NO_3^- in Danish oxic groundwater still exceed 50 mg/l in app. 40% of the oxic monitoring points in 2015 (Hansen e al. 2017). An evaluation by Hansen and Larsen (2016) and Hansen et al. (2017), also identify a link between NO_3^- in groundwater and N surpluses in agriculture. Effective

mitigation measures for NO_3^- are improved manure application techniques and thus a reduced need for mineral fertilizers. Cultivation of catch crops shows higher retention efficiency, especially in clayey soils. Changing the tillage timing from previously fall to spring is also a successful mitigation measure (Petersen et al. 2021).

Despite the pioneering role and slightly decreasing NO_3^- pollution, further reductions in NO_3^- concentrations are required. Hansen et al. (2019a) even point to a worsening of the NO_3^- situation in shallow groundwater below sandy soils. Further reductions in N supply to crops would be very expensive (Dalgaard et al. 2014). Therefore, a paradigm change is in progress in Danish agricultural policy, where the national N regulation is supplemented by more spatially differentiated N regulation. The idea is that mitigation measures can be relaxed in less vulnerable areas (Hansen et al. 2019a; Hansen et al. 2017; Dalgaard et al. 2014). This requires detailed knowledge of geological and geochemical conditions of aquifers, NO_3^- flux pathways, and locations of reduction processes (Hansen et al. 2021). Overall, there are numerous research projects that investigate and further develop spatially differentiated N regulation. In these research projects, several universities and research institutions cooperate and thus combine the entire know-how for these important investigations. An overview of some of the most recent individual projects and their objectives is summarized in Table **5**5.

Table 5: Overview of some of the most recent Danish research projects on N retention and mitigation measures (Hansen et al. 2019b)

Tabelle 5: Überblick über einige der aktuellen dänischen Forschungsprojekte zur Stickstoffrückhaltung und Minderungsmaßnahmen (Hansen et al. 2019b)

Altogether, Danish research on N regulation stands out for developing integrating modelling techniques using ground-based electromagnetic time-domain data (Bording et al. 2021) and 3D hydrogeochemistry models of NO_3^- transport (Kim et al. 2021). Despite extensive research on N regulation in Denmark, there are aspects that need further improvement. These include optimizing the dataflow, cost-effective mapping, sampling below 20 meters, integration of the riparian zone, mapping the riparian zone, integration of drains, mapping the upper 5 meters, likelihood for drains, methods for stakeholder involvement and demonstration (Hansen et al.

2019b). Furthermore, it is discussed that the classification of robust and non-robust soils may disadvantage some farmers, so that this approach is only practicable if no farmers are harmed (Nygaard et al. 2022). Moreover, the creation of a better understanding as well as the involvement of stakeholders is of utmost importance (Nygaard et al. 2022). Based on previous research, it can be shown that a more targeted approach can achieve an economic gain of 20 to 26 % (Jacobsen and Hansen 2016). The key to a sustainable method is to consider all aspects of agricultural production (Gu et al. 2011).

Nitrate in Ireland

Ireland's (hydro)geology is dominated by fractured and karstic aquifers. The central lowland part of the island is widely underlain by Carboniferous limestone, covered by glacial deposits and widespread bogs and wetlands. The coastal mountain ranges are more variable, with Devonian Old Red Sandstone in the south, metamorphic rocks and Paleogene basalts (including the famous Giant's Causeway) in the north, and granites and Ordovician sedimentary rocks in the east (GSI 2014).

Ireland has an even greater ratio of agricultural land, at 67.6 % of the total area. However, only 4.5 % are arable land, while 55.1 % are used as pasture, reflecting the dominant role of the dairy and cattle industries in Irish agriculture. The remaining land use is divided into 14.9 % wetlands, 9.5 % forestry, 8 % others including urban regions (EPA 2022). The Irish NO_3^- pollution monitoring program started in 2007. In the last report to the EU Commission, NO_3^- concentrations were recorded in 200 groundwater stations (EPA 2020). With an area of 70,273 km², we calculate a monitoring station density of 2.85 per 1000 km², the lowest value among the three countries compared. Ireland also applies the action program of the EU Nitrates Directive to their entire national territory, so the entire country is recorded as vulnerable zone. While only 2 % of the monitoring stations exceed the limit value of 50 mg/L, 21 % have a concentration > 25 mg/L (Figure 4; EPA 2021).

Figure 4: Groundwater NO_3^- concentration in Ireland. Circle chart: Monitoring wells subdivided into < 25 mg/L, > 25 to 50 mg/L and > 50 mg/L (modified according to EPA 2021)

Abbildung 4: Nitratkonzentration im Grundwasser in Irland. Kreisdiagramm: Beobachtungsbrunnen, unterteilt in < 25 mg/L, > 25 bis 50 mg/L und > 50 mg/L (modifiziert nach EPA 2021)

The trend shows an increase, with 5.5 % additional monitoring stations exhibiting concentrations > 25 mg/L compared to the previous 4-year report (EPA 2020). In fact, nearly half (47 %) of all groundwater stations show increasing NO_3^- concentrations from 2013 to 2020 (DHLGH 2021). Most sites with NO_3^- concentrations > 25 mg/L are located in the southeastern part of the country (EPA 2020), as the mostly sandy soils here are particularly susceptible to NO_3^- leaching (DHLGH 2021). There is a strong correlation between the intensity of agriculture and NO_3^- concentrations in water bodies. The main agricultural sources of N inputs are organic fertilizers, livestock excreta, and chemical fertilizers (DHLGH 2021).

Considering the described distribution of groundwater concentrations in lights of European standards for NO_3^-, the Irish situation appears to be comparatively less problematic. In terms of the gross N balance, Ireland's values have decreased from over 60 kg/ha agricultural area in the early 2000s to below 40 kg/ha at the end of that decade (however, this value was back to >60 kg/ha in 2017 (European Commission 2022). The country is keen to preserve its "green image" including its good water quality while further expanding agriculture, making 'no deterioration' in the sense of the EU Water Framework Directive one of its major aims (Wiering et al. 2020, McAleer et al. 2022). Consequently, much of the nutrient-related research in Ireland addresses the monitoring of implemented measure efficiency and N input control (Table 6).

Table 6: Selected current research projects on nutrient management measures in Ireland

Tabelle 6: Ausgewählte aktuelle Forschungsprojekte zu Maßnahmen des Nährstoffmanagements in Irland

Countermeasures Ireland

The first Irish Nitrates Action Program (NAP) was implemented in 2006 and is applied through the Good Agricultural Practices Regulation (Irish statute book 2017). Ireland applies the NAP

nationwide, covering over 139,600 farms in the country (DHLGH 2021). Table **7**7 summarizes the current measures of the Irish Nitrates Action Program.

Table 7: Measures of the Irish Nitrates Action Program (NAP) (Irish statute book 2017; DHLGH 2021)

Tabelle 7: Maßnahmen des irischen Nitrat-Aktionsprogramms (NAP) (Irish statute book 2017; DHLGH 2021)

Similar to other EU member states including Denmark, Ireland has taken an exemption from the fixed N limit of 170 kg N/ha*a for manure application. This derogation (permitted fertilizer quantity: 250 kg N/ha*a (EPA, 2020)) was granted by the EU Commission in 2007 and renewed in 2010, 2014 and 2017. Over 4,500 farms export livestock manure to comply with the limit. Currently, the Nitrates Action Program is being reviewed and the measures revised to make the environmental targets much more ambitious (DHLGH 2021). Ireland's Draft Nitrates Action Program 2nd Stage Consultation discusses, among other things, the introduction of a register of chemical fertilizer sales for the whole of Ireland. Tracking fertilizer sales should provide information on where fertilizers are applied. Another approach is to reduce the threshold to below 170 kg N/ha*a on grazing land. A financial incentive is planned for the dairy industry to reduce the amount of fertilizer used, similar to what is done in other member states such as Germany. Some of the measures will be implemented locally and some at the national level (DHLGH 2021).

Besides the revision of the NAP, there is the Agricultural Catchments Program (ACP) which examines the effectiveness of the Irish NAP. This program involves 300 farmers from six intensively managed catchments and is based on intensive counselling helping farmers make better decisions on fertilizer management to reduce nutrient losses and make better profits (DHLGH 2021). Ireland’s strategy broadly focusses on source-based and effect-based measures, with a strongly consensual governance approach relying on firm collaboration between the ministries and agencies involved in the agricultural sector, and a practiced co-responsibility of farmers (Wiering et al. 2020).

Discussion

The three investigated countries show a high agricultural land use of more than 50 % of the total area in all countries. Therefore, there is often a strong correlation between the intensity of agriculture and NO_3^- pollution. All three countries apply the action program of the EU Nitrates Directive to their entire national territory. It is noticeable that the density of observation wells for NO_3^- monitoring is very low in Germany (3.4 per 1000 km^2) and Ireland (2.85 per 1000 km^2) with the average value in all EU member states being 8 per 1000 km^2 (QDR 2015). In comparison, Denmark has a very high density of monitoring points (18.7 per 1000 km^2 (in the report to EU)) and is thus far above average. While NO_3^- concentrations are not necessarily better recorded if average values of the monitoring well density are achieved, a density of < 4 per 1000 km^2 seems very low. For a better recording of the NO_3^- pollution, the number of measuring points should be increased and in the best case, a minimum density should be specified for all EU countries for better comparison.

A comparison of NO_3^- pollution levels reveal a number of polluted areas in Germany, including Lower Saxony and Schleswig-Holstein in particular, but also parts of North Rhine-Westphalia, Bavaria, Saxony-Anhalt and Rhineland-Palatinate. In Ireland, the southeast is particularly affected by elevated NO_3^- concentrations. In Denmark, contaminated groundwater monitoring wells are distributed throughout the entire national territory. However, these occur more frequently in Northern Jutland, Thy, Himmerland and Djursland. Germany has the highest proportion (17.3 %) of groundwater monitoring wells above 50 mg/L among these three countries. Limit value exceedances are found at 14.4 % of the GRUMO monitoring wells, 23.2 % of the more shallow LOOP wells, and only 0.4% of the water supply wells in Denmark. In contrast, 50 mg/L is exceeded at only 1.5 % of observation wells in Ireland. Nevertheless, the different configuration of the groundwater monitoring networks must be pointed out again and thus a limited comparability must be emphasized. Moreover, major differences in (hydro)geological conditions are evident: almost half of the Republic of Ireland's land territory is underlain by Carboniferous limestone, most of which is substantially karstified. Lowland limestones, especially in the center of the island, represent the principal source of groundwater

473 in Ireland. They coincide with the most intensively farmed areas, suggesting intimate relations
474 to surface drainage systems and groundwater resources with a very high vulnerability to
475 anthropogenic influences (Drew 2008). Intuitively, these karstified limestones as well as locally
476 important terrestrial sandstone aquifers widely abundant in the southern parts of the country
477 (mainly Devonian Old Red Sandstone) likely provide a very limited effective natural NO_3^-
478 degradation capacity. However, previous research in this direction suggests substantial but
479 variable denitrification in several hydrogeological settings, both organotrophic and lithotrophic
480 (Fenton et al. 2009; Baily et al. 2011; Jahangir et al. 2012; Jahangir et al. 2017). Additional
481 research is required to address N dynamics and fate in the Irish subsurface.
482 It is noticeable that Denmark's agriculture is technology-oriented and focused on innovative
483 thinking. In Germany, research involving machine learning is still in its infancy. Thus, Germany
484 (and also Ireland) can learn a lot from Denmark's technology-oriented agriculture.
485 Comparing countermeasures, it can be concluded that some approaches are now included in
486 all three action programs of the studied countries. These comprise limits on maximum N
487 application, blocking periods for fertilization, buffer zones along surface waters and storage
488 capacities for manure. Denmark is in line with its pioneering role and introduced some of these
489 measures at a very early stage, whereas in the other countries a detailed program of measures
490 was not introduced until later. A closer analysis of the adaptation of the German Fertilizer
491 Regulation from 2007 to 2017 (Kuhn 2017) indicated that essentially a tightening of the already
492 existing measures was accomplished, without any fundamentally new measures being
493 implemented. Hence the need for the renewed adaptation in 2020. Kuhn (2017) already
494 suggests after the 2017 Fertilizer Regulation that the impact of the change in regulations is
495 highly dependent on enforcement. According to Kuhn (2017), however, empirical results
496 suggest that enforcement of the German Fertilizer Regulation has been poor in the past. There
497 is little research on the current implementation of the Fertilizer Regulation 2020 as well.
498 Nevertheless, international comparison shows the control of measures by satellite monitoring
499 in Denmark (Ministry of Environment of Denmark 2021) or the planned register for the sale of
500 fertilizers in Ireland (DHLGH 2021).

All action programs further include a livestock density limit, which, however, differs in the structure of the individual countries. In the Danish Action Program, a limit on the number of animals per area was one of the first measures already in 1985 (Hansen et al. 2017; Dalgaard et al. 2014). In Ireland, a precise number is even specified for pigs and poultry in terms of storage of manure (Irish statute book 2017). According to large livestock units ("Großvieheinheiten") per hectare, the limitation is calculated for livestock in Germany. One large livestock unit corresponds to 500 kg live weight. As a result, liquid manure is often transported from regions where the livestock units are exceeded, to areas in Germany where fewer livestock are kept than permitted. In addition to the large amount of manure, this also results in CO_2 pollution due to long transport distances (BLE 2022). In contrast, European studies have shown the potential for lower NO_3^- concentrations with organic farming with area-based livestock densities (Benoit et al. 2015; Hansen et al., 2000). Therefore, there have been subsidies for more organic farming in the Danish Action Program since 1998 (Hansen et al. 2017; Dalgaard et al. 2014). Consequently, organic farming should be considerably promoted based on resulting reductions in various environmental burdens, and subsidies should be increased.

A successful measure of the Nitrate Action Programs is the close cooperation with farmers, with included trainings for farmers and advisors, so a general better understanding on nutrient application and nutrient losses is created. Through this collaboration, agriculture also benefits through enhanced productivity (DHLGH 2021). In Denmark, much of the regulation is also based on a consensus-based approach without blame (Nygaard et al. 2022). Thus, a common understanding for groundwater protection as well as for the importance of surplus N fertilizers is created. Cooperations of water suppliers with farmers should not only be entered into for economic interest to obtain less treatment-intensive drinking water but developed even further. Cooperations of public utilities with agriculture including joint training, improved understanding of groundwater protection, consideration of all stakeholders without assignment of guilt, offers great potential to jointly reduce NO_3^- pollution. In this context, it is important that agriculture is not portrayed negatively, as a balanced approach must be found between successful

529 groundwater protection and agricultural productivity, consequently food production. Kuhn et al.
530 (2020) point out that stricter measures in the Fertilizer Regulation will result in costs for farmers.
531 These costs must not be covered by agriculture alone, otherwise the willingness to protect
532 groundwater will dissolve. In the best case, organic farming per se is more attractive for both
533 producers and consumers, also due to costs incurred in conventional farming.
534 Unlike the action programs of the other two EU member states, the German Fertilizer
535 Regulation has additional requirements for NO_3^- polluted areas (BMU 2020). However, since
536 these requirements have only been in force since the beginning of 2021, the effects can only
537 be fully recorded in the future. Nevertheless, Ortmeyer et al. (2021b) show with a model
538 approach that the additional measure of reducing fertilization by 20 % will reduce NO_3^-
539 concentrations in groundwater, but depending on NO_3^- degradation capacities of aquifers and
540 climate developments, these measures will likely not be sufficient to comply with the limit value
541 of 50 mg/L.
542 Probably the largest, but still most promising, adjustments to the measures programs is the
543 planned paradigm shift in Danish agriculture towards applying measures at the local level
544 (among others Hansen et al. 2017; Dalgaard et al. 2014). This will take the different
545 characteristics of the catchments into account. Ortmeyer et al. (2021b) also point out that
546 uniform measures for regions or countries will not be the strategy to solve NO_3^- pollution.
547 Implementing mitigation measures on catchments can improve management globally by
548 focusing measures on sites, which can achieve the highest reduction in NO_3^- pollution
549 (Petersen et al. 2021). But again, it is important not to disadvantage farmers in polluted areas
550 and low aquifer NO_3^- degradation potentials, but to create a fair balance through the
551 regulations.
552 When looking at food production, it is clear that the limit value of the maximum fertilizer amount
553 of 170 kg N/ha*a cannot be lowered further and further. In a long-term study from 1990 to
554 2015, a considerable decrease in the crude protein content of Danish grain crops by 2.4 to 2.9
555 % was observed. The change in N availability explains 53 to 70 % of the changed crude protein
556 content (Styczen et al. 2020). Reducing N fertilizer by 10 to 20 % does not seem to involve

any disadvantages for cereals and maize, as no considerable decreases in crop yields and only minor reductions in protein content were observed (Kühling et al. 2021). However, a substantial yield reduction is reported below the economically optimal N rate of 144 kg N/ha*a, with only a minor reduction in N leaching observed (Goulding 2006). The German Federal Environmental Agency (Umweltbundesamt, 2022a) reports frequent late application of N after completion of vegetative growth to achieve an increase in protein content. Farmers are encouraged to prefer high-protein varieties by classifying wheat varieties according to protein content, which ultimately means increased fertilizer use. However, it has been demonstrated that good baking quality of wheat flour can be achieved even with low N application in the late season (Rossmann et al. 2020). Thus, there is a need for more research and evaluation of late season N application and its reduction on protein levels and crop yields. If the result confirms that a low N application in the late season is sufficient, a limitation of this is a good possibility to avoid excess N. In the best case, a limitation should be directly prescribed at EU level, otherwise farmers in countries producing cereals with lower protein content but good baking quality will be disadvantaged.

The impossibility of indefinitely reducing the maximum fertilization rate further and further illustrates, however, that decreasing NO_3^- concentrations can only be achieved by a combination of several measures. In addition to implementing programs at the local level considering the characteristics of the subsurface (e.g., NO_3^- degradation potential), enhanced denitrification may be a powerful tool. Enhanced denitrification uses the addition of organic C as an electron donor for NO_3^- degradation (Paradis et al. 2021; Carrey et al. 2018; Carrey et al. 2014; Vidal-Gavilan et al. 2014). This method is not yet widely used because more research is needed for effective application. A temperature effect was identified by Ortmeyer et al. (2021c): with the addition of ethanol as an electron donor, NO_3^- degradation occurs more effectively at 10 °C than at room temperature. The temperature also has a crucial influence on the denitrifying microbiology (Ortmeyer et al. 2021c; Ortmeyer et al. 2022). These influences on enhanced denitrification highlight the need to investigate the impact of additional environmental factors. Since trace elements, such as uranium, could be mobilized from the

585 aquifer as a side-effect of biological treatment (Banning et al. 2017), secondary impacts on
586 hydrogeochemical cycles must also be investigated (Ortmeyer et al. 2021d) to ensure that this
587 method can be applied without negative consequences.
588
589 **Climate change**
590 Climate change will pose further future challenges for all countries. For example, it is expected
591 to further increase groundwater NO_3^- concentrations. Climate projections can be used to
592 project future water resource quantity and quality including NO_3^- concentrations. In a water
593 catchment at the Lower Rhine (Germany), a modelling approach projects an increase of NO_3^-
594 concentrations with all climate scenarios used. This increase is due to a decreasing water
595 resource and consequently reduced dilution (Ortmeyer et al. 2021b). Eulenstein et al. (2016)
596 describe with their model a threefold increase of NO_3^- concentrations in percolating water due
597 to lower precipitation and higher evapotranspiration, consequently lower percolation rates and
598 thus lower dilution potential. A considerable decrease in groundwater recharge was also
599 modeled for forest areas in northern Germany (Fleck et al. 2017). Paradis et al. (2016) modeled
600 changes in agricultural practices, triggered by future climatic conditions, resulting in higher
601 NO_3^- concentrations. Clearly, NO_3^- concentrations in groundwater, as well as transport from
602 the unsaturated zone, are strongly influenced by the dynamics of hydrogeological systems and
603 consequently, by climate change (Mas-Pla and Menció 2019). Among other factors,
604 precipitation is a critical factor for NO_3^- leaching, as this is closely linked to precipitation (Kane
605 et al. 2008). With the change to a warmer climate, there will be an increase in precipitation
606 extremes with more intense but less frequent precipitation (Kirtman et al. 2013). The change
607 in precipitation type and frequency will alter soil moisture and thus plant productivity (Fay et al.
608 2011). Lower plant productivity means less N uptake by plants (Gonzalez-Dugo et al. 2010).
609 Dry conditions can increase N retention or lack of onward transport, so N loads are all the
610 greater during rain events (Goodridge and Melack 2012; Kaushal et al. 2008; Lamersdorf et
611 al. 1998), and heavy rain events increase N leaching (Whitehead et al. 2009). Changes in the
612 seasonality of precipitation will alter the timing of N leaching (Collins et al. 2013). Moreover,

613 drought diminishes microbial activity (Manzoni et al. 2012; Baron et al. 2013). This, in turn,
614 leads to lower nitrification and denitrification rates (Larson et al. 2011; Schimel et al. 2007;
615 Stark and Firestone 1995).
616 These aspects illustrate how the complex N cycle is considerably influenced by climate
617 change. Thus, it will be even more difficult to comply with water quality standards in the future.
618 Current measures against NO_3^- pollution will also be directly affected by climatic change.
619 Petersen et al. (2021) highlight that the effects of implemented mitigation measures may be
620 covered by climate change. Lower plant productivity and consequently lower N uptake will
621 permanently change fertilizer requirements. And the blocking periods for fertilization must also
622 be checked regularly if the seasonality of precipitation changes. Major challenges will be the
623 increasingly frequent heavy rainfall events and its N leaching. Thus, it is recommended to
624 increase farmers' knowledge of soil drainage properties to reduce storm-induced nutrient
625 translocation (Shore et al. 2016). Different soil types react differently to water scarcity and
626 heavy rainfall events and show different behavior in water storage and NO_3^- retention. This
627 behavior underlines the need to apply measures not at the country level but, if possible, on a
628 regional scale as Denmark plans to implement. Ortmeyer et al. (2021b) also highlight that the
629 characteristics of an aquifer (e.g., NO_3^- degradation capacity) and the expected climate
630 changes in the region should be decisive factors to be considered in management strategies.
631 Among other things, innovative ecological-economic solutions are needed to make agriculture
632 resilient to adverse weather conditions (Bowles et al. 2018).
633 Beyond this, further measures are necessary, which combined can contribute to N reduction
634 in groundwater. An ever further limitation of N fertilizers alone is not sufficient due to the
635 necessary productivity. Among other things, improved N use efficiency of cultivated crops and
636 adapted agronomic strategies and measures (e.g., variety, planting date) are being
637 investigated (Eulenstein et al. 2017a; Eulenstein et al. 2017b; Lana et al. 2015).
638 Another way to reduce NO_3^- concentrations, as described in the previous chapter, is enhanced
639 denitrification, in which organic C is added as an electron donor for NO_3^- degradation (Paradis
640 et al. 2021; Carrey et al. 2018; Carrey et al. 2014; Vidal-Gavilan et al. 2014, among others). In

641 particular, the identified temperature effect, with a higher denitrification rate of the ethanol
642 addition substrate at 10 °C than at room temperature, highlights the importance of enhanced
643 denitrification research in the context of climate change (Ortmeyer et al. 2021c). The changing
644 microbiology (Ortmeyer et al. 2021c; Ortmeyer et al. 2022) using the two temperature
645 approaches (room temperature and 10 °C) illustrates the influence of temperature and
646 consequently climate change on this process. Ortmeyer et al. (2021c) expect climate change
647 and rising groundwater temperatures to dynamically change the most suitable electron donors
648 for biological denitrification. When treating groundwater by enhanced denitrification, it is
649 important to research the conditions under which NO_3^- is fully converted to climate neutral N_2
650 and as little N_2O as possible is released, which acts as a greenhouse gas. Otherwise, climate
651 change would be exacerbated by this treatment method.
652 To prevent these consequences of climate change from being driven further in part by
653 agriculture, making agriculture climate-neutral as soon as possible is a crucial contribution to
654 ensuring that climate impacts on agriculture itself does not become even more serious.
655
656 **Conclusions**
657 To manage the NO_3^- problem and reduce NO_3^- concentrations, the Nitrate Directive was
658 developed for Europe. In this review, the current situation of NO_3^- pollution and measures to
659 improve it were compared for three EU member states with intensive agricultures. The
660 completely different monitoring networks and different monitoring well densities of the three
661 countries are evident. For better comparability, the Nitrate Directive should specify uniform
662 requirements for the monitoring networks. Comparing the NO_3^- action programs shows that
663 numerous and often similar measures are applied, but they are designed differently. Overall,
664 Denmark leads the way in NO_3^- countermeasures – many are applied from which the other
665 countries can learn. In particular, the technology-oriented agriculture, the close collaboration
666 with farmers with included trainings, and a consensus-based approach without blame
667 (specifically towards agriculture), stick out. Also Germany and Ireland apply measures from
668 which other countries can learn. However, several approaches make it clear that in the long

term the solution for NO_3^- pollution will have to become multi-scale including EU, national, and especially measures at the more local level, as Denmark is currently implementing.

A decisive factor for the future development is the NO_3^- degradation potential of individual aquifers. Characterization and management of this finite resource will remain important research topics. However, innovative ideas and methods, such as enhanced denitrification, must be developed to provide clean drinking water even in catchments with exhausted NO_3^- degradation capacity. Climate change will present a new type of challenge for complying with the NO_3^- limit. Heavy rainfall events mean increased NO_3^- leaching, rising temperatures affect NO_3^- degradation and microbiology, and a smaller water resource entails lower dilution of NO_3^- loads. Thus, sooner or later, measures to address NO_3^- pollution can be undone by climate change. A constant adaptation of the NO_3^- action programs to the changed seasonality of the precipitation events will be necessary and should be considered at an early stage. A multi-measure approach of prevention and management combined with active treatment by enhanced NO_3^- reduction could be a promising solution option.

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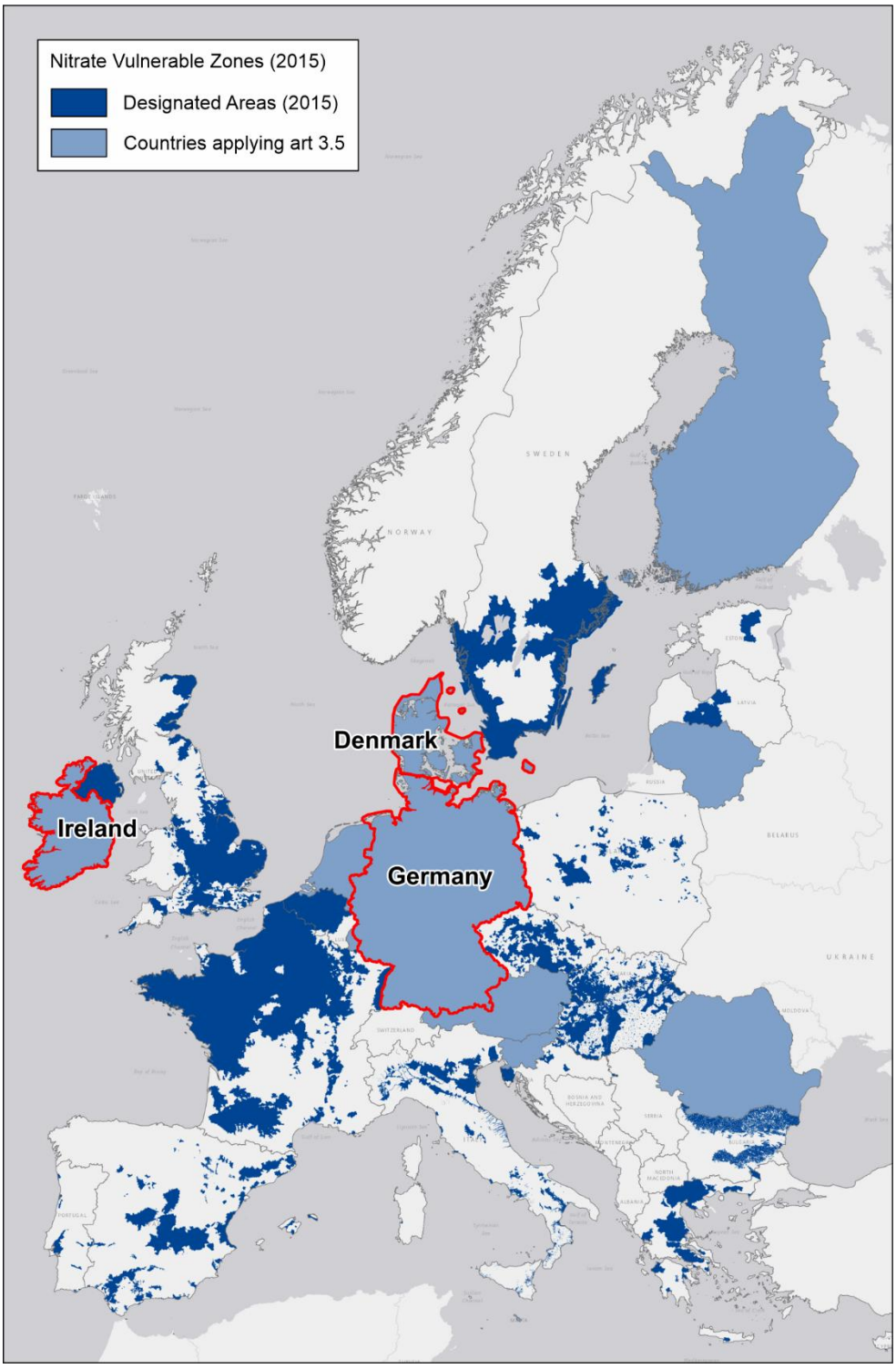


Figure 1: Nitrate Vulnerable Zones (NVZ) subdivided into designated areas (dark blue) and applied to the entire country (light blue)"; Germany, Denmark and Ireland highlighted (European Commission 2022)

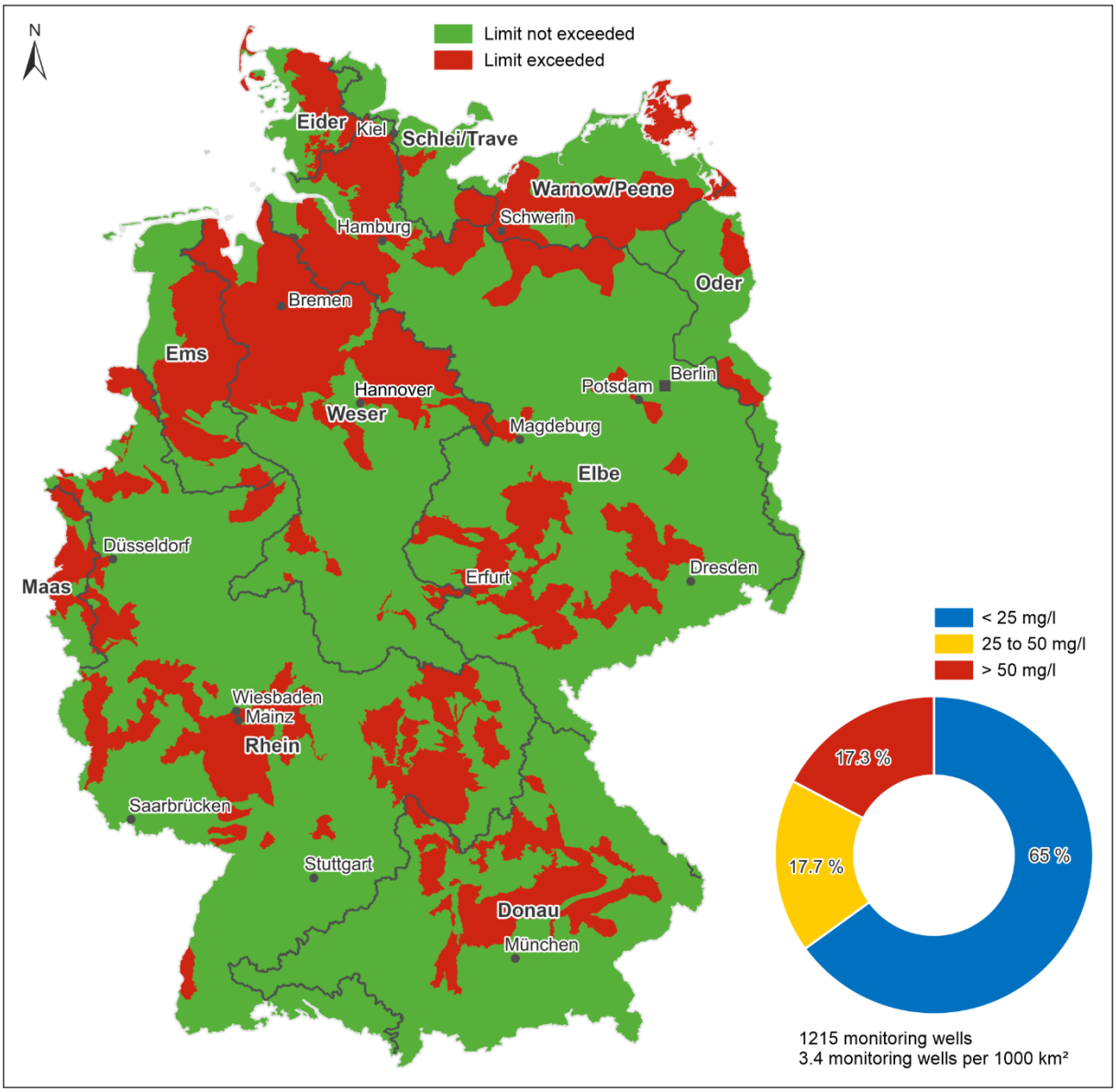


Figure 2: Distribution of groundwater NO_3^- contamination in Germany; monitoring wells of the EEA groundwater monitoring network subdivided into < 25 mg/L, > 25 to 50 mg/L and > 50 mg/L (modified according to Umweltbundesamt 2022a)

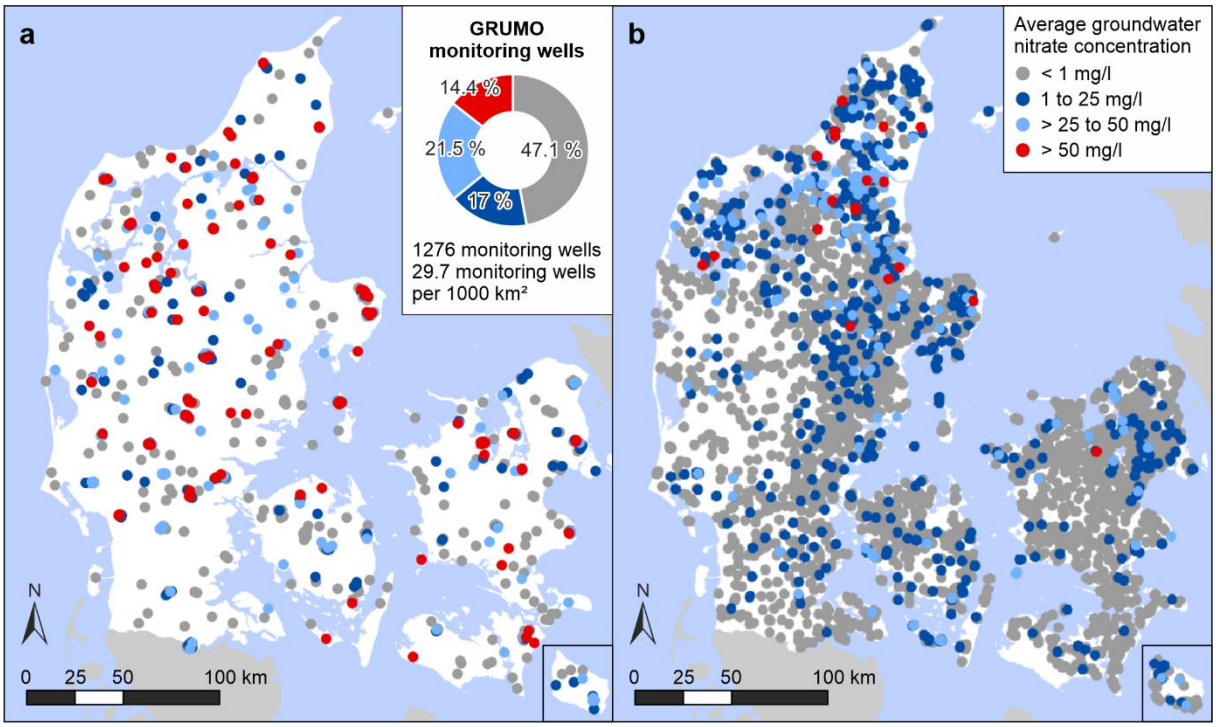


Figure 3: Groundwater NO_3^- concentration in Denmark. Left: Average NO_3^- concentrations in 1.276 GRUMO monitoring wells; Right: Average NO_3^- concentrations in 6.111 water supply wells from 2016 to 2020 (Thorling et al. 2021)

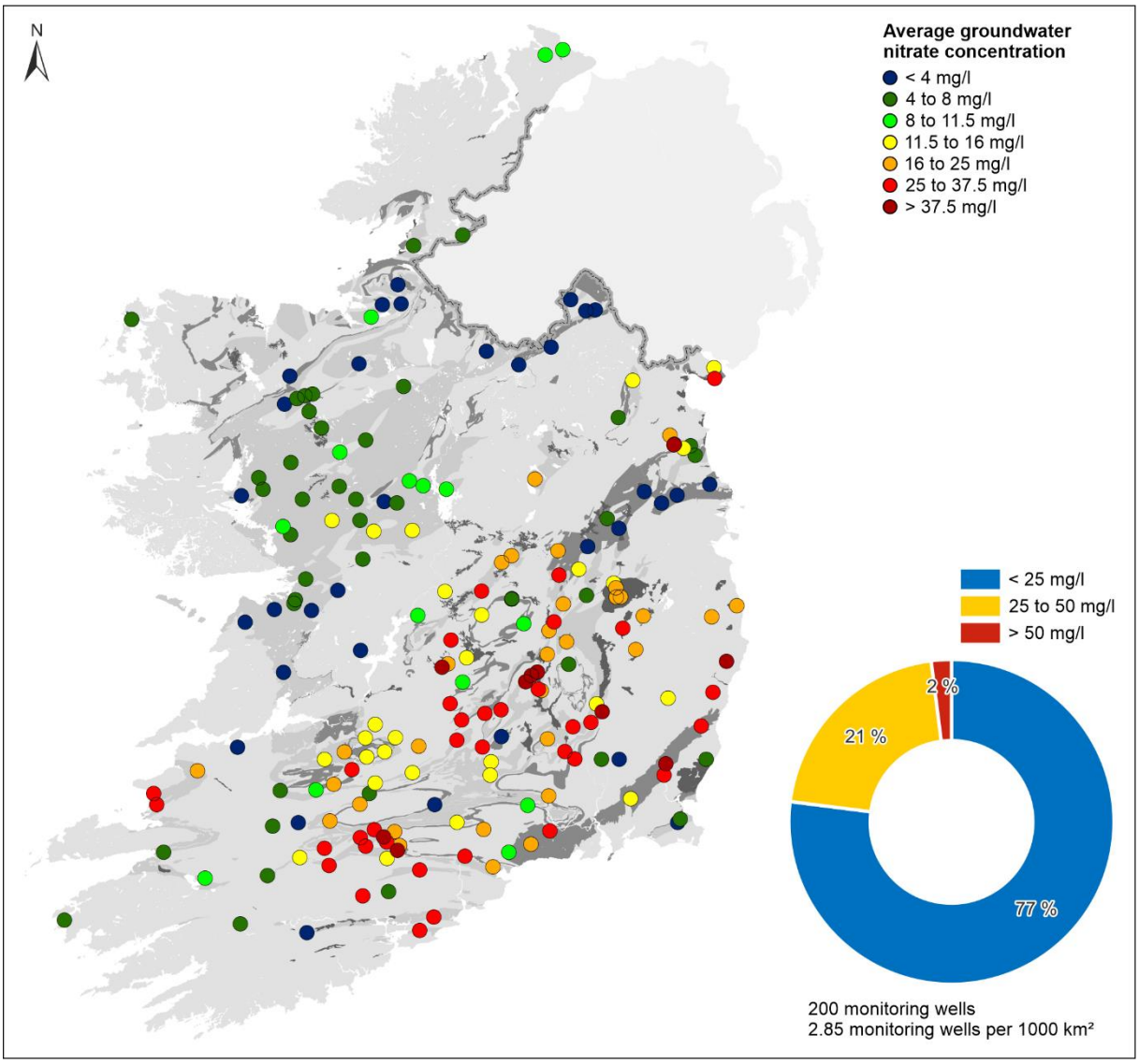


Figure 4: Groundwater NO_3^- concentration in Ireland. Circle chart: Monitoring wells subdivided into < 25 mg/L, > 25 to 50 mg/L and > 50 mg/L (modified according to EPA 2021)

Table 1: Overview of selected NO_3^- research and effects of climate change projects in Germany

Tabelle 1: Übersicht über ausgewählte Nitratforschungsprojekte und Projekte der Auswirkungen des Klimawandels in Deutschland

Project	**Short description**
Nitrate in groundwater - concentration level, degradation processes and depletion potential in the area of activity of the Erftverband (Cremer, 2015)	Overview of numerous water supplies, their trends in NO_3^- concentrations and NO_3^- degradation
Denitrification in the sediments of the Hessian Ried (Kludt et al., 2016)	Identification of denitrification processes and prognoses of denitrification potential
Decreasing denitrification capacity in aquifers (Wilde et al., 2017)	Determination of NO_3^- degradation potential and four-stage adaptation to area-specific conditions
Characterization of the denitrification potential of aquifers in Saxony-Anhalt (Hannappel et al., 2018)	Estimation of site-specific NO_3^- reduction potential
Nitrate reduction: hydrogeochemistry and clogging potential (Ortmeyer et al., 2021a)	Influence of denitrification on numerous saturation indices, calculation until NO_3^- breakthrough to wells
Reactivity of organically bound C (Kübeck et al., 2010)	Reactive mass transport model considering the reaction kinetics of organically bound C
DynAKlim (Umweltbundesamt, 2016)	Dynamic Adaptation to the Effects of Climate Change in the Emscher-Lippe Region (Ruhr Basin)
Modeling of water quality and quantity influenced by climate change; DynAKlim (Kübeck et al., 2014)	Effects of climate change on the water balance
Denitrification in the vadose zone (Lenhart et al., 2021)	Reactive transport modelling of denitrification potential in the vadose zone
Nitrate and trace elements (Riedel et al., 2022)	Quantification of potential health risk
Nation-wide estimation of groundwater redox conditions and NO_3^- concentrations (Knoll et al., 2020)	Estimation of groundwater quality based on spatial environmental predictors with machine learning

Table 2: Updated measures of the German Fertilizer Regulation 2020 (BMJ, 2020; BMEL and BMU, 2020; Landwirtschaftskammer NRW, 2021)

Tabelle 2: Aktualisierte Maßnahmen der Düngeverordnung 2020 (BMJ 2020; BMEL und BMU 2020; Landwirtschaftskammer NRW 2021)

Measures	Description
Determination of fertilizer demand	Yield level of the cultivated crop of the last 3 years is raised to 5 years
Nutrient comparison abolished	Recording of each fertilization action no later than 2 days after application
Minimum N efficiency	10 % increase in minimum N efficiency of cattle manure, pig manure and liquid digestate
Frozen ground	No application of N and P fertilizers
Shortened time until tilling	After 4 hours, from February 2025 after 1 hour
Blocking period	No application of solid manure as well as P fertilizer from 01.12. to 15.01.; N fertilizer depending on main crop and intercropping (partly from harvest, often October to January)
Permitted maximum manure quantities	application of fertilizer must be below the maximum value based on the average on agriculturally used areas of the farm
Distances to water bodies	Larger distances with increasing slope gradient
Further measures in polluted areas	Table 3

Table 3: Measures of the German Fertilizer Regulation for NO_3^- polluted areas (BMJ, 2020; BMEL and BMU, 2020, Landwirtschaftskammer NRW, 2021)

Tabelle 3: Maßnahmen der Düngeverordnung für NO_3^- belastete Gebiete (BMJ 2020; BMEL und BMU 2020; Landwirtschaftskammer NRW 2021)

Measures	Description
N fertilization under demand	Nitrogen fertilization 20 % below calculated fertilizer requirement
Upper limit management unit	Compliance with the 170 kg/ha*a N cap per management unit
Extension of the blocking periods	Extension for four weeks
Prohibition of autumn fertilization	Exceptions: • Intercrops with feeding use • Winter rape: Proof soil below 45 kg N/ha
Limitation of liquid organic fertilizers on permanent grassland in autumn	On green land to 60 kg N_{total}/ha
Intercropping	Mandatory

1340 Table 4: Major N policy measures in Denmark (Hansen et al., 2017; Dalgaard et al., 2014)

1341 Tabelle 4: Bedeutende Maßnahmen der Stickstoffpolitik in Dänemark (Hansen et al. 2017;
1342 Dalgaard et al. 2014)

Year	Measures
1985	Max. livestock stock density. Mandatory slurry tank floating barriers. No runoff from silage clamps and manure heaps. Min. slurry capacity and ban on winter spreading of slurry for spring crops
1987	Mandatory fertilizer and crop rotation plans. Min. proportion of area with winter crops. Mandatory manure application within 12 h
1991	Statutory norms for fertilizer N application for specific crops. Max. N applied to crops equaling economic optimum. Subsidies to low-N grasslands in environmentally sensitive areas
1998	Max. N applied 10 % below economic optimum. 6 % obligatory catch crops. Subsidies to more organic farming, wetlands, extensification and afforestation. Sites-specific groundwater protection zones
2001	Promotion of low excretion livestock feeding
2004	More catch crops. Tightened ammonia restriction (e.g., broadcasting banned), and special restrictions near sensitive nature areas. Subsidies to promote better manure handling and animal housing
2009	10 m buffer zones around streams, lakes, and sensitive habitats. Max. N applied ≈ 15 % below the economically optimal production. Optimized feed practice promotion
2016	Less national N regulation, but more spatial differentiated N regulation with locally targeted measures as e.g., constructed wetlands and additional catch crops. *Measures abandoned: 10 m buffer zones (back to 2 m). Max. N applied ≈ 15 % below the production economic optimum* (back to production at economic optimum).

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Table 5: Overview of some of the most recent Danish research projects on N retention and mitigation (Hansen et al., 2019b)

Tabelle 5: Überblick über einige der aktuellen dänischen Forschungsprojekte zur Stickstoffrückhaltung und Minderungsmaßnahmen (Hansen et al. 2019b)

Project	**Short description**
MapField (Field-scale mapping for targeted N-regulation and management) (2018-2022) www.mapfield.dk	Innovative environmental technologies for intelligent environmental regulation of N management
rOPEN - Open Landscape Nitrate Retention Mapping (2017-2019) http://hgg.au.dk/projects/rOPEN/	Innovative geophysical mapping combined with hydrogeological and geochemical modeling
DNMARK research alliance - Innovative solutions for a sustainable management of N in agriculture (2013-2019) http://dnmark.org/	List of targeted initiatives for consumers, farmers, agricultural extension agents, policymakers, and other decision-makers in the private and public sectors
TopSoil (2015-2021) https://northsearegion.eu/topsoil/	Investigates ways to solve current and future water problems and management of the top 30 m of the subsurface
Future Cropping (2015-2020) https://futurecropping.dk/	Integration of big data from agricultural and environmental technologies with land and climate data
T-REX - Near surface redox and retention mapping for a targeted differentiated mitigation within ID15 sub-catchments (2019-2022) https://gudp.lbst.dk/projekter/gudp-projekter/bedre-kortlaegning-af-kvaelstofretention-kan-styrke-landmaends-miljoeindsats/	Development of new technologies, mapping, and modeling tools

1351 Table 8: Selected current research projects on nutrient management measures in Ireland

1352 Tabelle 6: Ausgewählte aktuelle Forschungsprojekte zu Maßnahmen des
1353 Nährstoffmanagements in Irland

Project	**Short description**
Agricultural Catchments Program (ACP)	Monitoring the effectiveness of Ireland's measures since 2008. Delivered by Teagasc (the Agricultural and Food Development Authority) and funded by the Department of Food, Agriculture and the Marine
Teagasc Walsh program	Funding PhD projects for supporting and strengthening the ACP
Harmony	Catchment based project integrating research on soils and hydrology with socio-economic factors to derive locally relevant measures for agriculture in sensitive catchments
Several European Innovation Partnership (EIP) projects (e.g., Mulkear EIP, Duncannon EIP)	Supporting local farmers to work collaboratively with other stakeholders to develop catchment-sensitive farming practices to improve local water quality
COSAINT (funded by Ireland's Environmental Protection Agency EPA)	Cattle Exclusion from Watercourses: Environmental and Socio-economic Implications
AgriBenchmark (funded by EPA)	Benchmarking Sustainable Nutrient Management on Irish Farms
AgImpact Project (funded by EPA)	Systematic and Participatory Review of Research on the Impact of Agriculture on Aquatic Ecosystems in Ireland

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Table 7: Measures of the Irish Nitrates Action Program (NAP) (Irish statute book, 2017; DHLGH, 2021)

Tabelle 7: Maßnahmen des irischen Nitrat-Aktionsprogramms (NAP) (Irish statute book 2017; DHLGH 2021)

Measures	Description
Maximum legal values for application rates of N	170 kg N/ha*a
Limit values for livestock due to the amount of produced and storable manure	100 Pigs, 2000 poultry places
Application periods	Subdivided according to the type of fertilizer, as well as division of counties into three classes: Total period from October 15 to January 15
Minimum requirements for storage of livestock manure	Manure from pigs or poultry must be able to be stored for up to 26 weeks, manure from deer, goats and sheep 6 weeks, manure from cattle 16 to 22 weeks depending on counties
Detailed distance subdivision for fertilization	Depending on surface water; springs, boreholes, wells
Terrain slope	Fertilization prohibited on steeply sloping terrain and when there is a risk of water pollution
Fertilizing prohibited on waterlogged soil	Ground is waterlogged; land is flooded or at risk of flooding; land is snow-covered or frozen
Fertilizing prohibited during heavy rain	Heavy rain predicted within 48 hours